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Scour Countermeasures At Long Bridge Abutments

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I. INTRODUCTION

The most common cause of a bridge failure is found in the local scour produced at its piers and abutments. The scour mechanisms round the piers have been extensively treated in the scientific literature, which has allowed to develop estimation methods of the maximum scour depth and the scour evolution in time, quite acceptable according to certain parameters. In the case of abutments, Ref. [7] observed, that out of 383 bridge failures, 25% was due to pier problems while 72% involved the abutments. According to [3] out of 108 bridge failures observed in New Zealand during the period 1960-1984, 29 were caused by abutment problems.

The study of local scour, both at piers and abutments, involves highly complex phenomena and a great number of variables which could be grouped in hydraulic, geometric, sediment and obstacle ones.

In order to minimize these local scour effects and guarantee the abutment safety, the adequate design of abutment revetment is of key significance. Regardless the type of revetment used, the design variables are the same: material size, stratum thickness and plant dimensions, both in flow and cross direction. To dimension the size of revetment material, it is necessary to know the flow velocity, and depth and the dimensions of the pier, the abutment or obstacle, among other variables ([7], [1], [6], [4], [2]). Concerning the plant design, there are some recommendations on the revetment suggested in the technical literature. For example, in [5], it is recommended that the width should be equal to the estimated maximum local scour and extended in all directions round the obstacle. In the case of pier protection, although the recommended extension is between 1.5 and 6 times the pier width, these values are frequently increased.

Once built, the presence of the revetment prevents the development of scours at the abutment area. This produces a change in the flow pattern and, as a result, in the bed topography. Therefore, the revetment is subjected to different actions from the ones it was formerly designed for.

The experimental sequence presented here had as an objective to make an exploratory and introductory analysis of the resulting erosive effects at locating a bed protection by an abutment of a brief bridge, specially the interaction between the revetment, discharge distribution and scour development, ye.

Considering a specific bridge width, the presence of revetment and a non-erodible area at the abutment, can affect the in discharge distribution in the area. The revetment width becomes a fundamental variable as it defines the percentage of the opening liable to be scoured and the one remaining invariable. Another parameter analysed is the revetment´s roughness. Even if the riprap revetment is one of the most commonly used as protection, other types of material are also frequent such as concrete slabs, geotextile stratum with concrete blocks, etc., each one with a different surface roughness.

II. EXPERIMENTAL DESIGN

The experience was performed in a laboratory flume, 20m long, 10.2m wide and 0.8m deep, belonging to the Hydraulics Laboratory of the Facultad de Ingeniería y Ciencias Hídricas (FICH) – Universidad Nacional del Litoral, specially adapted for the aims of this investigation. The experimental flume has an initial 5 m long fixed-bed followed by a 10 m long erodible bed and a final section with another 5 m long fixed-bed. The erodible bed consists of a uniform sand streambed, which is 0.60 m thick, with a mean diameter, d_{50}, of 0.001 m and a standard deviation, σ_g, of 1.3. The cross-section development to the flow coincides with the one of the flume.

A 3.6 m long partial closure was placed in the erodible bed sector, 11 m downstream from the inlet section, this closure is achieved by means of a 0.12 m thick vertical-wall abutment on the right bank and was kept constant in all the test (Fig. 1).

The laboratory experiences detailed below have one of the geometric and hydraulic conditions developed by [8], where the scour hole was freely developed at the abutment, thus becoming a reference or model test (Fig. 2). The parameters related with the test were:

- Geometrical: Opening width (B): 4 m.
- Hydraulic: Total discharge (Q): 0.144 m^3/s, Opening unit discharge (q): 0.036 m^2/s
- Geometry of the scour hole at the abutment: Maximum scour depth (ye): 0.348 m, width: 0.84 m

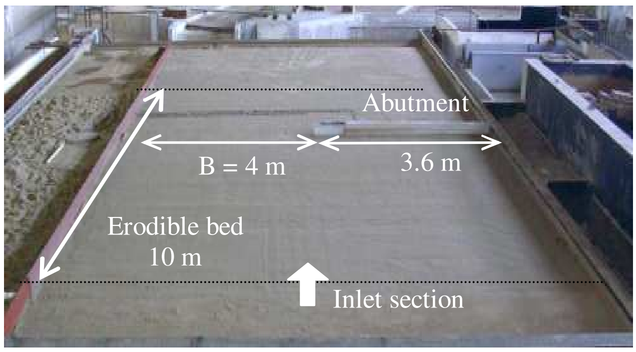

Figure 1. Laboratory flume

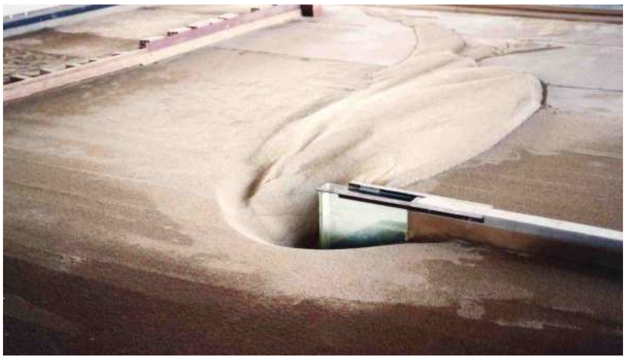

Figure 2. Scour hole in the reference test without protection [8].

The protection was made of a group of concrete slabs. The tests were performed varying the revetment width (b), while length in the flow direction (l) was kept constant (Fig. 3). The width was considered as the revetment extension, cross-section to the flow from the abutment. The tested b were 0.5 m, 1 m, 1.5 m, 2 m, 3 m and 4 m metres, for that case the opening section was completely protected.

Two different types of roughness were used for each revetment width, so as to observe in what way the resulting scour is affected by the flow structure in relation to the change of revetment material. The first type of roughness, considered as smooth, was obtained by placing a layer of sand similar to the rest of the flume (d_{50} = 0.001 m). The increase of roughness was achieved pouring broken stone directly onto the concrete slabs. The mean diameter of this material was 0.02 m (Fig. 4). It is worth mentioning that scale factors related to roughness are not taken into account as the study objective is the analysis of the qualitative effect of the revetment material size in the local scour produced by the presence of the abutment.

A 0.10 m wide boulder belt was placed acting as a transition between the rigid revetment and the surrounding erodible bed so as to avoid local perturbations (Fig. 3).

Since this was a preliminary study, the deformation of the revetment was not introduced as another element for analysis, by which reason only concrete slabs were used. This variable will be incorporated in a subsequent stage, with further details on the topic, including various types of flexible revetments.

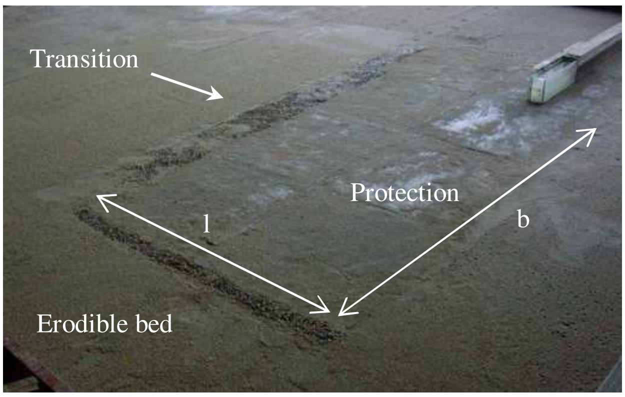

Figure 3. Location of boulder transition area in a protection, width b = 3 m

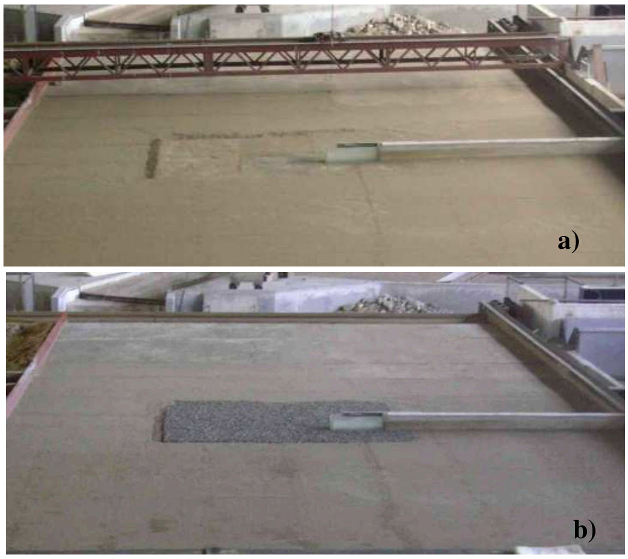

Figure 4. Revetments configuration for a protection width of 2 m. a) Sand roughness and b) Broken stone roughness

The sequence of the tests performed is presented in Table I. It shows the cross-section dimension of the revetment and the roughness used in each test. It is noted that the references to each test consists of a letter followed by a number; the letter identifies the type of roughness used, S for "smooth", with sand, and R for "rough", with broken stone, while the number shows the revetment width, b, in metres. In every case the tests lasted 24 hours.

Once the scours developed, the bed and water surface levels and velocity were measured in the following places:

- a cross section coinciding with the upstream side of the abutment.

- a cross section coinciding with maximum scour depth, generally located downstream of the opening section.

TABLE I.
SCHEDULE TESTS PERFORMED

Test	Protection width b (m)	Protection roughness
S 0.5	0.5	Sand
R 0.5	0.5	Broken stone
S 1	1.0	Sand
R 1	1.0	Broken stone
S 1.5	1.5	Sand
R 1.5	1.5	Broken stone
S 2	2.0	Sand
R 2	2.0	Broken stone
S 3	3.0	Sand
R 3	3.0	Broken stone
S 4	4.0	Sand
R 4	4.0	Broken stone

The bed and water surface levels were measured by means of a point gauge with a vernier scale, together with an optical level of precision. The three velocity components were measured in each of the mentioned sections with an Acoustic Doppler Velocimeter (ADV).

Once the test was finished and the flume was drained, a detailed survey was performed of the sector where the revetment and the developed scour hole were located. The measurements were taken in different verticals across the section´s width.

III. Analysis of Result

The results of the test are separately analysed below, in relation to the influence of the two studied parameters, the width and roughness of the bed protection. The aim is to understand which were the physical phenomena defining the problem and provide qualitative ideas about the design of bed revetment.

A. Influence of the protection width

First of all the analysis will concentrate on the results of the tests when its protections were covered with sand (called "smooth") especially those related to the characteristics of the resulting scour holes (their maximum depth, geometry and location) as much as the associated distributions of discharges. In this way we try to identify the answer of the phenomenon being studied only as regards the change in the length of the protection used. A posteriori it will be incorporated the effect introduced by the superficial roughness which will be watched comparing the previous results with the ones obtained in the experiences performed with those bed revetments whose roughness was represented by broken stone.

1) Maximum scour depth

The maximum scour values, y_{ep}, measured in the different tests were quite similar, when the width of revetment surpassed the metre. In every case, the scour value is smaller than the model test (y_e = 0.348 m) and was observed between 0.30 m and 0.70 m downstream from the end of the revetment, slightly varying its position in relation to the test (Fig. 5). The curves corresponding to revetments width less than the metre have a quite different behaviour from the others, this is because the hole was developed on one side of the revetment. The maximum scours are clearly higher than the other tests, although they are still smaller to the values obtained in the reference test.

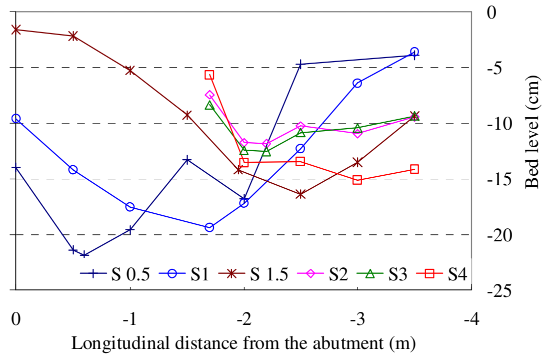

Figure 5. Longitudinal profile over maximum sour values

Considering the results obtained, it could be concluded that the protection is effective in reducing the maximum depth in the scour hole. However, it should be born in mind that, even if smaller, the scour shifted and affected other sectors which, without the revetment, would not be scoured.

2) Geometry and location of the scour hole

The width of the protected area in the abutment section does not only determine the maximum depth values but also define its location. When "b" is large, the presence of the revetment prevents the development of scours in the opening section. This is observed in the test S4, where the revetment covers the total flow section, and the complex three-dimensional configuration of the flow originated by the presence of the abutment makes it evident its removal capacity approximately 1.70 m downstream from the abutment section (Fig. 6a)

In tests S2 and S3 the results were similar, both as regards maximum scour values and location (Fig. 6b). Only when the revetment width is smaller than 1.5 m (S0.5, S1 and S1.5) there is a substantial change in the scour development. In this case, the flow was able to erode the material in the area next to the lateral limit of the revetment so that the hole was located upstream and had a greater extension in the direction of the main flow (Fig. 6c).

The scour hole geometry was significantly different if it placed totally downstream of the revetment instead of by its. In the cases located downstream of the revetment, the maximum depth value was kept almost constant in the flow direction, producing an elongated hole (Fig. 5), which differs from the typical cone-shape of most scour holes at the abutment (Fig. 2). When the hole was placed to one side of the revetment (S0.5, S1 and S1.5), after reaching its maximum depth, the bed quickly recovers downstream (Fig. 5).

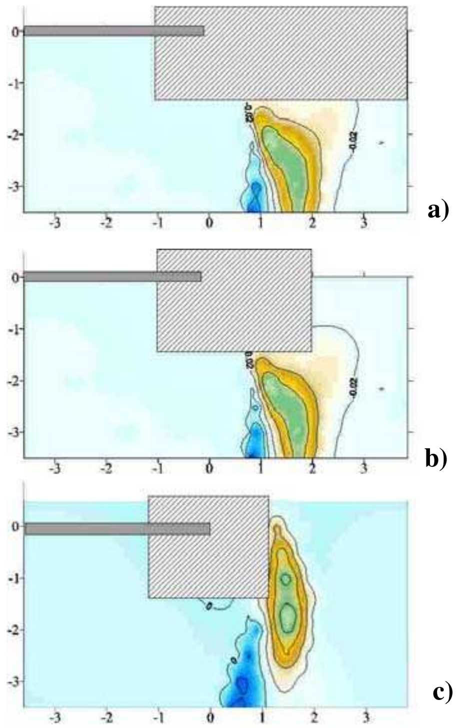

Figure 6. Bed level in the area near the abutment.

The appearance of the cross sections corresponding to the scour hole is characterised by the V-shape in the area of maximum scours, with steep slopes on the bank near the revetment (Fig. 7a). In some of them, the scour development is observed in the area next to the previous one, farther from the lateral limit of the revetment, but with a less steep cross-section slope (Fig. 7b). In some cases, there is a second hole in this area (Fig. 7c).

3) Unit discharges

From the velocities measured in different points of verticals strategically placed in the cross sections, the cross distributions of unit discharges were represented. This parameter was calculated as the product of the average velocity in the vertical and the depth of the flow in that point. The analysis of such results corresponding to the section of the opening shows that when the width of the protection was larger than 1.5 m the final distribution of unit discharges is similar to the ones obtained at the beginning of the tests, before the development of the scour holes. In effect, the unit discharges are uniformly distributed throughout the section, except in a small zone where there are values whose magnitude decreases as it approaches the abutment. This behaviour coincides with the one informed by [8] in reference to the initial distribution of the flow observed in the section of the abutment location without any protection.

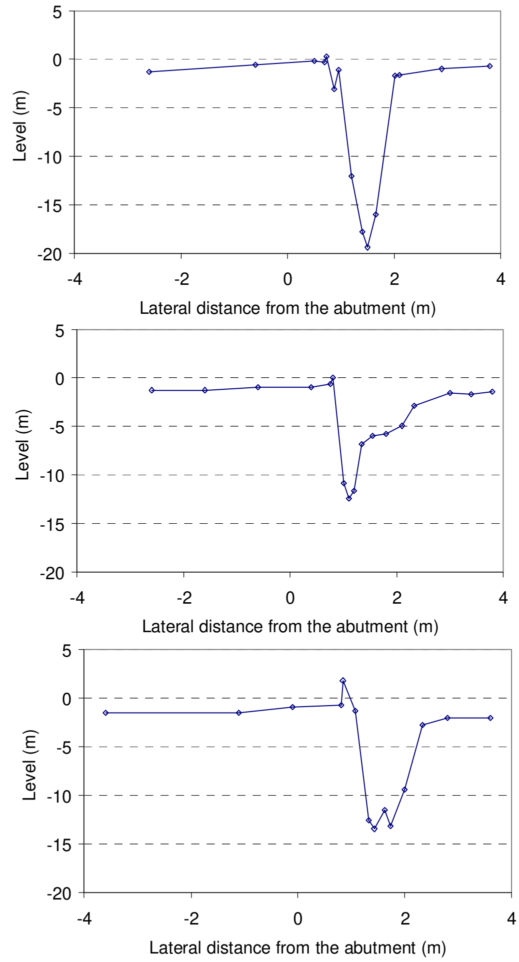

Figure 7. Cross sections of maximum depths

a) in S1 at -1.7 m downstream abutment, b) in S3 at -2m and c) in S4 at -2.5m

As it is shown in Fig. 8, the cross distributions of unit discharges showed a special behaviour in the experiments where the width of the protection was smaller than 1.5 m, that is to say that in those situations in which deepenings of the bed were developed at the side of the protection. In Fig. 8a the curves corresponding to S0.5 y S1 show an important concentration of discharges in agreement with the sector of maximum scour and a more uniform distribution, with remarkably inferior unit discharges, for the rest of the section that, without any revetment, does not show to have been exposed to significant scour processes. This situation could be comparable with the one verified in the case of a long abutment without any protection [8], as it is shown in Fig. 8b.

Fig. 9 show the discharge distribution along the sections where the largest scour was located also shows a higher concentration in the areas of bigger scours. However, the matching between the maximum unit discharge and maximum depth is not exact. Instead, the greatest discharge is found slighted displaced to the left bank, opposite the abutment´s location (Fig. 9). Once again, on comparing the tests with a revetment width of over 1 metre, it was observed that the discharge distribution was quite similar in all of them.

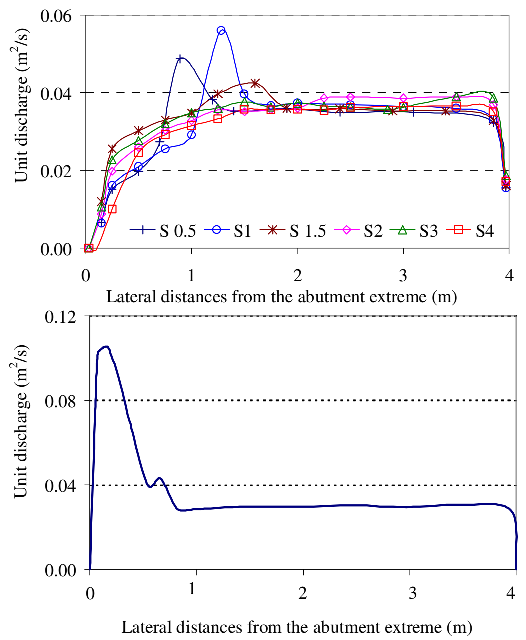

Figure 8. Unit discharge distribution along the opening section for: a) Tests with revetment; b) Reference test without revetment, [8].

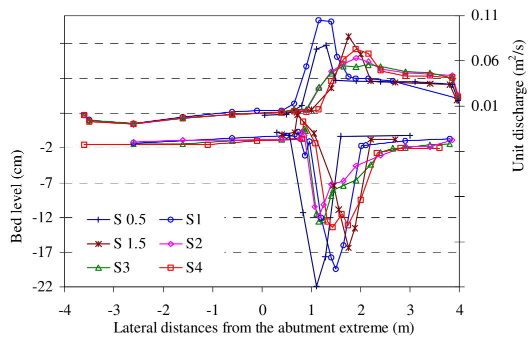

Figure 9. Unit discharge distributions and bed levels, in the maximum scour area.

B. *Influence of roughness*

1) *Maximum scour depth*

Fig. 10 shows a comparison between the tests that had protections covered by sand and those that had broken stone, in terms of the maximum scour depths that were reached. As there can be seen, both curves have the same tendency, but the one corresponding to the rough revetment shows deepenings slightly inferior, this fact is probably attributed to the greater dissipation of the flow energy due to the greater roughness of the bed in that sector. Notice that the depth differences decreased as the protection width was smaller.

2) *Geometry of the scour hole*

The behaviour of maximum depths within the resulting holes was similar to the tests in which the roughness was smooth. Once again, there is a clear difference between the geometry of the holes corresponding to narrower than 1.5 m revetment in relation to wider ones (Fig. 11).

3) *Unit discharges*

The behaviour of unit discharges in the opening section does not show significant changes when compared to the case in which sand provided the revetment roughness. It can be noticed how the discharge distribution is affected by the bed topography (Fig. 12). There are also significant increases in unit discharges in relation to smaller revetments (R0.5 and R1). The curves observed in tests R2 and R4 show a slight increase in the unit discharges, coinciding with the lateral extreme of the revetment, which remained constant along the adjoining sector liable to be scoured. This would show a lateral deviation of discharges from the protected to the unprotected area, originated by the strong resistance to the flow due to the presence of stones. It is worth mentioning that in such cases the scour holes were developed downstream from the revetment, approximately between the cross lateral distances 1 and 2 m from the abutment.

On comparing the discharge distribution with equal revetment's widths but different roughness, it is to be observed that in the section with the biggest scour, the distributions of unit discharges show the same tendency (Fig. 13). In the case of rough surface tests, the curve smoothes, probably as a consequence of energy loss produced by the increase in roughness, thus generating a much more uniform scoured section, where the limits of the hole in R4 are not so marked as in S4.

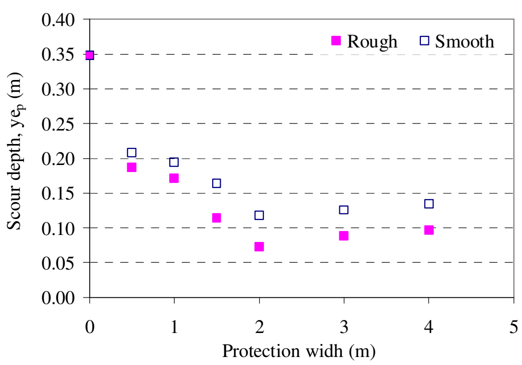

Figure 10. Maximum scour depth values, y_{ep}, grouped by type of roughness.

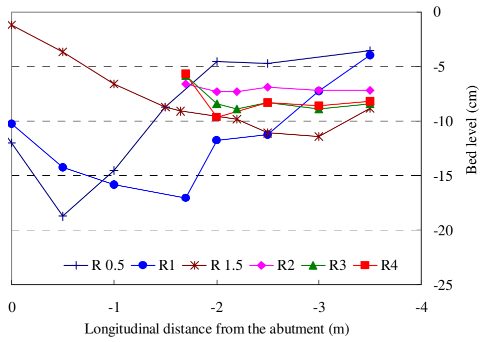

Figure 11. Longitudinal profile of scour holes for rough revetments.

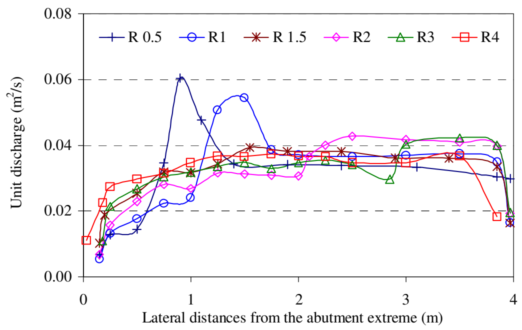

Figure 12. Unit discharge distribution along the opening section for rough revetments

Finally, it is worth noticing how the revetment becomes an important factor to be considered in the analysis of scouring processes at the abutment. Clearly, the complex three-dimensional flow pattern at the abutment, together with the disturbances due to the presence of the revetment, need to be adequately considered to understand the resulting phenomenon more accurately.

One way of observing the three-dimensional flow is to analyse the velocity component vectors. Figs. 14a and 14b show the deviation of velocity vectors in relation to the main flow direction along the opening cross section α, considering both the initial conditions as well as the final pattern, i.e., once the scour hole has developed.

In all of the tests performed, the velocity component in cross direction, v_y, at the beginning of the scouring process had significant values at the abutment, with angles over 50 degrees in relation to the main flow (Fig. 14a). Such values exponentially decreased as the analysis target was focused farther way from the abutment.

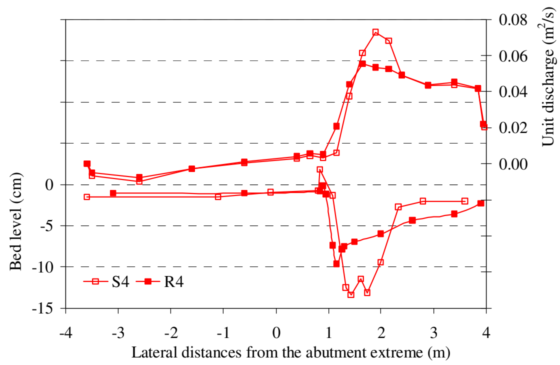

Figure 13. Unit discharge distribution and bed level in the maximum scour section.

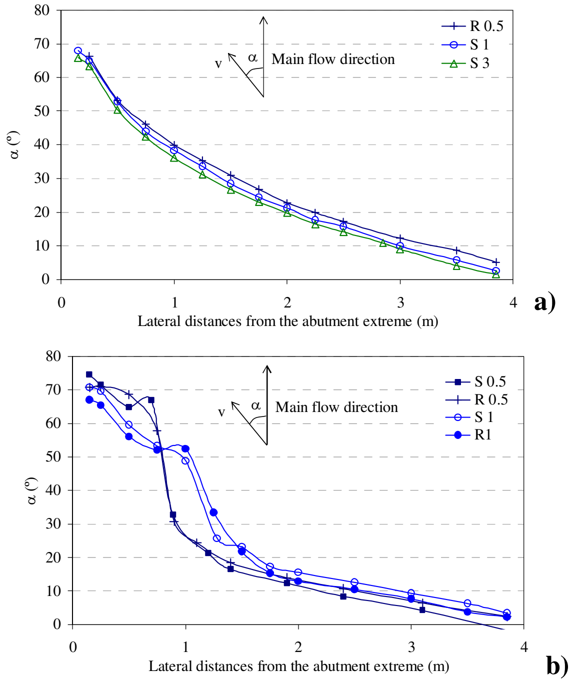

Figure 14. Deviation of velocity vector in relation to the main flow direction in the opening cross section: a) in initial conditions and b) after the development of the scour hole.

Once the scour hole had developed (Fig. 14b), the values of angles α, increased and noticeably moved away from the general tendency. These differences are observed in the lateral distances where the scour hole was located, thus matching the resulting scouring patterns.

IV. Conclusions

The laboratory tests performed constitute an exploratory analysis and a first approximation to the influence of a bed revetment at the abutment of a relief bridge on the flow pattern and the development of local scours next to it.

The results show that the presence of the revetment reduces, as expected, the maximum scours at the abutment but does not palliate the problem. On the contrary, it produces a displacement of the scour hole to areas which were not previously affected by the presence of the abutment, like the bridge piers. These observations warn about the importance of the correct design of an abutment revetment.

The location of the scour hole is clearly influenced by the revetment width. If it is big, the hole is shifted downstream and when it is small, it locates at one side upstream, nearer the abutment section. The existence or non-existence of a scour hole at the side would be related to the flow pattern at the abutment and the presence of developing cross flows.

The increase in roughness on the revetment surface for the range of the variables considering, produced a decrease in the maximum scours of about 15%.

Acknowledgment

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