SCOUR DOWNSTREAM OF BLOCK RAMPS*

STEFANO PAGLIARA

Department of Civil Engineering, University of Pisa, via Gabba, 22
56100 Pisa - Italy

WILLI H. HAGER

VAW, ETH-Zentrum
CH-8092 Zurich, Switzerland

The objective of the paper is to study scour downstream of a block ramp. Block ramps are often used for river restoration, because they dissipate a considerable amount of hydraulic energy. The experiments were carried out in two different channels. The first channel was 0.8 m wide whereas the second smaller channel had a width of 0.25 m. Different sediments for both the ramp and the downstream bed were used. Also, different ramp slopes were tested ranging from 1V:4H to 1V:12H; both the maximum and the medium scour depths were considered. The prominent non-dimensional parameters are highlighted first. Equations and graphs then demonstrate that the results can be interpreted by means of simple relationships for the condition in which a ridge is present downstream of the scour hole.

1 Introduction

Block ramps are hydraulic structures often used for river rehabilitation to preserve an ecosystem and to produce an acceptable and sustainable river environment (Pagliara, Dazzini 2002). Block ramps may substitute the classical check dams and in parallel are often used as fish passages. The toe of these structures is characterized by supercritical approach flow with the potential for a scour. The scour hole due to a jet has been recently investigated with new techniques by Canepa and Hager (2003). The objective of this study is to describe the end scour hole downstream of a block ramp to allow for a hydraulic design.

2 Experimental setup

The experiments were conducted at the Hydraulic Laboratory of Pisa University. Two channels were employed: Channel I was 0.8 m wide, 20 m long and 0.7 m high. Discharges up to 120 l/s were investigated. Channel II was 0.25 m wide and 3.5 m long, with discharges up to 10 l/s and continuously variable slope. In both channels filtration across the sediment matrix was inhibited to control the hydraulic conditions for the ramp

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flow. The tests involved exclusively stable ramp conditions with sediment erosion confined to the downstream reach of the ramp toe. A total of 72 tests were conducted.

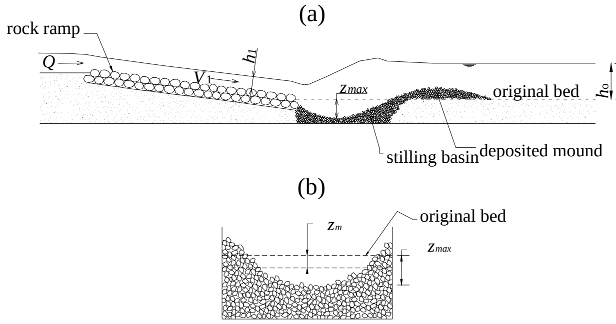

Figure 1. Sketch of the experimental apparatus (a) Longitudinal section, (b) Cross section of maximum scour

The bed and ramp materials used had a density of ρ_s=2690 kg/m^3. In total five crushed rock bed sediments and two ramp materials were employed, as shown in Table 1. There, d is the sediment size and the number indicates the percentage of passage across a sediment net. The sediment non-uniformity parameter is $\sigma=(d_{84}/d_{16})^{1/2}$**.** In all tests the ramp was not submerged, meaning that a hydraulic jump formed upstream from the scour hole at the toe of the ramp itself. This involves a minimum tailwater depth and consequently results in the maximum scour conditions.

Table 1. Materials used for the bed of the channel, and for the ramps

Material	d_{50} (m)	d_{90} (m)	σ	Notes
1	0.0123	0.0187	1.32	channel 1
2	0.0068	0.0118	1.35	channel 1
3	0.0313	0.0342	1.11	channel 1
4	0.0035	0.0047	1.44	channel 2
5	0.020	0.0239	1.21	channel 2
6	0.080	0.090	1.1	ramp channel 1
7	0.015	0.020	1.2	ramp channel 2

3 Results

Maximum scour depths

Two scour mechanisms were observed during the tests, depending on the presence or not of a ridge downstream of the end scour hole. In the following, only conditions with ridge presence are considered. Figure 2 shows the difference between the so called transport and non-transport conditions. In Figure 2 (a), no sediment is transported beyond the ridge, whereas Figure 2 (b) shows conditions with sediment transport in the downstream channel, i.e. no ridge is present. The second condition results in larger scour depths because the presence of a dune is a limiting factor for scour formation (Pagliara, et.al. 2005). In addition, no difference between static and dynamic flow conditions as for plunge pool scour was found (Pagliara, et.al. 2004).

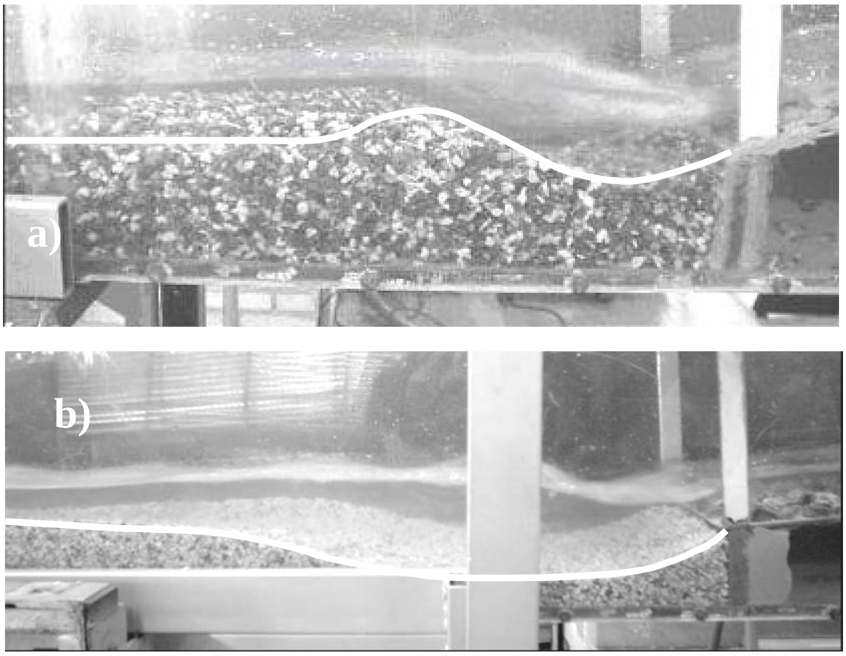

Figure 2 (a) Non-transport condition and ridge presence beyond scour hole, (b) transport condition beyond scour end associated with no ridge formation.

The medium (subscript *m*) cross-sectional scour depth z_m divided by the approach flow depth h_1 at the ramp toe ($Z_m=z_m/h_1$) was correlated with the densimetric Froude number $F_d=V_1/(g'd)^{1/2}$ with $V_1=Q/(Bh_1)$ as the average approach flow velocity, $g'=[(\rho_s-\rho)/\rho]g$ as the reduced gravitational acceleration where ρ_s=sediment density and ρ=water density with d as the sediment diameter of the scour hole and g as gravitational acceleration. Tests were terminated when sediment transport stopped, usually after test duration between 30 minutes and 2 hours in the present experimental configuration. All experiments had a relative tailwater depth $T=h_o/h_1$ between 1.5 and 2, where h_o=is the downstream flow depth.

The following relationship was found for the relative scour depth $Z_m = z_m/h_1$ in terms of the ramp slope i (Figure 3)

$$Z_m = A \cdot \ln(F_{d50}) + B \quad (1)$$

with

$$A = 2.93 \cdot i + 1.01 \ , \quad B = -0.83 \cdot i - 0.62$$

Using sediment size d_{90} instead of d_{50} gives (Figure 4)

$$Z_m = C \cdot \ln(F_{d90}) + D \quad (2)$$

with

$$C = +3.77 \cdot i + 1.25, \quad D = -0.92 \cdot i - 0.63$$

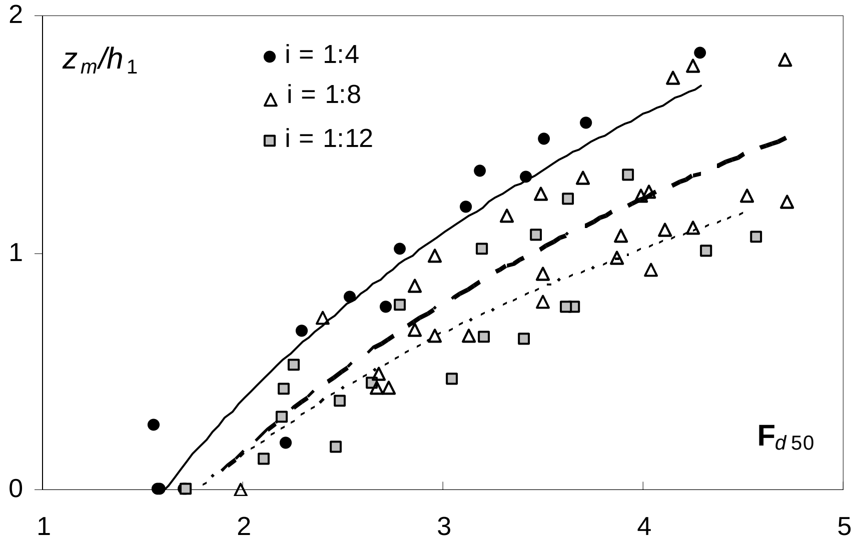

Figure 3. Mean scour depth Z_m versus F_{d50} for various ramp slopes i

Both figures 3 and 4 show a significant effect of the ramp slope i; for steep ramps, the relative scour depth is larger than for small ramp slope. Evidently, the approach flow velocity V_1 is then larger, and the approach flow depth h1 is smaller.

At the ramp end of short ramps, uniform flow conditions are normally not yet established because of limited ramp length. The scour hole geometry is not bi-dimensional such that a mean and a maximum scour hole depth at the same cross-section were observed. The maximum (subscript max) scour hole depth is located usually in the channel axis. Figure 5 shows the ratio between the maximum and mean scour hole depths zmax/zm as a function of the densimetric Froude number F_{d90}. As F_{d90} increases, the difference between the maximum and the mean scour depths decreases with the ratio z_{max}/z_m tending to unity.

As the approach flow velocity V_1 increases, the water jet at the end of the ramp generates more uniform scour in the transverse direction, therefore. The effect of ramp slope on the scour depth ratio in Figure 5 appears to be of minor importance.

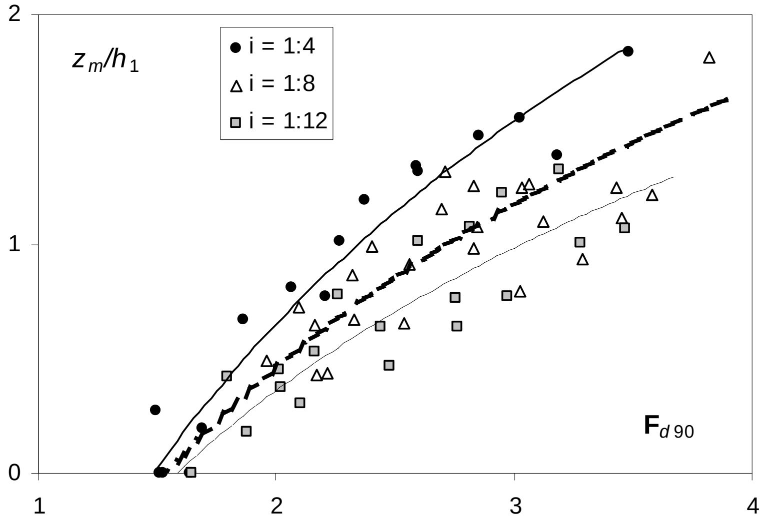

Figure 4 Mean scour depth Z_m versus F_{d90} for various ramp slopes *i*

If the maximum scour depth z_{max} at the ramp end instead of the average scour depth z_m is considered, the data may be expressed with $Z_{max}=z_{max}/h_1$ as (Figure 6)

$$Z_{max}=E\cdot\ln(F_{d50})+F \qquad (3)$$

with

$$E=+6.21\cdot i+0.74\ ,\ \ F=-2.18\cdot i-0.24$$

Using sediment size d_{90} instead of d_{50} gives alternatively (Figure 7)

$$Z_{max}=G\cdot\ln(F_{d50})+M \qquad (4)$$

with

$$G=+7.53\cdot i+1.00,\quad M=-2.04\cdot i-0.33$$

In Figures 3 to 7 the agreement between the data and the predictions is better for Z_m than for Z_{max}; this is due to the two-dimensional phenomenon for a supercritical approach flow and its typical non-uniformity due to the presence of the blocks along the ramp surface.

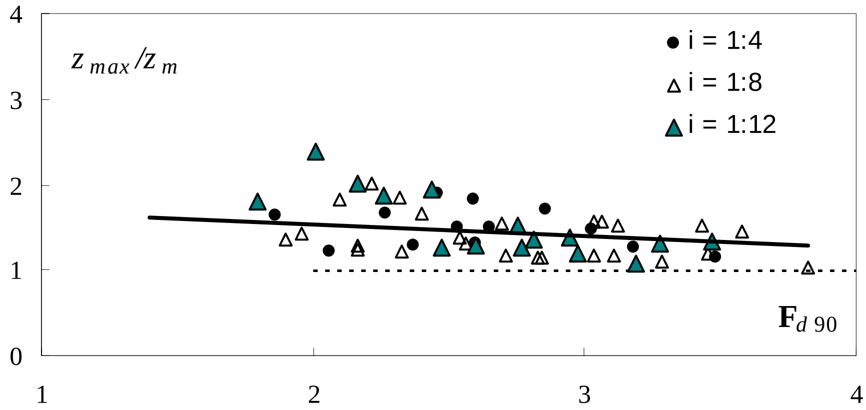

Figure 5 Ratio between z_{max}/z_m as a function of F_{d90} for different ramp slopes *i*

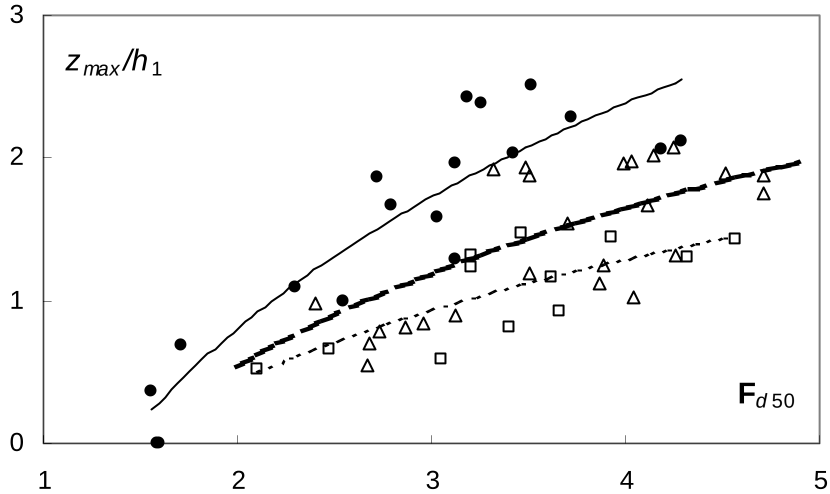

Figure 6. Non-dimensional maximum scour depth Z_{max} versus F_{d50}

Scour length

An important design parameter is the length *L* of the scour hole. Figure 8 shows the relative length L/h_1 as a function of average scour depth z_m/h_1 for the ramp slopes *i* previously considered. It may be observed that the ramp slope *i* is of relevance here.
The data may be described with the following relation

$$L/h_1 = 3.60\, i^{-0.54} \cdot Z_m \qquad (5)$$

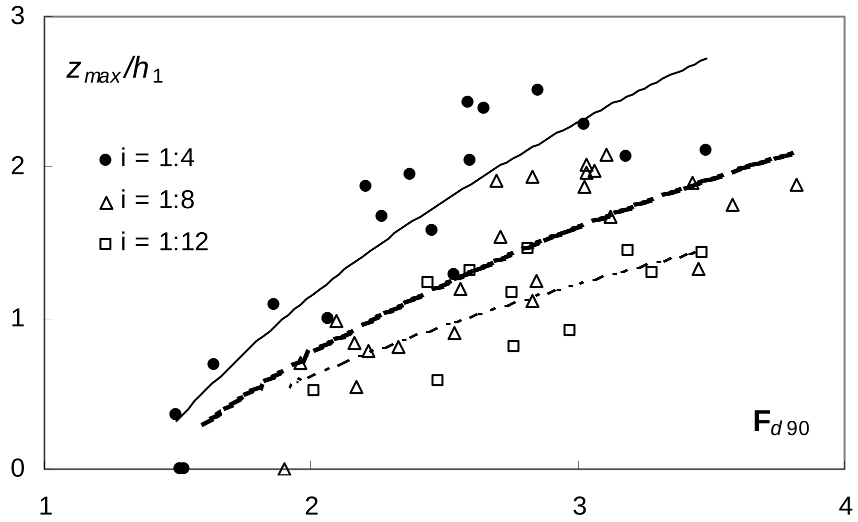

Figure 7 Relative maximum scour depth Z_{max} versus F_{d90} for various ramp slopes *i*

The length of scour hole thus increases as the scour hole deepens and as the ramp slope reduces.

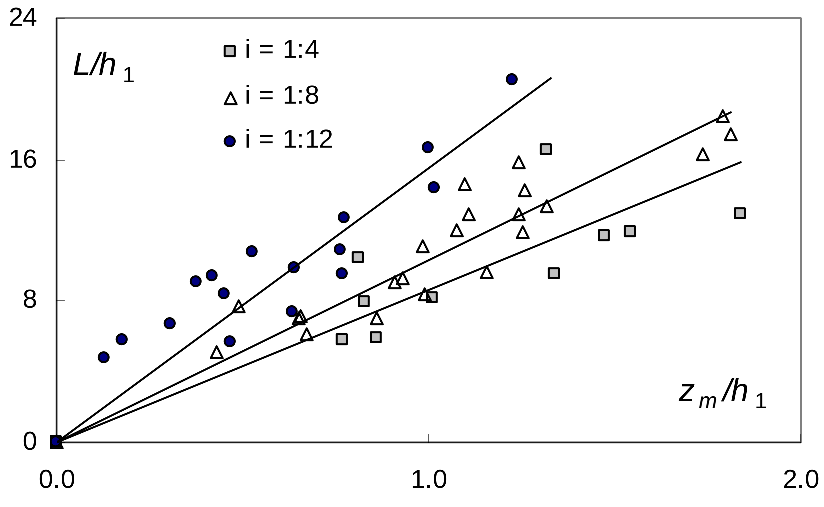

Figure 8 Relative length of scour hole L/h_1 as function of relative scour hole depth Z_m for various ramp slopes *i*

Conclusions

Data collected from experimental tests result in relationships among the scour depth, scour length, the densimetric Froude number and the slope of a block ramp. These apply to the particular condition when a ridge is formed downstream of the scour hole, corresponding to non-transport of sediment into the tailwater channel and for non-submerged hydraulic conditions on the ramp. These data may be of interest in preliminary design of block ramps, to determine the geometry of the end scour hole in terms of approach flow conditions at the ramp toe. More research is needed for the description of the flow along the block ramp; this was considered beyond the scope of the present research, however.

Acknowledgments

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