AN EXPERIMENTAL STUDY OF LIVE-BED SCOUR AT BRIDGE ABUTMENTS

FRANCESCO BALLIO, ALESSIO RADICE AND SILVIO FRANZETTI

Politecnico di Milano, Dept. I.I.A.R.
Piazza Leonardo da Vinci, 32 – 20133 Milano (Italy)

The results of a series of live-bed experiments around a rectangular abutment perpendicular to the incoming flow are presented. Measurements indicate that scour depths initially grow with decreasing rates; as a first approximation the time evolution can be interpolated by logarithmic trends, similar to those observed for clear-water. Scour rates increase with the flow intensity, while the time to reach equilibrium rapidly decreases for increasing intensities: these dependencies are qualitatively described in the literature but not quantitatively defined. The amplitude and frequency characteristics of scour fluctuations around the mean regime value are strongly affected by the flow intensity, but they appear not to be strictly correlated with those of the bed forms (dunes / antidunes) migrating along the flume bed.

1 Introduction

Literature experimental studies on local scour phenomena have been mainly focused on clear water (CW) conditions, where the flow average velocity, U, is smaller then the threshold value U_c for bed load. It is well known, however, that in typical real situations scour around bridge piers and abutments takes place under live bed (LB) conditions ($U > U_c$), where bottom sediments are transported by the flow over the whole river length and width. The preference to CW experiments can be motivated by the difficulty of running tests where the whole flume bed is moving; moreover, most researchers state that the maximum scour values are reached at the limiting CW conditions (i.e. for $U = U_c$), even if some others found a second maximum for $U/U_c \cong 4$. Technical literature suggests to design foundations on the basis of the maximum values of the temporal development of scour depths at $U = U_c$. It should be however noticed that the existence of temporal asymptotic CW scour values has been verified for piers, but not yet for abutments.

CW results may be a proper reference for design purposes, but they are not representative of the real evolution of the phenomenon. For more realistic modelling a proper parameterisation of the scour temporal process as a function of the flow under transient hydraulic conditions is needed; the dependence of scour depth on the parameters of the incoming flow should be investigated both in CW and in LB conditions.

In this paper we show the results of a series of LB experiments around a rectangular abutment perpendicular to the incoming flow. An automatic survey system allowed detailed measurements of the scour temporal evolution. Differently from most LB literature studies we were able to monitor the initial erosion transient; results are primarily analysed with reference to scour modelling, but phenomenological aspects are also considered.

2 Experiments

The experiments reported herein were run in a rectangular channel, 15 m long and 0.60 m wide. The channel was filled with natural sediments having mean diameter d_{50} = 1.9 mm and uniformity coefficient $\sigma = (d_{84}/d_{16})^{0.5} = 1.22$. A telescoping PVC rectangular abutment was placed at half length of the channel; its dimensions in the transverse and streamwise directions were 0.202 m and 0.100 m respectively. Both water and sediments were recirculated. Piezometric probes and a magnetic flowmeter were used to measure flow depth and discharge, respectively. Sediment discharge was measured during the experiment by placing a sieve at the end of the sediment recirculation duct. The optical device described in Ballio and Radice (2003) and in Radice et al. (2004) was used for automatic continuous measurements of bed elevation.

Prior to the execution of a LB scour test, uniform flow conditions were achieved with the abutment sank under the bed surface, to allow for slope adjusting and bed-forms development. Before the start of the actual scour test, continuous measurements of the bottom surface were taken at a fixed point in the section of the abutment upstream face, in order to monitor bed-forms migration and to determine the reference average non scoured bed level. The scour experiment was started by extracting the obstacle from the sediment layer. During the scour experiment, continuous measurements of flow depth, water and solid discharge were made to verify the maintenance of constant conditions. Erosion depth values were measured in some locations around the abutment; in this work we will refer uniquely to the abutment nose (see the sketch in Figure 1).

Table 1 shows the control parameters of the experiments. All the tests were run in LB conditions, with the exception of test P0, which was run at critical CW conditions.

Table 1. Experimental data collected during the present study. S is channel slope, h is water depth, U is flow velocity, U_c is the threshold value of flow velocity, Fr is Froude number and Q_s is the sediment discharge.

Test	S [%]	h [m]	U [m/s]	Fr [-]	U/U_c [-]	Q_s [kg/s]
P0	0.12	0.093	0.47	0.49	~1	~0
P1	1.05	0.085	0.80	0.87	1.71	$1.8\cdot10^{-1}$
P2	0.75	0.097	0.75	0.77	1.61	$9.2\cdot10^{-2}$
P3	0.37	0.099	0.69	0.70	1.48	$2.6\cdot10^{-2}$
P4	0.26	0.099	0.59	0.60	1.27	$9.1\cdot10^{-3}$
P5	0.13	0.099	0.54	0.55	1.15	$9.8\cdot10^{-4}$
P6	1.31	0.102	0.94	0.94	2.02	$2.3\cdot10^{-1}$

3 Results

Figure 1 plots the measured scour time evolution for the LB tests to be compared to the referenced CW test. The latter has the typical logarithmic trend, without any tendency to equilibrium after more than 100 run hours. Our measurements show that LB experiments are characterised by a similar behaviour in a development phase before they reach the typical equilibrium stage where the scour depth oscillates around a stable mean level d_{se}. As U/U_c values are increased scour transients are faster, in that higher values are reached for the same run time, and equilibrium is reached in shorter times with decreasing values

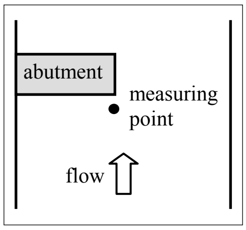
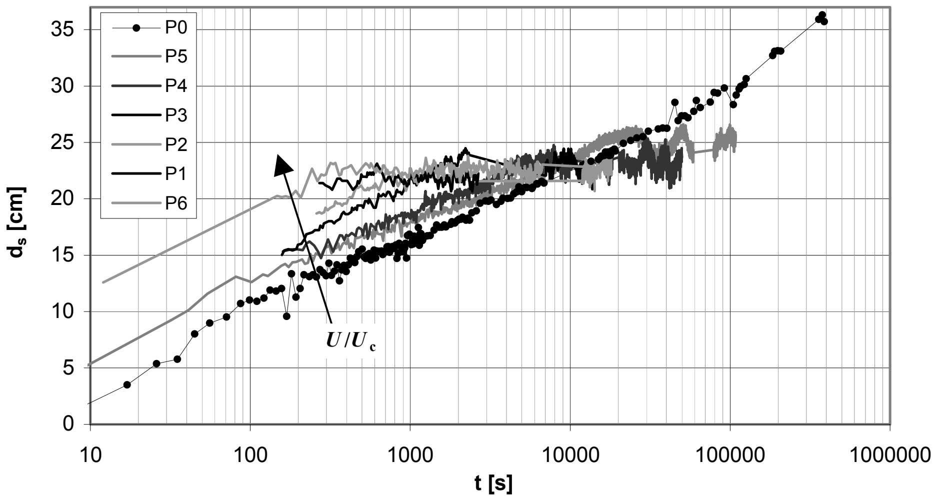


Figure 1. Temporal evolution of scour.



for d_{se}. The reduction of the equilibrium average erosion depth is qualitatively consistent with literature indications for abutment and pier scour (see for example Dongol, 1994); some quantitative differences from the literature may be inferred from the data, but the present data set is to small for any definitive evaluation of this point.

We are not aware of any quantitative description of the dependence of the characteristic time of the scour process on the flow intensity. As already noticed we could not recognise any tendency of equilibrium after $4 \cdot 10^5$ s for the CW experiment, while the development phase for the LB experiments ends for times of the order of

10^2–10^4 s depending on the flow intensity (U/U_c = 1.15–2.0). It can be therefore shown that the time scales of the scour process are strongly affected by U/U_c; since a logarithmic trend can be recognised for the development phase of all the experiments, following Radice, Franzetti and Ballio (2002) we defined a development time scale T_d by fitting the data with the equation:

$$d_s = a \log(t/T_d) \tag{1}$$

Since all temporal trends show relatively uniform slopes in the log-linear plot of Fig. 1, we kept a constant average value for a (a = 6.5 cm), so that all the effect of the flow intensity is attributed to the time scale. Resulting T_d values are shown in Fig. 2. The decay of T_d is approximately exponential, with a reduction factor as large as 25:1 for $U/U_c = 1 \rightarrow 2$. Data have been herein discussed in their dimensional form since there is no established literature of scaling factors for LB phenomena. If we refer to typical CW scaling structures we may define non-dimensional time indices:

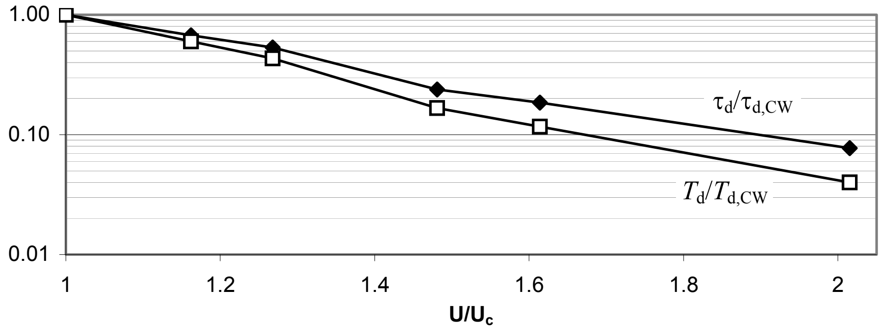


Figure 2. Dimensional (T_d) and non dimensional (τ_d) time scales of the development phase as a function of U/U_c. Times are normalized with the corresponding clear water values.

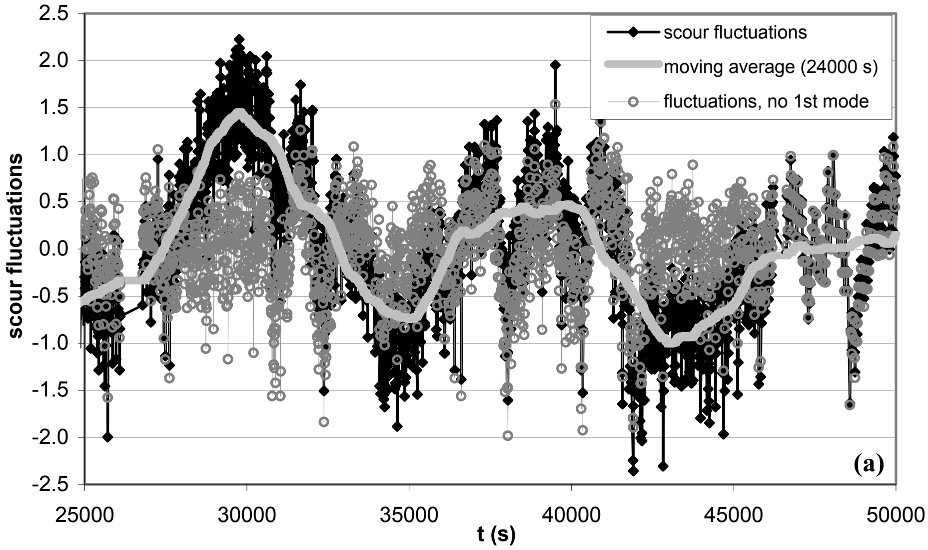
$$\tau = \frac{t\,U}{\lambda} \quad \text{(Melville and Coleman, 2000; Radice, Franzetti and Ballio, 2002)} \tag{2}$$

$$\tau' = \frac{t\,\sigma^{1/3}\left(g\Delta d_{50}\right)^{1/2}}{\lambda} \quad \text{(Oliveto and Hager, 2002)} \tag{3}$$

where λ is a suitable length scale of the phenomenon. In our experiments all length scales and sediment properties are almost constant, so that the dependence of τ'_d on the flow intensity is the same as that of its dimensional counterpart. If we consider the scaling structure (2), however, part of the dependence is interpreted as a pure scaling effect (see Fig. 2), so that the reduction factor for τ_d is approximately half of that for T_d. Since we have no references for LB scaling laws, we prefer not to give preference to any of the two trends.

Although present results for development time scales are evidently of no general value, they show how the evolution to equilibrium can be an extremely long or extremely short process for different U/U_c values. This point is crucial for the modeling of scour under flood waves, in that the adaptation of scour levels to variations of discharge (and therefore water depth) may or may be not considered to be instantaneous, depending on flow intensity which, on turn, varies along the wave.

Classical interpretation of LB scour processes indicates a dynamical nature for equilibrium stages, in which the sediment fluxes entering and leaving the scour hole are balanced on a sufficiently long temporal window. The migration of bed-forms makes the incoming sediment flux unsteady; this would be the cause of the oscillating behaviour of scour depths around the equilibrium value. An example of the characteristics of such oscillations is shown in Figure 3. A visual observation of the signal indicates the existence of a low frequency mode with a characteristic time T_1 of the order of 10^4 s; this mode can be identified by means of moving averages. The choice of the averaging window is somehow arbitrary, but the result is little affected by this choice if characteristic



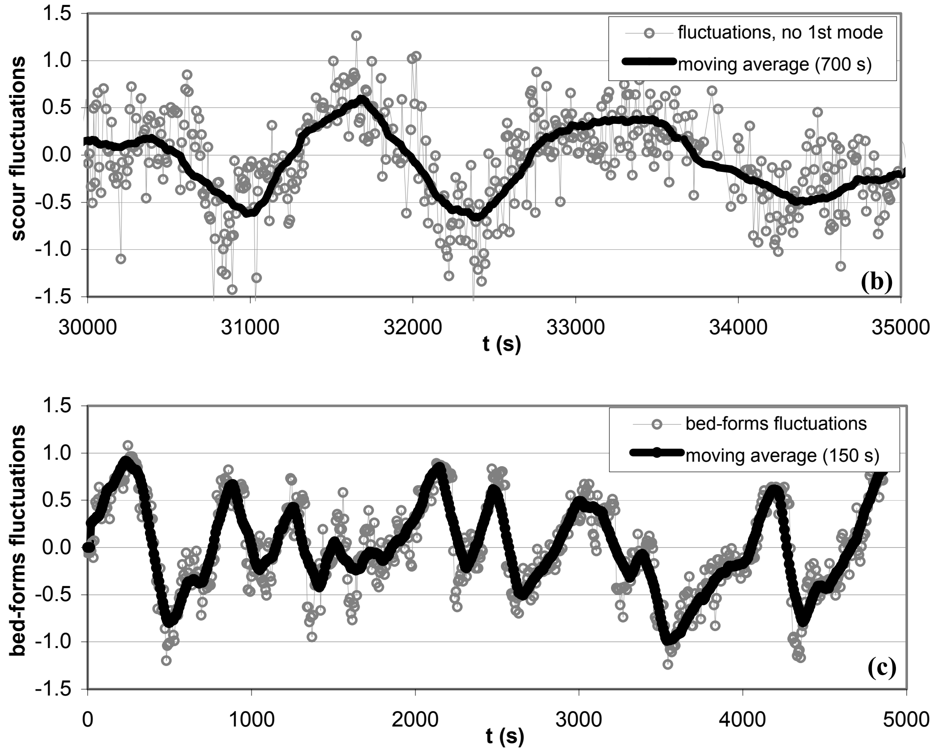


Figure 3. Test 4 (U/U_c = 1.3), scour and bed-forms fluctuations around equilibrium values. (a) Scour, complete signal; (b) scour, after subtraction of the 1st mode; (c) bed-forms.

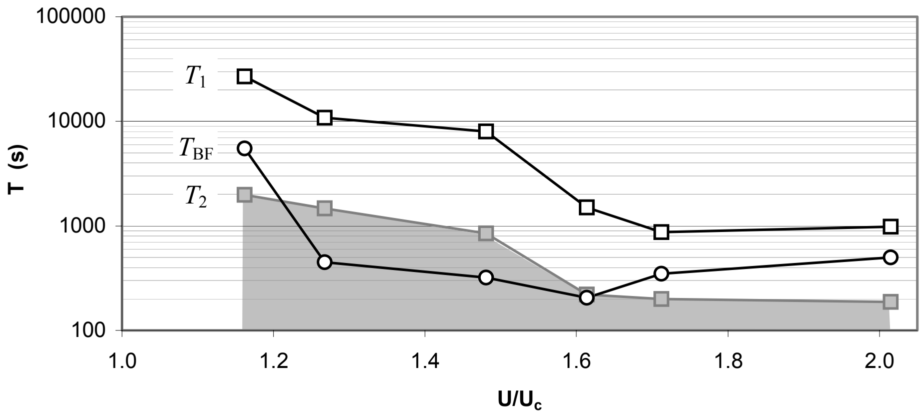


Figure 4. Characteristic times of fluctuations for scour depths (T_1, T_2) and bed-forms (T_{BF}).

frequencies are well separated from each other and the resulting averaged signal is multiplied by an amplification factor to compensate for the damping effect of the averaging. In Fig. 3b the signal resulting after the subtraction of the first mode is shown over an enlarged temporal scale. Moving averages help to identify further modes of oscillation (largest characteristic time: $T_2 \approx 10^3$). An accurate analysis of the data, however, showed that it is not easy to detect well defined and separated modes, so that we preferred to characterise the residual signal with a continuous band of characteristic times ranging from T_2 to the time resolution allowed by our measurements ($\approx 10^2$ s).

As already mentioned, bottom fluctuations due to the migration of bed-forms were measured before the start of the scour experiment (Fig. 3c). A well defined oscillation mode with characteristic time T_{BF} can be identified for most tests; higher frequency oscillations are also detectable, but their amplitude is typically much smaller than that of the main mode. Characteristic times for varying U/U_c are plotted in Fig. 4: the present data do not support the literature indication that scour fluctuations simply are the effect of bed-forms migration. Low frequency scour oscillations have characteristic times (T_1) significantly larger than those of the bed-forms; on the other hand, we could not enhance preferential modes corresponding to T_{BF} within the lower range of characteristic times of scour oscillations. Results of Fig. 4 do *not* imply that in our experiments bed-form migration has no role in the scour dynamics; it is however necessary to consider more complex mechanisms to explain the oscillation patterns, including instabilities of the scour hole, the unsteady nature of the macro-structures of the flow field, and the interactions between the two effects.

Root mean square (RMS) values of scour fluctuations are shown in Figure 5. Fluctuation intensities have a non monotonic trend with the flow intensity, with a maximum for $U/U_c \approx 1.3$. The behaviour is qualitatively consistent with the results of Chiew (1992), although he found a maximum for $U/U_c > 2$. Diminishing amplitudes for $U/U_c \to 1$ are consistent with the negligible fluctuations in CW experiments. In Fig. 5 we

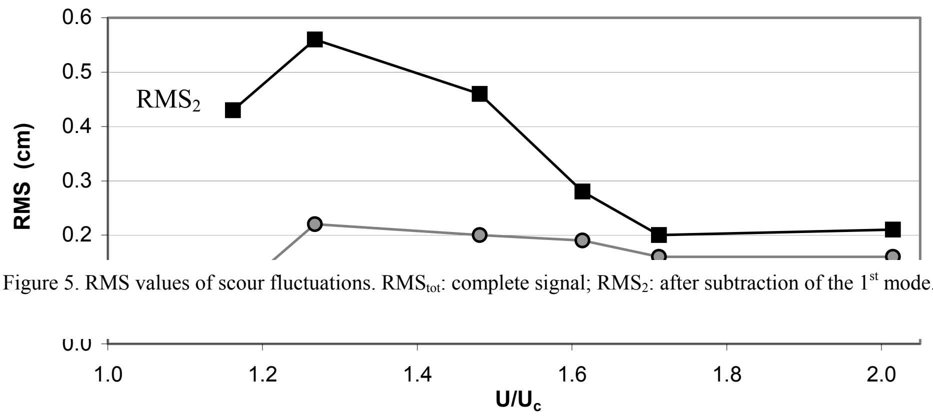


Figure 5. RMS values of scour fluctuations. RMS_{tot}: complete signal; RMS_2: after subtraction of the 1st mode.

also plotted the RMS values of the residual oscillations after the subtraction of the first mode: it is interesting to notice how the residual RMS_2 values vary very little for $U/U_c = 1.3–2.0$, so that most of the strong increase of the total RMS for decreasing flow intensities pertains to the first mode.

Figures 5 and 4 respectively indicate that the first oscillation mode dominates at low flow intensities ($U/U_c = 1.15–1.3$) and that characteristic times are much larger than those of bed-forms and of the residual modes. This behaviour may be explained by the assumption that the first mode be due to instabilities of the flume bed, such as periodic passages of sediment lumps or general variations of bed level, while oscillations with characteristic times smaller than T_2 may be generated by bed-forms migration and/or by endogenous instabilities of the scour hole – flow field interaction. It should be however noticed that time recordings of bed levels upstream of the scour holes and of the free surface elevation did not show any global instability of the flume bed level.

Probability distributions for scour fluctuations (not shown) indicate that the presence of a strong first mode component makes the distributions significantly deviate from normality, whereas the normal approximation holds whenever the first mode is either subtracted from the signal or relatively small. Oscillations around equilibrium values are small (maximum amplitude smaller than 20% of d_{se}), so that their characteristics are more significant from a phenomenological point of view than for engineering applications. This result is coherent with most literature data for abutments (Liu et al., 1961; Cunha, 1975; Kandasamy, 1989; Dongol, 1994) with the exception of some tests of Liu et al. (1961) where maximum scour values up to 60% higher than the average were measured.

4 Conclusions

The results of a series of live-bed experiments around a rectangular abutment perpendicular to the incoming flow are analyzed. In the development phase, scour evolution is similar to that of clear-water experiments (logarithmic increase in time), with increasing scour rates for increasing flow intensities; the time to reach equilibrium, conversely, rapidly decreases for increasing intensities: these dependencies are qualitatively described in the literature but not quantitatively defined. Times scales for the development phase were find to decrease with an exponential trend for growing flow intensities.

We analyzed the amplitude and frequency characteristics of scour fluctuations around the mean regime value; in particular, fluctuation frequencies are strongly affected by the flow intensity, but they appear not to be directly correlated with those of the bed forms (dunes / antidunes) migrating along the flume bed. Scour oscillations should rather be explained in terms of a more complex dynamics of the system, possibly connected to flow field instabilities interacting with the boundary, i.e. with the evolving local and global characteristics of the scour hole.

Acknowledgments

The present research has been supported by Italian Minister for Scientific Research under the contracts "Influenza di vorticità e turbolenza nelle interazioni dei corpi idrici con gli elementi al contorno e ripercussioni sulle progettazioni idrauliche" and "Strutture coerenti in fenomeni erosivi localizzati".

References

Ballio, F. and Radice, A. (2003). "A non-touch sensor for local scour measurements." Journal of Hydraulic Research, 41(1), 105-108.

Chiew, Y.M. (1992). "Effect of dune migration on scour at bridge piers." *Int. Journal of Sediment Research*, 7(1), 77-92.

Cunha, L.V. (1975). "Time evolution of local scour." *Proc. of XVI IAHR Congress, Sao Paulo, Brasil*, 285-299.

Dongol, D.M.S. (1994). "Local scour at bridge abutments." *Report n. 544, University of Auckland, Auckland, New Zealand*.

Kandasamy, J.K. (1989). "Abutment scour." *Report n. 458, University of Auckland, Auckland, New Zealand*.

Liu, H.K., F.M. Chang and Skinner, M.M. (1961). "Effect of Bridge Construction on Scour and Backwater." Colorado State Univ., Civil Engrg. Section, Ft. Collins, CER 60 HKL 22.

Melville, B.W. and Coleman, S.E. (2000). "Bridge scour." Water Resources Publications, Highlands Ranch, Colorado, USA.

Oliveto, G. and Hager, W.H. (2002). "Temporal evolution of clear-water pier and abutment scour." *Journal of Hydraulic Engineering*, 128(9), 811-820.

Radice A., Franzetti S. and Ballio F. (2002). "Local scour at bridge abutments." *River Flow 2002, I Int. Conf. on Fluvial Hydraulics, Louvain-la-Neuve, Belgium,* 2, 1059-1068.

Radice, A., Teruzzi, A. and Ballio, F. (2004). "Misure di erosione localizzata in *live bed* tramite un sensore ottico." *XXIX Convegno di Idraulica e Costruzioni Idrauliche, Trento, Italy*.