First International Conference on Scour of Foundations, ICSF-1
Texas A&M University, College Station, Texas, USA   November 17-20, 2002

Riprap at Rectangular Bridge Piers Under Oblique Incident Flow

By

José Angel Sáinz[1], Rodney Salgado[2]

ABSTRACT

The influence that protective riprap has on the scour holes that develop near bridge piers has been studied in clear water conditions with rectangular piers non-aligned with the flow. Non-dimensional graphs, relating the characteristic dimensions of the scour holes with the flow incident angle and with the riprap elevation above bed level and its width, are presented. Also, the necessary minimum width of riprap, deduced from tests, is compared to criteria proposed by various authors.

INTRODUCTION

In the last few decades the phenomenon of the localized scour holes around bridge piers has been investigated. Various authors (Breusers, 1977; Jain, 1981; Raudkivi, 1986; Melville, 1997) have analyzed experimentally, in clear water as well as live bed situations, the influence of the shape, size and situation of the pier, the size and gradation of the sediment, the flow depth, etc. on local scour magnitude.

The influence of the flow incident angle has been analyzed experimentally by various authors (Laursen et al., 1956; Chabert et al., 1956; Maza Alvarez, 1968; Témez 1988; Raudkivi et al., 1991; and Melville et al., 1988).

Countermeasures for local scour at bridge piers can be grouped in two categories: armouring devices and flow altering devices. Various authors have analyzed alternative armouring devices such as dolos, tetrapods (Fotherby, 1992), toskanes (Ruff et al., 1995), gabion mattresses (Simons et al., 1984) and cable-tied blocks (Bertoldi et al., 1994).

[1] Associate Professor, Departamento de Ciencias y Técnicas del Agua y del Medio Ambiente, Universidad de Cantabria, Avda. Los Castros s/n, 39005 Santander (España), (sainzja@unican.es)
[2] Civil Engineer, Consejo Nacional de Electricidad CONELEC, Avda.Amazonas N33-299 e Inglaterra, Quito (Ecuador), (rsalgado@conelec.gov.es)

In the case of protection by means of riprap, the size of the protective element as well as the riprap planform width must be defined.

The size of the riprap elements depends mainly on the flow velocity. Neill (1967) and Maynord (1989) studied the stability of the riprap elements in undisturbed flow. Various authors (Bonasoundas, 1973; Quazi et al., 1973; Breusers, 1977; Témez, 1988; Raudkivi et al., 1991; Parola, 1993; Chiew, 1995; and Lauchlan, 1999) have proposed equations for the specific case of protection of bridge piers. These formulations, applied to the same flow conditions, produce quite different results.

Concerning the necessary planform width of the riprap, various authors (Laursen et al., 1956; Maza-Alvarez, 1968; Bonasoundas, 1973; Témez, 1988; Chiew, 1995) have established criteria, that when applied to the same case, lead to very different solutions.

This work is an extension of Duarte et al. (1999) and its main purpose is to analyze the influence of the flow incident angle, the width of the riprap (w) and its placement level (d), on riprap stability as well as on the development of localized scour holes on rectangular bridge piers, in clear water situations under permanent subcritical flow.

EXPERIMENTAL PROGRAM

The tests were carried out in the Hydraulics Laboratory in the Civil Engineering School of the University of Cantabria (Spain) in a methacrylate horizontal channel, 9-m long, 0.90-m wide and 0.45-m high.

In the middle of the channel a 1.5-m long, 0.90-m wide and 0.18-m deep mobile bed zone was prepared and filled with sand of 2.65 t/m^3 specific weight and size between 0.84 mm and 1.19 mm (D_{50} = 1.0 mm).

In order to define the critical velocity of beginning sand motion, in conditions of undisturbed flow, several tests were carried out by gradually increasing the discharge. A value of 0.32 m/s was obtained for this velocity, with a discharge of 40 l/s and a water depth of 14 cm. In order to guarantee the flow in clear water conditions during the remaining tests, a discharge of 35 l/s was adopted with a corresponding velocity of 0.29 m/s (U/U_c = 0.9) and a water depth of 13.5 cm.

The characteristics of the channel have conditioned the dimensions of the piers and the flow incident angle to be tested. One type of pier was considered: a rectangular section with a 50-mm width (b) and 100-mm length. Four values of the flow incident angle (β) were considered: 0º, 10º, 20º and 30º.

Based on the results from Duarte (1996), a riprap element size in the range between 4,8 mm and 6,4 mm (D_{p50} = 5,5 mm) has been considered. This value is in accordance with the application of the criteria proposed by some of the aforementioned authors to test conditions.

Three types of cases have been considered, according to the elevation of the riprap:

- above the channel bed (d = -b/2 and -3b/4)
- at bed level (d = 0)
- below the channel bed (d = b/2 and b)

These cases attempt to represent the real situations in which the riprap can be found: above, at, or below bed level corresponding to the general scour during floods (Figure 1).

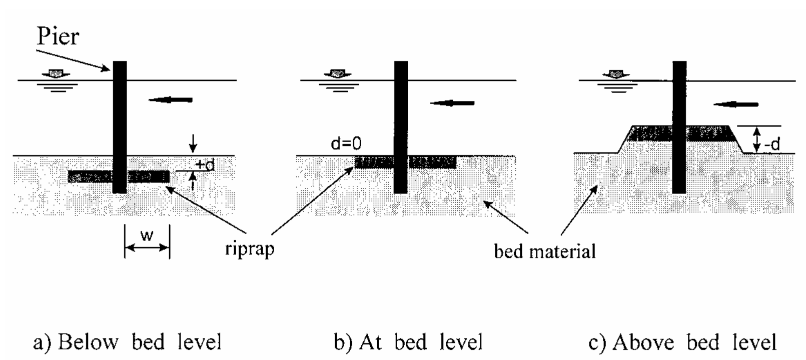


Fig. 1. Riprap arrangements with regard to the bed level.

Also, for every elevation of the riprap, different uniform widths (w = b, 3b/2 and 2b) around the pier were considered, using a rectangular format. A value of b/3 was adopted as protection thickness, which always constituted a minimum of two element layers.

Each of the 64 test cases was submitted for 10 hours to a practically uniform flow, of coincident direction with the alignment of the pier, with a flow depth y_0 =13.5 cm and a velocity U = 0.29 m/s.

EXPERIMENTAL OBSERVATIONS

Initially, the behaviour of unprotected rectangular piers was analyzed and used as a reference term. The maximum depth (d_s) observed was 63 mm, 76 mm, 84 mm and 95 mm for the flow incident angle values of 0º, 10º, 20º and 30º, respectively.

For all tests, qualitative and quantitative observations were made (Salgado, 1997). Qualitative observations include those related to the location of the scour hole.

In the case of an unprotected pier or when the riprap is located below bed level, the scour hole develops around the pier and the riprap is partially uncovered. When the riprap is located at or above bed level, the scour hole develops downstream the riprap.

From a quantitative point of view, a detailed analysis of the scour hole was carried out in each one of the tests. With the help of a device specially designed to move over the canal, the scour hole depth was determined on a grid. These data were processed by means of a computer program and a graphic representation was obtained in the form of elevation curves for each scour hole. Figures 2 and 3 show the scour holes corresponding to two specific tests.

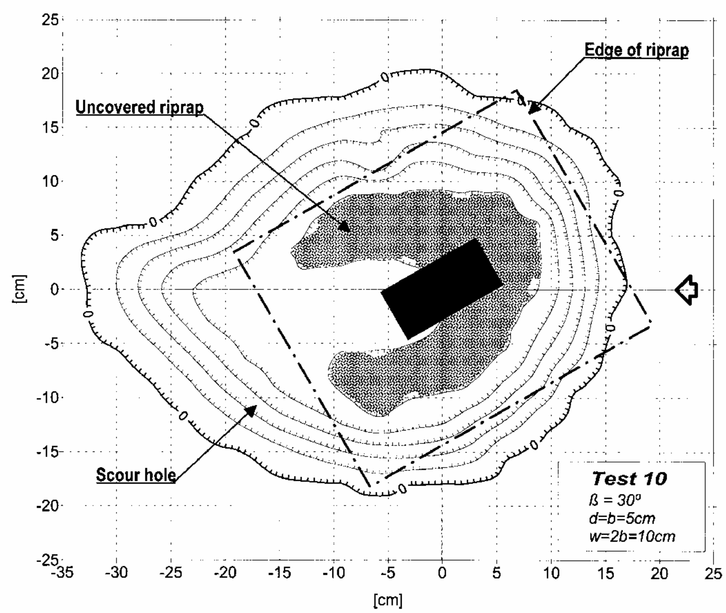


Fig. 2. Scour hole produced in test No. 10, with riprap below bed level.

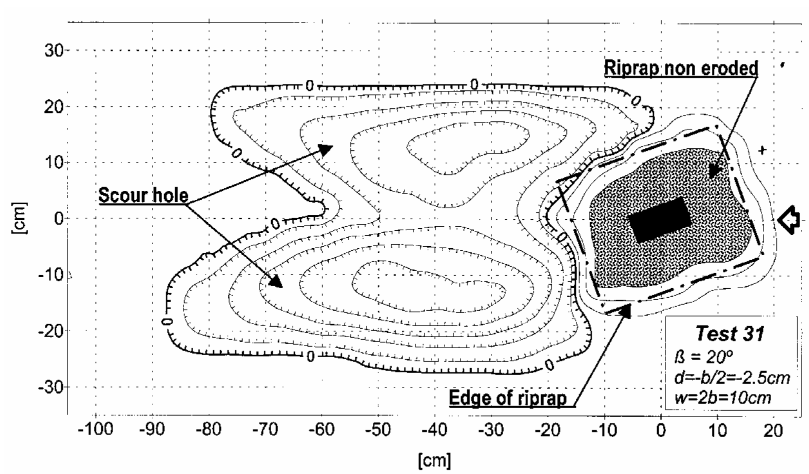


Fig. 3. Scour hole produced in test No.31, with riprap above bed level.

Figures 4 and 5 show the variables measured in the 64 scour holes drawn by means of the computer program: the frontal (L_1) and back (L_2) longitudinal extension of the scour hole, its maximum depth (d_{sm}) and the width of the uncovered riprap surface. This width is characterized by the maximum of the dimensions a_1, a_2, a_3 and a_4.

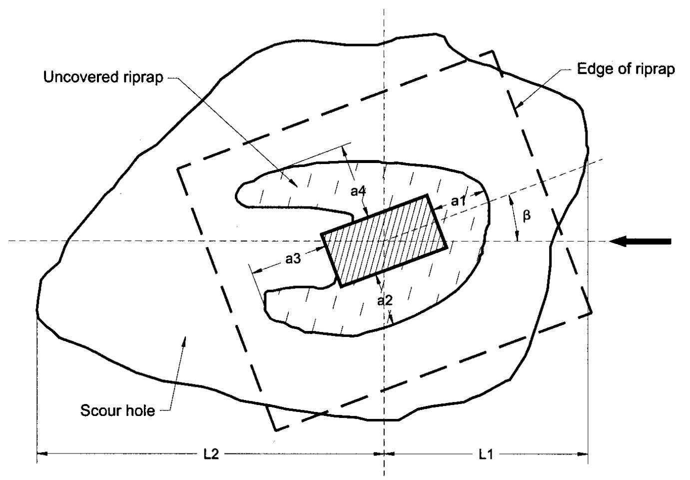


Fig. 4. Schematic definition of the variables with riprap below bed level.

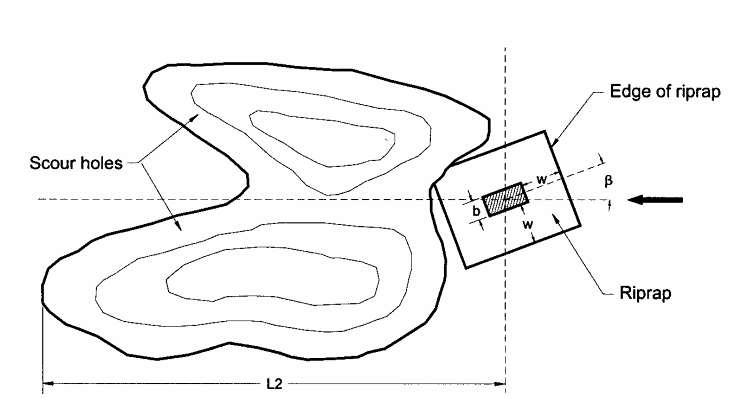


Fig. 5. Schematic definition of the variables with riprap above bed level.

ANALYSIS OF RESULTS

The values of the variables (L_1/b; L_2/b; d_{sm}/d_s; a/b) are presented in non-dimensional graphs. In said graphs, the points corresponding to each series of measurements, associated with the same symbol, have a straight line drawn through them, reflecting the result of a possible linear interpolation among them.

<u>Longitudinal extension of the scour hole</u>

The scour hole extends upstream mainly when the protection is located below bed level ($d > 0$). In which case, practically no variation of its length exists in function with d, nor does an influence of the parameters w and β exist ($L_1/b \cong 3.5$).

The downstream longitudinal extension is more important than the upstream longitudinal extension. Figure 6 illustrates the variations of the scour hole length downstream, as a function of *d*, *w*, and β. The greater values are produced for ripraps located above bed level, greatly increasing the length upon raising the placement level. The increase of downstream scour hole length is more sensitive to the raising of the placement level than to the increase of riprap width.

On the other hand, increasing β results in an increasing scour hole length. For every d/b value considered, the L_2/b variation is almost linear with β.

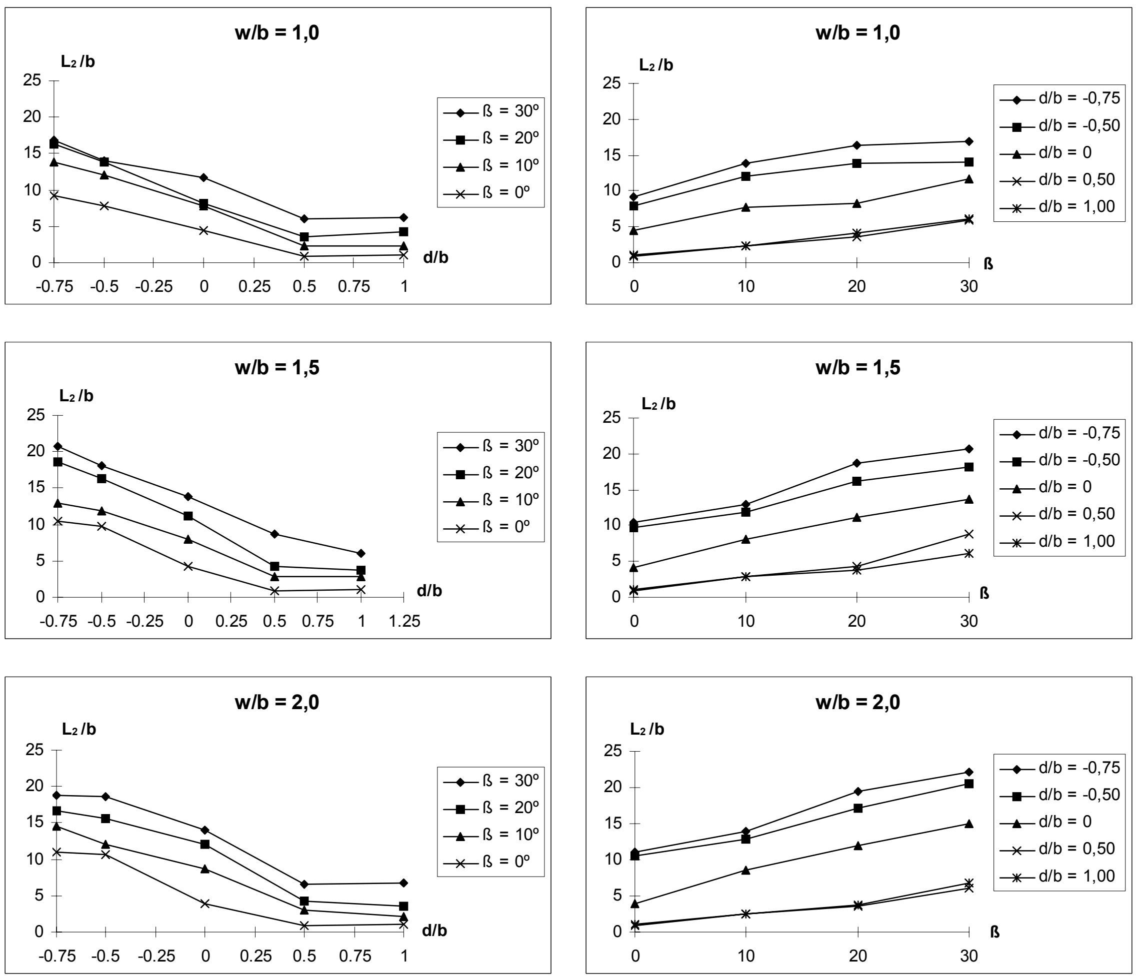


Fig. 6. Longitudinal extension of the scour hole downstream.

<u>Maximum scour hole depth</u>

In figure 7, the values of the maximum scour hole depth (d_{sm}) obtained from tests without protection are presented and compared with the values proposed by different authors, varying the flow incident angle. A very good agreement is observed.

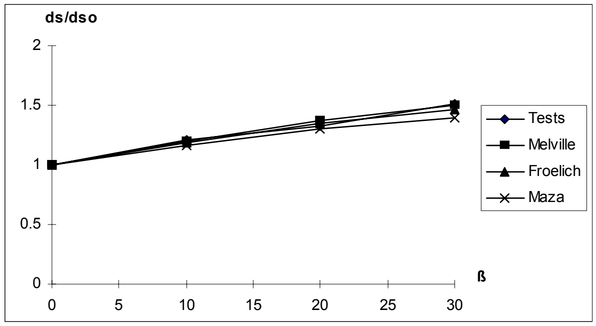
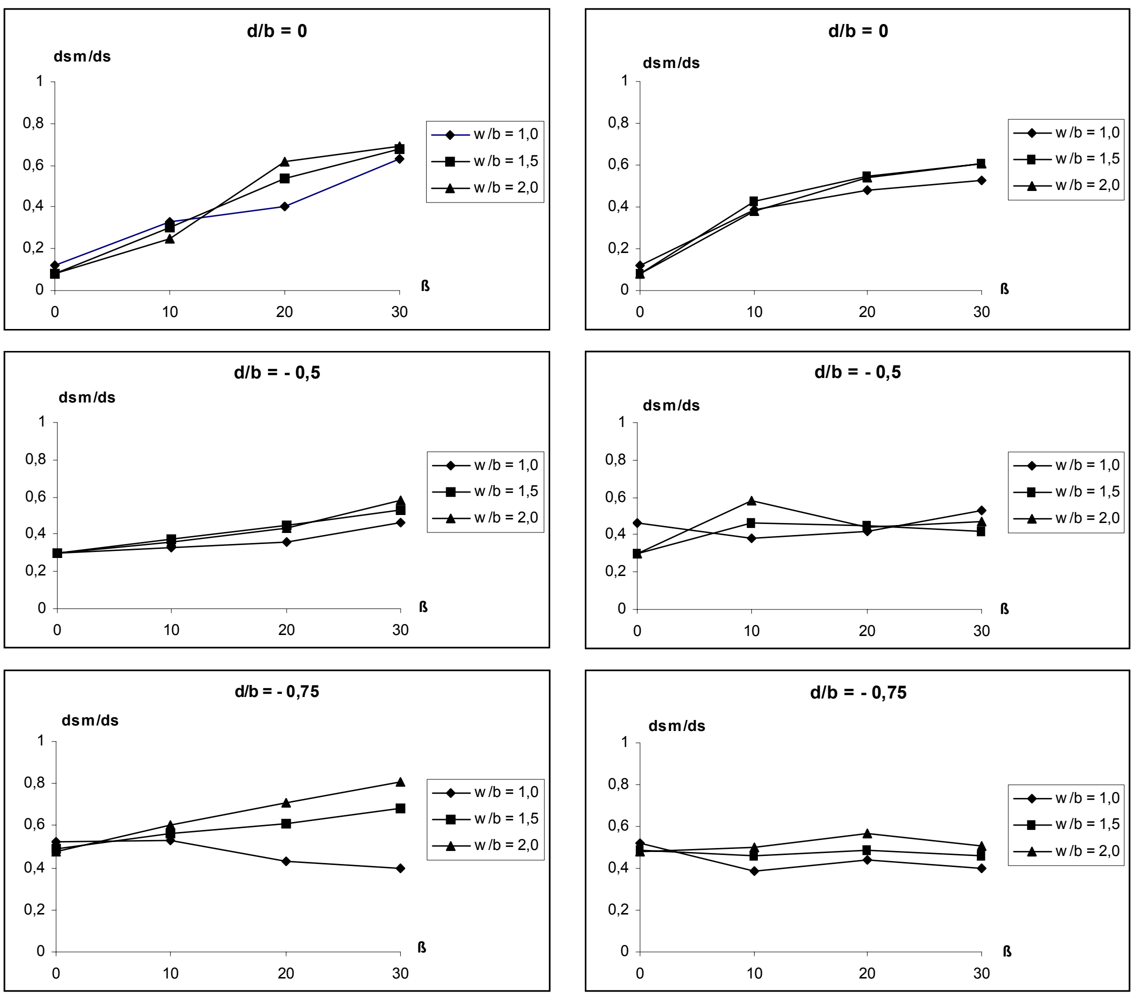


Fig. 7. Scour hole depth for unprotected piers. Comparative analysis

Obviously, when the riprap is located below bed level, the value of d_{sm} coincides with the riprap placement level. For d = 0 or d < 0, two almost parallel scour holes are developed downstream the riprap. Figure 8 illustrates the influence of d, w and β on the maximum scour hole depth (d_{sm}). The values obtained for w/b = 1.0 with β = 20º and β = 30º are anomalous due to the downstream edge of riprap failure.



a) Left hole b) Right hole

Fig. 8. Maximum scour hole depth

Results for right and left scour holes differ slightly. For the left hole, the relation between d_{sm}/d_s and β is almost linear, with decreasing slope for increasing β values. For the right hole d_{sm}/d_s is almost independent of β for d/b < 0.

Minimum riprap width

When the riprap is located below bed level, the graphic representation of the different scour holes show than the extension of the uncovered protection from the right lateral side is the greatest of the four dimensions considered. This value is associated with the necessary minimum extension of the riprap protection.

Figure 9 represents the values of *a/b* deduced from the tests carried out with different flow incident angles. The values obtained for $d/d_s = 0.26$ and $\beta = 30º$ are anomalous, due to the fact that the maximum width of the riprap protection considered has been insufficient.

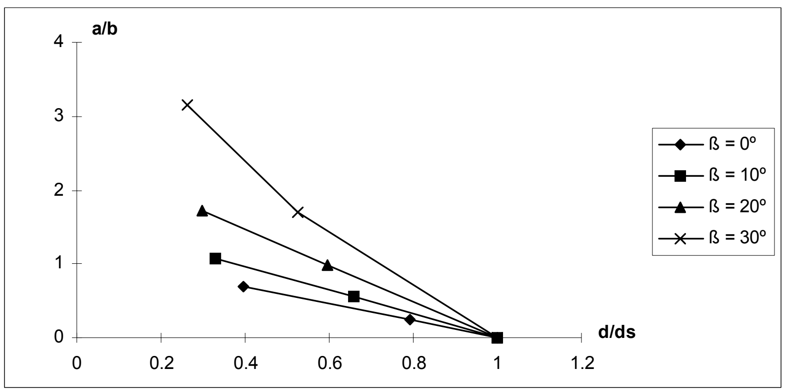


Fig. 9. Minimum width of the riprap. Test results.

The necessary minimum riprap width (*a/b*) decreases almost linearly upon increasing the depth of the protection below bed level (d/d_s), and grows upon increasing β.

On the other hand, the results obtained from tests and the values proposed by different authors have been compared. Neill (1967) and Lauchlan (1999) recommend a single value of *a* (*a* = 1.5 *b*), independent of *d*, while Témez (1988) and other authors relate such extension with the placement level (*d*) but also with the scour hole depth (d_s) of the unprotected pier.

Reorganizing the original equation proposed by Témez, in order to express it as a function of the non-dimensional variables *a/b* and d/d_s, results in:

$$\frac{a}{b} = \frac{ds}{b}\left(1-\left(\frac{d}{ds}\right)\right) \qquad (1)$$

considering the value of d_s deduced by applying the equation of Laursen:

$$\frac{ds}{b_*} = 1.5 \left(\frac{y_0}{b_*} \right)^{1/3} \tag{2}$$

to the test conditions, with:

$$b_* = b\,(\cos\beta + 2\,sin\,\beta) \tag{3}$$

Figure 10 represents the values of *a/b* deduced from the tests and those resulting from applying equations (1), (2) and (3).

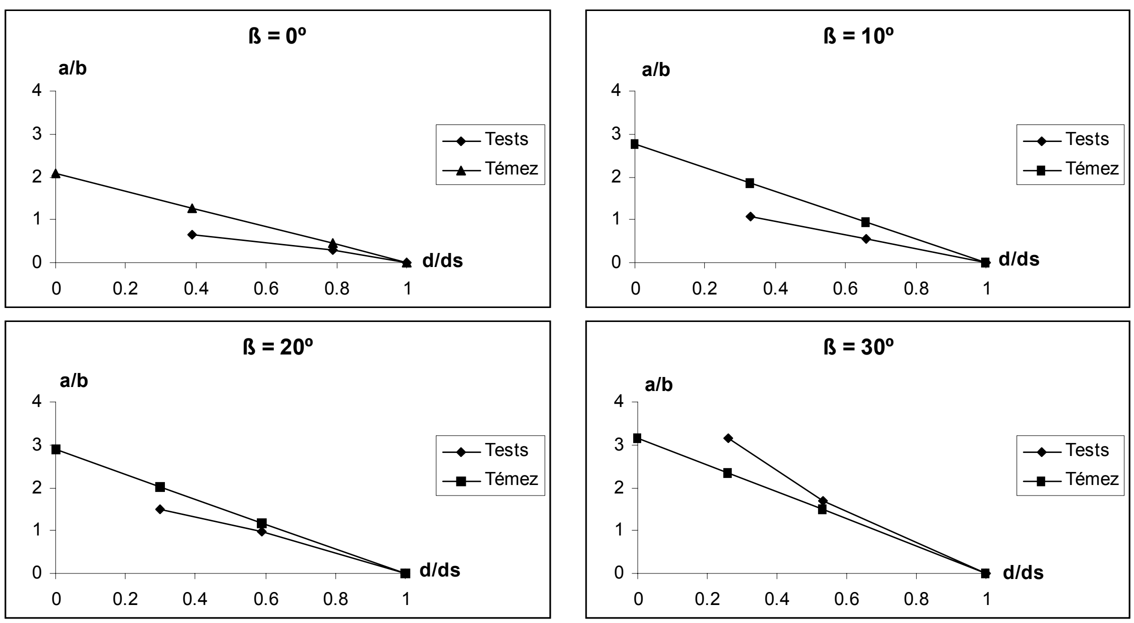


Fig. 10. Minimum width of the riprap. Comparative analysis.

By examining this figure, it is deduced that the measured values follow a similar trend to those calculated from the Témez equation; even though, the calculated numerical values are, on average, 80 %, 70 % and 25 % higher than measured test values in the cases of β = 0º, 10º and 20º, respectively, while they are 20 % lower in the case of β = 30º.

For β values equal to or greater than 20º, if the riprap protection is located at a small depth below bed level, the uncovered protection width is larger than the minimum width suggested by Neill and Lauchlan.

CONCLUSIONS

The qualitative and quantitative analyses of the results obtained in the experimental program from 64 laboratory tests lead to the following conclusions:

a) The maximum longitudinal extension of the scour hole is conditioned by the placement and width of the riprap and by the flow incident angle. For $d > 0$, the scour holes develop near the pier, with reduced extensions ($L_1/b \approx 3.5$ and $L_2/b \leq 7.5$) and without the influence of w/b. For $d \leq 0$, the scour holes develop downstream the riprap, with extensions that could become important ($L_2/b \cong 22.5$ for $d/b = -0.75$ and $\beta = 30^o$), and which grow slightly on increasing w/b and almost linearly on increasing β.

b) In relation to the scour hole depth, riprap functions best as a protection of bridge piers when placed at bed level ($d = 0$), since the scour hole is produced outside the protected zone and its depth is minimum for every value of β. When the riprap is located above bed level, even if the scour hole is developed downstream the protection, its depth could become important ($d_{sm}/d_s = 0.81$ or $d_{sm}/b = 3.2$ for $\beta = 30^o$).

c) The equation proposed by Témez is a good design tool to define the minimum riprap extension, as a function of placement level, for flow incident angles no greater than 25º. Its use is equivalent to adopting a safety factor, decreasing from 1.8 for $\beta = 0^o$ to an approximate value of 1.0 for $\beta \cong 25$.

d) According to the trend of the experimental observations, the application of Lauchlan's criterion for $\beta \geq 20^o$ results in unsatisfactory values of minimum width of riprap.

NOTATIONS

a = Necessary minimum extension of the riprap protection.
a_1, a_2, a_3, a_4 = Extension of the uncovered protection in frontal, lateral and back sides, respectively (see figure 4).
b = Width (or diameter) of the pier.
d = Placement level of riprap with regard to the bed level (positive downward).
d_s = Scour hole depth of the unprotected pier.
d_{so} = Scour hole depth of unprotected and aligned-flow piers.
d_{sm} = Maximum scour hole depth with riprap.
D_{50} = Mean size of the bed material.
Dp_{50} = Mean size of the riprap elements.
L_1, L_2 = Longitudinal and back extension of the scour hole, respectively (see figures 4 and 5).

U	= Flow velocity.
U_c	= Critical flow velocity.
y_0	= Water depth.
w	= Width of the riprap in all directions from the pier face.
β	= Flow incident angle.

REFERENCES

1. Bertoldi, D.A., Jones, J.S. (1994). “An experimental study of scour protection alternatives at bridge piers”. Report, Turner-Fairbank Laboratory, Federal Highway Administration, U.S. Department of Transportation, U.S.A.
2. Chabert, J., Engeldinger, P. (1956). “Etude des affouillements autour des piles des ponts”. Laboratoire d’Hydraulique, Chatou, France (in French).
3. Chiew, Y.M. (1995). "Mechanics or riprap failure at bridge piers". J. Hydraulic Engineering, ASCE, Vol. 121, no. 9, pp. 635-646.
4. Duarte, C.A. (1996). "Influencia de la extensión en planta y de la cota de colocación del manto de escollera en su estabilidad y en el desarrollo de la erosión local en pilas de puente". PhD. Thesis, Universidad de Cantabria, España. (in Spanish).
5. Duarte, C.A., Sainz, J.A. (1999). “Riprap at bridge piers”. J. Hydraulic Research, IAHR, Vol. 37, no. 3, pp. 291-302.
6. Fotherby, L.M. (1992). “Footings, mats, grout bags, and tetrapods: Protection methods against local scour at bridge piers”. M.S. Thesis, Colorado State University, Fort Collins, Colorado, USA.
7. Lauchlan, C.S. (1999). “Countermeasures for pier scour”. PhD. Thesis, The University of Auckland, Auckland, New Zealand.
8. Laursen, E.M., Toch, A. (1956). "Scour around bridge piers and abutments". Iowa Highway Research Board, Bulletin no. 4, Iowa, USA.
9. Maynord, S.T. (1989). "Riprap design". J. Hydraulic Engineering, ASCE, Vol. 115, no. 7, pp. 937-949.
10. Maza Alvarez, J.A. (1968). "Socavación en cauces naturales". Instituto de Ingeniería, U.N.A.M., Publ. no. 177, México. (in Spanish).
11. Melville, B.W., Sutherland, A.J. (1988). “Design method for local scour at bridge piers”. J. Hydraulic Engineering, ASCE, Vol 114, no. 10, pp 1210-1226.
12. Melville, B.W. (1997). "Pier and abutment scour: Integrated approach". J. Hydraulic Engineering, ASCE, Vol. 123, no. 2, pp. 125-136.
13. Neill, C.R. (1967). "Mean velocity criterion for scour of coarse uniform bed-material". Proc. 12th Congress AIRH, Fort Collins, paper C6, pp. C6.1-C6.9.
14. Parola, A.C. (1993). "Stability of riprap at bridge piers". J. Hydraulic Engineering, ASCE, Vol. 119, no. 10, pp. 1080-1093.
15. Quazi, M.E., Peterson, A.W. (1973). "A method for bridge pier riprap design". Proc., First Canadian Hydraulics Conf., University of Alberta, Edmonton, Canada, pp. 96-106.

16. Raudkivi, A. (1986). "Functional trends of scour at bridge piers". J. Hydraulic Engineering, ASCE, Vol. 112, no. 6, pp. 1-13.
17. Raudkivi, A., Breusers, H. N. (1991). "Scouring". Hydraulic Structures Design Manual, IAHR, Balkema Publishers, Rotterdam, The Netherlands.
18. Ruff, J.F., Fotherby, L.M. (1995). "Bridge scour protection systems using toskanes". Final Report Project 91-02, Engineering Research Center, Colorado State University, Fort Collins, Colorado, USA.
19. Salgado, R. (1997). "Erosión local y estabilidad de mantos de escollera en pilas de puente no alineadas con el flujo". Universidad de Cantabria, Spain. (in Spanish).
20. Simons, D.B., Chen, Y.H., Swenson, L.J. (1984). "Hydraulic test to develop design criteria for the use of Reno mattresses". Report, Colorado State University, Fort Collins, Colorado, USA.
21. Temez, J.R. (1988). "Control de la erosión fluvial en puentes". Ministerio de Obras Públicas y Transportes. España. (in Spanish)