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Sediment Transport over Labyrinth Weirs

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Abstract: *Fixed weir types are generally passive weirs and are supposed to be more prone to hold back sediments. Few model tests have been conducted for specific prototypes of labyrinth weirs which indicate that sediments will be scoured out upstream of the weir by the turbulent action. But an attempt to generalize the findings of the studies is missing. The question that arises is whether the self-cleaning is predictable in dependence of geometry, discharge, and sediment properties. The main purpose of this study is to describe and to quantify the self-cleaning process at labyrinth weirs and to predict scouring in various conditions. Therefore, systematic experimental tests were performed on a physical model in the laboratory of the Federal Waterways Engineering and Research Institute (BAW). The self-cleaning performance of a rectangular and a trapezoidal labyrinth weir are compared for different sediment types. Four sediments were tested under various flow conditions: fine quartz sand, fine gravel, medium-grained gravel, and polystyrene granules. In general, the present results confirm the self-cleaning ability of labyrinth weirs. The data of the tested sediments collapse to a single curve for the densimetric Froude number* F_d. *Accordingly,* F_d *is the dominant parameter and mainly affects the scouring mechanism. It can be seen that self-cleaning begins at a rectangular labyrinth weir at lower discharges compared to a trapezoidal labyrinth weir.*

Keywords: *Sediment transport, labyrinth weir, physical modeling, fixed weir, turbulence-sediment interaction.*

1. Introduction

1.1. Labyrinth Weirs

The discharge capacity of weirs is directly proportional to the crest length of the weir for a given upstream head. An insufficient weir capacity has been the cause of one-third of all dam failures (Schleiss 2011). Thus, the motivation to maximize the crest length and thereby the capacity of a weir has gained importance in the last decades. Different shaped weirs with higher crest length compared to straight linear weirs have been developed. In the 1930s, the labyrinth weir was introduced. It is a fixed weir which is folded in plan-view resulting in an increase of the total crest length by keeping the clear width constant. The total crest length is typically five to six times longer than the channel width. A short list of labyrinth weirs (for USA and Portugal) is given in Crookston et al. (2015). Examples are the Lake Brazos Dam in Texas or the Fort Miller Dam in New York. There are various designs of labyrinth weirs which differ from each other mainly in the shape of their plan view. In contrast to the Piano Key Weir, vertical walls form openings to the upstream (inlet keys) and to the downstream (outlet keys). Common designs are the trapezoidal, rectangular, and triangular labyrinth weir. Figure 1 shows the plan view (a) and a section (b) of a trapezoidal labyrinth weir with its nomenclature (based on Falvey (2003)) as well as the relevant hydraulic parameters.

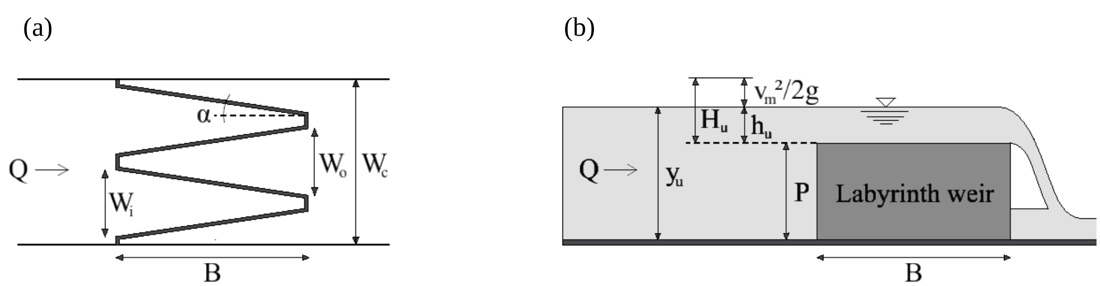

Figure 1. Plan view (a) and section (b) of a trapezoidal labyrinth weir with geometrical (based on Falvey (2003)) and hydraulic parameters.

Other relevant design parameters are the crest shape (sharp, flat, quarter-round, half-round, or ogee crest) and the alignment of the sidewalls α. The hydraulic performance for these three design parameters was investigated numerous times. The results are shortly presented in the following:

- Falvey (2003) gives a good overview of the hydraulic investigations on different weir geometries. Recent investigations by the BAW (Belzner et al. 2016) were focused on the hydraulic comparison of a triangular, trapezoidal, and rectangular labyrinth weir under same boundary conditions. It was shown that the discharge capacity of a triangular labyrinth weir is slightly lower compared to the capacity of a rectangular or trapezoidal weir. That can be explained by the runoff-ineffective section in the corner of the triangle.
- It has been shown that the capacity of a half-rounded crest shape is more significant for small upstream head ratios ($H_u/P \leq 0.4$) compared to quarter-rounded crest shapes (Crookston and Tullis 2011). The discharge capacity of these two crest shapes does not diverge significantly for higher upstream head ratios.
- Crookston (2010) pointed out that the discharge capacity of a weir with nearly parallel sidewalls ($\alpha = 6°$) is up to 7 times higher than the discharge capacity of a straight linear weir for very small upstream head ratios ($H_u/P = 0.05$). For higher sidewall angles α and higher upstream head ratios H_u/P, the capacity decreases considerably and converges to the capacity of a straight linear weir.

Based on these results, it is obvious that not all design criteria needs to be considered in this study. Only weir geometries with a good hydraulic performance will be regarded. More details of the chosen weir geometries are given in section 3.1.

1.2. Sedimentation and Self-Cleaning

During low discharge periods dams can generally hinder downstream transport of sediment. The increasing water level and accompanying decrease of the flow velocity lead to sedimentation upstream of the weir. Usually, the sediments will be remobilized during high discharge periods and transported downstream. Here, the question arises how the weir type, in particular the labyrinth weir, will affect this.

Wilmore (2004) investigated the impact of sedimentation on the upstream water head for a labyrinth weir at Lake Brazos. The tests showed that the upstream head H_u increased by 25%. However, the applicability of these results is limited to upstream head ratios of $0.1 \leq H_u/P \leq 0.6$ and stationary conditions because the deposits were not erodible. The sedimentation process on the upstream side of the Boardman labyrinth weir in Oregon during low discharge periods was illustrated by Babb (1976). For fine sand one third of the sediment was deposited in the low-velocity zones at the weir. The coarse sand was almost completely deposited on the upstream side of the weir.

The self-cleaning effect is also discussed by Falvey (2003) on the basis of two case studies: The Hellsgate labyrinth weir in Colorado and the Garland Power Canal in Wyoming. In both cases the weirs were self-cleaned. At Hellsgate a violent turbulent action was observed for $h_u/P = 0.4$, where h_u is the overflow depth and P the weir height.

1.3. Aim of the Study

As most studies on the self-cleaning process at labyrinth weirs were focused on practical prototypes such as the Hellsgate labyrinth weir or the Garland Power Canal, generalized statements are missing. Thus, a systematic study was conducted. The main purpose of this study is to describe and to quantify the self-cleaning process at labyrinth weirs and to develop a generally valid equation to predict scouring. By varying sediment characteristics and discharge states, the self-cleaning performance of a trapezoidal and a rectangular labyrinth weir was tested.

The following contribution is based in essential parts on Gebhardt et al. (2017).

2. Theoretical Background

2.1. Parameter Study

The scouring process is a local phenomenon near obstacles and cannot be explained by the classical erosion approaches on river beds. The sediment removal in a labyrinth weir (self-cleaning effect) is comparable to scouring at bridge piers, which is widely discussed in Breusers and Raudkivi (1991), Melville and Coleman (2000) or Hoffmans and

Verheij (1997). Melville (2008) gives a good overview of the dependent parameters on scouring at bridge piers. The controlling parameters for the self-cleaning effect at weirs are:

- time,
- geometrical weir parameters (e.g., height, width, length),
- sediment characteristics (e.g., grain density, particle size), and
- flow attributes (e.g., discharge).

In this study, the scouring process was considered to be time-independent. The discharge was held for 180 min until a steady state was reached before measuring the sediment bed in the axis of the inlet key. This duration was determined in preliminary tests by the use of polysterene granules and was considered to be sufficient for all other tests (Gebhardt et al. 2017). Since only two weir types were considered, without varying the geometrical parameters of the weir, the scouring process Φ can be described by the following dimensionless parameters:

$$\phi = f(F_d, R_d, d_{ch}/y_u) \quad (1)$$

with

$$F_d = \frac{v_{ch}}{\sqrt{\frac{\rho_S-\rho_W}{\rho_S} \cdot g \cdot d_{ch}}} \quad (2)$$

$$R_d = \frac{v_{ch} \cdot d_{ch}}{\upsilon} \quad (3)$$

The densimetric Froude number F_d describes the ratio between inertial forces and submerged weight of the sediment particle. R_d is the grain Reynolds number and describes the ratio between inertial and viscous forces. Both parameters were varied over the test series by considering different discharges, grain sizes, and grain densities. There are different approaches to define the characteristic velocity v_{ch}. Shields (1936) originally considered the near-bed velocity as characteristic parameter resulting in the Shields number and the particle Reynolds number. Here, neither the Shields number nor the Particle Reynolds number are adequate variables to predict critical flow conditions for the initiation of motion. Other studies regard a local mean velocity (Ettmer 2007). In this study the upstream mean flow velocity v_m for free flow was considered to be the relevant parameter. Other parameters in Eq. (2) and (3) are the sediment density ρ_s, the water density ρ_w, the gravitational acceleration g, and the viscosity of water v. The characteristic particle size d_{ch} corresponds to the averaged grain size d_{50}.

The relative roughness describes the ratio between the characteristic particle size d_{ch} and the upstream water depth y_u. According to Hager (2007), it can be expected that R_d and d_{ch}/y_u should be of minor importance if a cohesionless granular material is considered and flow regime becomes fully turbulent.

2.2. Model Laws and Scale Effects

Regarding the flow near hydraulic structures, the ratio of inertial forces to gravitational forces described by the Froude number is usually more significant compared to the ratio of inertial to viscous forces described by the Reynolds number. Thus, all geometrical and dynamic values can be calculated by keeping the Froude number constant. To neglect the Reynolds similarity, fully turbulent conditions must be ensured in the model. Furthermore, a certain minimum water level is required to neglect surface tension effects. Thus, dynamic and geometrical similarity were satisfied by the Froude model law.

As shown above, for the application of sediment investigations (such as initiation of motion, bed load transport, or bed geometry), it can be expected that the densimetric Froude model law can be considered, meaning that F_d is the same in the model and in the prototype. Sarathi et al. (2008) investigated the scour by submerged square wall jets and concluded that the densimetric Froude number is the most important parameter that influences scour. Thereby, the sediments are not only resized in a prototype by its diameter but also by the sediment density. This can help to dimension fine prototype materials in model tests. By choosing a lighter sediment (e.g., polystyrene), the particle size can be kept constant or even scaled up. To avoid scale effects, the particle size is restricted to a certain upper and lower limit. In their studies on scour at bridge piers, Breusers and Raudkivi (1991) describe the effect of oversized sediment particles on the scouring process. In their case, the erosion process is impeded when the ratio between pier width and sediment diameter is smaller than 25. For fine sediments it needs to be guaranteed that cohesion effects are excluded. A strict threshold for the diameter of a cohesive sediment was not found, but Hager (2007) avoided cohesive effects by using only sediments with a median grain size higher than 1 mm. Here, that threshold is not satisfied. The tested sand had a median grain size of 0.69 mm. However, cohesive effects were not observed during the test series.

3. Experimental Facilities

3.1. Materials and Weir Types

Four different grains differing in size d_{50} and density ρ_s were tested. The granulometry of the tested sediments is given in Table 1.

Table 1. Granulometry of tested sediments.

	ρ_s [kg m^{-3}]	d_{50} [mm]
Polystyrene	1.055	2.10
Fine sand	2.650	0.69
Fine gravel	2.650	2.04
Medium gravel	2.650	5.55

Two weir geometries were regarded in the physical model: a trapezoidal and a rectangular labyrinth weir, both with a half-rounded crest shape. Figure 2 shows the physical model of the trapezoidal and rectangular labyrinth weir. The geometry of the tested weirs is given in Table 2.

Table 2. Geometry of tested weirs.

	n [-]	P [m]	B [m]	L [m]	W_c [m]	T_w [m]	W_o [m]	W_i [m]	α [°]
Trapezoidal	5	0.25	0.59	6.25	1.25	0.01	0.035	0.20	7.24
Rectangular	5	0.25	0.51	6.25	1.25	0.01	0.115	0.115	-

The used nomenclature is in accordance with the one defined by Falvey (2003) where n describes the number of labyrinth cycles, P the weir height, B the weir length, L the crest length, W_c the width of the channel, T_w the thickness of the weir wall, W_o the width of the outlet key, W_i the width of the inlet key, and α the sidewall angle.

(a) (b)

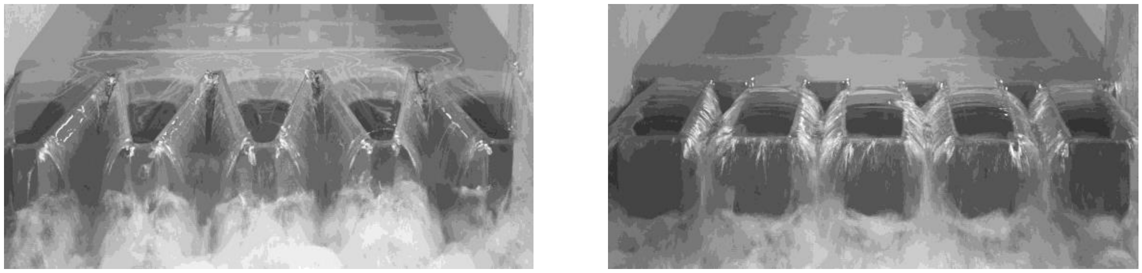

Figure 2. Physical model of the trapezoidal (a) and rectangular (b) labyrinth weir (view from downstream against flow direction).

3.2. Physical Modelling

Systematic physical tests were performed in the laboratory of the BAW. Therefore, the tested weir types were installed in a 1.25 m wide channel. Preliminary tests at the BAW have shown that if sediments are transported into an inlet key and the flow velocity is not high enough to transport the sediments over the weir, the deposit will be shaped like ramp. Therefore, a sediment ramp (slope: 1:2 at rectangular weir; 1:2.4 at trapezoidal weir) was modeled in the central inlet key on the upstream side of the weir. A 0.03 m thick sediment bed (0.7 m x 0.25 m x 0.03 m) was modeled in front of the inlet key. This sediment bed (reference bed) was intended to develop a velocity distribution, depending of the grain size before entering the weir. Between the reference bed and the channel bottom, a ramp (1:7) was modelled to provide a smooth transition. The ramp and the reference bed were modeled under dry conditions before the flume was filled carefully (< $5ls^{-1}$). Figure 3 illustrates the model configuration.

(a) (b)

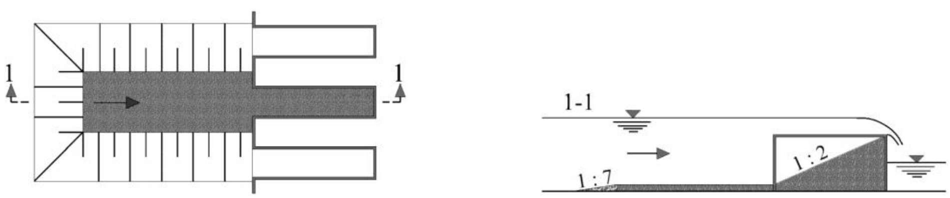

Figure 3. Physical model configuration for the rectangular labyrinth weir. Plan view (a) and longitudinal section (b).

The regarded discharge varied between 15 l/s and 370 l/s, depending on the sediment and the weir geometry. It was measured by a magnetic-inductive flowmeter (MID). The lowest regarded discharge corresponds to the discharge when sediment transport was first observed. That discharge was held for 180 min until no more sediment was moved. After measuring the geometry of the sediment ramp in the weir by point gauge, the discharge was increased and held again for 180 min. At the same time, the upstream water depth was measured by the use of ultrasonic probes. The maximum discharge of a test series was limited either by the discharge capacity of the model or by the remaining sediment at the weir.

(a) (b)

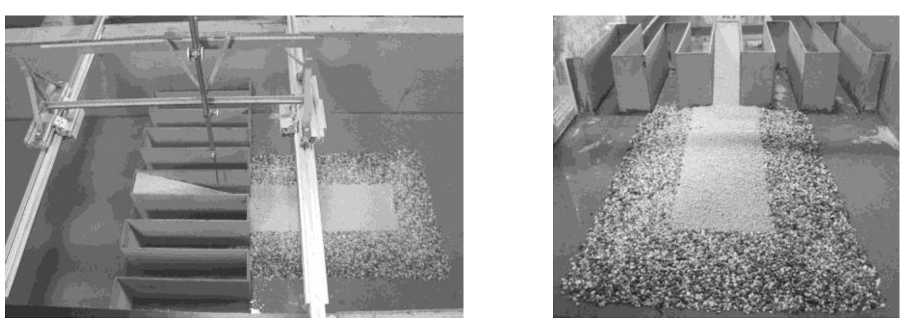

Figure 4. Model configuration and point gauge (a) and reference bed (b) for the rectangular labyrinth weir.

4. Results and Observations

4.1. General Observations

The self-cleaning effect was observed for all sediments and weir geometries. The flow was separated at the upstream facing weir wall. According to Breusers and Raudkivi (1991), the vertical velocity gradient of the flow is transformed into a pressure gradient. The resulting downward flow swept around the corner and formed a highly turbulent vortex system. This vortex system is also called a horseshoe vortex and is well known from the flow around bridge piers. The vortex was visualized by the use of tracer (Figure 5). Set in motion by the turbulences and the accelerated flow, the sediment rolled along the slope to the end of the inlet key where it was finally transported over the weir.

(a) (b)

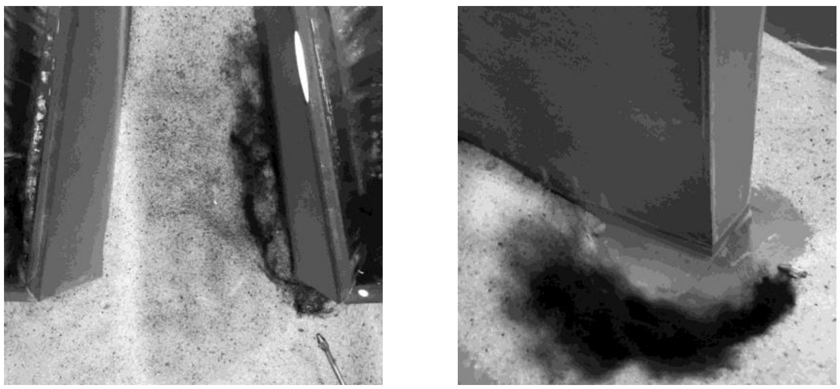

Figure 5. Visualization of vortex system for lower (a) and higher discharge (b). View into the inlet key with flow direction from bottom to top (a) and upstream facing weir wall with flow direction from right to left (b).

In all cases, the self-cleaning started before sediment mobilization on the reference bed was observed. As soon as the sediment of the reference bed was mobilized, it was directly transported over the weir. The fine sand moved slowly through the inlet key in the form of a drifting dune and finally over the weir.

4.2. Initiation of Motion

In dependence of the weir geometry and the sediment characteristics, the critical flow conditions for the initiation of motion was determined. Table 3 gives an overview of the critical discharges. Furthermore, the location of initial motion differed for the two weir geometries as it is illustrated in Figure 6.

Table 3. Critical discharges [l/s] at sediment mobilization for two weir types and tested sediment.

	Trapezoidal	Rectangular
Polystyrene	20	15
Fine sand	60	35
Fine gravel	110	70
Medium gravel	210	190

At the rectangular labyrinth weir erosion already began at lower discharges. This can be explained by the horizontal narrowing of the flow and the high transversal acceleration at the separation edge at the entrance of the rectangular weir. The width of the inlet key W_i = 11.5 cm (rectangular weir) is remarkably smaller compared to the trapezoidal weir (W_i = 20.0 cm). Additionally, comparing the model sediments, it is clear that for smaller and lighter grains, the critical discharge for the sediment transport is lower.

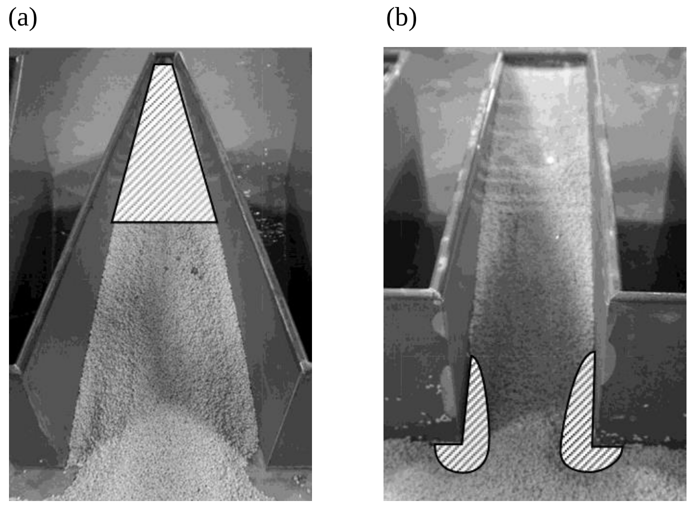

Figure 6. Location of initial sediment movement at trapezoidal (a) and rectangular (b) labyrinth weir.

The initial sediment movement (Figure 6) at the trapezoidal weir is located at the downstream part of the inlet key where the flow section is decreased by the ramp and the converging weir walls. At the rectangular weir the sediment was first moved at the entrance of the inlet key. The sharp edge causes a higher acceleration of the flow and height turbulences. There was no influence of the tested sediments on the location of mobilization.

4.3. Parameter Study

In order to identify the beginning of the self-cleaning process, the remaining sediment volume V_r was regarded. Therefore, the remaining sediment volume V_r in the key is normalized with the initial sediment volume V_0 and expressed as a function of the dimensionless parameters F_d and R_d. The volume in the inlet key was estimated on the basis of the ramp geometry, which was measured for every discharge state. F_d and R_d were determined on the basis of Eq. (2) and (3).

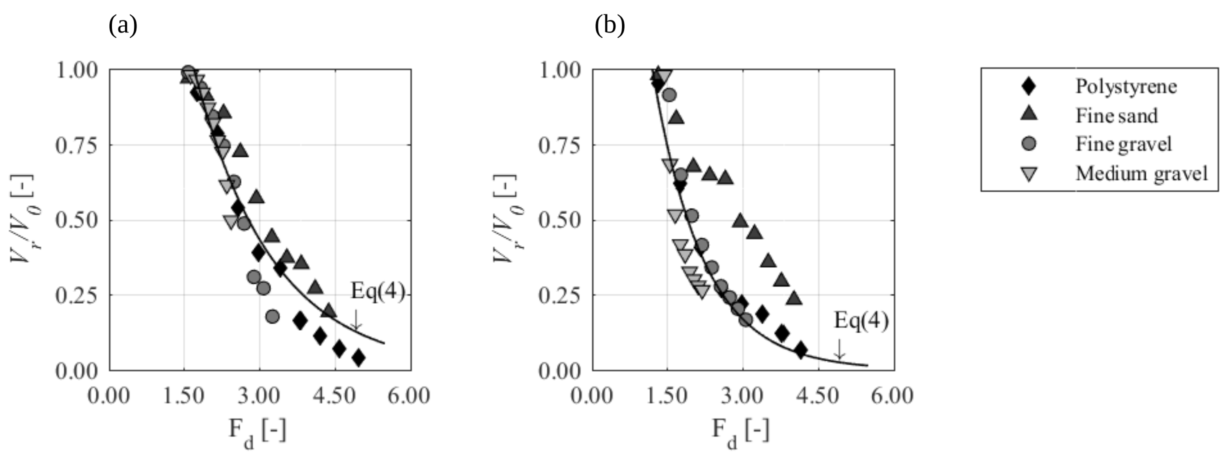

Figure 7. Remaining sediment volume as a function of the densimetric Froude number for the trapezoidal (a) and rectangular (b) labyrinth weir.

$$V_r/V_0 = a \cdot exp(b \cdot F_d) \quad (4)$$

As seen in Figure 7, a good correlation between the remaining sediment and the densimetric Froude number is given. The data collapses to a single curve, which is given in Eq. (4), if the fine sand test series at the rectangular weir is excluded. The coefficients *a*, *b*, and the coefficient of correlation R^2 are given in Table 4 for the rectangular and the trapezoidal labyrinth weir. Note that the test series for the fine sand is not considered in Eq. (4) at the rectangular weir. Here, sediment movement on the reference bed resulted in live-bed conditions in the inlet key. Hence, in this range ($2 < F_d < 3$) the sediment ramp is stabilized because there is almost equilibrium between sediment transport in the inlet key and the reference bed.

Overall, it can be seen that the densimetric Froude number is a dominant parameter to describe the self-cleaning effect. Self-cleaning begins for F_d = 1.6 to 1.8 at the trapezoidal weir and for F_d = 1.1 to 1.4 at the rectangular weir. With increasing discharge and densimetric Froude number the remaining sediment decreases regressively. Finally, the sediment is nearly ($V_r/V_0 < 10\%$) washed out for $F_d > 5$.

Table 4. Equation coefficients and coefficient of correlation for Eq. (4).

	a	*b*	R^2
Trapezoidal weir	2.97	-0.64	0.77
Rectangular weir (all materials)	2.32	-0.74	0.64
Rectangular weir (without sand)	3.31	-1.00	0.83

Figure 8 shows also that the grain Reynolds number R_d is not an adequate parameter to predict the scouring process universally. While the data follows a trend for a single sediment, a universal correlation between R_d and V_r/V_0 for all material (differing in particle size and density) is not given.

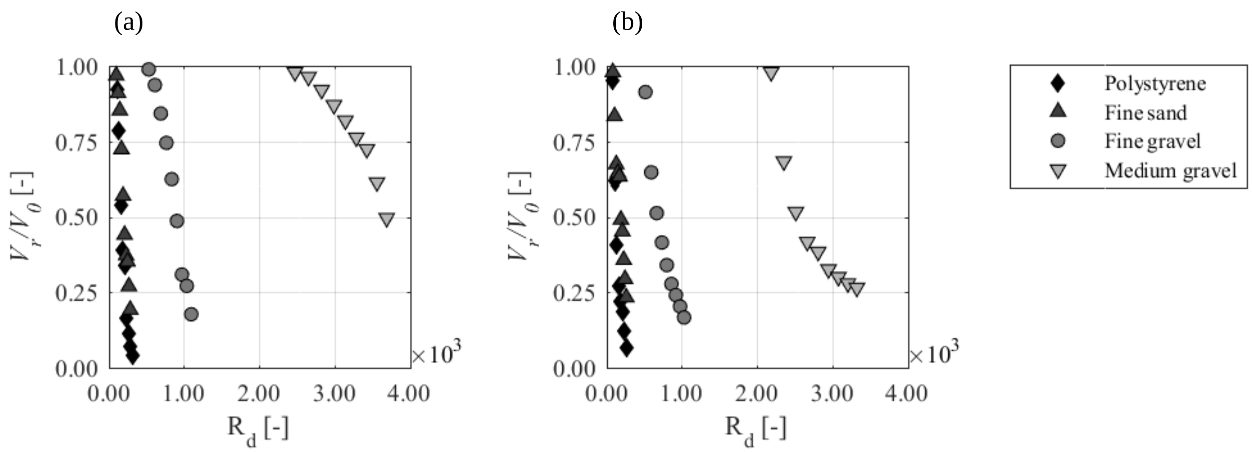

Figure 8. Remaining sediment volume as a function of the grain Reynolds number for the trapezoidal (a) and rectangular (b) labyrinth weir.

5. Conclusion

The purpose of this study was to describe and to quantify the self-cleaning process at labyrinth weirs. Therefore, systematic experimental tests were performed with a rectangular and a trapezoidal labyrinth weir. Four sediments were tested under various flow conditions: fine sand, fine gravel, medium grained gravel, and polystyrene granules. The following conclusions can be drawn:

- The experimental studies confirm the self-cleaning ability of labyrinth weirs with increasing discharge and confirm the model studies which are discussed by Falvey (2003).
- Comparing the two weir geometries, it can be observed that at the rectangular labyrinth weir, sediment transport begins at lower discharges compared to the trapezoidal labyrinth weir. Furthermore, the location of initial motion differs for both weirs.

- It is shown that the densimetric Froude number F_d describes the self-cleaning effect adequately. Thus, the results can be applied on other models or prototypes for the same densimetric Frounde number. Scale effects such as cohesion must be excluded.
- Self-cleaning begins at F_d = 1.6 to 1.8 (trapezoidal weir) and F_d = 1.1 to 1.4 (rectangular weir). For both weirs the sediment is nearly washed out for $F_d > 5$.
- It is also shown that a universal statement on the self-cleaning effect cannot be derived from the grain Reynolds number R_d.

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