SCOUR DEVELOPMENT IN BASINS OF CROSS-BAR BLOCK RAMPS

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Abstract

Cross-bar block ramps are a common nature-like solution to conquer large river bottom steps. Thereby, the level difference between the upstream and downstream part of the structure will be managed by several basins, which are separated by lateral cross-bars. These cross-bars are made of large stones with diameters up to 1.0 m and more. To guarantee stable cross-bar block ramps, two main factors have to be analyzed. On the one hand, the large boulder's stability is in the main focus of interest due to cost-reduction issues after flood events. On the other hand, also the base material within the basins has to be stable, because it is creating a relevant resistant force for the balance of total forces (uplift, drag, resistance, weight). If the base material will be eroded, the structure's stability can be at risk and a malfunction might occur. To analyze the base material's stability on cross-bar block ramps, an experimental investigation program has been carried out in a physical scaled model. For various discharges, slopes, cross-bar heights, and base material diameters the scour development and particle transport have been analyzed. Model runs were carried out with and without arranged openings in the cross-bars. Resulting particle densimetric Froude numbers give information about the material transport. Critical particle densimetric Froude numbers were developed in dependence of relevant parameters.

Introduction

To design cost effective cross-bar block ramps (an example photograph is given in Fig. 1), it is essential to know about occurring forces and scour developments on such structures. In this regard, Oertel (2012) analyzes drag forces F_D on single boulders in rows of cross-bar block ramps for various configurations with different discharges Q and slopes S. But also the basin material's stability has to be analyzed, since it creates a relevant resistant force F_R for the balance of total forces (Fig. 2), including the weight force G and the uplift force F_z. Within scaled experimental investigations it is quite complicated to model the scour development and to find adequate formulas, which express the occurring phenomena.

Figure 1: Example cross-bar block ramp under construction (source: Wupperverband)

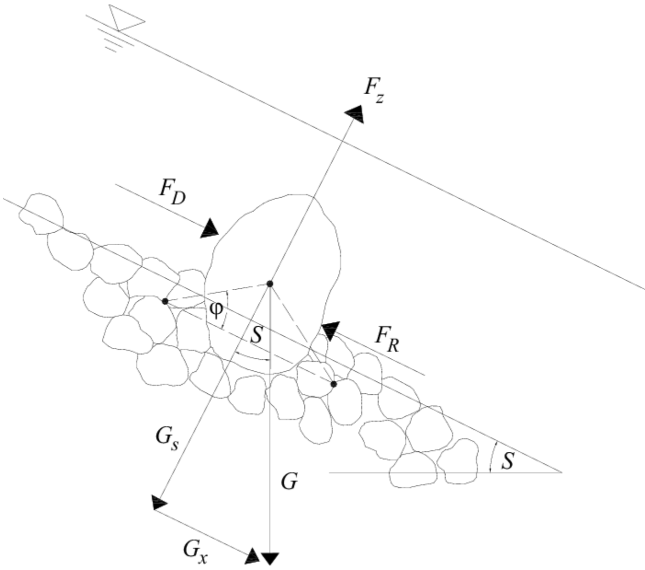

Figure 2: Schematic plot of total forces on single boulders

Shields (1936) gives an investigation on initial particle movement due to the shear stress for nearly horizontal beds. Herein, the Shields parameter is given by:

$$\theta = \frac{\tau}{g(\rho_p - \rho)D_{50}} \qquad (1)$$

where: τ = bed shear stress, g = acceleration due to gravity, ρ_p = particle density, ρ = water density, D_{50} = particle diameter for which 50 % is finer.

Thereby, the Shields parameter is a function of the Particle Reynolds number:

$$\mathrm{R}_p = \frac{U^* D_{50}}{\nu} \quad (2)$$

where: $U^* = (ghS)^{0.5}$ = shear velocity, h = uniform flow depth, S = channel slope, ν = kinematic viscosity.

Aguierre-Pe et al. (2003) mention that for ratios of flow depth to bed particle diameter less than 10 (very rough conditions) neither the particle Reynolds number nor the Shields parameter are adequate variables to predict critical flow conditions for the initiation of particle motion. Hence, Aguierre-Pe et al. (2003) give a particle densimetric Froude number as:

$$\mathrm{F}_p = \frac{U}{\sqrt{g\left(\frac{\rho_p}{\rho} - 1\right) D_{50}}} \quad (3)$$

where: U = uniform flow velocity.

Generally, the critical particle densimetric Froude number represents the beginning of particle movement and can be calculated by implementing the Darcy friction factor:

$$\mathrm{F}_{p,c} = \sqrt{\frac{8rS}{f\left(\frac{\rho_p}{\rho} - 1\right) D_{50}}} \quad (4)$$

where: r = hydraulic radius, f = friction factor.

Aguierre-Pe et al. (2003) give a critical boundary as:

$$\mathrm{F}_{p,c} = 0.9 + 0.5\ln\left(\frac{h}{D_{50}}\right) + 1.3\frac{D_{50}}{h} \quad (5)$$

Pagliara and Chiavaccini (2007) define the critical condition for block ramps with:

$$\mathrm{F}_{p,c} = 1.98S^{0.18}\left(\frac{h}{D_{84}}\right)^{0.36}(1 + \Gamma)^{-2.2} \quad (6)$$

where: D_{84} = particle diameter for which 84 % is finer, Γ = boulder concentration.

Experimental model

A scaled physical model is build up at the University of Wuppertal's Hydraulic Laboratory. The model scale is approximately 1:15. Simplified cross-bar structures are made of synthetic materials and arranged in a tilting flume (length L = 9.0 m, width W = 0.8 m, height H = 0.4 m, maximum slope S = 1:10). The flume is made of Plexiglas and cross-bars are glued on the channel's bottom. Fig. 3 shows a photograph of the basic model configuration. Fig. 4 gives a photograph with the measurement technique.

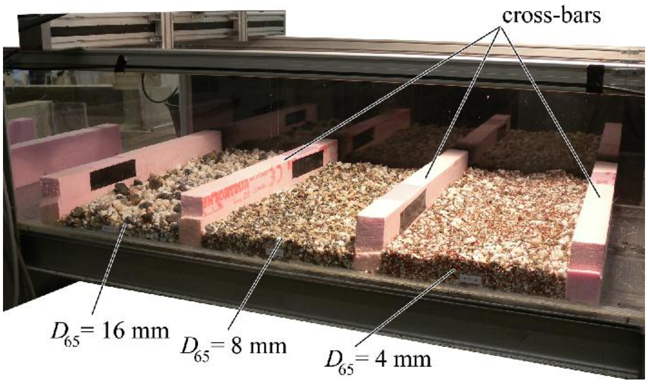

Figure 3: Photograph of model configuration

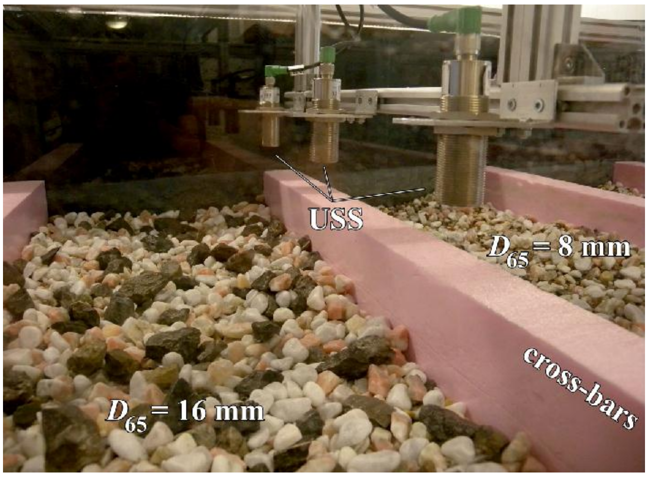

Figure 4: Measurement technique set-up

Two main model runs have been carried out: (1) scour development, (2) identification of critical discharges for particle movement. The first set is done without openings in the cross bars (Fig. 3). For the second set, lower openings were arranged to create major three-dimensional effects. For all model runs, three basins have been filled with various materials (D_{65} = 4 mm, D_{65} = 8 mm, D_{65} = 16 mm). The scour developments have been measured after six time steps (0, 5, 10, 15, 20, 30 minutes) for model runs without openings. Therefore, the model was slowly switched off and the water was removed. Two time steps (0, 30 minutes) were analyzed for model runs with lower openings within the cross-bars. The basin material's surface has been

longitudinally measured with ultrasonic probes (fabricate: general acoustics, type: USS635, accuracy: ± 1 mm).
Next to the general time-depending scour development, the critical discharges for particle movement were determined for three particle fractions (2 to 4 mm, 4 to 8 mm, 8 to 16 mm). Thereby, the particle movement has been separated into four conditions (moderate bounce, clear bounce, moderate transport, clear transport). Table 1 gives an overview of investigated model runs.
Discharges have been measured using an electromagnetic flow meter (fabricate: Krohne, type: Optiflux, accuracy: ± 1 mm/s). USS sensors have been placed by an automatic positioning system (fabricate: isel, type: step motor and spindle, accuracy: 2.5/400 mm).

Table 1: Investigated model runs

model runs	S [-]	Q [l/s]	CB openings	h_B [cm]	L_b [cm]	T [min]
(1) scour development						
24	1:50	40 to 100	no	6	42	0, 5, 10, 15, 20, 30
30	1:30	20 to 100	no	6	42	0, 5, 10, 15, 20, 30
24	1:20	40 to 100	no	6	42	0, 5, 10, 15, 20, 30
20	1:30	10 to 100	yes	6	42	0, 30
(2) critical particle movement						
3	1:50 1:30 1:20	5 to 100	no	6	42	--
3	1:50 1:30 1:20	5 to 100	no	9	42	--

Results and discussion

Longitudinal scour development

Fig. 5 gives example photographic results for the longitudinal scour development in the three basins. It can be shown, that the material will be transported upstream. The main erosion takes place at the downstream basin end, while the deposition occurs at the upstream basin area. For smaller basin particle sizes (D_{65} = 4 mm) more particle movement can be observed. Larger particles (D_{65} = 16 mm) are more stable for the investigated discharges. With increasing slopes and discharges, also the particle movement increases. Figs. 6 and 7 give example USS results for longitudinal scour development.


(a) (b) (c)

Figure 5: Example photographs of longitudinal scour development, S = 1:30, Q = 100 l/s, T = 30 min, (a) basin 1: D_{65} = 4 mm, (b) basin 2: D_{65} = 8 mm, (c) basin 3: D_{65} = 16 mm, flow direction from left to right

Three-dimensional scour development

For model runs with arranged lower openings within the cross-bars, USS sensors have been placed on a 1 cm grid at each basin. The results show the basin material's surface for the initial time step (T = 0 min) and after 30 min. Again, it can be found that the material will be transported upstream and deposited at the upstream basin area (Fig. 8). Additionally, downstream the openings a local scour is developed due to a jet through these openings. As described before, the material transport will increase with increasing discharges and increasing slopes.
Within the first basin (D_{65} = 16 mm) the material will not be majorly transported unless discharges reach higher values, comparable with major flood events. For small and intermediate discharges the bed is comparable stable. Contrary, for smaller basin material sizes (D_{65} = 8 mm and less) the erosion process takes place with smaller discharges and hence, the stability might be at risk.
To quantify the critical discharge limits, the next section deals with critical particle densimetric Froude numbers.

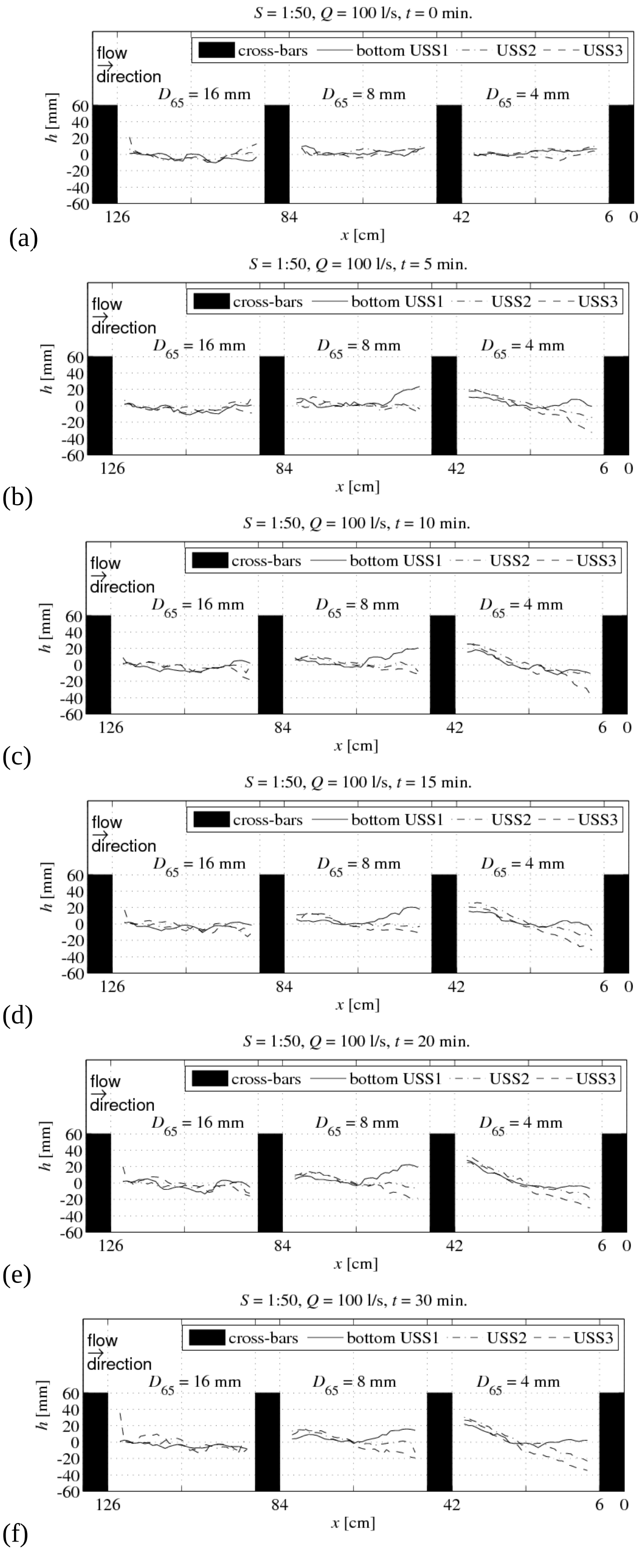

Figure 6: USS results for scour development, S = 1:50, Q = 100 l/s, (a) T = 0 min, (b) T = 5 min, (c) T = 10 min, (d) T = 15 min, (e) T = 20 min, (f) T = 30 min

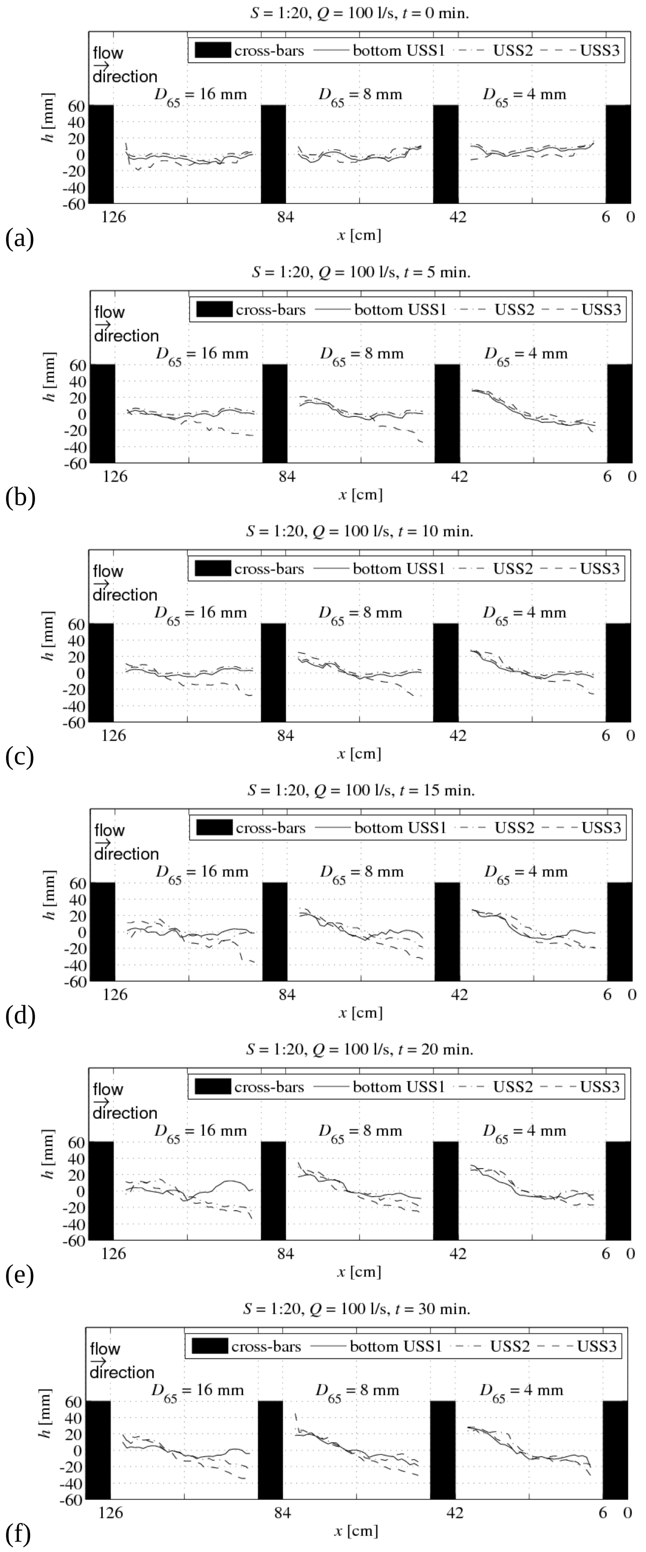

Figure 7: USS results for scour development, S = 1:20, Q = 100 l/s, (a) T = 0 min, (b) T = 5 min, (c) T = 10 min, (d) T = 15 min, (e) T = 20 min, (f) T = 30 min

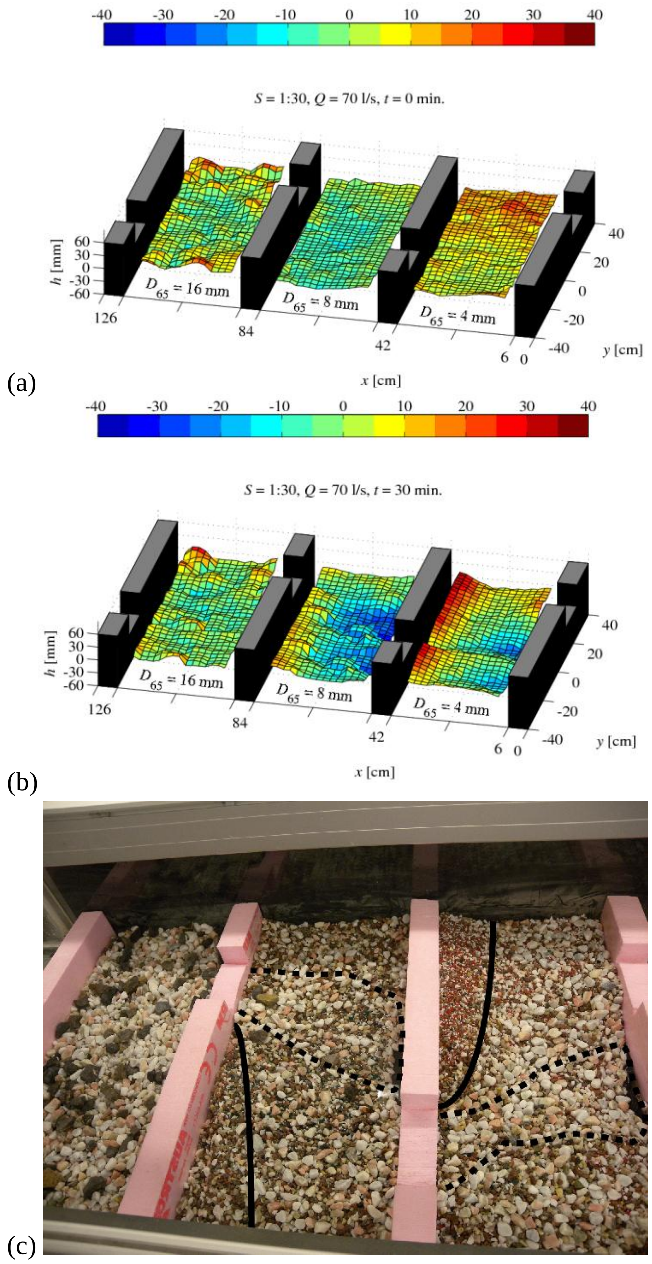

Figure 8: Example three-dimensional scour development, S = 1:30, Q = 70 l/s, (a) T = 0 min, (b) T = 30 min, (c) photograph T = 30 min (– deposition, - - erosion), flow direction from left to right

Critical particle densimetric Froude numbers

The critical particle densimetric Froude numbers can be calculated by Eq. 4. Herein, the flow velocity is given as a depth averaged velocity with pre-calculated uniform flow depths. Therefore, Oertel and Schlenkhoff (2012) developed a formula to calculate friction factors on cross-bar block ramps by:

$$\sqrt{\frac{8}{f}} = \left(4.4 + \frac{0.09}{S}\right) \log\left(\frac{h}{h_B}\right) + \left(2.2 - \frac{0.0023}{S}\right) \tag{7}$$

where: h_B = large boulder's height.

With these friction factors uniform flow depths and hence, mean flow velocities on the structure can be calculated. When analyzing critical discharge values for the clear particle bouncing and the particle fraction 8 to 16 mm, the following equation can be developed for critical particle densimetric Froude numbers (cmp. Fig. 9):

$$\mathrm{F}_{d,c} = 0.6 \left(\frac{D_{65}}{h_B}\right)^{0.18} \left(\frac{h}{D_{65}}\right)^{0.58} \tag{8}$$

It can be shown, that $\mathrm{F}_{d,c}$ will decrease with decreasing flow depths or increasing basin material diameters, while the ramp slope is implicitly included. Fig. 9 also gives critical $\mathrm{F}_{d,c}$ values by Aguierre-Pe et al. (2003) and Pagliara and Chiavaccini (2007). Both approaches will lead to varying results, while the newer one is closer to the given experimental results.

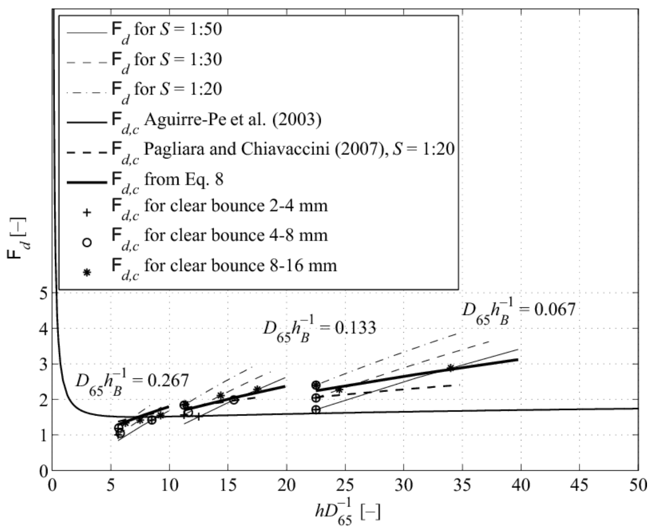

Figure 9: Critical and reached particle densimetric Froude numbers, clear particle bouncing

Conclusions

The presented paper deals with scour developments on cross-bar block ramps. Within an experimental investigation program, time-dependent scours have been measured via ultrasonic sensors. It can be found, that the base material will be transported upstream, against the flow direction, and deposited at the upstream basin area. Scouring will increase with increasing slopes and discharges. Cross-bars with lower openings lead to three-dimensional scour effects.

Critical particle densimetric Froude numbers have been investigated and a new formula in dependence of the friction factors has been developed.

References

Aguierre-Pe, J. & Olivero, M. L. & Mocada, A. T. (2003). Particle Densimetric Froude Number for Estimating Sediment Transport. *J. Hydr. Engng.*, 129(6), 428-437.

Oertel, M. (2011). Strömungsvisualisierung auf Blocksteinrampen in Riegelbauweise. *WasserWirtschaft WaWi*, 9/2011, pp. 34-41.

Oertel, M. (2012). Cross-Bar Block Ramps - Flow Regimes, Flow Resistance, Energy Dissipation, Stability. *Habilitation Thesis*, University of Wuppertal, in print.

Oertel, M. & Schlenkhoff, A. (2012). Cross-Bar Block Ramps, Flow Regimes, Energy Dissipation, Friction Factors, Drag Forces, *J. Hydr. Engng.*, in print.

Pagliara, S. & Chiavaccini, P. (2007). Failure mechanisms of base and reinforced block ramps. *J. Hydr. Res.*, 45(3), 407-420.

Shields, A. F. (1936). Anwendung der Ähnlichkeitsmechanik der Turbulenzforschung auf die Geschiebebewegung. *Mitteilungen der Preussischen Versuchsanstalt für Wasser-, Erd- und Schiffbau*, Vol. 26, Berlin, in German.