A BRIEF HISTORY OF THE JUMP OF BIDONE

Mossa M. and **Petrillo A.**
Department of Civil and Environmental Engineering
Water Engineering Division; Polytechnic University of Bari,
Via E. Orabona, 4 – 70125 Bari, Italy;
ph.: + 39 080 596 3288; fax: + 39 080 596 3414;
e-mail: mossa@poliba.it; petrillo@poliba.it

Abstract: The paper presents a brief history of the jump of Bidone or hydraulic jump. Sketched by Leonardo da Vinci, observed in nature, and utilized by engineers for a century, it might be thought that the hydraulic jump had yielded all its secrets some time ago. The history of its scientific study dates al least from the paper of Bidone (1820). One of the most complete investigations of the average jump profile and length was that of Bakhmeteff and Matzke (1936). Some years later Rouse et al. (1958) proposed their air model. Hoyt and Sellin (1989) proposed the mixing or shear layer model. In the present paper a new scenario of the turbulence of the hydraulic jump is also shown.

Keywords: hydraulic jump, history, Bidone.

1. INTRODUCTION

The jump of Bidone in Italy is no other than what we today call the "hydraulic jump"; a phenomenon that Bidone had described with the following words: "If, when a stream has been established in a rectangular channel… the flow of water is totally impeded by lowering a gate in any section of the channel itself, the waters thus restrained rise immediately up to a certain height against the gate and form an intumescence." It is precisely this abrupt "jump" that we understand to be the "hydraulic jump" (figure 1).

Although Leonardo da Vinci was not the first to advocate the experimental method, he differed considerably from others in the degree to which he exemplified what he advocated. His basic premise was "remember when discoursing on the flow of water to adduce first experience and then reason".

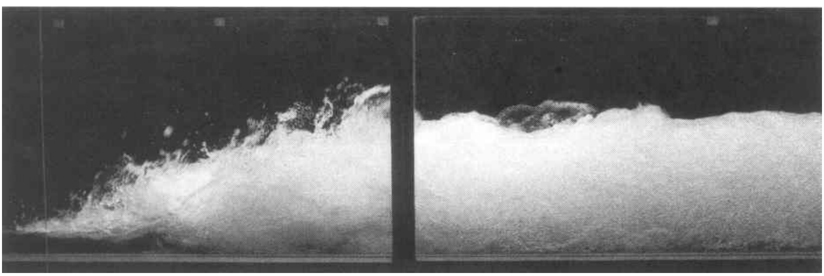


Fig. 1. A typical hydraulic jump with inflow Froude number equal to 5 (by Hager, 1990).

Typical of the phenomena that he was the first to sketch or describe are the velocity distribution in a vortex, the formation of eddies at abrupt expansions (figure 2), and the hydraulic jump.

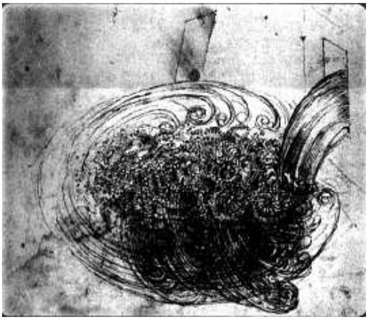


Fig. 2. A free water jet issuing from a square hole into a pool (by Leonardo da Vinci, from the Catalogue of the Windsor Royal Library).

Actually Bidone (1820) had not been the first to notice the phenomenon. For instance, plate 9 (figure 3 of the present paper) of the book *Dalla natura de' fiumi* (Guglielmini, 1739) shows an hydraulic jump accompanied by the following comments: "Let us assume… that the water, running out of B and entering channel BG, less inclined but wider, requires to discharge a height BI less than CH: in such a case, it is observed that the water descending through AB does not take its surface CD to join that of DE, but it sinks, as in ED, below level EF; and the water in ED is left hanging, so that the stream surface is maintained at CDEF."

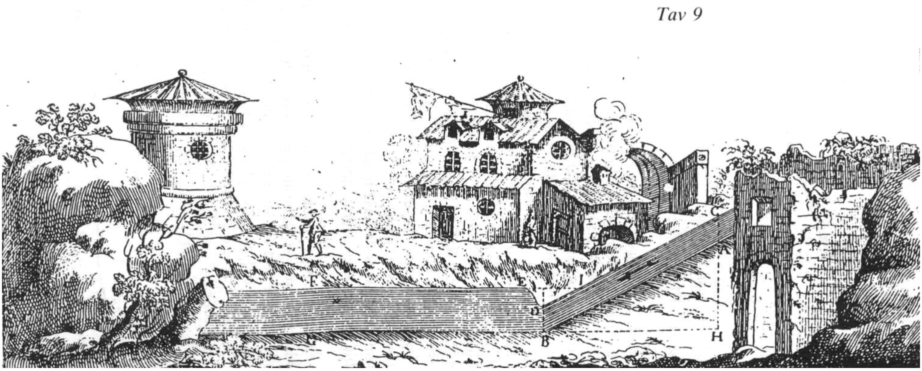


Fig. 3. Hydraulic jump (by Guglielmini, 1739).

It is well known that the jump implies an abrupt change in the depth, and a depth variation assumes an opposite variation in the velocities: before the jump, the depth is lower and the stream fast; after, the depth is high and the stream slow: Bidone tested many configurations; in each case he modified the lower upstream depth d_1 and measured the higher downstream depth d_2. Bidone realized that the two depths were linked. He assumed that what was lost in level would be gained in velocity head, with the following equation

$$d_2 - d_1 = \frac{V_1^2 - V_2^2}{2g}. \tag{1}$$

But the experimental result did not agree with this equation, because the first member was always less than the second. Bidone did not know how to explain this inconsistency.

About ten years later, Jean Baptiste Bélanger (1828) analyzed Bidone's measurements. He found discrepancies with respect to equation (1), and initially blame the experiments. But Bidone assessed good measurements. Thus Bélanger decided to deal with the problem starting from the principle of momentum conservation, obtaining the well known equation of Bélanger for undeveloped inflow (see Leutheusser and Alemu, 1978), that takes into account the head loss of the flow.

In the next paragraphs a brief recent history of the hydraulic jump is presented, starting from the dynamic similarity of Bakhmeteff and Matzke (1936).

2. RECENT HISTORY OF THE HYDRAULIC JUMP

During 1932-33 the longitudinal elements of the jump was the subject of systematic research in the Fluid Mechanics Laboratory of Columbia University, in New York, N.Y., using the principle of dynamic similarity. Bakhmeteff and Matzke (1936) observed that their experiments were referred to a general dynamic characteristic called "the kinetic flow factor":

$$\lambda = 2\frac{\varepsilon_k}{\varepsilon_p} = \frac{V^2}{gd} = \frac{q^2}{gd^3} \tag{2}$$

which gives a measure of the "kinetic of flow", expressed by twice the ratio of the kinetic energy head to the potential energy head contained in each unit of weight of liquid, flowing at the depth d, velocity V and unit discharge q. In the terms ordinarily used in studies of dynamic similarity the kinetic flow factor λ is equivalent to the so-called Froude number. Bakhmeteff and Matzke (1936) obtained general dimensionless characteristics of the jump in terms of λ.

Rouse et al. (1958) simulated the jump in an air duct because the fluid discontinuities produced by entrapped air interfere with the measurement of turbulence in the hydraulic jump itself. Therefore the authors replaced the air interface of a typical hydraulic jump profile with a solid wall, and used air in their model. In an initial analytical section of their paper the modeling method was justified and the differential and integral forms of the momentum and energy equations were explained. Through the analysis of turbulence measurements conducted in the air-flow model of the hydraulic jump under conditions simulating three representative Froude numbers, the authors obtained significant information on the energy transformation. The manuscript of Rouse et al. (1958) could be classified in the group of papers where an analogy of the hydraulic jump with other flows is used. In this branch the papers of Rajaratnam (1965) and Wu and Rajaratnam (1995) are well known. In the first paper, the author presented a study of the hydraulic jump as the case of a plane turbulent wall jet under adverse pressure gradient and with a finite depth of flow, observing that the pressure distribution is not hydrostatic and the velocity distribution in the boundary layer part of the jump follow closely the velocity defect law for two dimensional channel flow.

Using his experimental results, Rajaratnam (1965) developed a more accurate form of the momentum equation

$$\left(\frac{d_2}{d_1}\right)^3 - \frac{d_2}{d_1}\left(1 - \varepsilon + 2F_1^2\right) + 2F_1^2 = 0 \tag{3}$$

where F_1 is the inflow Froude number and ε is the dimensionless integrated shear force introduced by the author.

Peregrine and Svendsen (1978) observed that a spectrum of quasi-steady breaking flows is as follows: spilling breakers in deep water, spilling breakers in shallow water, bores, hydraulic jumps, flow below sloping weirs and waterfalls. In investigating the properties of waves the authors observed that the most obvious extension is to hydraulic jump, since, in the simplest view, it is equivalent to a bore but in a frame of reference moving with the wave on a beach. The authors showed that a model for this spectrum of flow field is the mixing layer. According to Peregrine and Svendsen (1978), Hoyt and Sellin (1989) used the model of mixing or shear layer in order to describe a hydraulic jump. They observed that in the free surface water flows the hydraulic jump has usually been considered a turbulent reverse roller supported by an underlying and expanding stream. In their investigation the character of the turbulence in the jump was normally a predominant feature. Hoyt and Sellin (1989) showed that the hydraulic jump may be interpreted as a mixing or shear layer with associated coherent structure, between air and water with density ratio of about 800 (another analogy with other flows).

Another aspect of the hydraulic jump, which attracts attention, is the air entrainment. Resch et al. (1974) used the hot-film anemometer for exploring the details of the hydraulic jump. In their investigation the authors adopted a digital method of data treatment, which permitted separating the hot-film signal component corresponding to the gaseous phase from that of the liquid phase on the basis of a well-defined fluctuation threshold. The results of Resch et al. (1974) suggested that the hydraulic jumps with both undeveloped and fully developed inflow would function as effective aerators. Mossa and Tolve (1998) investigated bubbly two-phase flow in a hydraulic jump using a flow visualization technique. This was possible by evaluating the gray levels of the first principal axes of transformed images starting from RGB images. The technique proposed allows the evaluation of air concentration in a hydraulic jump without interfering with the flow. Unlike the other techniques existing in literature, it is possible to evaluate the concentration in an entire region of the flow. Furthermore the images obtained permit one to visualize the coherent structures of turbulence.

On this aspect of the problem Roshko (1976) shows that it has become increasingly evident that turbulent shear flows do contain structures or eddies whose description is more deterministic than had been thought, possessing identifiable characteristics, existing for significant lifetimes, and producing recognizable and important events. Roshko observed that a fundamental property of turbulent shear flow (for instance the hydraulic jump) is the phenomenon of entrainment, according to Resch et al. (1974). Roshko (1976) concluded that the organized, periodic motion is superimposed on a background of turbulence.

The importance of the analysis of such phenomena is also linked to design and constructive concern of the spillway stilling basins. It is well known that one of the objective of the designer is to ensure that the jump will not be swept out of the basin and the design process would involve determination of optimum basin floor elevation, required tailwater elevation, adequate basin length, and desired blocks and end sills. The researchers of the Polytechnic University of Bari (Italy) carried out theoretical and experimental studies on the design and constructive concern of the spillway stilling basins with jumps (Damiani, 1970; Frega, 1970; Gioia et al., 1979b, 1979c). Associated with this problem are pressure fluctuations under hydraulic jumps, which must be a matter of concern in the structural design of the linings of spillway stilling basins. In fact design criteria based on steady uplift evaluations proved unsatisfactory. This topic came to great practical interest when the protection beneath the hydraulic jump stilling basins in some hydraulic plants was seriously damaged by floods lower than the maximum design value (i.e. Malpaso dam in Mexico and Karnafuli dam in Bangladesh). The numerous studies all agreed that the phenomenon was due to the fluctuating pressures under the jump (Gioia et al., 1979a; Toso and Bowers, 1988; Fiorotto and Rinaldo, 1992; Di Santo et al., 1995).

For the sake of brevity, many papers, milestones of the literature of hydraulic jumps, have not been mentioned in the present manuscript. However, the interested Reader could refer to Chow (1959), Rajaratnam (1967) and Chanson (1999) for a rich, even if not complete, bibliography on the hydraulic jump, its characteristics and types.

3. NEW APPROACH TO THE HYDRAULIC JUMP

Taking into account the considerations of Roshko (1976) and Dimotakis (1986), it is believed that the flow of a jump must be analyzed in its actual configuration of air-water mixture, an aspect that cannot be overlooked. Experiments by Abdel Ghafar et al. (1995) on local scour due to hydraulic jump formed on the sand bed after a horizontal apron pointed out the existence of oscillating characteristics under some conditions. Analysis of those experiments showed that, for some runs, the hydraulic jump tended to repeat itself in a periodic form, from clockwise to anti-clockwise rotation of the vortex, allowing for determination of a period of the phenomenon. Mossa (1999) takes into account previous studies by Long et al. (1991), Habib et al. (1994), Abdel Ghafar et al. (1995) and by Nebbia (1942) to investigate the oscillating characteristics of hydraulic jumps, i.e. 1) changes of the different types of hydraulic jumps (variation from one type to another); 2) horizontal movements of the jump toe; 3) variations of the velocity components and pressure in the region close the jump roller; 4) process of formation, development and coalescence of the large scale flow structures. Some oscillating characteristics in the hydraulic jumps were evidenced by Nebbia (1942), who observed that "in the scour processes taking place downstream of spillways, the flow often transforms into two different types which follow one another with quasi-periodic oscillation. The shift from one type to another may be sudden or gradual, due to causes which are still unknown, through a swift following of instantaneous transition profiles". The author emphasizes these phenomena were described by Roth during the flooding of the Sihl in Zurich, as well as by Gruner and Locker, who observed them in laboratory. "Yet even when they are almost familiar they amaze us each time we come across them: we seem to be present at a harmonious game of nature of which the proposed explanations give a logical explanation of the formal aspect rather than of the internal causes which, to a certain extent, still appear rather mysterious" (Nebbia, 1942).

Mossa (1999) analyzes oscillating characteristics typical of a hydraulic jump with an abrupt drop. Figure 4 shows oscillatory flow patterns between B-jump and Wave jump, typical in the presence of an abrupt drop (Hager and Bretz, 1986; Ohtsu and Yasuda, 1991; Chanson and Toombes, 1998).

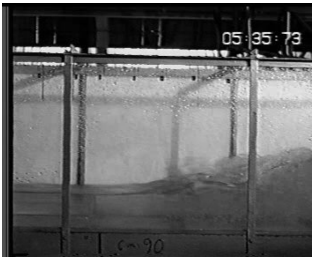
Although they have been regularly observed under several experimental conditions few authors mention these phenomena in literature. This study shows how it could be appropriate to design basins taking in consideration different types of jump, because the variations of the hydrodynamic upstream and downstream conditions (gates opening, discharge, etc.) could bring alternative phenomena. For design purposes it is necessary to know the basic characteristics of the flow conditions.

In addition, Mossa (1999) shows the existence of an orderly and deterministic framework typical of flow structures even for those configurations that do not present specific macroscopically visible oscillating characteristics. The conclusions, which at present may be reached, are as follows:

- Although oscillations of hydraulic jump types with a non-flat bottom do not depend on whether the bottom is made of erodible or nonerodible material, oscillations are present when the hydrodynamic conditions typical of the analyzed configurations lie between two or more stable configurations.
- Since oscillating characteristics analyzed appear with a certain degree of regularity, a

suitable time scale may be defined both for oscillations of the jump types and for fluctuations of the jump toes with a flat and outlined bottom.

- Analysis of the oscillating phenomena indicates a correlation among the surface profile elevations, velocity components and pressure fluctuations. This observation leads to conclude that the oscillating phenomena are particularly important for the analysis of turbulence characteristics.
- By analyzing a single cycle of the oscillating phenomena of a jump (periodic formation of different jump types or fluctuations of the jump toe) it is in all cases possible to indicate their correlation with the vortex structures of the roller. Regularity of the analyzed oscillating phenomena can be described as a nonrandom and orderly process superimposed on a background of turbulence considered in the classical way as disorderly and random motion.
- Oscillating characteristics are accompanied by changeable configurations of the surface profile of a hydraulic jump, as a function of air concentration present in the roller.
- Analysis of the flow through modern visualization techniques encourages one to carry on studies of turbulence coherent structures, as further investigations into these structures might add significantly to the understanding of hydraulic jumps.



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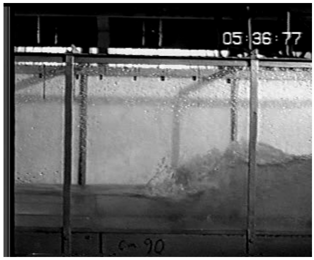

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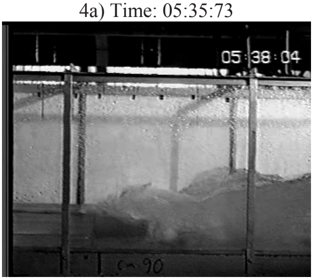

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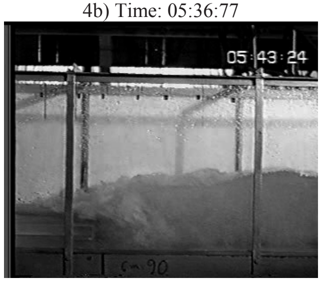

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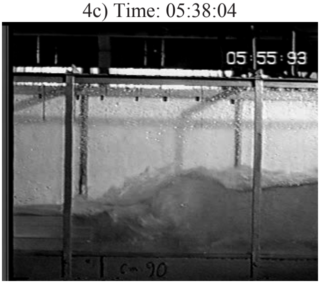

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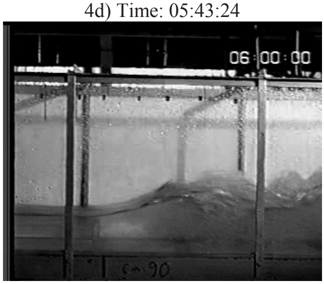

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Fig. 4. Typical oscillatory flow patterns between B-jump and Wave jump; time is expressed in minutes, seconds and hundredths of seconds from the shooting start.

4. CONCLUSIONS

This paper presents a brief history of the jump of Bidone with particular reference to the Research Group of the Polytechnic University of Bari (Italy). Sketched by Leonardo da Vinci, observed in nature, and utilized by engineers for a century, it might be thought that the hydraulic jump had yielded all its secrets some time ago. Recent papers show that this not true. A new look of the structure of turbulent shear flows highlights that it is necessary to separate the random processes from the nonrandom processes. Taking into account this new approach other research works are necessary in order to analyze the flow characteristics of hydraulic jumps.

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