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Design of a Meandering Ramp located at the River “Große Tulln”

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ABSTRACT: In a physical model test a meandering ramp which is a special kind of step-pool ramp was designed for the river “Große Tulln” in Austria. The final ramp design includes 12 step-pool units with a horizontal pool after the first six pools. The first four pools are armored with boulders with a diameter of 25-50 cm (full scale). A 100-year flood wave (live bed condition) was simulated. Taking the bed levels after this flood simulation another series of high flood events was performed under clear water conditions. The ramp proved stable during all these tests. Moreover a potential failure mechanism for step-pool ramps on the transition from tumbling to rapid flow is identified.

Keywords: step-pool ramp, sediment transport, failure mechanism

1 INTRODUCTION

The social and political consensus on the importance of conserving and reestablishing the natural environment has led, inter alia, to the Water Framework Directive (WFD) within the European Union. It came into force in December 2000.

One basic objective of the WFD is that all surface waters should achieve a “good ecological status” until 2015. This implies the river and the instream habitat continuity which is often interrupted by man-made lateral structures. According to its river basin management plan, Austria has about 28,000 lateral structures that are not fish-passable.

Step-pool-ramps are an ecological means for replacing old weirs and vertical drops. A step-pool ramp consists of a sequence of “steps” made of natural boulders and “pools” in between. Step-pool systems develop naturally in steep mountain streams and have been adopted for man-made ramps for streams and mildly sloped rivers alike. As step-pool-ramps provide better river continuity than the traditional, often steeper, block ramps, they have become more and more popular in recent years, especially in the Alpine region.

In this paper the results of a physical model test are presented in which a design for a so called “meandering ramp” was developed for the River “Große Tulln” in Neulengbach.

1.1 *Existing Meandering Ramps*

Step-pool systems develop naturally in steep mountain streams (e.g. Schächli (1991)). Step-pool ramps are based on this very stable natural bed form.

Table 1. Existing meandering ramps

location	ramp height (m)	slope ramp (%)	slope stream (%)
Grünauerbach, Austria	2.15	6.9	2.0
Stübmingbach, Austria	2.26	6.8	3.9
Scherlibach, Switzerland	3.17	4.2	2.0

The “meandering ramp” is a special kind of a step-pool ramp. The steps of a “meandering ramp” are alternately inclined to the left and the right bank. This lateral inclination induces a meandering flow on low discharges which leads to reduced velocities along the ramp (Figure 1). If possible the pools of the ramp consist of the natural river bed material. No additional armoring is needed. This enables natural processes of scouring and deposition. The steps are made of large boulders with a diameter of approximately 1.5 m. At least 4/5 of a boulder are embedded into the natural river bed (Figure 5). The meandering ramp has been developed by the Austrian engineer Otmar Grober and has been installed two times in Austria and once in Switzerland so far (Table 1).

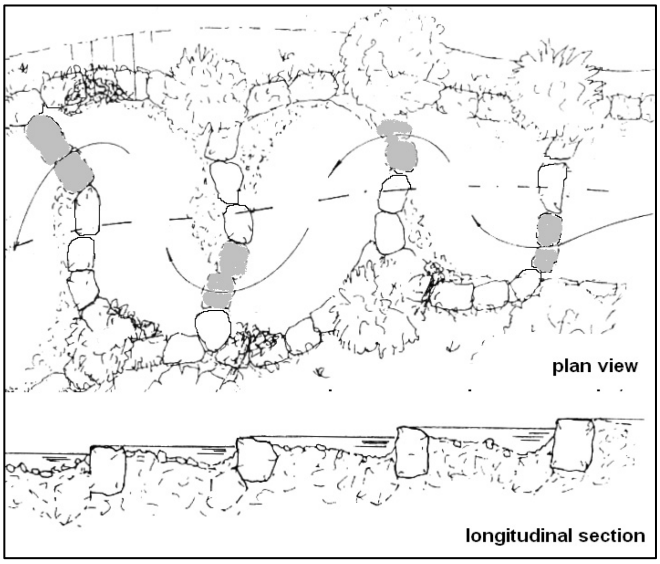

Figure 1. Sketch of a meandering ramp (by O. Grober, grey shaded boulders represent the lowest parts of the steps, bent arrows indicate the direction of flow for low discharges)

2 PROJECT AREA

The river “Große Tulln” is a tributary to the Danube River with its mouth 22 km northwest of Vienna. The project area “Neulengbach” is located 18 km south of the confluence. Morphological and hydrological properties of the project area are presented in Table 2. Neulengbach is situated in the flysch zone. Typical for that zone are layers of sediments that are almost water impermeable. The flood events are thus characterized by an abrupt rise. Figure 2 shows a 100-year flood hydrograph that was calculated from a rainfall runoff simulation model. The Große Tulln river has been channelized and straightened in the 1970es. It has a uniform cross sectional profile and many vertical drops due to the straightening. Within the major part of the project area it is not possible to give the river more space because of populated and agricultural areas.

2.1 *Morphology and Hydrology*

Table 2. Morphology and Hydrology

Morphology		Discharge (m^3/s)	
bed slope	5.8 ‰	mean flow	1.22
bed width	10 m	1-year flood	30
bank slope	1:3	10-year flood	66
Roughness k_{st} ($m^{1/3}/s$)		30-year flood	91
channel	26	100-year flood	123
banks	11-14	300-year flood	153

2.2 *Location of the Meandering Ramp*

At the beginning of the model test there was the idea to design a ramp for a particular location in the Große Tulln river with an old weir that should be replaced.

As there are many vertical drops to be replaced in the project area it is desirable to make the result of the model test applicable to several places. This is possible because of the uniformity of the bed geometry throughout the project area. Therefore a straight physical model was built having the typical morphological properties of this area (Table 2).

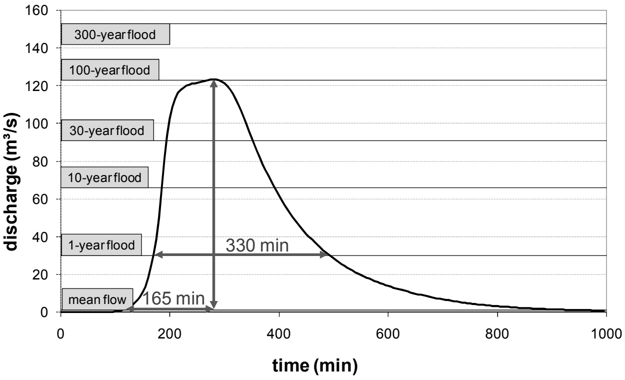

Figure 2. 100-year flood hydrograph in the project area calculated from a rainfall runoff simulation model

In May 2007 eight representative sediment samples were taken from the Große Tulln river and analyzed according to the Austrian standard ÖNORM B4412. Some characteristic diameters of the sediments are presented in Table 3. The mean diameter d_m is defined as

$$d_m = \sum_{i=1}^{n-1} \Delta p_i \cdot \overline{d_i} \tag{1}$$

where n, Δp_i and $\overline{d_i}$ denote the number of grain size classes of the sieve analysis, the fraction of the grain size class i and the mean diameter of the grain size class i, respectively.

Table 3. Sediment samples of the Große Tulln river

Sediment samples Große Tulln	d_{90} (mm)	d_{65} (mm)	d_m (mm)	d_{60}/d_{10} (-)
Averaged	105	50	41	45.2

3 EXPERIMENTAL SETUP

The experiments were carried out in the hydraulic laboratory of the department of Hydraulic Engineering and Water Resources Management of the University of Technology Graz in Austria. The model has a scale of L=1:10, Froude similitude is used. As can be seen in Figure 3 the model consists of a 3 m long inlet section with a slope of

0.58 %, a ramp section with a length of 8.4 m and a slope of 2.5% and an outlet section (3.6 m long, slope = 0.58%). The banks and the inlet section are fixed. Except for the model calibration where the whole model had a fixed bed, the top layers of the ramp channel and the outlet section consist of a 15 cm thick mobile bed (Figure 3).

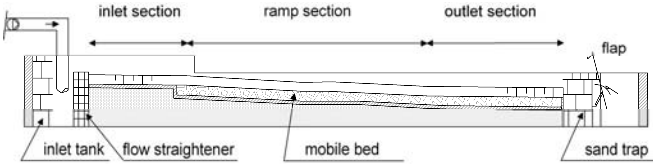

Figure 3. Sketch of the physical model, longitudinal section

The water supply is realized by the laboratory's water recirculation pipe system. The water runs into a tank located at the upstream end of the model. From there it enters the inlet section via bricks that serve as a flow straightener. Adjacent to the outlet section there is a sand trap to collect the sediments of the mobile and live-bed experiments. The tailwater level can be regulated via a flap at the end of the sand trap.

The tailwater depth is adjusted to the normal depth of a given discharge. For the calculation of the normal depth in the model the Strickler roughness values k_{st} (Table 2) have to be multiplied by $10^{1/6}$ (Froude similitude). This yields Strickler values in the model of k_{st} = 38 $m^{1/3}/s$ (channel) and k_{st} = 18 $m^{1/3}/s$ (banks), respectively. In the course of the model calibration the roughness of the banks and the channel was increased by gravel glued to the surfaces with a thin mortar until the desired water levels for a given discharge were achieved.

3.1 *Measurement equipment*

The discharge was measured with a magnetic flowmeter. Water levels were determined with a hook gauge. Bed changes after a test run were photogrammetrically surveyed. The resolution of the resulting digital elevation model was 5 x 5 mm. For the velocity measurements a hydrometric impeller and an ADV-probe were used.

3.2 *Model sediments*

Different model sediments were used as can be seen in Table 4 and Figure 4. To improve the comparability with the field samples of the Große Tulln river the model sediments are converted to full scale in Table 4. Experiments were run with gravel S1, S2 and S3. The gravel S3 was found to be most appropriate because its shape bore a close resemblance to that of the field samples.

Table 4. Model sediments (converted to full scale)

	d_{90} (mm)	d_{65} (mm)	d_m (mm)	d_{60}/d_{10} (-)
S1 rounded gravel	78	67	58	1.5
S2 rounded gravel	152	132	120	1.5
S3 gravel	145	85	73	11.0
S4 gravel with 4-fold fine fractions	139	71	58	8.2
Averaged sediment samples Große Tulln	105	50	41	45.2

Comparing gravel S3 to the grain size distribution of the Große Tulln samples shows that the fine grain sizes are missing in S3. Quadrupling the fine grain sizes up to 0.25 mm of gravel S3 then the resulting gravel S4 lies within the range of the Große Tulln samples. Assuming that this procedure does neither enlarge the volume of the gravel nor ameliorate the bed stability then gravel S3 can be used instead of gravel S4.

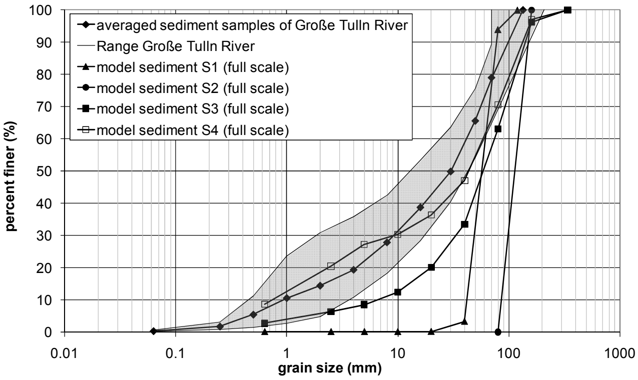

Figure 4. Model sediments & field samples

Different materials for the steps of the ramp were used in turn: concrete bars, cobblestones, casted concrete stones and finally natural boulders.

For the live bed experiments the sediments were supplied manually at the upstream end of the model.

3.3 *Ramp design*

If not otherwise stated all measures are given in full scale dimensions. The initial ramp design was provided by O. Grober whose experimental knowledge of the already existing meandering ramps was invaluable. The initial ramp consists of 12 step-pool sequences with a length L of 6 m each and a step height H of 0.15 m. This results in a ramp slope I = H/L = 0.025 (Figure 5). Between the first and the last six pools two horizontal pools of 8 m length are arranged (see Figure 6). The first and the last six pools will be referred to as ramp 1 and ramp 2, respectively. Six meters downstream of the ramp toe a boulder step leveled with the bed stabilizes the structure.

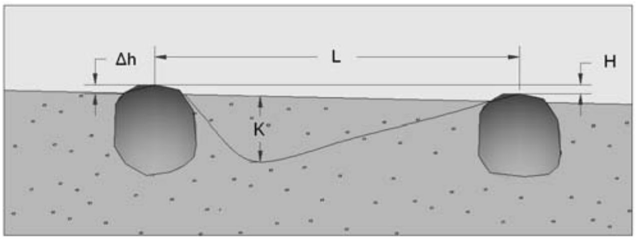

Figure 5. Step-pool sequence, dimensions, scour pattern

The pools are separated by boulder steps. The steps are alternately inclined to the left and the right bank. The dimensions of the boulders of the steps are approximately 1 m x 1 m x 1.5 m. The boulders are embedded into the bed. In the initial ramp design they protrude Δh = 0–15 cm from the bed surface. In plan view one step has an S-shape and connects to the banks at half length of the pool where it joins the next downstream step seamlessly. The steps thus form a continuous sinuous line. The lowest point of a step is aligned with the bed level and is located a quarter distance from one bank to the other. The upper part of each step (which is alternately located near the left and right bank) is reinforced with boulders downstream of the step (Figure 6).

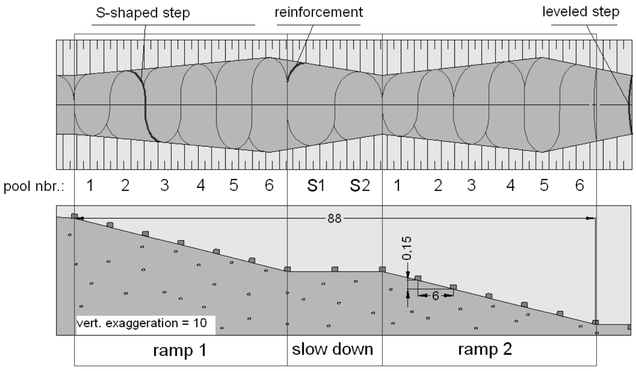

Figure 6. Sketch of initial ramp design, measures in (m)

The steps of the ramp can be considered as submerged groins. The reinforcement boulders not only serve a stabilizing purpose but also serve to direct the flow towards the channel center. Without these boulders the flow over the step would be directed towards the banks.

Altogether 10 different ramp designs were tested in 38 test runs with discharges ranging from a 1-year-flood to a 100-year-flood.

3.4 *Test run*

Prior to each test run the channel bed was leveled and then surveyed photogrammetrically (Figure 7). During a test run a flood event was simulated under live bed or clear water conditions. For the live-bed experiments the sediments were supplied manually at the upstream end of the model. During the live-bed experiments no velocity measurements were possible so as not to endanger the measurement devices by the moving sediments. Water levels were measured in the centerline of the model. Due to the high turbidity of the water the sediment movements could not be observed during a test run. After a test run the bed was again surveyed photogrammetrically.

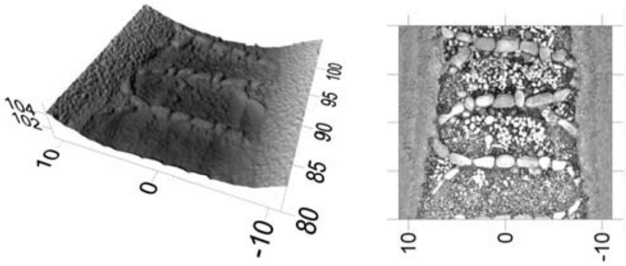

Figure 7. Results from the photogrammetric survey: 3D-surface (left) and orthophoto (right) of three step-pool sequences

A test run typically took 2¼ hours (~ 7 hrs full scale) with a constant discharge. For those ramp designs that yielded promising results for the constant discharges a 100-year flood wave simulation was performed.

4 RESULTS AND DISCUSSION

In this section relevant findings in the development of the final ramp design are presented.

The maximum height Δh of a step protruding from the channel bed was increased from 15 cm (initial design) to 30 cm to induce a distinct meandering flow at low discharges. Moreover this increase enforces the direction of the flow towards the channel center.

The combination of the channel width extension of ramp 2 and the high tailwater depth (because of the rough, flat outlet section) led to depositions downstream of the ramp. Therefore the lateral channel extension is omitted in the final design.

At the beginning of the experiments the tailwater level was regulated with a flap gate. This led to sediment depositions in the outlet section. To make sure that these depositions were not caused by the influence of the flap gate the experiments were eventually performed without the flap gate. This way critical depth occurred at the downstream end of the model, so the energy gradient was steeper then the bed slope in the outlet section. If the stability of the ramp could be achieved under these conditions it would also prove stable for normal flow conditions.

4.1 *Scour patterns*

Throughout the experiments one major concern was the development of scours upstream of a step

(Figure 8). This was unexpected because upstream scour patterns as in Figure 8 have not been observed at the prototype ramp in the Stübmingbach (Table 1). Two surveys (Stübmingbach, Dec. 2007 & Dec. 2009) of the bed levels show scour patterns as in Figure 5. Undoubtedly the grain size distribution of the pool material is a crucial point in the appearance of the scour pattern. The same experiment as shown in Figure 8 does not yield upstream scour holes if the coarser sediment S3 is taken instead of sediment S1 (Table 4). Increasing the discharge from a 1-year-flood to a 30-year flood (Table 2) then upstream scour holes develop also for sediment S3. (Korecky 2007) reports the occurrence of upstream scours in a physical model test on flat sloped step-pool ramps. No further explanation is given. Korecky concludes that in these cases the pool sediments should be coarser.

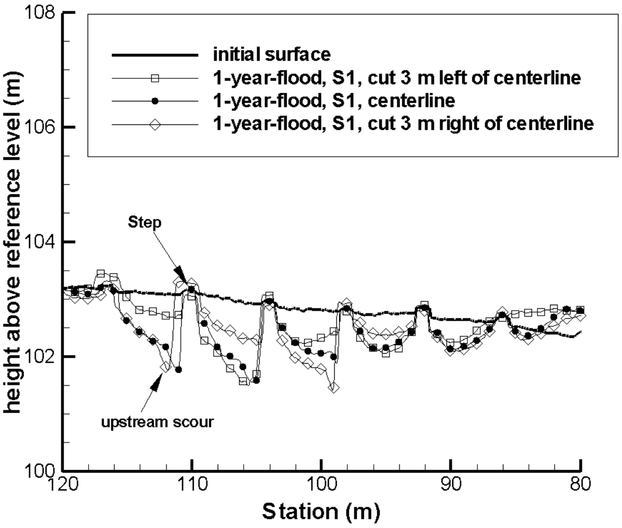

Figure 8. Bed levels after a 1-year-flood, 5 step-pool units of ramp 1, ramp design no. 5, model sediment S1, no flap gate

In a series of model tests on sediment transport in step-pool streams Whittaker (1987) also observes upstream scours. He bonds such scour patterns to the unstable tumbling phenomenon (see 4.2). Moreover he presumes that upstream scours do not occur in natural step-pool systems because of armoring processes of the pools. This is probably true for natural step-pool streams where the sediment sizes and the slope of the stream have adjusted to a dynamic balance. Designing a ramp structure that is steeper than the natural river slope leaves the critical question of the required sediment sizes of the steps and the pools to the engineer. Design criteria for block ramps without step-pool structures exist (eg. Schauberger 1975, Knauss 1979, Whittaker and Jäggi 1986, Platzer 2000). Vogel (2003) presents design criteria for step-pool ramps with trough-shaped armored pools. Korecky (2007) derives design criteria for flat-sloped step pool ramps with plane pools and steps that are not embedded into the river bed. A formula for the required mass of the step boulders subject to a given slope and a given design discharge is provided. As a rule of thumb Korecky recommends that the equivalent spherical diameter of the step boulders is five times larger than that of the pool sediments.

4.2 *Flow regimes*

Peterson and Mohanty (1960) investigate flow characteristics in steep, rough channels. The roughness elements have a constant height Δh and a constant spacing L. Three major flow regimes can be distinguished: tranquil flow, tumbling flow and rapid flow (Figure 9).

Figure 9. Tranquil flow, tumbling flow and rapid flow (from left to right)

The tumbling flow phenomenon is characterized by a succession of flow transitions from supercritical to subcritical in a cyclic order. Due to the consecutive hydraulic jumps the tumbling flow regime dissipates a lot of energy. (Morris 1968) derives a formula for the maximum discharge q_{cr} for which the tumbling flow can be preserved:

$$q_{cr} = \Delta h^{3/2} \cdot (3 - 3.7 \cdot I) \cdot \sqrt{g} \qquad (2)$$

$$L / \Delta h \approx 8.5 - 10 \qquad (3)$$

where Δh = roughness height (m), g = gravity acceleration (m/s^2), I = bed slope (-), L = spacing (m), respectively. Equation (3) should be fulfilled to prevent the generation of roll waves that are superimposed on the stable tumbling flow. If roll waves are present Morris speaks of an “unstable tumbling flow”. It occurs on the transition from stable tumbling to rapid flow.

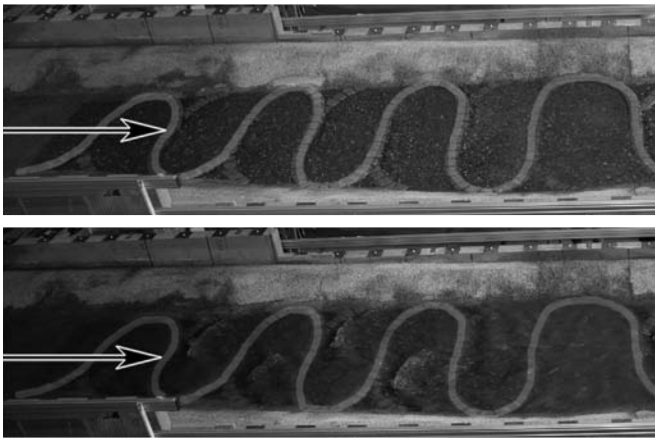

Figure 10. top: Initial bed surface; bottom: tumbling flow at a 1-year flood discharge, ramp design no. 8, ramp 1, model sediment S3 (note: to show the flow from left to right the pictures have been mirror-inverted)

The three flow regimes could be observed in the physical model test described in this paper. Due to the lateral inclination of the steps the hydraulic jumps were observed only in parts of the pools at a 1-year flood discharge (Figure 10).

It follows from equation (2) that for increasing discharges the roughness height has to be increased in order to preserve the tumbling flow regime. During a flood wave the rising discharge produces deeper scour holes in the pools of a step-pool ramp thus prolonging the tumbling flow regime. As the flood subsides, the transported sediments fill up the scour holes again.

During the experiments the transition from stable tumbling flow to rapid flow took place as follows: At stable tumbling flow the wave length of the undulating free surface equals the spacing of the steps L. Increasing the discharge also enlarges the free surface wave length, the hydraulic jump migrates to the next downstream step until it is finally washed over this step. The transition from tumbling to rapid flow didn't occur simultaneously in all the pools. Due to the high turbidity of the water the scour depths could not be determined during a test run. Therefore Morris' proposed equation (2) could not be verified. A valid criterion for the upper boundary of the tumbling flow regime would be a useful tool in designing a ramp though. Ramp slope I, spacing of the steps L and the roughness height Δh could be chosen such that the tumbling flow (and thus good energy dissipation) could be preserved for the given design discharge. An analysis of Morris' own experiments shows however that equation (1) greatly overestimates the maximum discharge for mild slopes up to 10 %. (Morris' main focus was the design of steep drainage chutes for highways.)

Although it could not be observed visually during the experiments the results suggest that the transition from tumbling to rapid flow promotes the development of scour holes upstream of the steps and endangers the stability of the steps.

To prevent upstream scour holes in the experiments the steps were eventually reinforced with smaller boulders upstream of the steps.

4.3 *Failure mechanisms*

Whittaker and Jäggi (1986) describe three failure mechanisms for block ramps: 1.) entrainment of the blocks out of the ramp, 2.) entrainment of bed material from between the blocks and 3.) blocks are swept away from the end of the ramp into the scour hole. Pagliara and Chiavaccini (2007) point out that failure mechanism patterns for reinforced block ramps (step-pool ramps with different arrangements of the steps) depend on the ratio ζ between the diameter of the boulders and the mean diameter of the base material. For $\zeta < 3.5$ and $3.5 \leq \zeta \leq 5$ the respective failure mechanism patterns are different. Pagliara and Chiavaccini do not connect the failure mechanism to the unstable tumbling flow regime.

The results from the physical model test described in this paper suggest that the potential failure mechanism due to the flow transition from tumbling to rapid flow must not be neglected for step-pool ramps. This assumption is supported by pictures in Vogel (2003) showing ramp experiments at discharges just before the failure of the ramp. Some of these critical discharges mark the transition from tumbling to rapid flow.

4.4 *Shape of boulders, pool armoring*

The shape of the step boulders is important. Some experiments were performed with cobblestone steps for ramp 1 and casted concrete steps for ramp 2. The casted boulders had a spherical shape. As can be seen in Figure 11 the reinforcement made of cobblestones directs the flow into the next pool. The hydraulic jump takes place downstream of the reinforcement (first pool, left side). On the other hand the reinforcements made of spherical boulders do not act as one single structure. The individual boulders are not able to direct the flow towards the channel center (second pool, right side). For the construction of the ramp it is therefore recommended to use boulders that are rather cubic than spherical, and to place the boulders close to one another.

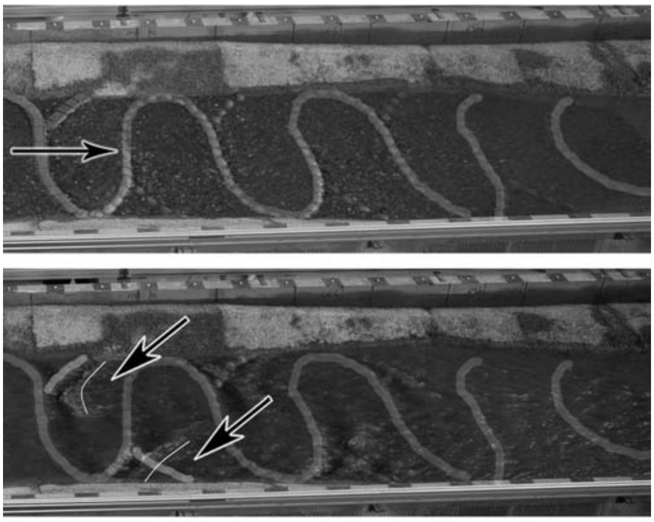

Figure 11. Ramp design no. 8, ramp 2, model sediment S3, 1-year-flood; top: Initial bed surface; bottom: different flow patterns over the cobblestone reinforcement and the reinforcements made of spherical bouders (note: to show the flow from left to right the pictures have been mirror-inverted)

It turned out that a stable ramp design could not be found without armoring at least some of the pools. In the final ramp design the first four pools are armored with two layers of boulders with a diameter of 25-50 cm (full scale). This armoring layer is trough-shaped (maximum depth 0.5 m). The trough is filled up with sediment S3 (Table 4). During the experiments some of these armoring boulders were entrained and deposited again further downstream thus stabilizing also the ramp downstream of the armored pools.

4.5 *Final ramp design*

The final ramp design includes 12 step-pool units with a horizontal pool after the first six pools. All steps are reinforced with boulders (diameter=1m) up- and downstream of the step. The first four pools are armored with two layers of boulders with a diameter of 25-50 cm (full scale). This armoring layer is trough-shaped (maximum depth 0.5 m). The trough is filled up with the sediment S3. The "triangles" bounded by step, reinforcement and bank are filled up with the armoring boulders (diameter 25-50 cm full scale). The channel width expansion on ramp 2 (Figure 6) is omitted. Figure 12 shows an orthophoto of the final ramp design.

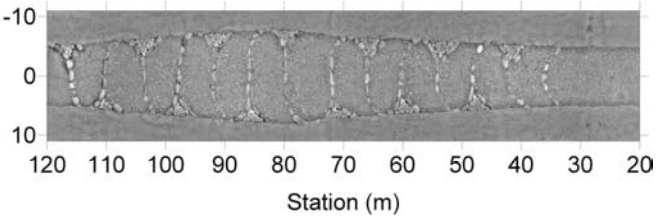

Figure 12. Orthophoto of final ramp design

4.6 *Stability tests*

A 100-year flood wave was simulated for the final ramp design under live-bed conditions. The downscaled 100-year flood hydrograph from a rainfall runoff simulation model was used. A pump control could adjust the discharge according to the hydrograph at 1-min intervals (Figure 13).

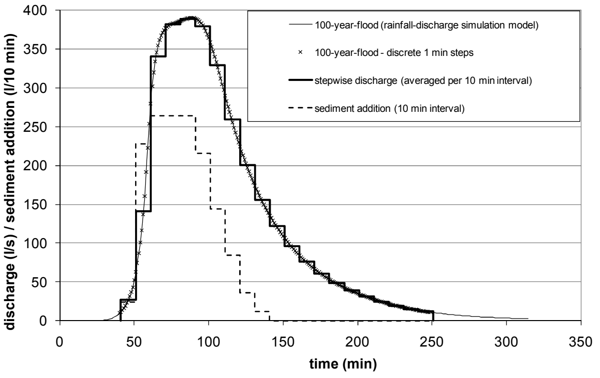

Figure 13. 100-flood wave in model scale, discharges regulated automatically by the pumps at 1-min intervalls, sediment addition equals a quarter of the calculated sediment transport according to Meyer-Peter Müller's formula.

Sediment was added to the model at the upstream end of the model. The sediment rate was calculated using Meyer-Peter Müller's formula (Meyer-Peter, Müller 1949) in which the mean diameter as given by equation (1) is applied.

The inlet section slope (0.58%) was used in the sediment transport formula. Only a quarter of the calculated sediment rate was added (Figure 13). The higher the sediment input rate the better the stability of the ramp. To be on the safe side a low sediment rate is thus assumed. The lower sediment rate also takes into account the fact that sediment inputs in natural rivers do not occur at a constant rate but may vary.

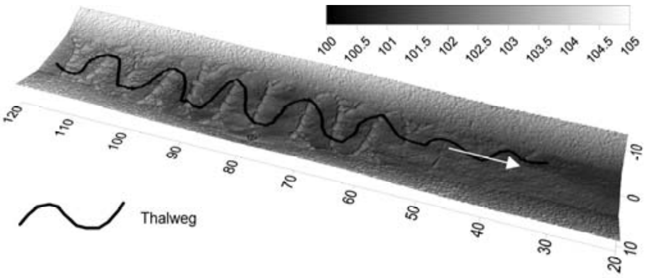

Figure 14. 3D-surface of the bed levels after a 100-flood wave simulation under live bed conditions (bed levels and station in (m))

Taking the bed levels after the 100-year flood simulation (Figure 14) another series of high flood events was performed under clear-water conditions. Discharges ranged from a 1-year flood to a 10-year flood. These final tests took 100 hours (full scale). The ramp proved stable during all these tests.

5 CONCLUSIONS AND OUTLOOK

In a physical model test a design for a meandering ramp for the Große Tulln river was developed. It proved stable during a series of flood events under both live-bed and clear-water conditions. At low discharges a meandering flow develops along the ramp which reduces the velocities because of the elongated thalweg. The meandering ramp is an ecological means of replacing non-fish-passable drop structures.

A failure mechanism for step-pool ramps has been identified on the transition from tumbling to rapid flow.

More detailed investigations are required to derive general design criteria for meandering ramps. Currently basic flume experiments are performed at the hydraulic laboratory of the department of Hydraulic Engineering and Water Resources Management of Graz University of Technology. The aim is to derive a criterion for the maximum discharge for which the tumbling flow regime can be preserved for arbitrary combinations of ramp slope, spacing and height of the roughness elements.

In the project area Neulengbach at the Große Tulln river the planning for a meandering ramp based on this model test is ongoing.

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