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INVESTIGATIONS ON ALLUVIAL BED PROTECTION DOWNSTREAM A MOBILE DAM STILLING BASIN

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ABSTRACT

Laser-Doppler Anemometry (LDA) has been used to study experimentally energy dissipation behind the hydraulic structure of a mobile dam. Flow field characteristics over the rock protection have been defined aiming to a better understanding of the complex flow behaviour at and downstream the stilling basin.

The experimental study was carried out by using a physical model of the Crestuma dam, located in the Douro River, built and installed in a water channel at the Hydraulics Laboratory of the University of Porto. Those studies were carried out for different rock fill characteristics and dimensions, taking into account the most critical flow and gate operating conditions, and the dimensions and location of the generated scour holes. Those results can provide a better insight in the rock fill protection behaviour and they can help to achieve a more economic and safer design of the rock fill protection.

KEY WORDS: sediment transport, mean critical velocity value, shear stress value.

INTRODUCTION

The design of hydraulic structures of a dam requires special attention to flood energy dissipation problem. The difference of the water surface levels between upstream and downstream sections of the dam originated by its construction leads frequently to the development of hydraulic jumps downstream the flood discharge devices as for example spillways or gates, resulting in very important flow energy losses, which are, mainly, due to the high turbulence of the flow and to the friction of the flow with its boundaries. Stilling basins, with concrete slabs with enough length and appropriate characteristics to allow, within them the development of the occurring hydraulic jumps of the flow under study, are commonly used.

At the flow sections downstream the hydraulic jump the flow turbulence level can still be too high requiring a convenient protection of the structure foundation bed in order to avoid the occurrence of scour, especially if that foundation regards an alluvial bed type. Filters and rock fill bed protections are commonly used for river bed protection which characteristics definition will require an analysis of the flow velocity field downstream the concrete slab stilling basin. Important velocities and high turbulence levels can originate the lifting and the drag of rock fill protection elements and scour effects can occur. An analysis of the flow field in which concerns velocity values and turbulence levels can provide a better insight on rock fill bed protection behaviour.

Initiation of movement of sediments is associated with the equilibrium of the forces acting on the particles and is mainly dependent on two factors: the flow velocity value and the shear stress value at the channel bottom. Criteria like the critical bottom shear stress value and the critical velocity value enable the establishment of limit values for flow velocity and for shear stress, which allow initiation of sediments transport analysis.

In the present study a physical model of Crestuma dam in Douro river, in Portugal has been analysed. Several flow conditions with different rock fill protection characteristics have been considered. Laser Doppler anemometry has been used to define the different flow fields for the different flow conditions studied. Mean flow velocity values have been evaluated and critical mean velocity criteria has been applied to the different flow conditions and different rock fill protections studied in order to compare the obtained results with the ones resulting from the application by the authors (2006) of the shear stress criteria.

LITERATURE SURVEY

Several criteria are used to define river bed protection systems. The diameter of the elements of the several layers that constitute the protection systems increases from their bottom to their top layer. From the elements of that layer is expected that they stay stable and that they will not move under the several flow conditions occurring downstream the concrete slab stilling basin. Flow velocity and bottom shear stress values are the main factors that influence transport sediment, leading to criteria like the critical bottom shear stress value and the critical velocity value which establish limit values for flow velocity and for shear stress, allowing rock fill behaviour analysis.

Critical mean velocity U_{cr} of the flow it is the maximum mean velocity value that corresponds to initiation of movement of sediments. Several comments about this criteria have been made due to the fact that it is used, as the comparison element, the mean velocity value instead of the flow velocity near the bottom which is, in fact, the one responsible for sediments transport. Nevertheless its simplicity of application makes its use very frequent, especially if the available data about the flow is reduced to its mean velocity value. Several expressions, based on empirical studies and mainly referred to uniform flows occurring in channels with uniform size bed grains and, in certain cases, for specific flows conditions as for example the flow depth, have been established by different authors. Those expressions allow U_{cr} evaluation. Some of the most common expressions are presented on table 1.

Table 1- Critical velocity expressions

Neil, 1967	Garde, 1970
$\frac{U_{cr}^2}{(\frac{\gamma_s}{\gamma}-1).g.d} = 2,5.Z^{0,2}$ [1]	$\frac{U_{cr}}{\sqrt{\frac{(\gamma_s-\gamma).d_{50}}{\rho}}} = 0,50.\log(Z)+1,63$ [2]

where h is the flow depth; d the grain size; z = h/d the relative submergence; and ρ the specific mass of the fluid.

As a result of experiments carried out with particles of uniform size, Hjülstrom, 1935, has presented the diagram of figure 1, which relates, directly, particles diameter with flow mean

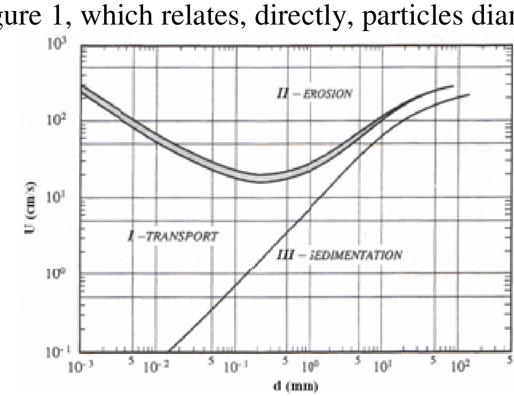


Figure 1.– Hjülstrom diagram, (1935)

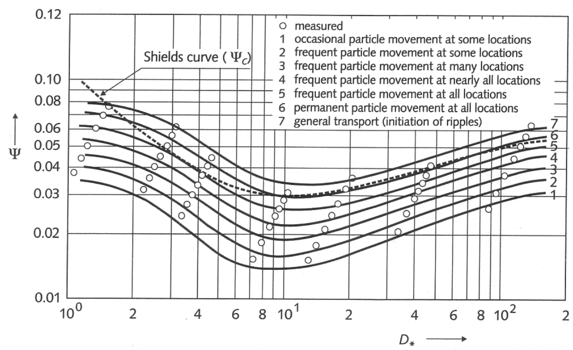
velocity value.On the diagram three different areas are defined concerning the different sediment transport characteristics.

I – Erosion area: particles, with diameters between 1,0 mm and 0,1mm, will be easily lifted and will cause scour; for smaller diameters cohesion effect will avoid scour occurrence;

II – Transport area: particles in suspension are subject to transportation;

III – Sedimentation area: for velocities smaller than the correspondent to the separation line between areas II and III, deposition of particles in suspension will start.

In which concerns shear stress criteria application the modified Shields diagram, shown in figure 1, was made.



$$\Psi = \frac{u_*^2}{\Delta g d} \quad and \quad D_* = d\left(\frac{\Delta g}{\nu^2}\right)^{\frac{1}{3}} \qquad [3]$$

where:

Δ = relative density ((ρ_s/ρ) -1);

d = particle diameter (d = d_{50});

u_* = friction velocity;

g = acceleration of gravity;

ν = cinematic viscosity;

ψ, mobility parameter;

D_*, dimensionless diameter

Figure 2.– Modified Shields Diagram (Hoffmans et al. 1997)

For a particular situation the critical shear stress value can be obtained through the Shields parameters ψ and D_* definition, according to expressions [3].

Both criteria require information about the velocity fields corresponding to each flow situation under study which was provided by Laser Doppler measurements.

As demonstrated by the authors (2006) flow characteristics under study correspond to non-uniform flows, fact that has been taken into account when evaluating friction velocity values u_*.

EXPERIMENTAL SET UP

Facilities and measuring equipment

Experiments have been carried out in a water channel of the Hydraulics Laboratory of FEUP.

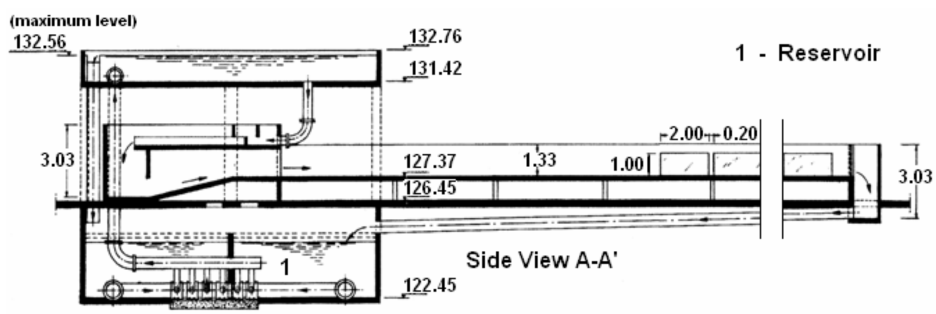


Figure 3.– Water channel of Hydraulics laboratory

The water channel, with a length of 32,3m, a width of 1,0m and a bottom slope of 0,5%, is provided with side windows allowing visual access to the test sections and is presented in figure 3.

Flow values can be controlled, upstream through a flow meter, Sparling Waterhawk series 600, flangeless version, and downstream through a sluice crested weir, whose discharge value is obtained measuring the water level by means of a Bestobell Mobrey MSP90 system.

Table2- Laser Doppler anemometer characteristics

Laser wave length	514,5 nm	Minor axis of control volume in air	0,162 mm
Half angle of measuring beams in air	3,65º	Fringe Spacing	4,04 µm
Beam expansion ratio	1,95	Frequency Shift	0,6 MHz
Major axis of control volume in air	2,53 mm		

Velocity measurements have been made using a single component fibre optics Laser System from Dantec, working in forward scatter mode and as laser source a 100 MW Argon-Ion laser, operating in multi-mode. The main characteristics of the Laser Doppler Anemometer system are shown in table 2.

Physical model characteristics and similarity conditions

In order to achieve the experimental work a physical model of Douro river Crestuma dam was built. Crestuma dam is a mobile type dam founded on alluvial bed, which floods discharge is made through double slicing gates installed on 8 spans of 28m each and supported by 49m length and 6m width piles. The double slicing gates can move independently and allow discharges over or underneath their body or both simultaneously. Flow discharge energy dissipation is achieved on a concrete slab stilling basin with a length of 42m from gate axis position, followed by the rock fill protection with a length of 80m. Taking into account that gravitational forces are predominant in this case the Froude number similarity was used for a Perspex model construction. A 1/80 geometric scale was considered.

Due to the width of the water channel of Hydraulics Laboratory, of (1m) and the geometric scale value of 1/80, the portion of Crestuma dam represented by the model included one central span, two piles and two lateral incomplete spans (approx. half spans) as represented in figure 4.

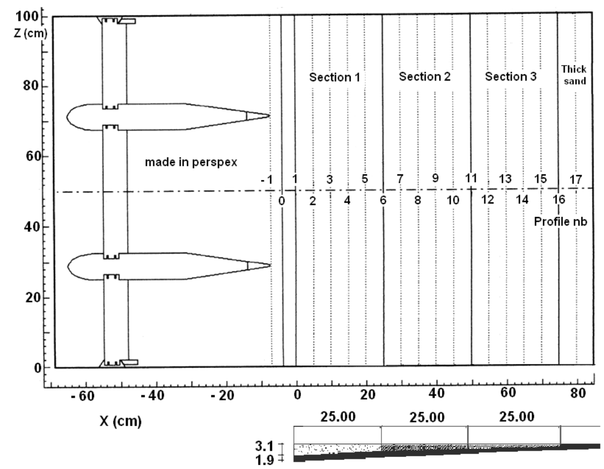


Figure 4.– Crestuma Model - plan , rock fill bed protection characteristics and measured velocity profiles location

Rock fill protection of Crestuma plant has a variable depth as shown on figure 4 and was modelled by means of granite and sand grains which specific weights are as follows: granite grains ($26KN/m^3$), sand grains ($16KN/m^3$) and wet sand grains ($18KN/m^3$). The four top layer sections, with 20m each at Crestuma plant, had in the model 25cm length each and will be defined as section 1, 2, 3 and 4. Section 4 corresponds to the natural foundation bed material. Rock fill elements size distribution, used for the different sets of experiments corresponds to the three different rock fill protection characteristics, A, B and C shown in figure 5. Type A rock fill protection corresponds to the scaled rock fill protection existing at Crestuma dam. Type B, section 1 grain size was chosen bearing in mind the possibility of its execution in a real situation. Type C, section 1 bed protection was defined using the following formula proposed by U.S. Corps of Engineers, and used on Crestuma project (LNEC, 1972):

$$d \geq k \frac{U^2}{2g} \frac{\gamma}{\gamma_s - \gamma} \qquad [4],$$

where γ and γ_s are respectively the specific weights of water and rock material, k is dependent on flow turbulence and was taken equal to 1,35.

Mean grains dimension of type B and C protection are respectively 33% and 100% higher than the Crestuma one. The same ratio to section 1 grains dimension, regarding Crestuma rock fill protection, has been used for section 2 and 3 material dimensions.

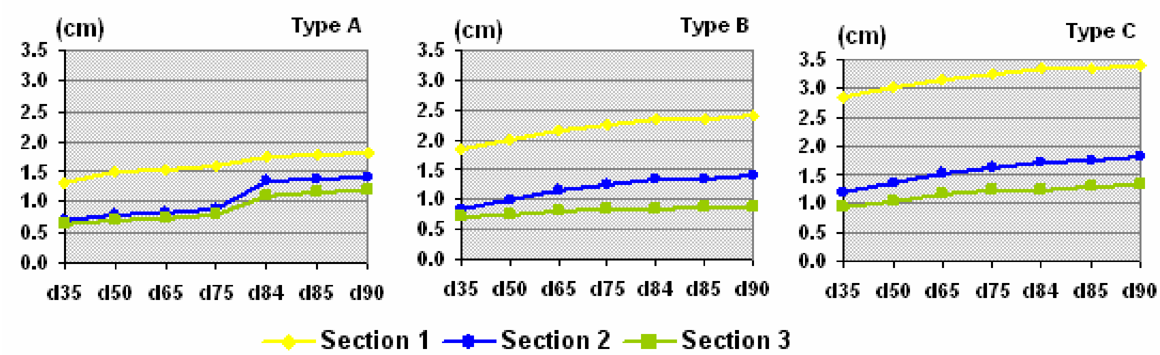


Figure 5.– Model rock fill bed protection characteristics for type A, type B and type C rock fill protections.

Flow Conditions

Two different flow values of 11,5l/s and 12,2l/s and three different rock fill bed protections, types A, B and C have been considered on those experiments. In the present work flow discharges have been considered to be done underneath the gates and keeping equal gate openings at all the three spans of the model. The main flow characteristics are presented on table 3, where H_1 is the upstream water level and y_0 is the downstream water level.

Table 3.- Main flow characteristics

Flow value [l/s]	11,5	12,2
H_1 [mm]	165	165
y_0 [mm]	58,5	60,5
Froude nb	5,81	5,79
Gate opening [mm]	9	12,5

EXPERIMENTAL RESULTS

Taking into consideration the referred flow conditions and the three different types of rock fill bed protection, four sets of velocity measurements have been carried out. Velocity profiles have been measured at different flow sections downstream the hydraulic structure, as shown on figure 4, for the flow values of 11.5l/s, and type A rock protection and for 12.2l/s flow value using the three different bed protection types A, B and C.

Four sets of experiments have been considered, within two different groups as follows:
- First group: flow value of 11.5l/s and type A rock fill protection,
- Second group: flow value of 12.2l/s and types A, B and C rock fill protections,

allowing:
- the analysis of the influence of flow characteristics (11,5l/s and 12,2l/s) on the behaviour of the same bed protection type;
- the comparison of the situations originated by the same flow on the three different types A,B and C of bed protections.

The presentation of the results will be made in a dimensionless form using:
- the ratio of velocity values by the mean flow velocity values at downstream sections where the flow characteristics correspond to a non disturbed flow, and which values are 0.197m/s and 0.202m/s, respectively for 11.5l/s and 12.2l/s flows;
- the ratio of the lengths on the horizontal and vertical directions respectively by the bed protection length, 100cm and the flow depth at downstream sections above referred, which are equal to 5.85cm for 11.5l/s flow value and 6.05cm for 12.2ls one.

Concerning the first group of experiments, using type A rock fill bed protection it could be noticed the occurrence of a quite stable hydraulic jump formed within the stilling basin slab. Laser Doppler measurements have been carried out at the different measuring sections. Velocity field characteristics are shown on figure 6. The highest velocity values have been registered at profile $P_{0,}$

before entering the rock fill protection, due to the reduced flow depth at that section. From profile 10 to 15 the velocity profile are quite similar and correspondent to a flow being almost stabilized.

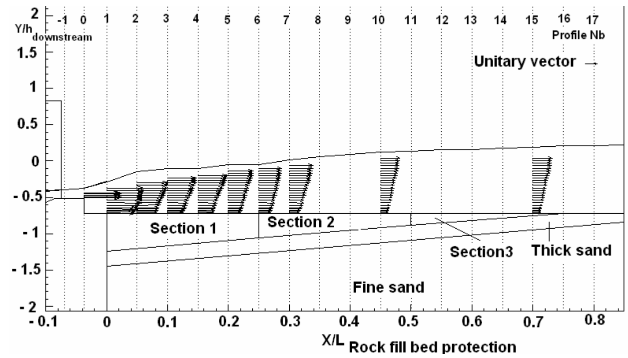
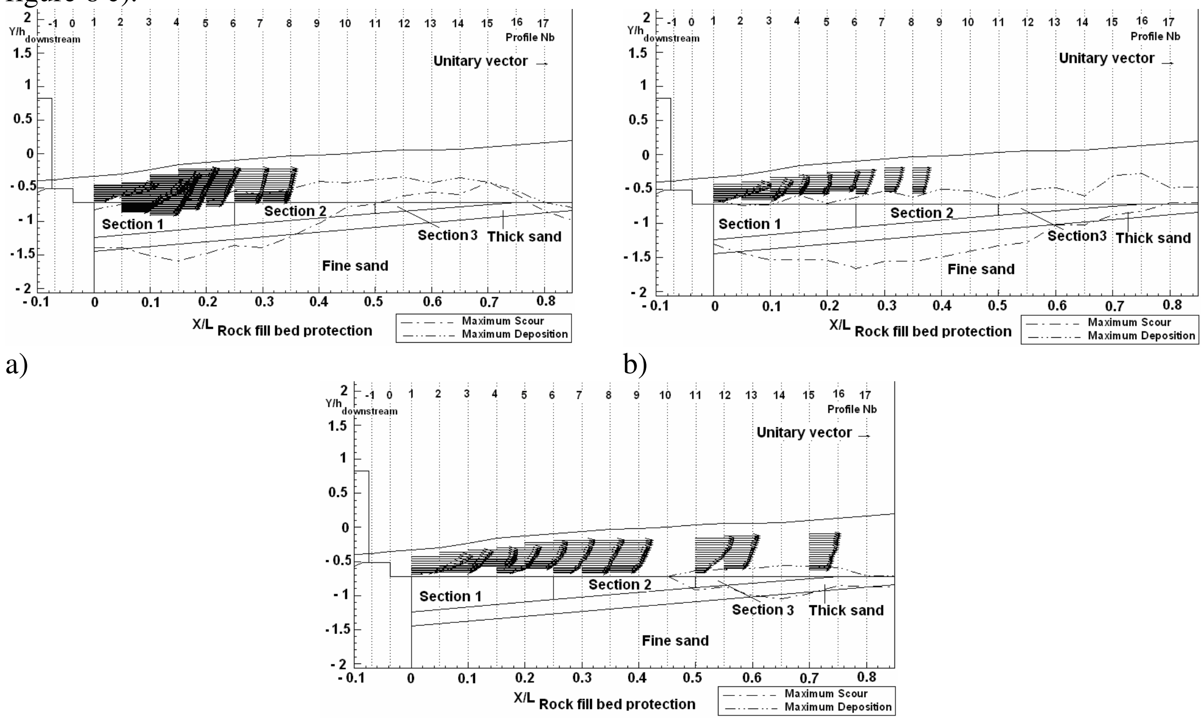


Figure 6 – Flow field for 11,5 l/ gate flow discharges, for type A rock fill bed protection

Due the stable characteristics of the hydraulic jump no erosion was detected during experiments.

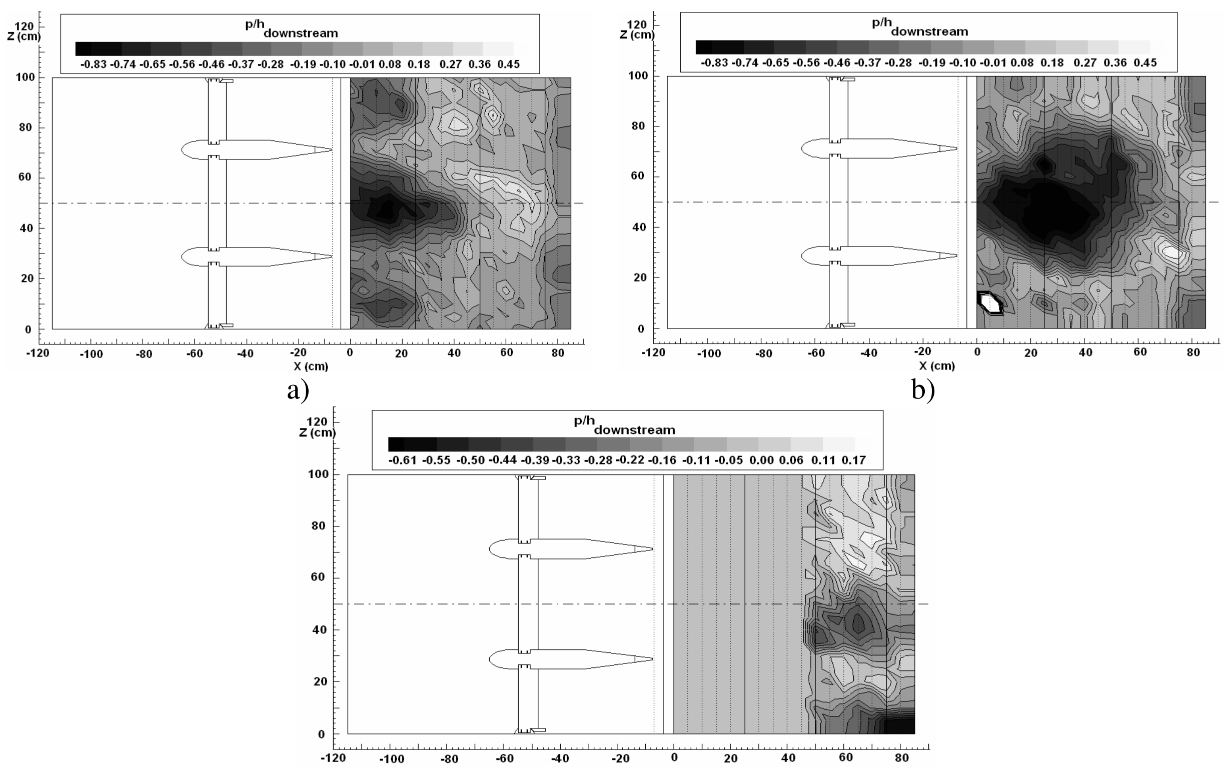
The second group of measurements concerned the 12,2l/s flow value and the three different types of rock fill protections, A, B and C. The flow characteristics regarding 12,2l/s flow value presented a quite unstable hydraulic jump with tendency to move, periodically, away from the stilling basin. Consequences of this type of gate discharge flow, on sediment transport occurrence, were dependent on the rock fill type. For type A rock fill protection there was an immediate starting of the formation of a scour hole on the rock fill bed protection. Eroded material was transported to the downstream flow sections. Figures 7 a) represents the mean flow velocity field for 12,2l/s flow value. Longitudinal profiles of maximum scour and of maximum deposition, the first corresponding to the central channel axis and the other to the pile axis. The deposition of eroded material turned the velocity measurement on some downstream profiles impossible because measuring points were out of reach of laser beams. It must be pointed out as well that only horizontal velocity component could be measured due to the very low flow depth associated with very high flow surface fluctuations and because of LDA system characteristics, namely beam separation at front lens probe. Comparing flow fields for 11,5l/s and 12,2l/s flow values it can be noticed that much higher velocity values and velocity gradient values, on rock fill bed protection, have been registered for 12,2l/s value. Scour hole characteristics, concerning dimensions and location, are shown on figure 8 a). Scour hole depth values were made dimensionless by considering the ratio to the downstream flow depth value. The scour hole was mostly located in front of the central gate span, along section 1 of the rock fill bed protection. Velocity measurements have been made after stabilization of sediment transport which occurred, approximately, two hours after starting the test. When using type B rock fill instead of type A, the scour process did not start immediately at the beginning of experiments; during the first 24 hours of test, oscillations on the materials of the top layer of the sections 1 and 2 of the rock fill protection could be noticed, which have been followed by the scour hole formation. Figure 7 b) shows the corresponding mean velocity flow field. As explained before not all the velocity profiles could be measured by the reasons already stated. Figure 7 b) shows also the longitudinal profile of maximum scour and deposition respectively at the cannel centre line and at piles centre line. Scour hole moved downstream as shown on figure 8 b), being now the deepest points located at the end of section 1 beginning of section 2. It can also be remarked that upstream velocity profiles are quite similar. Higher differences can be noticed on velocity profiles P5 to P8, corresponding to the end of section 1 and beginning of section 2 of the top rock fill layer protection where scour hole formation took place. Considering finally type C rock fill protection type and the same 12,2l/s flow value no erosion could be noticed on sections 1 and 2 of the rock fill protection and only on section 3 a slight sediment transport was registered resulting in the formation of a small scour hole. Figure 7 c) shows the velocity flow field which is in fact quite similar to the one corresponding to 11,5l/s flow value. Longitudinal profiles indicating maxima scour and deposition at channel and piles centre lines are also presented. Scour location and characteristics are shown in figure 8 c).



a) b)

c)

Figure 7.– Flow fields for 12,2 l/s flow and a) type A, b) type B (after scour occurrence) and c) type C rock fill protections



a) b)

c)

Figure 8.– Scour hole caused by a 12,2 l/s gate discharge on a) type A, b) type B and c) type C rock fill protections

Velocity data was used for the calculation of the necessary values for sediment transport criteria application. Table 4 shows the main profile characteristics for the different test situations.

Table 4.- Velocity profile characteristics

Flow [l/s]	Rock fill bed protection	Profile	x [cm]	h [cm]	U_m [m/s]	U [m/s]	$U_{0,4h}$ [m/s]
11.5	Type A	P_1	0	2,7	0.43	0,541	0,568
		P_2	5	3.5	0,33	0,432	0,430
		P_3	10	3,8	0,30	0,384	0,378
		P_4	15	3,8	0,30	0,372	0,351
		P_5	20	4,1	0,28	0,312	0,298
		P_6	25	4,1	0,28	0,292	0,286
		P_7	30	4,5	0,26	0,290	0,269
		P_{10}	45	5,1	0,23	0,224	0,209
		P_{11}	70	5,1	0,21	0,230	0,213
12.2	Type A	P_1	0	2,4	0,51	0,863	0,859
	Type B	P_1	0	2,4	0,51	0,730	0,704
	Type C	P_1	0	2,4	0.51	0,821	0,834
		P_2	5	3.6	0,47	0,758	0,781
		P_3	10	3,0	0,41	0,729	0,833
		P_4	15	3,4	0,36	0,652	0,680
		P_5	20	3,6	0,34	0,599	0,632
		P_6	25	3,8	0,32	0,592	0,581
		P_7	30	4,0	0,31	0,623	0,601
		P_8	35	4,2	0,29	0,630	0,644
		P_{11}	50	4,6	0,27	0,518	0,543

(x- profile coordinate; h- flow depth; U_m- mean velocity equal to Q/S; U- mean velocity obtained by integration of velocity profile; $U_{0,4h}$- mean velocity at 0,4h distance from bottom channel, Graf (1998)).

SEDIMENT TRANSPORT ANALYSIS

The criteria of mean critical velocity will be used in the analysis of the results .and a comparison with shear stress criteria will be made.

For the first group of measurements (11,5l/s flow value and type A rock fill protection) and using the calculated mean velocity value U, presented in table 4, for profile P1, the highest velocity value registered, a comparison with the literature mean critical velocity values as shown (table 5).

Table 5.- Measured and critical velocity values for 11,5l/s flow value and type A rock fill protection

Profile	Measured Values	Neil (1967)	Garde (1970)
	U [m/s]	U [m/s]	U [m/s]
P1	0,54	0,83	0,87

Measured velocity values for 11,5ls are lower than the mean critical velocity values calculated according to Neil and Garde, through respectively expressions [1] and [2], indicating that no scour should occur which in fact has been observed.

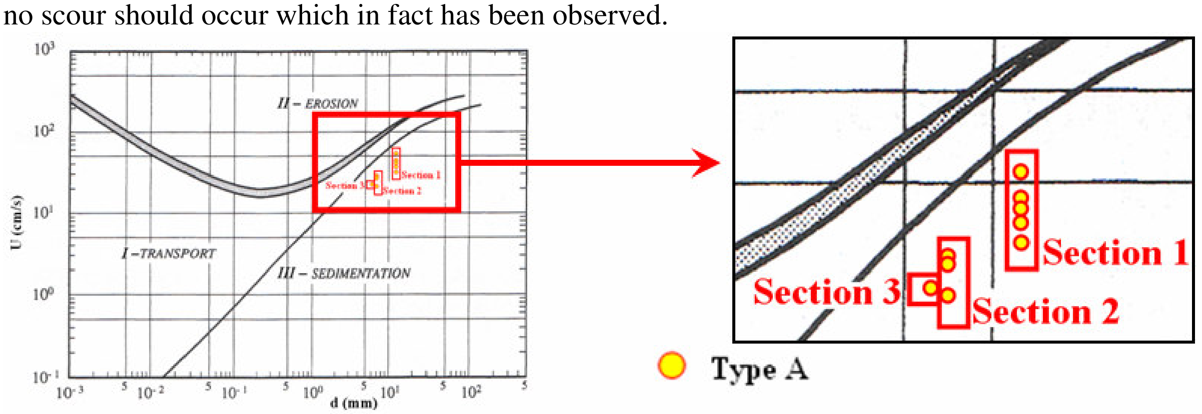


Figure 9.– Diagram of critical mean velocity flow according to Hjülstrom -1935, and for 11,5l/s flow value and type A rock fill protection

Hjülstrom criterion was also applied using the diagram of figure 1. All the results concerning the several velocity profiles measured for 11,5l/s flow value have been plotted and are presented on figure 9. As can be shown, for 11,5l/s flow value, all the results are laying on sedimentation area. The point the nearest located from the transport area is the one corresponding to profile P1 at the beginning of the rock fill protection

Proceeding as above and considering the second group of measurements with flow value of 12.2l/s and types A, B and C for rock fill protections, mean velocity flow values are presented on table 6, where they can be compared with the critical velocity values resulting from Neil and Garde expressions. As previously reported scour was occurring on section 1 of type A and B rock fill protections and on section 3 type C one. As can be observed in this case, according to Neil and Garde expressions scour only was supposed to occur on type A rock fill protection situation which in fact did not happen in the experiments.

Table 6.- Mean velocity values U in m/s for12,2l/s flow value and rock fill A, B and C types some scour has been registered.

Profile	Measured				Neil 1967			Garde 1970		
	Type A	Type B	Type C		Type A	Type B	Type C	Type A	Type B	Type C
P1	0,86	0,73	0,82		0,82	0,92	1,08	0,85	0,95	1,1
P2	-	-	0,76		-	-	1,09	-	-	1,11
P3	-	-	0,73		-	-	1,1	-	-	1,14
P4	-	-	0,65		-	-	1,12	-	-	1,15
P5	-	-	0,60		-	-	1,12	-	-	1,16
P6	-	-	0,59		-	-	0,82	-	-	0,87
P7	-	-	0,62		-	-	0,82	-	-	0,87
P8	-	-	0,63		-	-	0,83	-	-	0,88
P11	-	-	0,52		-	-	0,76	-	-	0.81

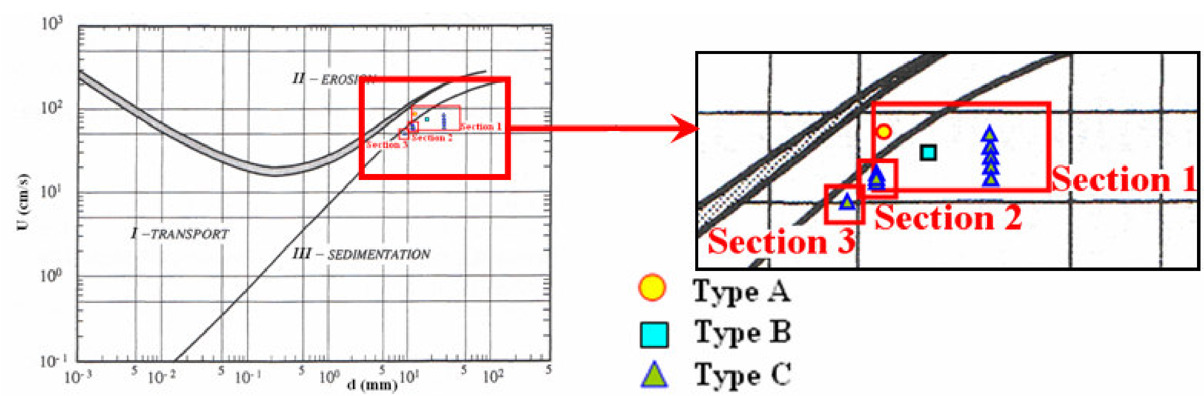


Figure 10.– Diagram of critical mean velocity flow according to Hjülstrom -1935, and for 12.2l/s as flow value and for types A, B and C rock fill protections

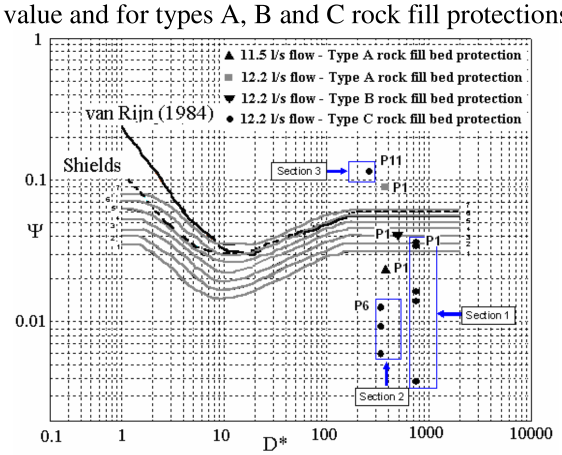


Figure 11– Modified Shields diagram for 11,5 l/s and 12,2 l/s flows and for type A, B and C rock fill bed protections, assuming the non uniform flow case

A comparison with shear stress criteria can be performed using the results referred by the authors (2006). Experimental data obtained from LDA measurements allowed the calculation of Shields parameters and the plotting on the modified shields diagram. Due to the characteristics of non-uniformity of the flow situations under study, reported by the authors in the referred work Shields parameters have been calculated accordingly and results presented in figure 11. It can be concluded that for A and B rock type protections movement of materials shall occur, which was confirmed by the experiments, and that for C type only on section 3 of the rock fill protection, profile P11, erosion will occur, in accordance with what was, in fact, reported on experiments.

CONCLUSIONS

A physical model of Crestuma dam was built and tested for two flow values and for three different types of rock fill bed protections, in order to analyse their behaviour in which concerns scour occurrence.

Laser Doppler anemometry was used for flow velocity measurements in order to define the corresponding flow fields for the different test conditions. The obtained data enabled the calculation of the different parameters required for sediment transport criteria application.

Two different limit flow discharges were studied, enabling the analysis of scour effects on different rock fill bed protections; one close to incipient motion of particles of (type A) rock fill bed protection and the other with scouring effects on the three different studied (growing in dimension, types A, B and C) rock fill types.

Mean critical velocity criterion was used for sediment transport analysis. Some discrepancies between limit velocity values proposed by some authors and the situations reported during the experiments have been found. A comparison was made with the application of shear stress criterion, considering the non-uniformity of the flow situations, being concluded that this criterion leads to results more in accordance to the registered facts during experiments

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