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INTRODUCTION

In the wake of the European Water Framework Directive (EU-WFD 2000) all water bodies with significant anthropogenic impacts have had to be retreated into nature-orientated good ecological conditions. A standard solution for renaturing lateral structures is the arrangement of so called rough ramps or block ramps. Within these structures large boulders and bed roughness dissipate energy and reduce flow velocities, thus increase flow depth. A classification of block ramps can be done into (see Fig. 1)

- block carpets (interlocked blocks or dumbed blocks), and
- block clusters (structured, unstructured or self-structured blocks).

A special case of structured block ramps are so called cross-bar block ramps (Oertel and Schlenkhoff 2012). A step-pool-system reduced the bottom level difference from upstream to downstream while adequate flow velocities occur. Cross-bars are made of huge stones with diameters up to $D_B = 1.5$ m and more. Lower openings within the cross-bars guarantee minimum water depths and fish paths (Figs. 2 and 3). The structures can be arranged over the complete width (Fig. 4) as well as partially (Fig. 5).

In-Situ Measurements on Cross-Bar Block Ramps

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ABSTRACT: Cross-bar block ramps can be used to conquer large river bottom steps with adequate flow velocities and water depths. Therefore, the slope will be reduced by arranging several basins with maximum drop heights of 0.2 m. By following general design guidelines acceptable energy dissipation can be achieved and fish climbing is possible. While the flow can be separated into basin, waved and channel flow regimes, the Poleni formula can be used to calculate water depths on the structure for basin flow regimes. With increasing discharges the flow changes into waved and finally into channel flow regime, where an approach using friction factors and the Darcy equation lead to good results for water depths calculations. To validate results for the basin flow regime, a measurement campaign was arranged on three varying cross-bar block ramps structures in North Rhine-Westphalia. The present paper compares example results and gives limiters for measurement purposes.

Keywords: Cross-Bar Block Ramp, in-situ measurement, MID, ADCP, flow regime

1 INTRODUCTION

In the wake of the European Water Framework Directive (EU-WFD 2000) all water bodies with significant anthropogenic impacts have had to be retreated into nature-orientated good ecological conditions. A standard solution for renaturing lateral structures is the arrangement of so called rough ramps or block ramps. Within these structures large boulders and bed roughness dissipate energy and reduce flow velocities, thus increase flow depth. A classification of block ramps can be done into (see Fig. 1)

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Current research investigations deal with flow characteristics, stability criteria and ecological aspects. Therefore, physical and numerical models were built up to analyze occurring flow (e.g. Pagliara and Chiavaccini 2006, Pagliara et al. 2008, Oertel and Schlenkhoff 2012, Oertel 2012). Thereby, Oertel (2012) separates three various flow regimes on cross-bar block ramps:

1. Basin flow regime \( (h < h_B) \),
2. Wave flow regime \( (h_B < h < 1.5h_B) \), and
3. Channel flow regime \( (h > 1.5h_B) \).
where \( h \) = mean flow depth and \( h_B \) = large boulder height. For the basin flow regime the regular Poleni approach lead to acceptable results for flow depth calculations (see DVWK, DWA 2010):

\[
Q = \frac{2}{3} C_w C_b C_s \sum W_w \sqrt{2gh^1.5}
\]

(1)

where:

- \( Q \) = discharge,
- \( C_w = 0.65 \) = overfall coefficient,
- \( C_b = 0.94 \) = backwater coefficient,
- \( C_s = 1.1 \) = stone factor,
- \( W_w \) = total opening width small boulders,
- \( g \) = acceleration due to gravity,
- \( h_w \) = overfall height small boulder.

If \( Q \) increases, the flow changes into the waved flow regime and a research deficit can be identified. For the channel flow regime the water surface slope becomes equal to the bottom slope and flow depth can be calculated by using friction factors (Oertel 2012):

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

(2)

where:

- \( f \) = friction factor,
- \( S \) = ramp slope.

In Eq. (2) \( h \) represents the water depth from basin bottom to water surface. Using the Darcy formula lead to mean flow velocities:

\[
U = \sqrt{\frac{8}{f}} \sqrt{grS}
\]

(3)

where:

- \( U \) = mean flow velocity in \( x \)-direction,
- \( r \) = hydraulic radius.

Figure 6 give example results for analytical approach, numerical model and laboratory measurements.

![Figure 6](image)

a) b) c) d)

Figure 6. Example results for basin (a), waved (b) and channel (c, d) flow regime (Oertel 2012), with \( h_c = (Q^2g^{-1}b^{-1})^{1/3} \) = critical water depth and \( H \) = ramp height.

Generally, scaled physical model results of free surface flow will be transformed into prototype scale via Froude model (USBR 1980). Therefore, main boundary conditions must be considered – e. g. minimum water levels – to obviate scaling effects by surface tension or viscosity. To validate numerical and laboratory results, in-situ measurements will be necessary. It will be difficult to measure in field during flood events, thus to get results for channel flow regime. But for basin flow regime in-situ measurements are possible with adequate complexity. The present paper picks up this requirement and deals with in-situ measurements on cross-bar block ramps.

2 INVESTIGATION PROGRAM AND MEASUREMENT TECHNIQUE

2.1 River Ruhr

To arrange field measurements on cross-bar block ramps, three varying ramps in North Rhine-Westphalia were selected. The first block ramp is a bypass channel at the River Ruhr next to the Harkort power plant.
(Harkort reservoir), see Figs. 7 and 8. The ramp was built in 2004 and designed for \( Q = 700 \) l/s. The total length is \( L = \sim 375 \) m, partitioned into 57 basins. The level difference is approx. \( H = 6.8 \) m, the width around \( W = 6.0 \) m.

2.2 River Brückerbach

The second chosen structure is located in Düsseldorf in the River Brückerbach and represents a cross-bar block ramp over the full channel width (Figs. 9 and 10). The ramp was built in 2009 and is made of 12 cross-bars on a total length of \( L = 58 \) m. The resulting basin length is \( L_b = 3.3 \) to \( 5.8 \) m. The ramp width varies between \( W = \sim 9.8 \) m in the upstream part and \( W = \sim 5.0 \) m in the downstream part.

2.3 River Wupper

The third investigated cross-bar block ramp was built in the River Wupper and is designed as a partial ramp (Figs. 11 and 12). The total channel width is \( \sim 25.5 \) m, while the ramp was constructed with a width of \( W = 10.5 \) m. The ramp length is \( L = 20.0 \) m and the height \( H = 1.0 \) m. Hence, the resulting slope is \( S = 1:20 \) with a drop of \( \Delta h = 0.2 \) m for each basin. Five cross-bars create \( L_b = 4.2 \) m long basins. Large stones are approx. \( h_B = 1.0 \) m in height and \( 0.6 \) m in width. The total opening width (small boulders) is \( W_w = \sim 3.25 \) m.
2.4 Investigation program

To analyze the flow on the structure, flow depths and flow velocities were measured in selected basins. Therefore, two to three cross-sections were selected (~1.0 m downstream the upstream cross-bar and ~1.0 m upstream the downstream cross-bar, and in between). Figure 13 shows example cross-section measurement points, where flow depths were collected at P1, P2, … , PX. Flow velocities were measured 5 cm under the free surface as well as 5 cm above the basin bottom. Between the water surface and basin bottom velocities were collected with a distance of approx. 20 cm.

2.5 Measurement technique

Flow velocities were measured by using a portable velocity flow meter with electromagnetic sensor. Therefore, the Flo-Mate 2000 (manufacturer: Hach) was chosen (Fig. 14). It is fully water resistant and the mobile measurement device allows data collection of mean values. Specifications can be found in Morgenschweis (2010).

Within the first basin of the cross-bar block ramp in the River Wupper a mobile Acoustic Doppler Current Profiler (ADCP) measurement was additionally carried out to compare results with those collected by electromagnetic measurements. Therefore, a StreamPro (manufacturer: RDI) was placed on a small boat (Fig. 15), which was pulled twice through the cross-section.
3 RESULT ANALYSIS

3.1 Discharge

In the present paper, results will be presented only for the cross-bar block ramp in the River Wupper. Here, flow velocities determined via electromagnetic sensor will be analyzed in comparison with those measured by ADCP. Measurements were carried out in the first and second upstream basin (see Fig. 5). In both, two cross-sections were selected.

Measurements were carried out 12th June 2012. On that day a discharge of $Q_{river} = 4.0 \text{ m}^3/\text{s}$ was measured at gauge Kluserbrücke a few hundred meters upstream the ramp. Since the investigated cross-bar block ramp was partially built up, the flow is separated into the ramp and over the weir. The weir overfall height was measured with $h_w = 0.08 \text{ m}$. An overfall discharge coefficient of $C_w = 0.8$ lead to the weir discharge $Q_{weir} = 2/3 \cdot C_w \cdot W_{weir} \cdot (2g)^{0.5} \cdot h_w^{1.5} = 2/3 \cdot 0.8 \cdot (25.5−10.5) \cdot (2 \cdot 9.81)^{0.5} \cdot 0.08^{1.5} = 0.80 \text{ m}^3/\text{s}$. A power plant located next to the block ramp continuously extracts $Q_{powerplant} = 1.0 \text{ m}^3/\text{s}$. Another part of the discharge is guided through a bypass ($Q_{bypass} = 0.8 \text{ m}^3/\text{s}$). Hence, the total discharge on the cross-bar block ramp can be assumed as $Q_{ramp} = Q_{river} - Q_{weir} - Q_{bypass} - Q_{powerplant} = 4.0 - 0.8 - 0.8 - 1.0 = 1.4 \text{ m}^3/\text{s}$.

Large boulders are marginally overflown and the lower opening ($h_w = 0.4 \text{ m}$) represents the main flow area. Hence, using the Poleni formula (Eq. 1) for the given basin flow regime, the discharge can be calculated as:

$$Q_{ramp} = \frac{2}{3} C_w C_b C_s \sum W_w \sqrt{2g h_w^{1.5}} = \frac{2}{3} \cdot 0.65 \cdot 0.94 \cdot 1.1 \cdot 3.25 \cdot \sqrt{2 \cdot 9.81 \cdot 0.4^{1.5}} = 1.63 \text{ m}^3/\text{s}$$

Using the ADCP boat and pulling it twice through the cross-section, a discharge of $Q_{ramp} = 1.45 \text{ m}^3/\text{s}$ results. It can be shown, that theoretical approaches, ADCP measurements and gauge measurements give comparable results for discharge amounts on the cross-bar block ramp.

3.2 Flow velocity

Sectional flow velocities were measured via electromagnetic sensor. For one profile in the upstream basin, ADCP measurements were additionally carried out. It must be mentioned, that ADCP measurements can only be used if no major air entrainment occurs and a clear water surface is given. Otherwise, signals cannot be processed and errors are resulting. In contrast, MID measurements present the best way to detect flow velocities on these structures, even if air entrainment exists.
Figures 16 and 17 give results for flow velocities within the first two basins. It can be shown, that maximum values reach $U = \sim 1.2$ m/s downstream lower openings within the cross-bars. Maximum allowed velocities of $U_{\text{max}} = 2.0$ m/s (DWA 2010) were not detected. Due to displaced lower openings horizontal huge vortexes will be created, leading to negative flow velocities of few centimeters per second. Generally, areas with low flow velocities are created, generating rest areas for fish during climbing.

![Flow velocities in [m/s] measured with electromagnetic sensor.](image)

(a) basin 1, cross-section 1, (b) basin 1, cross-section 2, (c) basin 2, cross-section 1, (d) basin 2, cross-section 2.

Comparing MID results with those determined by ADCP measurement (Fig. 18), a basically good agreement can be found. This was also confirmed by discharge measurements, where velocity profiles will be integrated over the flow area (see Section 3.1). Main differences come by averaging values from MID measurements. Here, the ramp bottom as well as ramp banks will not be detected exactly. Thus, Fig. 18 shows displaced minimum bottom depths over the width. Problems of ADCP measurements can be assumed due to negative flow velocities. Since negative values are very small, these were not reproduced well.

Summarizing, MID measurements represents a state-of-the-art solution for in-situ measurements on block ramps. Neither air entrainment nor huge flow velocities will influence measuring accuracy. Hence, MID sensors should be preferred for these structures.

![Flow velocities in [m/s], three dimensional view of all four measured cross-sections.](image)
4 SUMMARY AND CONCLUSION

4.1 General

Cross-bar block ramps separate large river bottom steps into several basins with adequate flow velocities and flow depths concerning fish climb capabilities. Hydraulic phenomena on those structures were frequently investigated during the last years. Formulas for flow resistance and energy dissipation were developed and flow regimes were defined as basin flow, waved flow, and channel flow. Usually, the basin flow regime occurs and flow depth calculations can be done by using the regular Poleni approach. For flood events the free water surface slope equals the ramp slope and developed friction factors lead to acceptable results. The waved flow regime is still investigated since a research leakage can be identified.

In-situ measurements confirm the applicability of the Poleni formula. Water depths within the basins can be described well. But for detailed flow velocity distribution in-situ measurements or numerical simulations are necessary. The present paper deals with in-situ measurements on cross-bar block ramps and results for an exemplary structure were presented.

4.2 Outlook

Further in-situ investigations will be necessary to confirm those approaches using friction factors for the channel flow regime during flood events. Collected data are rare, because measurements will be very difficult to arrange. Huge flow velocities and flow depths on the structure will increase the risk of measuring significantly. Hence, new ideas for measurement facilities are necessary.

NOTATION

- $C_w$: overfall coefficient
- $C_b$: backwater coefficient
- $C_s$: stone factor
- $D_B$: boulder diameter
- $f$: friction factor
- $g$: acceleration due to gravity
- $h$: mean flow depth
- $h_c$: critical water depth $= (Q^2g^{-1}b^{-2})^{1/3}$
- $h_B$: large boulder height
- $h_w$: overfall height small boulder
- $H$: ramp height
- $L$: ramp length
$L_b$ basin length  
$Q$ discharge  
$r$ hydraulic radius  
$S$ ramp slope  
$U$ mean flow velocity in $x$-direction  
$W$ ramp width  
$W_w$ total opening width small boulders

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