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DISTRIBUTION OF MAXIMUM VELOCITIES AND FROUDE NUMBERS ON A RAPID HYDRAULIC STRUCTURE APRON

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ABSTRACT

Four different arrangements of cobbles and of an upstream top sill on a rapid hydraulic structure (RHS) apron were taken into consideration. For three different values of experimental discharges it was found that the construction of the top sill is crucial in terms of dissipating water energy. The maximum velocity range was between 1.35 and 2.74 m/s and maximum Froude number values were between 1.16 and 2.75, respectively. Model discharges values were: 0.0245, 0.0490 and 0.0735 m^3/s.

Key words: rapid hydraulic structure, Froude number, energy dissipating, artificial roughness, water discharge, water velocity

INTRODUCTION

There is very often a necessity to regulate a river or a stream by changing its slope (what is called: river training works), especially in mountain regions where streams are characterized by high gradients and heavy scouring and erosion tend to occur. In such cases designing and constructing of hydraulic structures has been advised for

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stabilizing a riverbed and riverbanks (Blaisdell et al., 1954, Houk, 1956, Rhone 1977, Wołoszyn et al., 1994, Ratomski, 1992). Usually such structures are drop hydraulic structures. Their construction is well known to designers and they are described in detail in the professional literature.

Unfortunately in many places, if a structure is built, it can spoil the natural beauty of a mountain stream. If it functions properly in terms of hydraulics, it is rarely similar to the natural geomorphological features of a stream (Ratomski, 1992).

Construction of rapid hydraulics structures (RHS) similar to natural river riffles is advised when considering a channel slope reduction (Houk, 1956, Kajak, 1992, Ślizowski, 1993). Such hydraulic structures are environmentally friendly, since they simulate a natural river bed and river bed forms (riffles), do not require additional fish passage consideration, and aerate flowing water naturally (Novak et al., 1996, Żbikowski et al., 1993). Above all they are similar to natural river features and do not disturb a river cross-section appearance when well constructed. The aim of this study was to show the importance of the existence of artificial roughness on a slope apron of the RHS, and the importance of construction of an additional top sill situated at the upstream entrance of the RHS apron. The changes in maximum water velocities and Froude numbers were determinated with different adjustments of the elements fixed to the RHS apron (top sill and stones). Those elements reduced the energy of flowing water in terms of hydraulic calculations.

MATERIALS AND METHODS

The experiment was carried out in the laboratory flame shown in Photographs 1-3. The banks and a bed of the model were stable and wash-resistant. The elements of the model were as follows:

- top/upstream water-tank with calibrated notch
- top/upstream calming water-waves and energy dissipating devices
- top/upstream flow-directing channel
- exchangeable rapid structure module in terms of a sill and stones arrangement
- bottom/downstream flow-directing channel
- measurement devices: velocitimeters, pin-gauges, calibrated notches

A rapid structure was constructed to allow the stone arrangement to be changed on a rapid apron. Sixteen different models of the RHS with different stones arrangement, RHS base length and inclination angle of the rapid apron were tested (only four of them are presented in this paper since they are similar in terms of dimensions: height of the structures, length of the basis of them and the apron inclination angle). The model was scaled using Froude similarities. The whole laboratory channel was 24.65m long, where the part of the channel situated upstream of the RHS was 6.00m long, the RHS base length was 1.35 and finally the tail-water part of the channel was 17.30m long. The depth of the channel was 0.35m and its width was 0.60m. The measured water flume width to which later all analysis and remarks are considered was 0.30m, since the measurement points in all research cross sections were situated as follows: one in the middle of the channel and two on both sides of the channel, 0.15 m from its sides. It was done to eliminate the side-wall effect on the water flume. As previously mentioned, four different types of RHS's were constructed in the lab-experiment and considered for a purpose of this study (Fig. 1.)
In both cases cobbles of diameter D = 0.045m were fixed into the RHS slope apron and arranged in a checker board pattern. The reason for this was to reduce the energy of flowing water (Peterka, 1964, Slizowski, Radecki-Pawlik, 1996, Radecki-Pawlik 1993) and eventually to avoid construction of an energy-dissipating pool downstream the RHS. The 0.06m high top sill was additionally constructed on two of the four RHS's on the upstream side of the ramp. Two of RHS's had no stones on the ramp. For three values of run discharges ($Q1=0.0245m^3/s$, $Q2=0.0493m^3/s$ and $Q3=0.0735m^3/s$), velocities values v were measured in 0.2m intervals along slope aprons using a micro-laboratory velocity-meter. The first measuring point was 4.2m upstream from the top edge of the RHS whereas the farthest downstream measuring point was 12m downstream from the bottom edge of the RHS. Simultaneously, the water depths h were measured using a pin gauge in the same places where the velocity was measured. RHS's investigated water flume width (0.3m), inclination of the RHS's apron (n:1 = 4.5:1), channel inflow length and channel outflow length were constant in all experimental cases.
Water discharge was measured using a rectangle notch with +/- 2% accuracy. For water stage steel pin-point gauges were used with +/- 0.1mm accuracy. There were also mobile track-pin gauges installed along plastic walls of the channel for measuring the water level. Velocity measurements were done with micro-velocitimeters with 15.3mm diameter propeller with +/- 1% accuracy. Because of the diameter of the propeller the closest measurements to a channel bed were done from 7.6mm above it. A sketch of the RHS model graph is presented in Figure 2.

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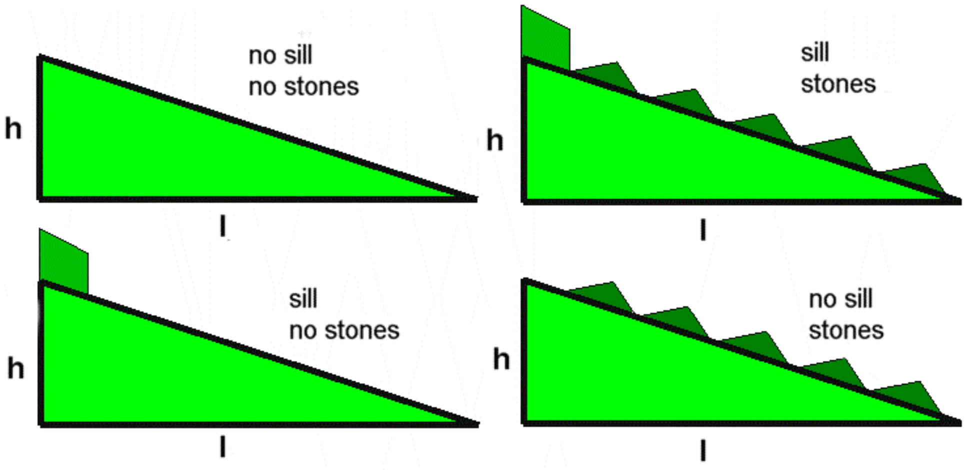
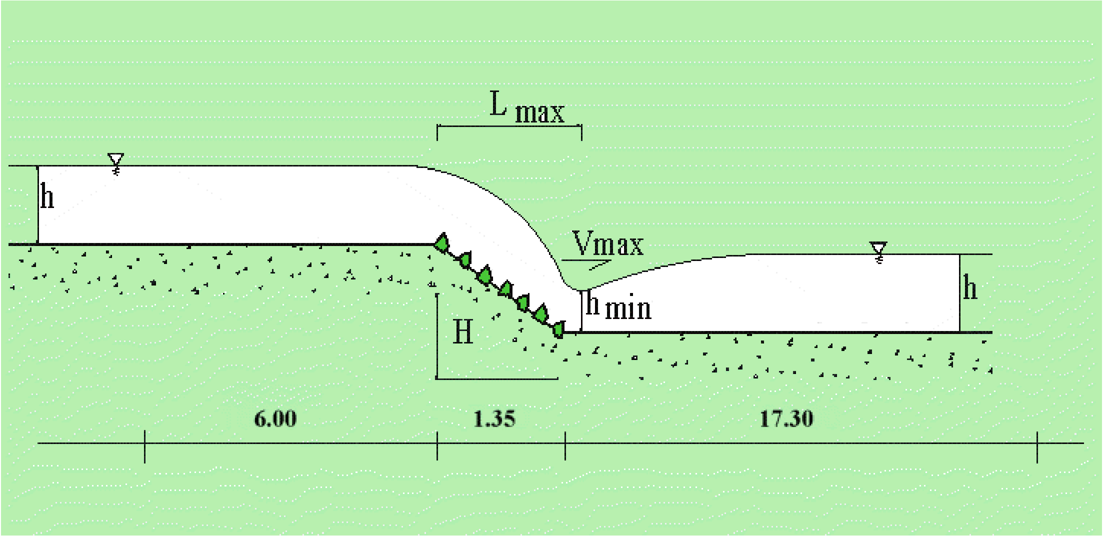
Phot. 1-3. RHS in the laboratory research site: RHS with stones arranged in a checker board pattern; experimental channel; flow over the sill and the stone-lined apron of the RHS.

Fig. 1. Rapid hydraulic structures outlines



h = 0.3 m   l = 1.35 m

Fig. 2. RHS structure sketch within a laboratory channel



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RESULTS

For four different adjustments of stones and a top-sill on the slope apron of the RHS and three values of run discharges, velocity distributions and Froude number values were determined. Figure 3 shows the maximum velocity values as a function of width and length of the RHS. As the maximum velocities, for the purpose of this study, the local maximum velocities along the vertical axis were taken into consideration. For $Q1=0.0245m^3/s$ velocities v1 values range between 1.35 and 1.84m/s, for $Q2=0.0493m^3/s$ v2 velocities were between 2.19 and 2.31m/s and for $Q3=0.0735m^3/s$ v^3 velocities were between 2.54 and 2.74m/s, respectively.

Figure 3a. The maximum velocities as a function of a position in the channel for Q1 values

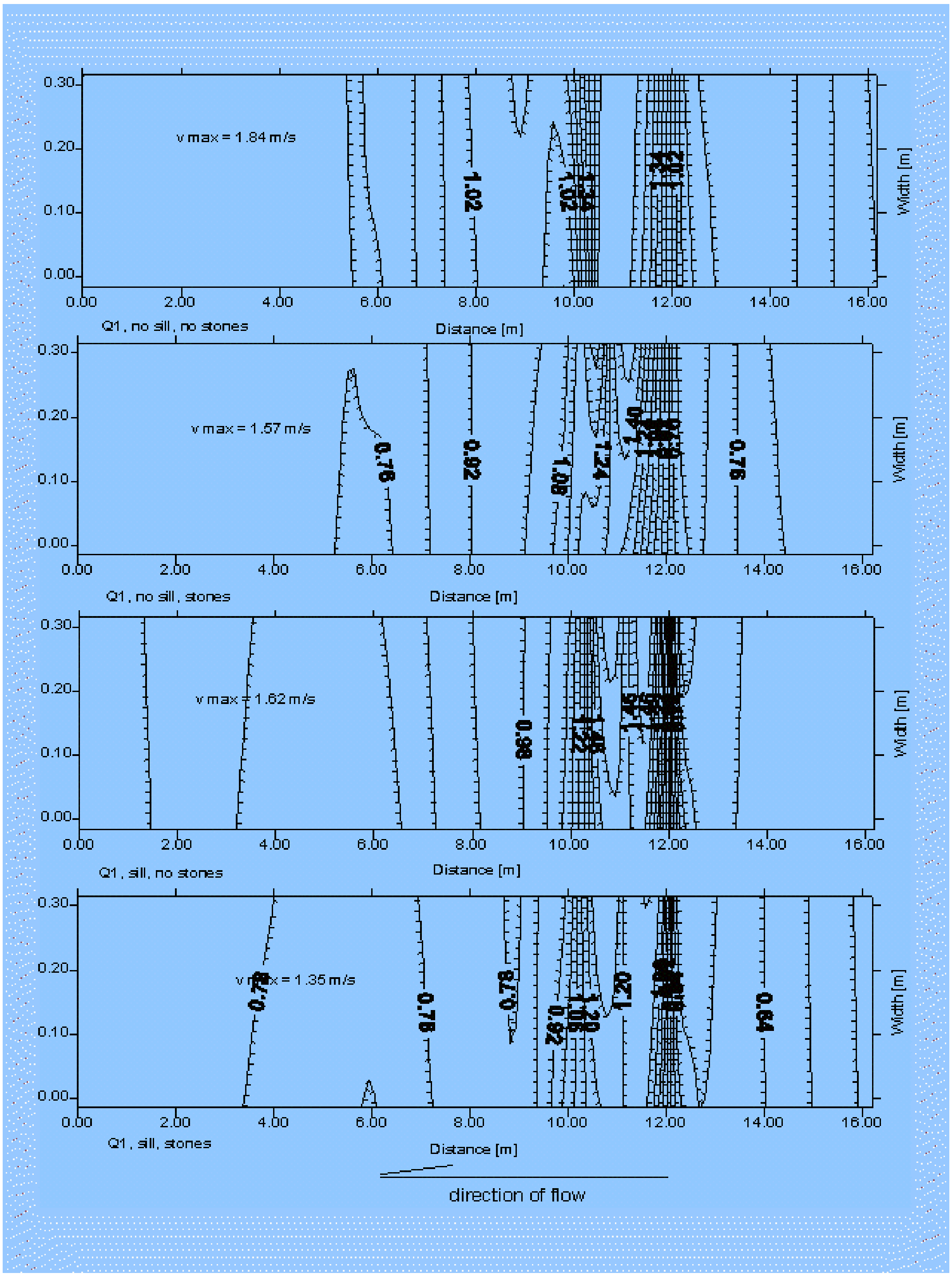

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Figure 3b. The maximum velocities as a function of a position in the channel for Q2 values

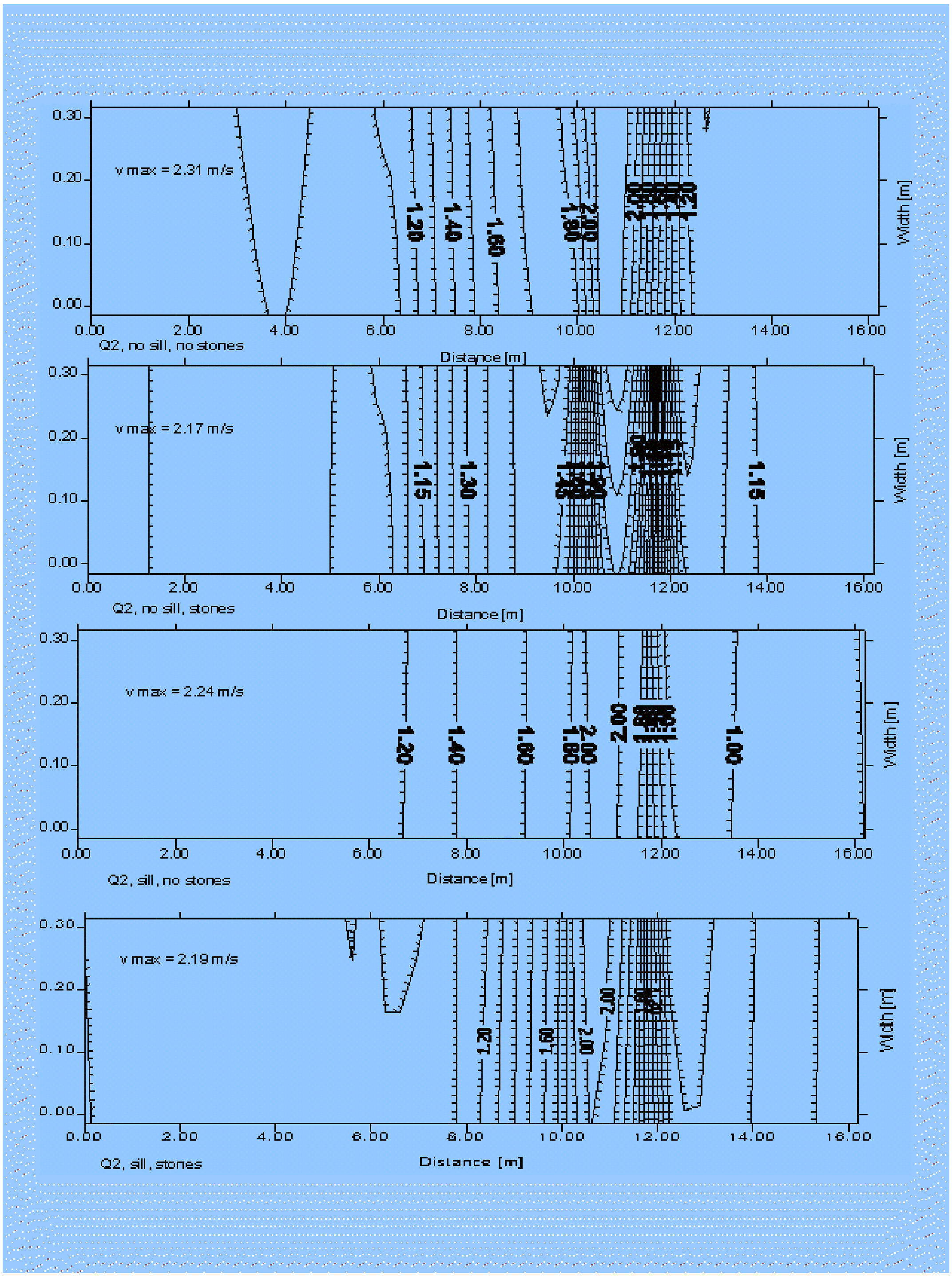

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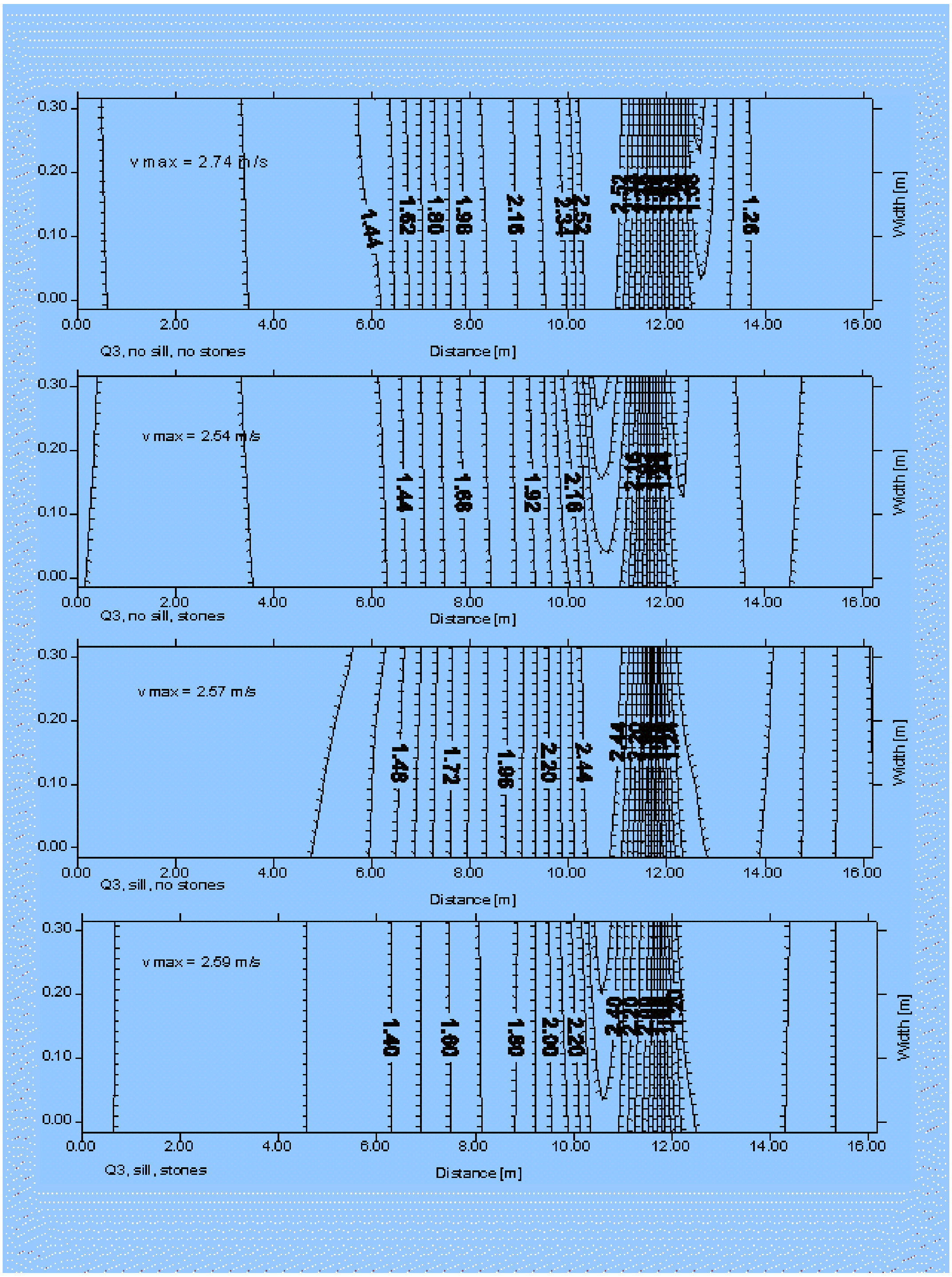
Figure 3c. The maximum velocities as a function of a position in the channel for Q3 values



At the same time maximum Froude numbers were found for all cases. The maximum value of Froude numbers for Q1, Q2 and Q3 were $Fr_{max1}=2.62$, $Fr_{max2}=2.73$ and $Fr_{max3}=2.75$, respectively. The appropriate minimum Froude numbers were as follows: for Q1 - $Fr_{min1}=1.16$, Q2 - $Fr_{min2}=1.51$ and for Q3 - $Fr_{min3}=1.84$. The results are shown in Figure 4.

Finally, in all measured cross sections along the RHS's aprons (those stoned: NS/S and S/S - see farther in the paper for the explanation of symbols) water depths were measured over the stones. Since stone dimensions remained constant the ratio of flow depth to height of the stones was established. For all the run discharges such ratio values are presented in the Figure 5.

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Fig. 4. Froude number values changes in terms of discharges and a type of RHS's

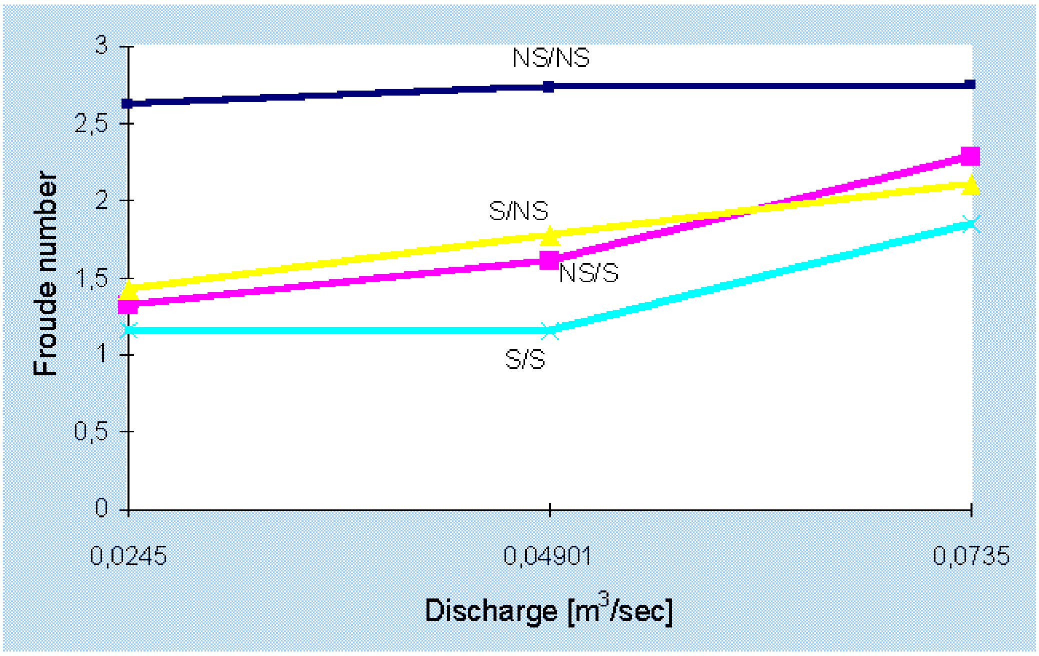

Fig. 5a. Ratio of flow depth to height of the stones on RHS apron: NS/S case

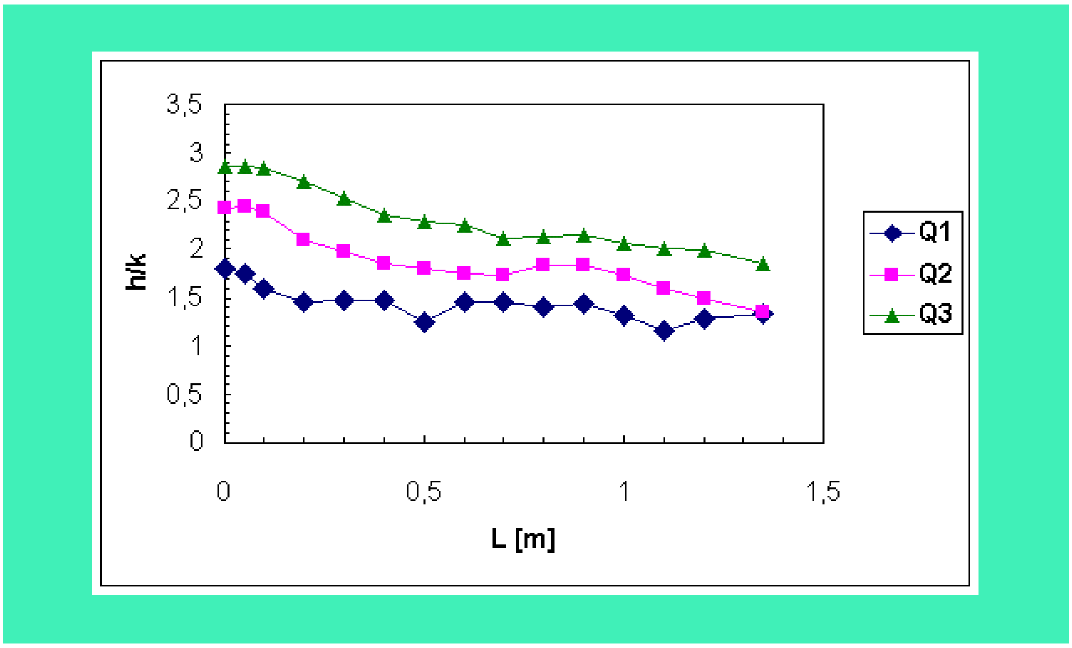

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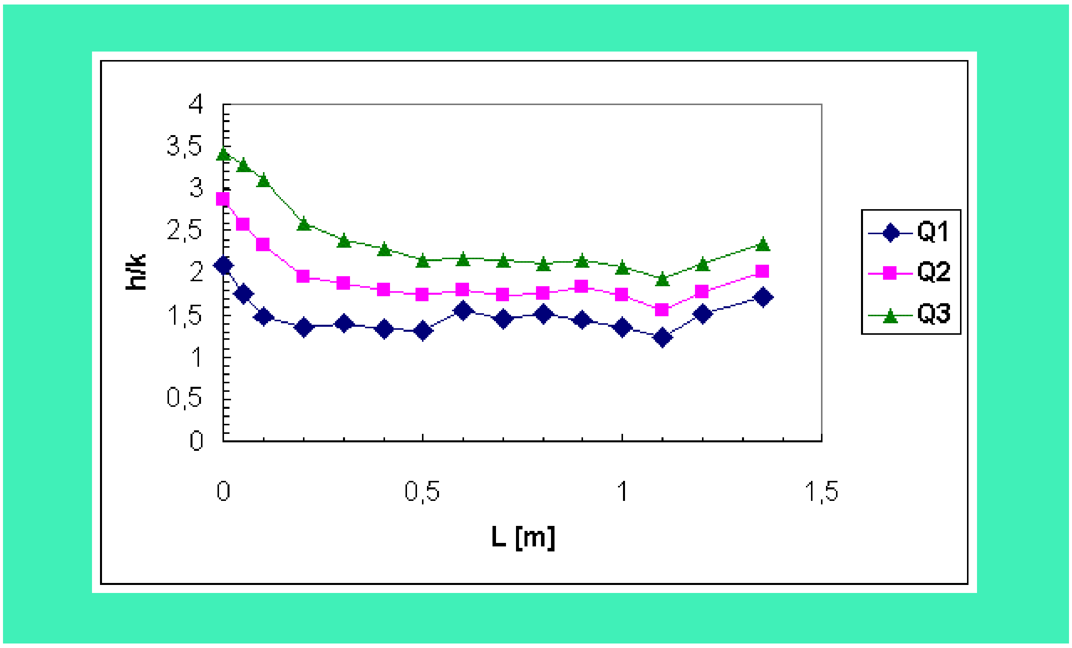
Fig. 5b. Ratio of flow depth to height of the stones on RHS apron: S/S case



SUMMARY AND CONCLUSIONS

The changes in adjustment and location of cobbles and a top sill on a slope apron of rapid hydraulic structure have a substantial influence on velocities distribution and Froude numbers for that kind of a hydraulic construction. Flow velocity and Froude number are the two variables directly responsible for the kinetic energy and the hydraulic jump occurring downstream of any hydraulic structure. Since the RHS is such a structure, one can expect that it would be possible to estimate the hydraulic jump quality by using Froude number values and eventually to find the way of dissipating the energy of flowing water on the slope apron and below the structure. At first it is interesting to trace the velocity distribution along the slope plate of the RHS. For the convenience of the discussion, it is easier to name all four slope-plate features adjustments as follows:

NS/NS - no sill, no stones features
NS/S - no sill, stone features
S/NS - sill/ no stone features
S/S - sill/stone features

In terms of changes of water velocity values for Q1=0.0245m^3/s, there is a big difference in the range of 27% between the NS/NS and S/S ($v_{(NS/NS)}$=1.84m/s, $v_{(S/S)}$=1.35m/s). When looking at the NS/NS and NS/S velocities, this difference is 15% ($v_{(NS/S)}$=1.57m/s) and consequently between the NS/NS and S/NS the difference is 12% ($v_{(S/NS)}$=1.62m/s). Thus, there is only a 3% difference in reducing the maximum velocity when one would compare NS/NS with NS/S or S/NS structure. Such numbers suggest that it really does not matter if we use stones fixed to a rapid apron as the energy-reducing factor or if we simply use a top-sill separately with no stones on the RHS. In both cases we would achieve the same effect as far as reduction of velocity is concerned.

When looking at the largest values of the run discharge Q3=0.0735m^3 the differences in obtained velocities values are as follows: for the NS/NS - S/S structures is 6% ($v_{(NS/NS)}$=2.74m/s $v_{(S/S)}$=2.59m/s), for the NS/NS - S/NS is again 6% ($v_{(S/NS)}$=2.57m/s) and consequently for the NS/NS - NS/S is 7 % ($v_{(NS/S)}$=2.54m/s). In that case (for Q max=Q3) it seems to have not any difference what kind of energy/velocity reducing arrangement we use (stones or a top-sill or both) - the same hydraulic effect would be achieved (reduction of maximum velocity value of 6-7%).

The changes of the roughness of the RHS apron are more interesting when considering the Froude number values. Figure 4 shows all four cases of the RHS structures in terms of changes of the discharge values and the Froude numbers. It is clear that there is a difference between the NS/NS and S/S cases. For Q1=0.0245m^3/s, the Froude's number value difference is 140%, whereas for Q3=0.735m^3/s it drops down to 50%. That comes with structures, which are in one case unlined and in the another case covered with stones and equipped with a sill.

One could say that such differences were just expected. But particularly interesting is, that differences between the Froude number values for the NS/S and S/NS are marginal for all discharge runs. They are as follows:

for Q1 - $Fr_{(S/NS)}$= 1.42, Fr(NS/S)=1.32
for Q2 - $Fr_{(S/NS)}$=1.78 Fr(NS/S)= 1.61
and for Q3 - $Fr_{(S/NS)}$= 2.11, $Fr_{(NS/S)}$=2.28, respectively,

Such results could be interpreted in a way that: it is not a significant difference in applying a stoned apron of RHS or just a single top-sill to achieve similar results as far as reducing the Froude number values is concerned.

Behind such numbers are specific consequences. When talking about Froude number, one has to remember that in terms of dissipating energy, engineers desire a Froude number below 1, which means no rapid flow, and no hydraulic jump; or less than 2.5 when dealing with supercritical flow and standing waves only. In that case the hydraulic jump is very easily dissipated (e.g. using simple chute blocks). Engineers also like to have a bigger Froude number than 4.5, when the full hydraulic jump is developed. In such cases special hydraulics constructions are designed to dissipate the energy of the flume (e.g. dissipating pools). The real trouble is in dealing with the range of the Froude numbers between 2.5 and 4.5. In this case the hydraulic jump is very dangerous and difficult to dissipate. Thus, for practical reasons, it is sometimes better to increase the kinetic energy of flowing water by increasing its velocity upstream (e.g. by changing a structure drop height) to achieve a Froude number greater then 4.5 downstream and consequently deal with a well-shaped hydraulic jump.

For all 4 run discharges, for the NS/NS (stone-bare) structure Froude numbers were between 2.5 and 4.5, which is the least desirable result. However, the situation changes for the S/S NS/S and S/NS arrangements when Froude number values were always below 2.5. It is obvious that the S/S case has the most desirable Froude number value, because it has a sill and cobbles fixed on the slope plate at the same time. But the other two examples (S/NS, NS/S) also give very good approaches as far as dissipating energy is concerned. In other words that means that engineers could build aprons of RHS's with fixed stones or just a single top-sill and expect similar results in term of energy reducing. Finally, the ratios of flow depth to height of the stones on RHS's aprons where stones are present were considered (NS/S and S/S cases). Here one could notice that for NS/S case the minimum value of the ratio is within the apron area only for the Q1 value, whereas for larger discharges (Q2 and Q3) it is below the RHS. The different situation is faced for the S/S case, where for all considered discharges the minimum value of the ratio is placed c.a. in 80% of the RHS apron base length. It means that here one could expect a presence of the hydraulic jump, which in this spot is not dangerous for the structure in terms of energy dissipating and was expected from theoretical predictions [Rhone 1977, Zastera 1984]. Basically, it means that no additional energy dissipaters are needed below the structure (e.g. energy dissipating pool).

As a final conclusion, it has to be said strongly, that RHS structures are environmentally and riverbed friendly since they are similar to the natural river riffles. They could be designed as structures with or without artificial roughness on the slope plate. The consequences of using the top sill are significant, if not essential, in terms of dissipating energy along the RHS plate. However, putting stones on the slope plate would change the visual picture of it making it similar to the environmental site and avoiding spoiling a natural beauty of a gravel stream.

It should also be noted that no additional energy-dissipating device is needed below the RHS (e.g. an energy dissipating pool). However sometimes one would like to construct other additional structures which could be built for different reasons (e.g. for recreating reasons: swimming pools [Radecki and Ślizowski 1998]).

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