



BERGISCHE
UNIVERSITÄT
WUPPERTAL

Cross-Bar Block Ramps

Flow Regimes – Flow Resistance – Energy Dissipation – Stability

Habilitationsschrift

zur Erlangung der Lehrbefähigung
für das Fachgebiet Wasserbau und Wasserwirtschaft

von

Dr.-Ing. Mario Oertel

© 2011/12 Dr. Mario Oertel, Hydraulic Engineering Section, Bergische University of Wuppertal.
Duplication only with author's permission.

Submitted:	06. October 2011
Examination:	25. May 2012
First reviewer:	Univ.-Prof. Dr.-Ing. Andreas SCHLENKHOFF LuFG Wasserwirtschaft und Wasserbau Bergische Universität Wuppertal
Second reviewer:	Univ.-Prof. Dr.-Ing. habil. Torsten SCHLURMANN Franzius-Institut für Wasserbau und Küsteningenieurwesen Leibniz Universität Hannover
Third reviewer:	Prof. Dr. sc. techn. Robert BOES Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie Eidgenössische Technische Hochschule Zürich
Chairman:	Univ.-Prof. Dr. agr. Jörg RINKLEBE LuFG Boden- und Grundwassermanagement Bergische Universität Wuppertal
Other committee members:	Univ.-Prof. Dr.-Ing. habil. U. JANOSKE, Universität Wuppertal Univ.-Prof. Dr.-Ing. A. NIEMANN, Universität Duisburg-Essen Univ.-Prof. Dr. A. SEYFRIED, Universität Wuppertal Jun.-Prof. Dr.-Ing. A. WITTMANN, Universität Wuppertal Univ.-Prof. Dr.-Ing. habil. W. ZAHLTEN, Universität Wuppertal

Bericht – Lehr- und Forschungsgebiet
Wasserwirtschaft und Wasserbau

Band 20

Mario Oertel

Cross-Bar Block Ramps

Flow Regimes – Flow Resistance – Energy Dissipation – Stability

Shaker Verlag
Aachen 2012

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

Zugl.: Wuppertal, Univ., Habil.-Schr., 2012

Copyright Shaker Verlag 2012

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without the prior permission of the publishers.

Printed in Germany.

ISBN 978-3-8440-1225-5

ISSN 0179-9444

Shaker Verlag GmbH • P.O. BOX 101818 • D-52018 Aachen

Phone: 0049/2407/9596-0 • Telefax: 0049/2407/9596-9

Internet: www.shaker.de • e-mail: info@shaker.de

Für Kathrin, Helga, Bianca und Hardy.

"The wise rejoice in water."

Confucius (551 BC – 479 BC)

Danksagungen – Acknowledgments

Ich möchte mich bei allen Personen bedanken, die mir auf dem Weg zur Fertigstellung dieser Arbeit behilflich waren. Mein besonderer Dank gilt Prof. Dr. Andreas Schlenkhoff, der mich über viele Jahre hinweg beruflich begleitet, unterstützt und gefördert hat. Die von ihm übertragenen Verantwortungen und Freiheiten waren ein Schlüssel für meine berufliche Entwicklung. Neben zahlreichen Projektarbeiten sind auch viele gemeinsame Veröffentlichungen ein Indiz für eine fruchtbare Zeit. Ein großer Dank geht an Prof. Dr. Torsten Schlurmann. Er hat mich über all die Jahre stets unterstützt und aufgebaut; es braucht einen Menschen, der einem den Weg weist und Optionen aufzeigt. Weiterhin danke ich allen Gutachtern und Mitgliedern der Kommission: Prof. Dr. Robert Boes, Prof. Dr. Jörg Rinklebe, Prof. Dr. Uwe Janoske, Prof. Dr. André Niemann, Prof. Dr. Armin Seyfried, Jun.-Prof. Dr. Andreas Wittmann, sowie Prof. Dr. Wolfhard Zahlten. Viele fruchtbare Diskussionen sowie eine freundschaftliche und kollegiale Zusammenarbeit haben mir die Arbeit stets erleichtert. Ich danke meinem geschätzten Freund und Kollegen Prof. Dr. Daniel Bung für wöchentliche Telefonate, fachliche Diskussionen und eine enge Verbindung seit Beginn unseres Studiums. Ungeahnte Entwicklungen beginnen manchmal auf einer hölzernen Bank. Mein Dank gilt zudem vielen Kolleginnen und Kollegen; u. a. Prof. Dr. Gerd Morgenschweis, B. Sc. Svenja Peterseim, B. Sc. Tobias Motz, Andrea Mayer, Jan Balmes, Melanie Sichelschmidt.

Ein großer Dank geht an meine Familie; an meine Mutter Helga sowie Hardy, meine Schwester Bianca sowie Frank, meine Nichten und Patenkinder Lea sowie Kim und an meine Schwiegereltern Waldi sowie Margit. Es ist wichtig Menschen zu haben, die einem den Rücken stärken und einen Ausgleich zum Job schaffen; sei es freundschaftlich, geistig oder sportlich. Mein tiefster Dank gilt meiner Frau Kathrin. Danke für die Unterstützung und die Absorption meiner Launen. Ich liebe dich.

Wuppertal, Mai 2012

Dr. Mario Oertel

Kurzfassung

Die vorliegende Forschungsarbeit befasst sich mit Blocksteinrampen in Riegelbauweise. Diese Art von rauen Rampen kann als Instrument des naturnahen Wasserbaus angewendet werden und ermöglicht den schrittweisen Abbau großer Längsgefälle mit Hilfe von stufenartigen Beckenkonstruktionen. Querriegel unterteilen das Bauwerk dabei in die einzelnen Becken, wobei ergänzend niedrig liegende Öffnungen in den Riegeln zum Abführen von Mindestwassermengen sowie für den Fischeufstieg angeordnet werden.

Neben der Strömungsvisualisierung für unterschiedliche geometrische und hydraulische Randbedingungen – wie Neigung, Riegelabstand, Riegelhöhe und Durchfluss – erfolgt die Entwicklung neuer Berechnungsformeln für die Energiedissipation und Reibungsbeiwerte auf dem Bauwerk. Somit ist es u. a. möglich, die zu erwartenden mittleren Abflusstiefen für variierende Strömungszustände zu berechnen und beispielsweise die Höhe einer anzuordnenden Uferböschung zu ermitteln. Ergänzende Untersuchungen befassen sich mit angreifenden Strömungskräften auf große Störsteine in den Riegeln sowie mit der Stabilität des Sohlmaterials innerhalb der Becken. Auch hier werden neue Berechnungsformeln zur Verfügung gestellt, um die zu erwartenden Kräfte abschätzen und die Durchmesser unterschiedlicher Kornfraktionen des Sohlmaterials dimensionieren zu können.

Eine Beispielberechnung am Ende des Dokuments zeigt dabei die einzelnen Rechenschritte zur Dimensionierung einer Blocksteinrampe in Riegelbauweise auf. Die aufgeführte Vorgehensweise ermöglicht schlussfolgernd eine grundlegende hydraulische Planung derartiger Bauwerke.

Abstract

The present study deals with cross-bar block ramps. This kind of rough ramp can be used as an instrument for nature-like hydraulic engineering and allows a stepwise decrease of large longitudinal river bottom slopes via stepped basin structures. Cross-bars divide the structure into the basins, where additionally arranged lower openings within the cross-bars allow the flow for minimum discharge events and fish climbing.

Next to general flow visualizations for varying geometric and hydraulic boundary conditions – like slope, cross-bar distance, cross-bar height and discharge – new formulas are developed to determine the energy dissipation and friction factors on the structure. Hence, it is possible to calculate mean flow depths for varying discharges and e. g. to identify necessary bank slope heights. Additional investigations deal with drag forces impacting on large boulders within the cross-bars, as well as with the stability of the bed material. Again, formulas are provided to estimate drag forces on single boulders and to dimension diameters for the bed material within the basins for various particle fractions.

An example calculation at the end of the document shows the separate calculation steps to design a cross-bar block ramp. The given procedure allows a general hydraulic design of these structures.

Contents

Danksagungen – Acknowledgments	i
Kurzfassung	iii
Abstract	v
List of figures	xi
List of tables	xix
Notations	xxi
I Introduction	1
1 General	3
2 Classification of block ramps	5
2.1 General	5
2.2 Sills	6
2.3 River bottom steps	7
2.4 Block ramp design	8
3 State of the art	13
3.1 General	13
3.2 Guidelines and norms	13
3.3 Fish climbing capabilities	14
3.4 Flow resistance and energy dissipation	15
3.5 Stability	23
3.5.1 Forces on single boulders	23
3.5.2 Bed material	28

II	Modelling	33
4	Physical and numerical models	35
4.1	General	35
4.2	Physical models	36
4.2.1	Cross-bar block ramp model	36
4.2.2	Tilting flume	37
4.2.3	Measurement technique	41
4.3	Numerical model	43
5	Measuring campaigns and calibration	45
5.1	General	45
5.2	Physical model runs	45
5.3	Numerical model runs	50
III	Result analysis	53
6	Flow visualization and flow regimes	55
7	Energy dissipation and flow resistance	61
7.1	Energy dissipation	61
7.2	Flow resistance	66
8	Stability criteria	75
8.1	Boulder stability	75
8.2	Bed material stability	87
8.2.1	General	87
8.2.2	Scour development	87
8.2.3	Critical flow conditions	90
IV	Conclusions	101
9	Summary and outlook	103
10	Example calculation to design a cross-bar block ramp	105
10.1	General	105
10.2	Chosen boundary conditions	108
10.2.1	Geometry	108

10.2.2	Given discharges	109
10.3	Water depths	109
10.3.1	$h < h_B$	109
10.3.2	$h_B < h < 1.5h_B$	110
10.3.3	$h > 1.5h_B$	111
10.4	Energy dissipation	112
10.5	Stability	114
10.5.1	Single boulders	114
10.5.2	Bed material	116
	Bibliography	121
V	Appendices	131
A	Photographs of physical model results	133
B	Graphical results for mean water surface levels, numerical model	139
C	Graphical results for flow velocities, numerical model	153
D	Graphical results for velocity vectors, numerical model	181
E	Graphical results for impacting parameters, tilting flume	195
F	Dimensionless drag forces, numerical model	205
G	Graphical results for scour development, tilting flume	212
	Résumé – Curriculum Vitae	225

List of figures

2.1	River bottom structures	6
2.2	Sills	6
2.3	Flow conditions on a block ramp with increasing discharges	8
2.4	Block ramp design diagram	9
2.5	Block ramp designs	10
2.6	Cross-bar design	11
2.7	Example photographs of a cross-bar block ramp, Wupper	11
2.8	Example photograph of a cross-bar block ramp, Brückerbach	12
3.1	Definitions for cross-bar block ramps	15
3.2	MOODY diagram	20
3.3	Drag force and lift force on a body	24
4.1	Schematic plot of the cross-bar block ramp model	37
4.2	Photographs of the cross-bar block ramp model	37
4.3	Grain size distribution curve	38
4.4	Schematic plot of the tilting flume	39
4.5	Photographs of the tilting flume	39
4.6	Photographs of physical model for bed material stability investigations . . .	40
4.7	Measuring software Ultrasonic_GUI	42
4.8	Measuring software Loadcell_GUI	42
4.9	Example FLOW-3D model	43
5.1	Numeric vs. laboratory water depths	50
6.1	Uniform flow over roughness elements	56
6.2	Water surface and velocity vectors for various discharges, $S = 1:50$ and $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	58

6.3	Water surface and velocity vectors for various discharges, $S = 1:20$ and $S = 1:10$, $L_b = 33$ cm, $h_B = 6$ cm	59
7.1	Example energy heads and relative energy dissipation in physical and numerical model, $L_b = 33$ cm, $h_B = 6$ cm	63
7.2	Comparison between measured relative energy dissipation and approaches by several authors	63
7.3	Relative energy dissipation, model results and new approach	65
7.4	Relative energy dissipation, comparison between measured and calculated results	65
7.5	Comparison between measured friction factors and approaches from several authors	67
7.6	Friction factors, model results and new approach	68
7.7	Friction factors, comparison between measured and calculated results	68
8.1	Forces on a single boulder	76
8.2	Drag forces on boulders in various rows in physical and numerical model, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	77
8.3	Numeric vs. laboratory drag forces	77
8.4	Drag forces for boulder in cross-bar 4, cross-bar within the ramp	79
8.5	Drag forces for boulder in cross-bar 1, last cross-bar of the ramp	80
8.6	Drag forces for boulder in cross-bar 7, first cross-bar of the ramp	81
8.7	Example photographs of bed material surface after $t = 30$ min, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 125.00$ l/(sm), flow direction from left to right	89
8.8	Example photograph of bed material surface after $t = 30$ min with cross-bar openings, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 87.50$ l/(sm), flow direction from left to right, deposition (-), erosion (- -)	90
8.9	Critical and achieved particle densimetric Froude numbers, moderate particle bouncing	93
8.10	Critical and achieved particle densimetric Froude numbers, clear particle bouncing	94
8.11	Critical and achieved particle densimetric Froude numbers, moderate particle transport	95
8.12	Critical and achieved particle densimetric Froude numbers, clear particle transport	96
8.13	Comparison between measured and calculated critical particle densimetric Froude numbers for particle fraction 8 to 16 mm	98

8.14 Critical specific discharges for various bed material particle sizes, example for $S = 1:30$	100
10.1 Wupper Association area	106
10.2 Discharge hydrograph Kluserbrücke	107
10.3 Discharge duration curve Kluserbrücke	108
10.4 Discharge curve determined for the example	112
10.5 Relative energy dissipation determined for the example	114
10.6 Single boulder drag forces determined for the example	115
10.7 Particle densimetric Froude numbers determined for the example	117
A.1 Photographs of physical model runs, top view, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	135
A.2 Photographs of physical model runs, side view, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	137
B.1 Mean water surface level, $S = 1:50$, $L_b = 33$ cm, $h_B = 6$ cm	140
B.2 Mean water surface level, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	141
B.3 Mean water surface level, $S = 1:20$, $L_b = 33$ cm, $h_B = 6$ cm	142
B.4 Mean water surface level, $S = 1:10$, $L_b = 33$ cm, $h_B = 6$ cm	143
B.5 Mean water surface level, $S = 1:50$, $L_b = 39$ cm, $h_B = 6$ cm	144
B.6 Mean water surface level, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	145
B.7 Mean water surface level, $S = 1:20$, $L_b = 39$ cm, $h_B = 6$ cm	146
B.8 Mean water surface level, $S = 1:10$, $L_b = 39$ cm, $h_B = 6$ cm	147
B.9 Mean water surface level, $S = 1:50$, $L_b = 33$ cm, $h_B = 9$ cm	148
B.10 Mean water surface level, $S = 1:30$, $L_b = 33$ cm, $h_B = 9$ cm	149
B.11 Mean water surface level, $S = 1:20$, $L_b = 33$ cm, $h_B = 9$ cm	150
B.12 Mean water surface level, $S = 1:10$, $L_b = 33$ cm, $h_B = 9$ cm	151
B.13 Mean water surface level, no cross-bar openings, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	152
C.1 Depth averaged flow velocities, z -axis exaggerated, $S = 1:50$, $L_b = 33$ cm, $h_B = 6$ cm	155
C.2 Depth averaged flow velocities, z -axis exaggerated, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	157
C.3 Depth averaged flow velocities, z -axis exaggerated, $S = 1:20$, $L_b = 33$ cm, $h_B = 6$ cm	159

C.4	Depth averaged flow velocities, z -axis exaggerated, $S = 1:10$, $L_b = 33$ cm, $h_B = 6$ cm	161
C.5	Depth averaged flow velocities, z -axis exaggerated, $S = 1:50$, $L_b = 39$ cm, $h_B = 6$ cm	163
C.6	Depth averaged flow velocities, z -axis exaggerated, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	165
C.7	Depth averaged flow velocities, z -axis exaggerated, $S = 1:20$, $L_b = 39$ cm, $h_B = 6$ cm	167
C.8	Depth averaged flow velocities, z -axis exaggerated, $S = 1:10$, $L_b = 39$ cm, $h_B = 6$ cm	169
C.9	Depth averaged flow velocities, z -axis exaggerated, $S = 1:50$, $L_b = 33$ cm, $h_B = 9$ cm	171
C.10	Depth averaged flow velocities, z -axis exaggerated, $S = 1:30$, $L_b = 33$ cm, $h_B = 9$ cm	173
C.11	Depth averaged flow velocities, z -axis exaggerated, $S = 1:20$, $L_b = 33$ cm, $h_B = 9$ cm	175
C.12	Depth averaged flow velocities, z -axis exaggerated, $S = 1:10$, $L_b = 33$ cm, $h_B = 9$ cm	177
C.13	Depth averaged flow velocities, z -axis exaggerated, no cross-bar openings, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	179
D.1	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:50$, $L_b = 33$ cm, $h_B = 6$ cm	182
D.2	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	183
D.3	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:20$, $L_b = 33$ cm, $h_B = 6$ cm	184
D.4	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:10$, $L_b = 33$ cm, $h_B = 6$ cm	185
D.5	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:50$, $L_b = 39$ cm, $h_B = 6$ cm	186

D.6	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	187
D.7	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:20$, $L_b = 39$ cm, $h_B = 6$ cm	188
D.8	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:10$, $L_b = 39$ cm, $h_B = 6$ cm	189
D.9	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:50$, $L_b = 33$ cm, $h_B = 9$ cm	190
D.10	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:30$, $L_b = 33$ cm, $h_B = 9$ cm	191
D.11	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:20$, $L_b = 33$ cm, $h_B = 9$ cm	192
D.12	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), $S = 1:10$, $L_b = 33$ cm, $h_B = 9$ cm	193
D.13	Velocity vectors, basin 2 and 3 from downstream ramp end, longitudinal section at ramp center (left) and plane section at 3 cm above bed (right), no cross-bar openings, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	194
E.1	Influence of cross-bar distance on water surface level for various discharges, $S = 1:50$, $L_b = 30$ cm (left) or 42 cm (right), $h_B = 6$ cm	197
E.2	Influence of cross-bar distance on water surface level, no cross-bar openings, $S = 1:30$, $L_b = 30$ cm (left) or 42 cm (right), $h_B = 6$ cm	199
E.3	Influence of cross-bar distance on water surface level, no cross-bar openings, $S = 1:10$, $L_b = 30$ cm (left) or 42 cm (right), $h_B = 6$ cm	201
E.4	Influence of cross-bar form on water surface level, no cross-bar openings, $S = 1:50$, $L_b = 30$ cm, $h_B = 6$ cm	202
E.5	Influence of cross-bar form on water surface level, no cross-bar openings, $S = 1:30$, $L_b = 30$ cm, $h_B = 6$ cm	203

E.6	Influence of bed material on water surface level, no cross-bar openings, rectangular cross-bars, $S = 1:50$, $L_b = 30$ cm, $h_B = 6$ cm, left: no bed material and structured roughness, right: no bed material and stones	204
F.1	Dimensionless drag forces, $S = 1:50$, $L_b = 33$ cm, $h_B = 6$ cm	206
F.2	Dimensionless drag forces, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	206
F.3	Dimensionless drag forces, $S = 1:20$, $L_b = 33$ cm, $h_B = 6$ cm	207
F.4	Dimensionless drag forces, $S = 1:10$, $L_b = 33$ cm, $h_B = 6$ cm	207
F.5	Dimensionless drag forces, $S = 1:50$, $L_b = 39$ cm, $h_B = 6$ cm	208
F.6	Dimensionless drag forces, $S = 1:30$, $L_b = 39$ cm, $h_B = 6$ cm	208
F.7	Dimensionless drag forces, $S = 1:20$, $L_b = 39$ cm, $h_B = 6$ cm	209
F.8	Dimensionless drag forces, $S = 1:10$, $L_b = 39$ cm, $h_B = 6$ cm	209
F.9	Dimensionless drag forces, $S = 1:50$, $L_b = 33$ cm, $h_B = 9$ cm	210
F.10	Dimensionless drag forces, $S = 1:30$, $L_b = 33$ cm, $h_B = 9$ cm	210
F.11	Dimensionless drag forces, $S = 1:20$, $L_b = 33$ cm, $h_B = 9$ cm	211
F.12	Dimensionless drag forces, $S = 1:10$, $L_b = 33$ cm, $h_B = 9$ cm	211
G.1	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:50$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 50.00$ l/(sm) (left) and $q = 75.00$ l/(sm) (right)	213
G.2	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:50$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 100.00$ l/(sm) (left) and $Q = 125.00$ l/(sm) (right)	214
G.3	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 25.00$ l/(sm)	215
G.4	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 50.00$ l/(sm) (left) and $q = 75.00$ l/(sm) (right)	216
G.5	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 100.00$ l/(sm) (left) and $Q = 125.00$ l/(sm) (right)	217
G.6	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:20$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 50.00$ l/(sm) (left) and $q = 75.00$ l/(sm) (right)	218
G.7	Scour development in three basins with varying bed materials, no cross-bar openings, $S = 1:20$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 100.00$ l/(sm) (left) and $Q = 125.00$ l/(sm) (right)	219

- G.8 3D scour development in three basins with varying bed materials, flow direction left to right, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 12.50$ l/(sm) . 220
- G.9 3D scour development in three basins with varying bed materials, flow direction left to right, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 37.50$ l/(sm) . 221
- G.10 3D scour development in three basins with varying bed materials, flow direction left to right, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 62.50$ l/(sm) . 222
- G.11 3D scour development in three basins with varying bed materials, flow direction left to right, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 87.50$ l/(sm) . 223
- G.12 3D scour development in three basins with varying bed materials, flow direction left to right, $S = 1:30$, $L_b = 42$ cm, $h_B = 6$ cm, $q = 125.00$ l/(sm) 224

List of tables

3.1	Formulas for friction factor calculation	18
3.2	Formulas for relative energy dissipation calculation	22
3.3	Formulas for bed material stability calculation	32
4.1	Upscaling via Froude model	35
4.2	Material properties of bed materials in the basins	38
4.3	Technical characteristics and photograph of ultrasonic probes	41
4.4	Technical characteristics and photograph of load cells	41
5.1	Physical campaigns 1 and 2, $L_R = 2$ m, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm .	46
5.2	Physical campaign 3, no cross-bar openings, $L_R = 1.56$ m, $S = 1:50$, $L_b = 30$ cm, $h_B = 6$ cm (rectangular cross-bars)	46
5.3	Physical campaign 4, no cross-bar openings, $L_R = 1.56$ m, $L_b = 30$ cm, $h_B = 6$ cm	47
5.4	Physical campaign 5, no cross-bar openings, $h_B = 6$ cm (rectangular cross- bars)	48
5.5	Physical campaign 6, bed material stability, $L_b = 42$ cm, $h_B = 6(9)$ cm, initial material depth = 6 cm (rectangular cross-bars)	49
5.6	Numerical campaign 1, $L_R = 2$ m, $L_b = 33$ cm, $h_B = 6$ cm	51
5.7	Numerical campaign 2, $L_R = 2$ m, $L_b = 39$ cm, $h_B = 6$ cm	51
5.8	Numerical campaign 3, $L_R = 2$ m, $L_b = 33$ cm, $h_B = 9$ cm	52
5.9	Numerical campaign 4, no cross-bar openings, $L_R = 2$ m, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	52
7.1	Flow regimes and relative energy dissipation in physical model, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	69
7.2	Flow regimes, relative energy dissipation and friction factors for numerical model, $S = 1:50$ and $1:30$, $L_b = 33$ cm, $h_B = 6$ cm	70

7.3	Flow regimes, relative energy dissipation and friction factors in numerical model, $S = 1:20$ and $1:10$, $L_b = 33$ cm, $h_B = 6$ cm	71
7.4	Flow regimes, relative energy dissipation and friction factors for numerical model, $S = 1:50$ to $1:10$, $L_b = 39$ cm, $h_B = 6$ cm	72
7.5	Flow regimes, relative energy dissipation and friction factors for numerical model, $S = 1:50$ to $1:10$, $L_b = 33$ cm, $h_B = 9$ cm	73
7.6	Flow regimes and relative energy dissipation for numerical model without cross-bar openings, $S = 1:30$, $L_b = 39$ cm, $h_B = 9$ cm	74
8.1	Dimensionless drag forces in physical model, $S = 1:30$, $L_b = 33$ cm, $h_B = 6$ cm	82
8.2	Dimensionless drag forces in numerical model, $S = 1:50$ and $1:30$, $L_b = 33$ cm, $h_B = 6$ cm	83
8.3	Dimensionless drag forces in numerical model, $S = 1:20$ and $1:10$, $L_b = 33$ cm, $h_B = 6$ cm	84
8.4	Dimensionless drag forces in numerical model, $S = 1:50$ to $1:10$, $L_b = 39$ cm, $h_B = 6$ cm	85
8.5	Dimensionless drag forces in numerical model, $S = 1:50$ to $1:10$, $L_b = 33$ cm, $h_B = 9$ cm	86

Notations

Symbol	Description	Unit
α	ramp angle	–
$a_{1,2,...i}$	parameter	–
a_B	boulder form parameter	–
a_x	boulder distance in x direction	m
a_y	boulder distance in y direction	m
A	flow area	m ²
A_B	boulder flow area	m ²
C_D	drag coefficient	–
C_D^*	modified drag coefficient	–
C_p	packing factor	–
C_w	overfall coefficient	–
ΔE	energy dissipation	m
ΔE_r	relative energy dissipation	–
Δh_b	basin height difference	m
D	equivalent sand roughness	m
D_B	boulder width	m
D_{CB}	cross-bar width	m
D_{xx}	material/rock size of which xx % is finer	m
E	energy head	m
f	friction factor	–
f_B	boulder friction factor	–
F	force	N
F_D	drag force	N
F_L	force due to local losses	N
F_R	resistant force	N

Symbol	Description	Unit
F_s	hydrostatic force	N
F_y	lift force in y -direction	N
F_z	lift force in z -direction	N
F	Froude number	–
F_d	particle densimetric Froude number	–
$F_{d,c}$	critical particle densimetric Froude number	–
g	acceleration due to gravity	m/s ²
G	proper weight	N
Γ	boulder placement density	–
h	mean water depth	m
h_B	boulder height	m
h_c	critical water depth	m
h_L	energy loss height	m
$h_{L,c}$	continuously losses	m
$h_{L,l}$	local losses	m
h_s	scour depth	m
h_w	overfall height small boulders	m
H	ramp height	m
I	impulse force	N
λ	model scale	–
L	flow length	m
L_m	model length	m
L_b	basin length	m
L_R	ramp length	m
LC	load cell	–
ν	kinematic viscosity	m ² /s
N	number of boulders	–
N_b	number of basins, cross-bar construction	–
N_{CB}	number of cross-bars	–
p	pressure	Pa
p_d	dynamic pressure	Pa
p_s	hydrostatic pressure	Pa

Symbol	Description	Unit
P_D	power density of energy dissipation	W/m^3
q	specific discharge	$\text{m}^3/(\text{s m})$
q_c	critical specific discharge	$\text{m}^3/(\text{s m})$
q_P	specific discharge in prototype	$\text{m}^3/(\text{s m})$
Q	discharge	m^3/s
ρ	water density	kg/m^3
ρ_p	particle density	kg/m^3
r	hydraulic radius	m
R	Reynolds number	–
R_p	particle Reynolds number	–
S	ramp slope	–
σ	air content parameter	–
τ	shear stress	N/m^2
θ	Shields parameter	–
U	mean flow velocity	m/s
U^*	shear velocity	m/s
U_c	critical flow velocity	m/s
U_p	flow perimeter	m
U_P	flow velocity in prototype	m
V_b	basin water volume	m^3
w	small boulder height	m
W	channel width	m
W_B	boulder width	m
W_w	opening width small boulders	m
W_y	displacement width small boulders	m
z	geodetic height	m
ζ	resistance coefficient	–