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Analysis of local scour downstream of bed sills: preliminary results of experimental work

DONATELLA TERMINI
Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, Università di Palermo, Viale delle Scienze, I-90128 Palermo, Italy
dony@idra.unipa.it

Abstract Bed sills are often used to limit bed degradation, to control bed erosion around bridge piers or downstream stilling basins of dams. In this paper, the local scour that takes place downstream of the bed sill, in addition to the general erosion process, is examined. The data collected during experimental work are used to analyse the applicability of the relationship found in the literature and to define the relation between the maximum scour depth and the flow rate.

Key words bed sills; experimental analysis; fluvial hydraulics; scour

INTRODUCTION

The designs of structures in streams with erodible beds have to include adequate protective measures against scouring problems. The erosive action of flow can cause significant local scouring around bridge piers and abutments or downstream of grade-control structures that can endanger their structural stability and create the risk of failure. The design of adequate protective measures therefore needs knowledge of the mechanics, location and depth of maximum scour.

Theoretical prediction of the scouring process is not simple due to the complexity of flow dynamics downstream of a hydraulic structure. Previous experimental works (Melville, 1992; Fiorotto & Cividin, 1996) have shown that the formation of intense turbulent motion by a system of horseshoe vortices around structures, strongly affects the evolution of the erosive process. In consequence, investigations of local scouring processes around different kinds of structures (energy dissipators, gates, bridges, crossings, etc.) have been usually conducted in laboratory channels and specific observations of the process examined can be found in literature. Most studies focus attention on local scour around bridge piers (Roshko, 1961; Roper *et al*., 1967; Franzetti *et al*., 1994; Graf & Istiarto, 2002) or near abutments (Melville, 1992; Cardoso & Bettess, 1999; Ballio *et al*., 2000; Radice & Franzetti, 2002a,b). There is also an extensive literature on scour by jets at grade-control structures (Rajaratnam, 1981; Rajaratnam & Nwachukwu, 1983; Hogg *et al*., 1997; Mossa, 1998; D'Agostino & Ferro, 2004). More recently, studies have been made to predict the equilibrium scour depth and length of the scour hole downstream of bed sills (Gaudio *et al*., 2000; Lenzi *et al*., 2002), often used to limit bed erosion near bridge piers, where local scour takes place in addition to the general erosion process. On the basis of non-dimensional analysis, some empirical relationships to predict the maximum depth of the scour hole have been proposed but, due to the complexity of the phenomenon, hitherto these relationships have not allowed examination of the evolution of the scouring process through time.

In this paper, the evolution of the scouring process downstream of a bed sill is investigated through experimental observations performed in the laboratory of the Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali, University of Palermo (Italy).

EXPERIMENTAL SETUP

The experiment was conducted in a rectangular channel 6 m long, 0.40 m wide and 0.40 m in depth. The planview of the channel is shown in Fig. 1. The banks of the channel were rigid and the bed was of quartz sand (D_{50} = 0.65 mm, s_g = 1.334). The thickness of the sand at the downstream section of the flume was maintained constant by a bed sill. Two runs were carried out, respectively with flow rates of 0.013 $m^3 s^{-1}$ and 0.007 $m^3 s^{-1}$. For both runs the initial bed slope was 0.45%. In Table 1 the hydraulic characteristics for each run are reported; *Q* is the flow rate, h_o is the flow depth, *B* is the channel width, *Re* is the shear Reynolds number and *Fr* is the Froude number. The experiments were carried out until the equilibrium bed configuration was reached and, in particular, after 8 hours for run 1, and after 7 hours for run 2. During each run, the bed topography was measured along five longitudinal axes using a profile indicator produced by Delft Hydraulics (precision of 0.1 mm). The measurement axes are shown in Fig. 2. In order to analyse the evolution of the scouring process through time, the bed profile measurements were carried out with time steps increasing gradually, starting from a time step of 3 minutes.

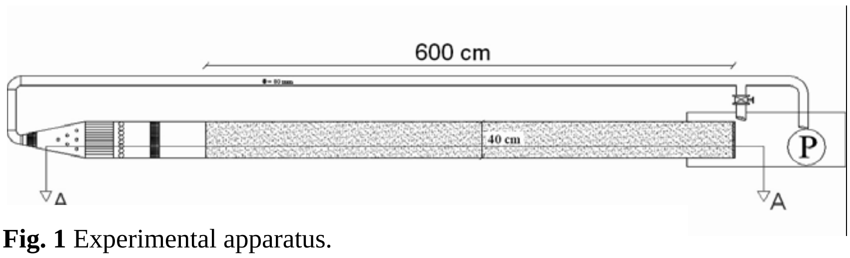

Fig. 1 Experimental apparatus.

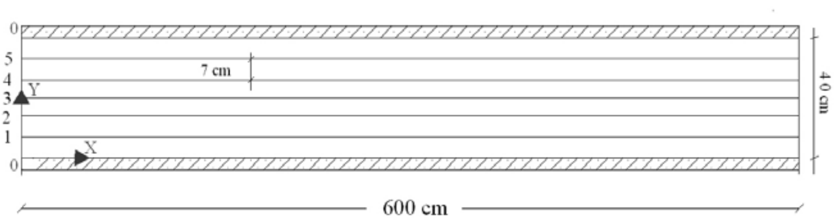

Fig. 2 Measurement axes.

Table 1 Hydraulic characteristic of runs.

Run	h_0 (m)	Q ($m^3 s^{-1}$)	B/h_0	$Re*$	Fr
1	0.038	0.007	10.5	58.43	0.46
2	0.06	0.013	6.7	70.35	0.54

DATA ANALYSIS

In Figs 3 and 4 the longitudinal bed profiles measured at the channel axis (axis 3 of Fig. 2) with a time step of one hour are reported, respectively for run 1 and for run 2. The profile measured at this axis is considered representative for the analysis of the process evolution because very small differences compared with those measured near the channel banks have been observed. In these figures *z* is the bed level relative to a horizontal reference plane and *x* is the longitudinal axis having its origin at the first section of the erodible bed reach of the channel (hereafter referred to as the initial section).

From Figs 3 and 4 it is clear that downstream of the initial section an evident scour hole forms. It is then followed by a deposit with a sharp crest. During the evolution of the process both the maximum depth of the scour hole and the crest of the deposit move gradually downstream; the depth of the scour hole increases through time and the height of the deposit crest decreases. In accordance with previous research (Lenzi *et al*., 2002), the crest of deposit occurs at a distance of 0.3–0.4 L_s (where L_s is the

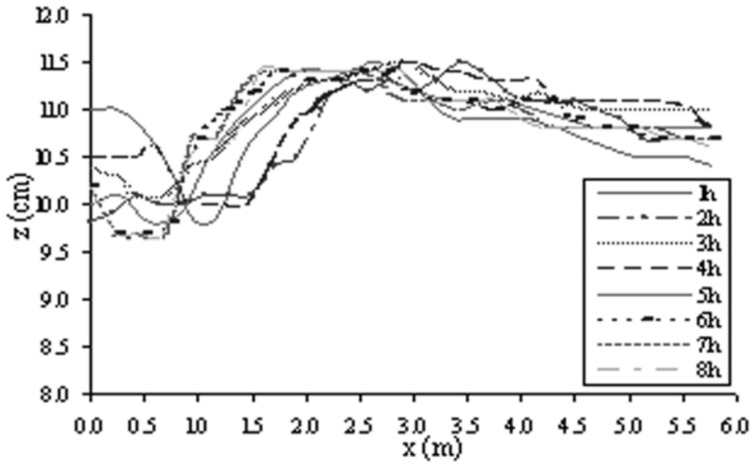

Fig. 3 Longitudinal bed profiles – run 1.

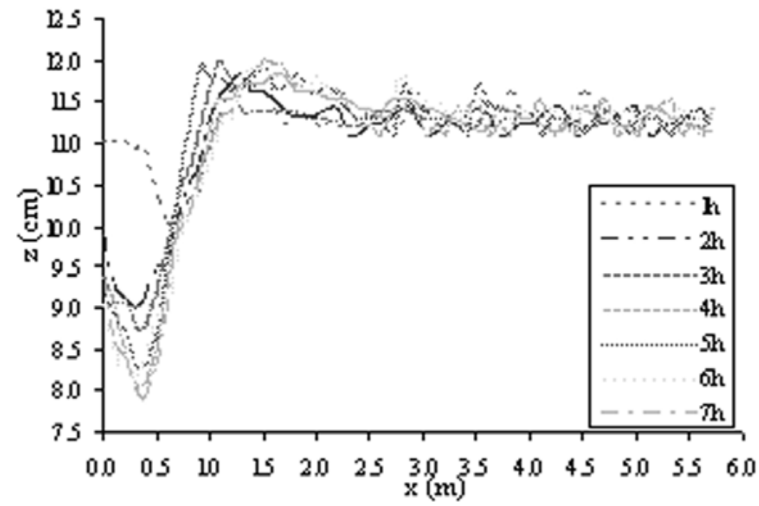

Fig. 4 Longitudinal bed profiles – run 2.

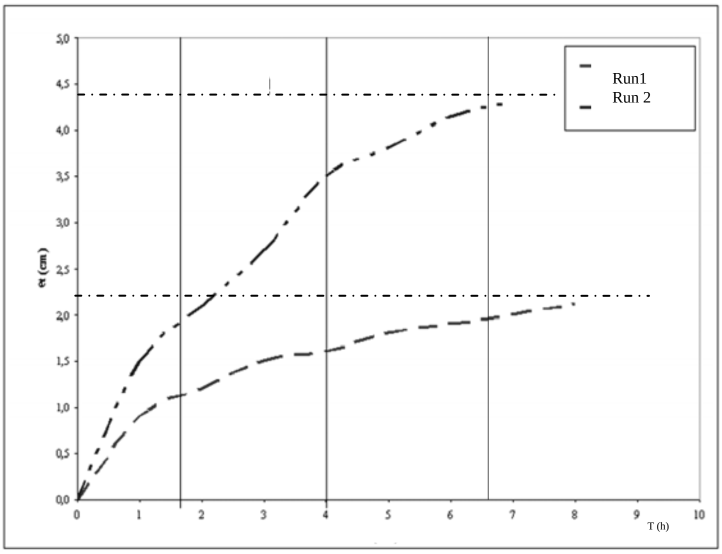

Fig. 5 Evolution of the erosive process.

scour hole length) from the initial section. Furthermore, the maximum depth of the scour hole, e_{max}, increases with the flow rate, but maintains a value approximately equal to 0.6 ÷ 0.7 h_o. The temporal evolution of the maximum scour depth, e_t, is shown in Fig. 5 for both runs 1 and 2. In common with previous research (Cardoso & Bettess, 1999; Radice & Franzetti, 2002a,b; Adduce *et al*., 2004) four evolutionary phases can be distinguished in Fig. 5: a first phase where the erosive process evolves rapidly, a second phase where scouring is gradual, a third phase where the bed level variation is very small; Fig. 5 also shows that after 7 h for run 1 and 8 h for run 2, a final phase, called the equilibrium phase, starts and the maximum scour depth and the dimension of the scour hole no longer change significantly.

SCOUR DEPTH ESTIMATION

Comparison with empirical relationships found in the literature

Many empirical and semi-empirical relationships have been proposed in the literature to estimate the scour hole at generic time *t*; each is obtained by analysing the scouring process around a particular hydraulic structure (piers of bridge, abutments, etc.). Thus, each relationship refers to specific water flow conditions and contains a certain number of parameters that depend on the particular conditions examined.

The relationship proposed by Hoffmans & Pilarczyk (1995), that analysed the local scour downstream of a protection bed sill, in a flowing water condition similar to that presented in this work, has been considered. These authors, using experimental data found in literature, verified that during the development phase of the scour process the maximum scour depth could be estimated by the following expression:

$$\frac{e_t}{h_0} = \left(\frac{t}{t_{\max}}\right)^{\gamma} \tag{1}$$

where t_{max} is the time at which the maximum scour depth reaches the equilibrium phase, γ is a non-dimensional parameter that has to be estimated on the basis of the experimental data. Breusers (1966) proposed that when the maximum scour depth is about $0.5h_o$, γ can be assumed as constant and equal to 0.38; Dietz (1969) proposed the use of a value variable in the range 0.34–0.4. Hoffmans & Pilarczyk (1995) demonstrated that this parameter cannot be constant but it has to assume an increasing value as the turbulent characteristics of flow in the scour hole evolve.

Here, the data collected, during both run 1 and run 2, have been used to estimate the value of the parameter γ and to analyse the influence of the parameter t_{max}. The parameter γ has been estimated by the best data-fitting and the mean square error, σ, has been assumed as index of the quality of the interpolation:

$$\sigma = \sqrt{\frac{\Sigma(e_{t,est} - e_{t,meas})^2}{N}} \tag{2}$$

where $e_{t,est}$ represents the scour depth estimated by (1), $e_{t,meas}$ is the scour depth measured during each run, N is the number of data measured.

The values of γ obtained are very different from the value of 0.38 suggested by Breusers (1966) and are equal to 1.27 and to 1.10, respectively for run 1 and run 2. In Table 2 (second column) the values of σ obtained by the best data-fitting are reported. In Fig. 6(a)–(b) the variation through time of the measured maximum scour depths is compared with the variation of the depths estimated by equation (1), respectively for run 1 and run 2. In these figures the maximum scour depths are normalized with the water depth h_o and the time is normalized with t_{max}. In this case t_{max} has been assumed equal to the duration of each run and, thus, equal to 8 h for run 1 and 7 h for run 2. In order to analyse the influence of the parameter t_{max}, the interpolation has been repeated by assuming different values of t_{max}. This analysis has allowed verification that the mean square error assumes small values when $t_{max} \geq 24$ h. In particular, by assuming $t_{max} = 24$ h, the best data-fitting gives $\gamma = 0.48$ for run 1 and $\gamma = 0.40$ for run 2. In Figs 7(a)–(b) the data interpolations, respectively with $\gamma = 0.48$ (run 1) and $\gamma = 0.40$ (run 2) are reported. Comparison of Fig. 6 and Fig. 7 suggests that the parameter t_{max} has a great influence on the application of equation (1). In particular, equation (1) allows the interpolation of experimental data satisfactorily when t_{max} is assumed higher than the duration of the development phases of the erosive process (phases 1–3 in Fig. 5). In the third column of Table 2, the values of the mean square error obtained by assuming $\gamma = 0.48$ (run 1) and $\gamma = 0.40$ (run 2) are reported. In the fourth column of the Table 2 the values of the mean square error estimated by assuming $\gamma = 0.38$ (Breusers, 1966) are also reported. The comparison shown in Table 2 highlights that low values of the mean square error are obtained only if the value of

Table 2 Mean square error values.

	Equation 1	Equation 1	Equation 1	Equation 3
Run 1	$\gamma = 1.27$ 7.22E-03	$\gamma = 0.48$ 6.74E-04	$\gamma = 0.38$ 1.25E-02	5.21E-04
Run 2	$\gamma = 1.10$ 7.44E-03	$\gamma = 0.40$ 3.34E-03	$\gamma = 0.38$ 1.68E-02	1.11E-03

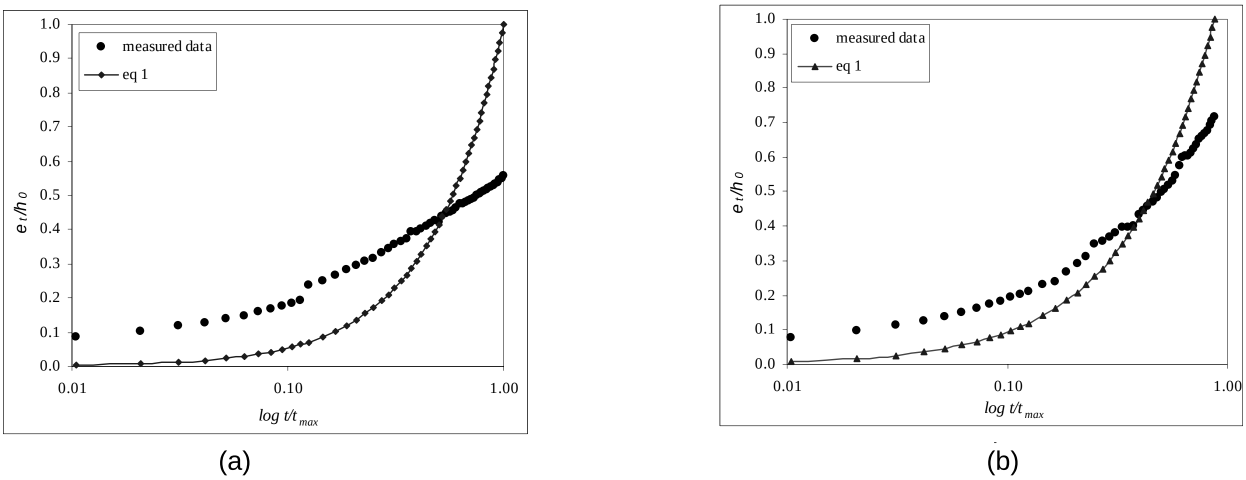

Fig. 6 Best data-fitting: (a) t_{max}= 7 h – run 1; (b) t_{max} = 8 h – run 2.

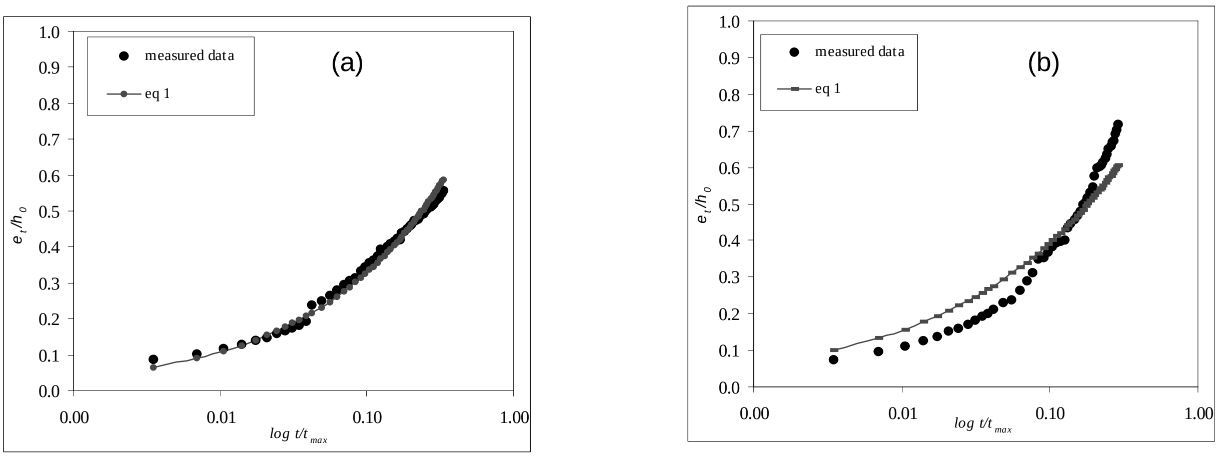

Fig. 7 Best data-fitting: (a) t_{max}= 24 h – run 1; (b) t_{max}= 24 h – run 2.

the parameter γ is not constant but it varies with the flow rate. Furthermore, the value of γ strongly depends on the value of the parameter t_{max}. Thus, it can be concluded that equation (1) contains two strongly interrelated parameters and the results obtained are very sensitive to the duration of the phenomenon (t_{max}) considered for the analysis; furthermore it does not include the flow rate.

Proposed empirical relationship

The maximum scour depths measured during each run have been investigated in order to evaluate the relationship between e_t, the flow rate and the time t. The regression analysis of all the measured data has allowed determination of the following relationship:

$$\frac{e_t}{h_o} = m(Q)^{n(Q)} \qquad (3)$$

where $m(Q)$ and $n(Q)$ are functions expressed as:

$m(Q) = 1.167Q + 0.2155$

$n(Q) = 16.58Q + 0.355$

with a coefficient of determination, $R^2 = 0.98$.

In Fig. 8, the measured values of maximum scour depths are plotted against the estimated depths according to equation (3). As Fig. 8 shows, the points are arranged around the equiline demonstrating that equation (3) describes the erosive process of both experiments correctly. In Fig. 9(a)–(b), the interpolation of equation (3) to the normalized data measured, respectively during run 1 and during run 2, is reported.

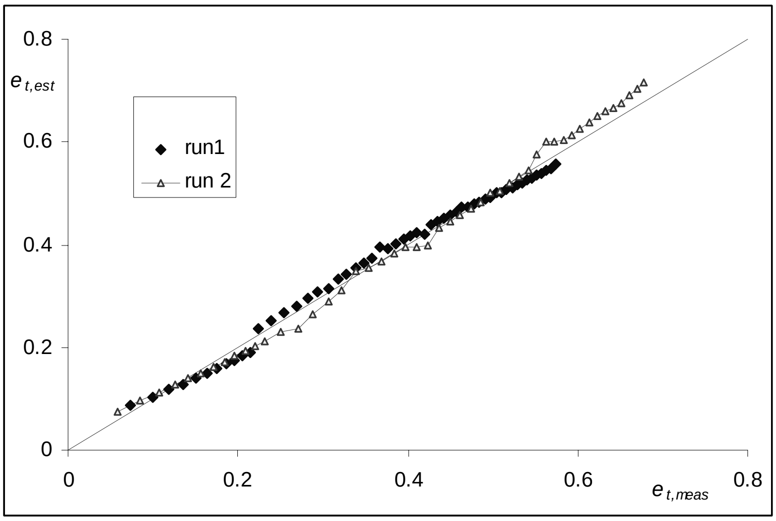

Fig. 8 Comparison between estimated and measured data - equation (3).

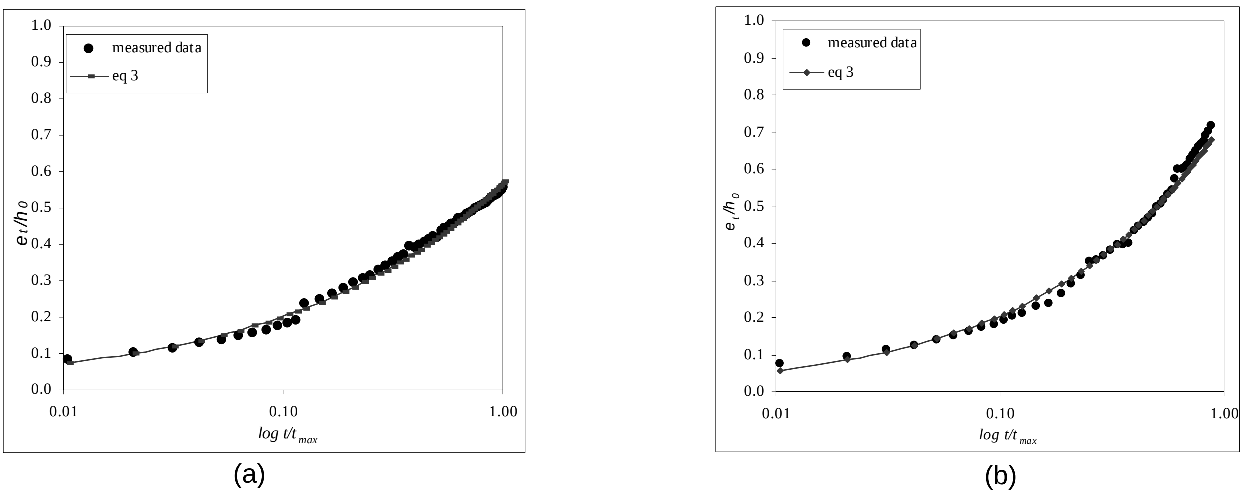

Fig. 9 Best data-fitting equation (3): (a) run 1; (b) run 2.

These figures show that equation (3) allows simulation of the evolution in time of the scouring processes. Furthermore, as can be observed from Table 2, where the corresponding values of mean square error are shown in the fifth column, equation (3) allows small values of σ to be obtained for both the runs. Equation (3) contains four coefficients that have to be estimated by using the experimental data, but they assume a constant value for both runs considered.

CONCLUSION

In this work the evolution of the scour hole downstream of a bed sill is analysed on the basis of experimental work carried out in a mobile bed flume. After having verified the applicability of relationships found in literature, the data collected have been used in order to analyse the relationship between the maximum scour depth at generic time t and the flow rate. By means of regression analysis, an empirical relationship is proposed. The proposed relationship correctly describes both the erosive processes examined in the present work. Further experiments and analyses are required in order to generalize applicability of the relationship.

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