Conference Paper, Published Version

Comiti, Francesco; Andreoli, Andrea; Lenzi, Mario A.

Dimensions Of Scour Holes And Effectiveness Of Grade-Control Structures In Two Cobble-Gravel Bed Rivers

DIMENSIONS OF SCOUR HOLES AND EFFECTIVENESS OF GRADE-CONTROL STRUCTURES IN TWO COBBLE-GRAVEL BED RIVERS

FRANCESCO COMITI

ANDREA ANDREOLI

MARIO A. LENZI

Dept. Land and Agroforest Environments – University of Padova
Viale dell'Università 16, 35020 Legnaro (PD), Italy

This paper analyses scour dimensions and grain size distributions surveyed in the Maè and Cordevole Rivers (Italian Alps), two steep (2-7 %) cobble/gravel bed mountain streams controlled by check-dams and bed sills. In particular, non-dimensional maximum scour depth and longitudinal grain size sorting are addressed. It also presents an assessment of the degree of stability of these structures in relation with their spacings.

1 Introduction

Grade-control works in steep rivers are built in staircase-like sequences. Incision is controlled both by fixing the bed height at several points and by reducing stream transport capacity through the lowering of the initial longitudinal channel slope S to a lower value S_{eq} (ultimate or equilibrium slope). Foundations height is generally assigned to equal the maximum scour depth y_s to avoid undermining., thus a reliable prediction of the maximum scour depth is needed to design effective control works, usually for flood events having return periods of 50-100 years (Lenzi et al. 2003_a). Structure stability is heavily conditioned by the spacing L between two consecutive works, because this design variable determines – along with the initial and equilibrium gradients – the drop height responsible for jet acceleration and its scouring capacity (Gaudio et al 2000; Lenzi et al 2002). Strong statistical analogies between natural and artificial (i.e. grade-control structures) step pool sequences have been presented in Comiti (2003) and Comiti et al (2004).

Several predictive equations for maximum depths of pools scoured downstream of grade-control structures which explicitly account for spacing L are available, mostly derived from flume experiments (Gaudio et al 2000; Lenzi et al 2002). As to field-derived formula, Comiti (2003) and Lenzi et al (2003_a) found for steep (>0.02) Alpine cobble/boulder-bed streams that maximum scour depth y_s is approximately 0.6 – 1.4 times the virtual jet energy per unit width $E = z+H_s$, where z is the drop height and H_s is the specific critical energy of the flow ($=1.5 \cdot h_c$, where h_c is the critical flow depth). They proposed also a non-dimensional relationship with the maximum scour depth normalized by drop height:

$$\frac{y_s}{z} = 0.80\frac{h_c}{z} + 1.34 \tag{1}$$

To the authors' knowledge, sediment sorting along a channel with grade-control structures, which presents many implications for sediment transport and stream ecology, has not been addressed yet in the scientific literature (Comiti 2003). The evaluation of the degree of armoring of pool bottom should help identify which grain size of the original bed mixture is the limiting one in the scouring process, since field quantitative descriptions of pool armoring are still lacking, as well as validation of lab results like those by Hallmark (1955) and Kuroiwa (1999). Hallmark found that the material constituting the bottom surface of scour holes was approximately D_{85}; Kuroiwa reported median grain size at the bottom ranging from D_{77} to D_{85}, and selected D_{85} to be used in his maximum scour depth equation.

This paper analyses scour dimensions and grain size distributions surveyed in the Maè and Cordevole Rivers (Italian Alps). It also presents an assessment of the degree of stability of these structures in relation with their spacings.

2 Field measurements

Two channels represent the field sites of this research: the Cordevole River at Arabba and the Maè River at Forno di Zoldo (Italian Alps, Figs. 1-2). The former is a small basin (drainage area of 12.5 km^2), with a rather steep (S=0.06 m/m) and narrow (width B=10m) channel, whereas the latter – a much larger basin, 79 km^2 – features a gentler slope (S=0.02) and a wider channel (B=14.5-27 m). Macro-roughness conditions dominate in both streams, but to a greater extent in the Cordevole River.

Overall, 19 plunging pools downstream of grade-control structures were surveyed, 13 in the Cordevole (Lunardi 2002) and 6 in the Maè (Pepato 2003). As to pool dimensions, the main measured features (Fig. 3) are maximum scour depth y_s, scour length l_s, drop height z, berm distance l_b, pool exit gradient S_e. Additionally, work's crest width B was also measured in order to calculate water discharge per unit width. In turn this allowed the estimation of the thickness of issued jets. Peak discharges of recent flood events were used as formative discharges. The maximum scour depth y_s was taken with respect to the elevation of the structure crest, whereas the drop height z was measured as the difference in level between the crest and the point at which the river bed was no longer affected by local scouring, thus showing a positive gradient representing the "equilibrium" slope. In most cases such a "borderline" between local and general scouring was marked by a naturally-formed berm made up of coarse clasts. This sedimentary structure has been commonly observed in many other rivers downstream of grade-control works (Comiti 2003).

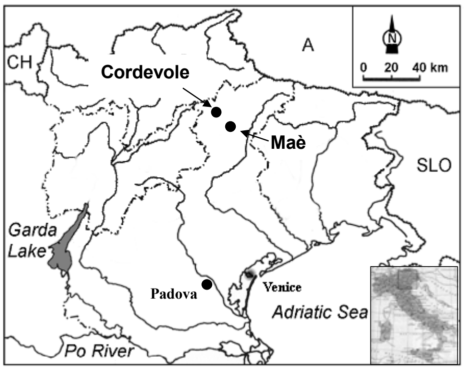

Figure 1 – Location of two study sites.

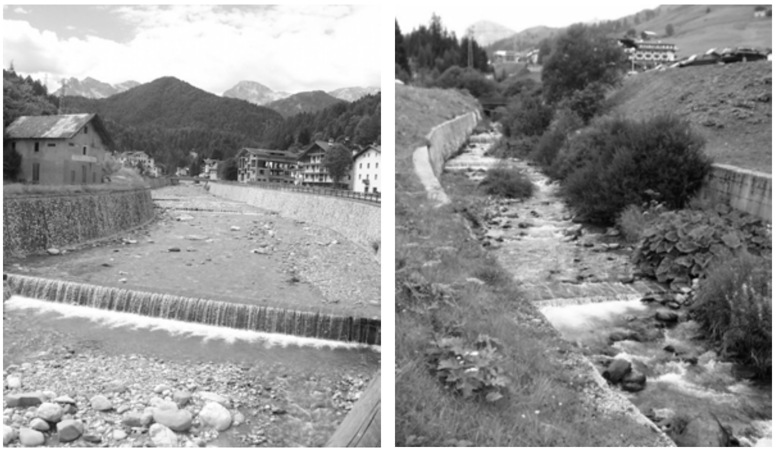

Figure 2 – Pictures of the two channels surveyed: the Maè (left) and the Cordevole (right).

Scour hole dimensions and structure heights were measured directly by a 5m-long telescopic stadia. Measurements were taken at different transects across each pool, in order to provide a significant mean value.

Extensive grid-by-number pebble counts were carried out in both sites on the stream bed area downstream of pools, where the "equilibrium" slope was present, between l_b and L (see Fig. 3). The grain size distribution of this zone will serve as a reference for the other distributions referring to different pool areas such as pool bottom, pool exit slope (between l_{max} and l_s), pool end (between l_s and l_b) and finally berms.

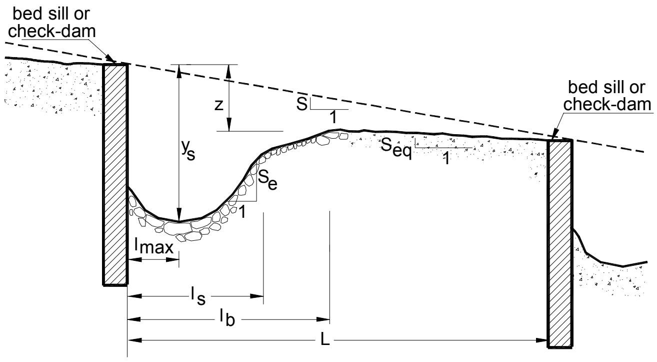

Figure 3 – Characteristics dimensions of scour holes.

The reference grid counts in the sloping bed length were performed using the systematic, spatially integrated methodology described in Bunte and Abt (2001), whereas for the other zones different local methods were required, and they differed between the two field sites due to their strongly dissimilar width. On the sloping bed downstream of pools, in the Cordevole four grids – each featuring more than 200 sampling points – were set up along the reach and then all the clasts were put together and treated as a single sample (total of 951 points) to produce the reference surface grain size distribution. Also in the Mae' River four grids were performed, but with a larger overall sample size: 1614 clasts. At each pool, all the measurements referring to the four pool zones were added up and treated as a single sample, in order to come up with a single grain size distribution for each of them. Subsequently, putting together and considering as a single sample all the pools, each river could be characterized by 4 curves for its pool areas, plus the one stemming from the equilibrium sloping span downstream.

3 Results

3.1 *Maximum scour depth*

Comiti (2003) and Lenzi et al. (2003_a) demonstrated that scour dimensions in steep, coarse grained streams can be effectively analyzed neglecting the grain size variable. This finding seems to hold also for the comparison between Cordevole's and Maè's scour holes, which feature different grain size distribution (D_{50} = 93 mm and 30 mm respectively). The scour holes in the Maè river were also part of the dataset analyzed in those studies, but they have been resurveyed by using 6 transects across each pool, in order to have a more significant average depth instead of a single thalweg depth.

Figure 4 shows the plot of the non-dimensional scour depth y_s/z as a function of the drop ratio h_c/z only, indicating that points referring to mean pool depth below each structure in the two rivers overlap considerably and follow a common trend.

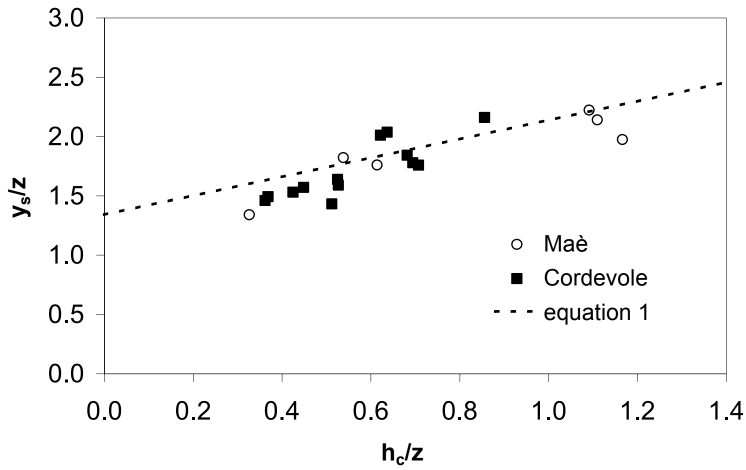

Figure 4 – Non-dimensional scour depth vs drop ratio for the two channels. Equation 1 is drawn too.

Equation 1 (see introduction) is plotted too in Figure 4, and appears to fit the new field data very nicely. A further indication that these pools are similar to the dataset presented in Comiti (2003) and Lenzi et al. (2003_a) is the energy-based normalization (see introduction). First of all, the average value of the ratio y_s/E for Cordevole's pools is 0.93, for Maè is 0.87 and for the previous dataset is 0.92, thus confirming the approximate invariance of this ratio. Figure 5 shows instead the decrease in scour efficiency (where *s* is the the residual pool depth, $s = y_s - z$) for increasing ratios z/h_c – i.e. for higher structures having similar jet initial thickness – an hypothesis already put forward in Comiti (2003) and Lenzi et al. (2003_a).

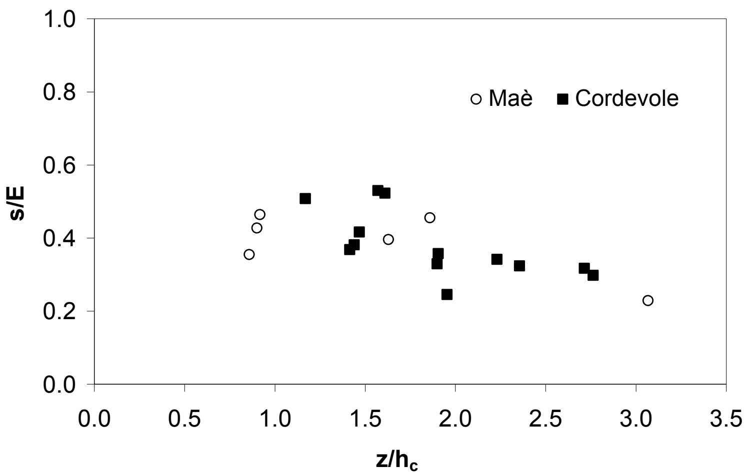

Figure 5 – Scour efficiency (*s/E*) vs the inverse of drop ratio (z/h_c) for the two channels.

3.2 *Grain size longitudinal sorting and degree of armoring in the pools*

In the Cordevole, the mean *phi* (φ=-$\log_2 D$) value for particles at pool bottoms is –7.86, equal to 232 mm. This size approximately corresponds to the D_{80} of the equilibrium slope stretch (Fig. 6). A larger degree of armoring is apparent for the Maè, where the mean φ value for the pool bottom is –7.24 (152 mm), matching the D_{87} of the reference, undisturbed bed (Fig. 7). These findings thus support Hallmark's (1955) and Kuroiwa's (1999) laboratory results about the armoring of the scour hole bottom.

In both rivers, particles collected at pool ends and exit slopes show similar distributions, finer and well-sorted compared to the reference curve of the sloping bed downstream (D_{30}-D_{35} for the Maè, D_{33}-D_{38} in the Cordevole). Particles found at berms represent the coarsest – and more uniform too – group: in the Maè φ_m= -8.2 (295 mm) equivalent to the D_{95} of the undisturbed downstream bed, for the Cordevole the φ_m is -8.42 (342 mm), corresponding to the D_{90} of the reference distribution.

4 Structures' stability

When a relationship between maximum scour depth and discharge (or critical flow depth) is determined, one can evaluate the degree of safety of grade-control structures for different scenarios, i.e. for flood events having different recurrence intervals. However, designers should be aware that the spacing between grade-control structure is crucial for the dimensions of scour holes, being involved in the formation of the drop height (Gaudio et al. 2000; Lenzi et al. 2002) and leading – if short enough – also to interference processes reducing pool depth (Comiti 2003; Lenzi et al. 2003_b; Marion et al. 2004). Therefore, if a sequence of grade-control structures is built using different spacings, the foundation depth of each structure must be calculated considering its actual distance from the next downstream. If all the works feature the same foundation size, the stability of the overall sequence is determined by the one having the longest spacing, assuming the equilibrium slope to be the same along the whole controlled reach. Once a structure fails for undermining, all the upstream ones are likely to collapse in a "domino" way for the absence of a downstream fixed bed level. In the Maè River, all the bed sills present a 2.5m-deep concrete body but the spacing varies from 30 m to 130 m. Assuming the present equilibrium slope (S_{eq} ~ 1%) to remain unchanged, and using the regression curve y_s/z – h_c/z for Maè points (equation not presented), the longest-spaced sill (i.e. the one having the longer distance to the next downstream, which in this case corresponds to the lowermost one) would become destabilized, i.e. maximum scour depth y_s = 2.5 m, for a discharge of 80 m^3s^{-1}. On the contrary, closer-spaced structures would be endangered only for discharges from 260 to 400 m^3s^{-1}, and this last value is similar to the largest flood ever recorded in the stream (in 1966, 402 m^3s^{-1}, return period >1,000 yr). The occurrence a flood with peak water discharge around 80 m^3s^{-1} (still a high magnitude event, but a more frequent one) might threaten the stability of the whole sequence just undermining the downstream-most bed sill and commencing a dangerous upstream-migrating erosion. If a reduction of the equilibrium slope during an extraordinary event was taken into account, an even greater instability of the longest-spaced sill would be evident, due to the multiplying effect of the sill spacing. In fact the drop height is given by $z = (S-S_{eq})\cdot L$ (Gaudio et al. 2000; Lenzi et al. 2002).

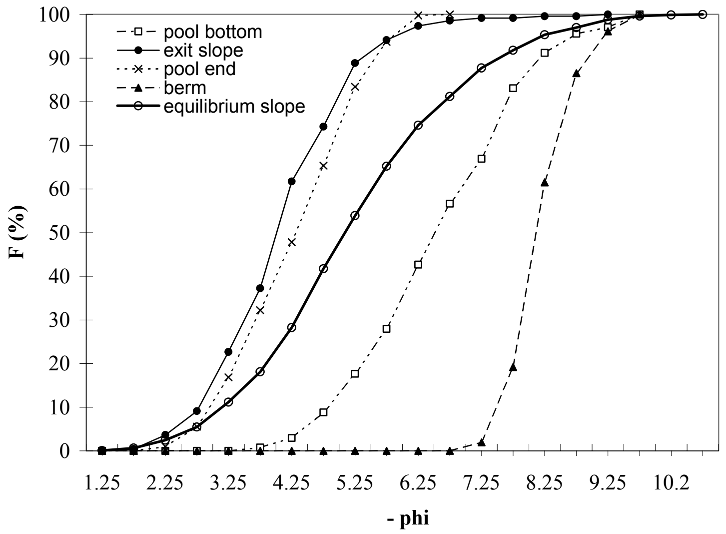

Figure 6 – Surface grain size distributions in the Cordevole river.

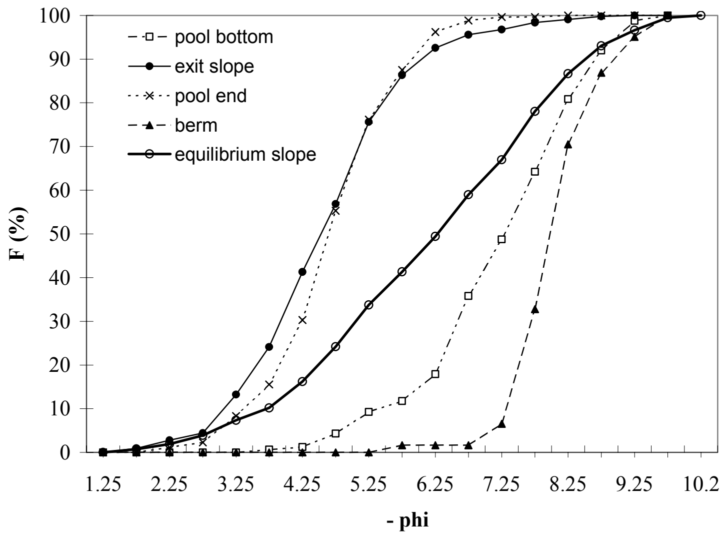

Figure 7 – Surface grain size distributions in the Maè river .

5 Conclusions

This paper has presented a field study on two mountain rivers controlled by sequences of grade-control structures. The longitudinal surface grain size sorting occurring within pools – i.e. pool bottom, pool exit slope, pool end and berms – has been quantified with reference to the grain size distribution of the equilibrium slope downstream. In particular, mean grain size at pool bottoms results to range between D_{80} and D_{87} of the reference undisturbed bed. Non-dimensional maximum scour depth y_s/z turns out to be linearly correlated with the drop ratio h_c/z, while using the virtual jet energy $E=z+H_s$ it turns out y_s/E=0.9. Finally, the importance of the spacing between structures has been pointed out using a numerical example from the Maè River grade-control structures, which present different degrees of safety.

Acknowledgments

This research was funded by the University of Padova, project "Valutazione della pericolosità connessa a colate detritiche sui conoidi Alpini" directed by Prof. M. Lenzi, and by the Italian Minister "MIUR ex 60% 2003" granted to Prof. Lenzi.

References

Bunte, K. and Abt, S.R. (2001). "Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analysis in sediment transport, hydraulics, and streambed monitoring". *Report RMRS-GTR-74*, USDA Forest Service, 409 pp.

Comiti, F. (2003). "Local scouring in natural and artificial step pool systems". *PhD dissertation*, University of Padova, Italy, 211 pp..

Comiti, F., Andreoli, A. and Lenzi, M.A. (2004). "Influence of local scouring on natural step pool geometry". *Proc. Riverflow 2004* Intl. Conf, IAHR, Naples, 23-25 June, Balkema, 173-179.

Gaudio, R., Marion, A., and Bovolin, V. (2000). "Morphological effects of bed sills in degrading rivers". *J. Hydr. Res.*, IAHR, 38(2), 89-96.

Hallmark, D. E. (1955). "Influence of particle size gradation on scour at base of free overfall". *MSc thesis*, Colorado State University, Fort Collins, USA.

Kuroiwa, J.M. (1999). "Scour caused by rectangular impinging jets in cohesionless bed". *PhD thesis*, Colorado State University, Fort Collins, USA, 365 pp..

Lenzi, M.A., Marion, A., Comiti, F. and Gaudio, R. (2002). "Local scouring in low and high gradient streams at bed sills". *J. Hydr. Res.*, IAHR, 40(6), 731-739.

Lenzi, M.A., Marion, A. and Comiti, F. (2003_a) "Local scouring at grade-control structures in alluvial mountain rivers". *Water Resourc. Res.,* 39(7), 1176-1188.

Lenzi, M.A., Marion, A. and Comiti, F., (2003_b). "Interference processes on scouring at bed sills". *Earth Surf. Process. Landforms*, 28(1), 99-110.

Lunardi, S. (2002). "Indagine sperimentale presso il torrente Cordevole (Arabba, BL) sullo scavo a valle di soglie di fondo: aspetti sedimentologici e geometrici". *MSc thesis*, University of Padova, Italy, 117 pp. (in Italian).

Marion, A., Lenzi, M.A. and Comiti, F. (2004). "Effect of sill spacing and sediment size grading on scouring at grade-control structures". *Earth Surf. Process. Landforms*, 29 (in press).

Pepato, A. (2003). "Indagine sperimentale presso il torrente Maè (Forno di Zoldo, BL) sullo scavo a valle di soglie di fondo: aspetti sedimentologici e geometrici". *MSc thesis*, University of Padova, Italy, 95 pp. (in Italian).