Physical modelling optimization of a filter check dam in Switzerland

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ABSTRACT

After a major flood with a peak discharge of 177 m³/s in the city of Martigny (Valais, Switzerland) by the alpine river Drance in October 2000, the local authorities are strengthening efforts for the protection of the urban area. The Drance has an annual average discharge of 10 m³/s and the most important floods occur in the late summer. Two lateral torrents potentially supply the Drance with debris flow directly upstream of the urban area, where the installation of a filter check dam is foreseen for the retention of sediments in case of flood events. The functionality of the structure was analyzed on a physical model at a geometric scale of 1:42 for different scenarios, i.e. clear water conditions, regular bedload and driftwood transport. The flow pattern and the sediment retention upstream of the filter check dam were analyzed and the energy dissipation downstream was optimized by modifications of the stilling basin.

KEYWORDS

filter check dam; physical model; retention of bedload; flood protection; driftwood.

INTRODUCTION

After a major flood event in the city of Martigny (Lower Rhone Valley, Switzerland) in October 2000, the local authorities are strengthening efforts for the protection of the urban area, like recently in the neighboring municipality of Riddes (Bianco et al. 2014). Martigny is crossed by the alpine river Drance, whose catchment area is under the influence of several hydropower reservoirs and which suffer from floods mainly in late summer, due to superimposed glacier melting and rainfall runoff.

As indicated in Figure 1, the upper branch of the Drance River is flowing from south-east to north-west. Downstream of the village of Les Valettes, a canyon stretch with steep hill slopes receives five lateral torrents just upstream of the urbanized area of Martigny-Croix and Martigny.

In the framework of the flood protection program, the trapping of sediment is foreseen at the downstream end of the canyon stretch by means of a filter check dam. The project site is confined laterally by steep hill slopes which impede the excavation of a retention basin. Therefore the height of the filter check dam is designed to retain the sediments in the canyon

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for a 100-year flood. In this study, the hydraulic behavior of the pre-designed filter check dam was analyzed and optimized by means of a physical model.

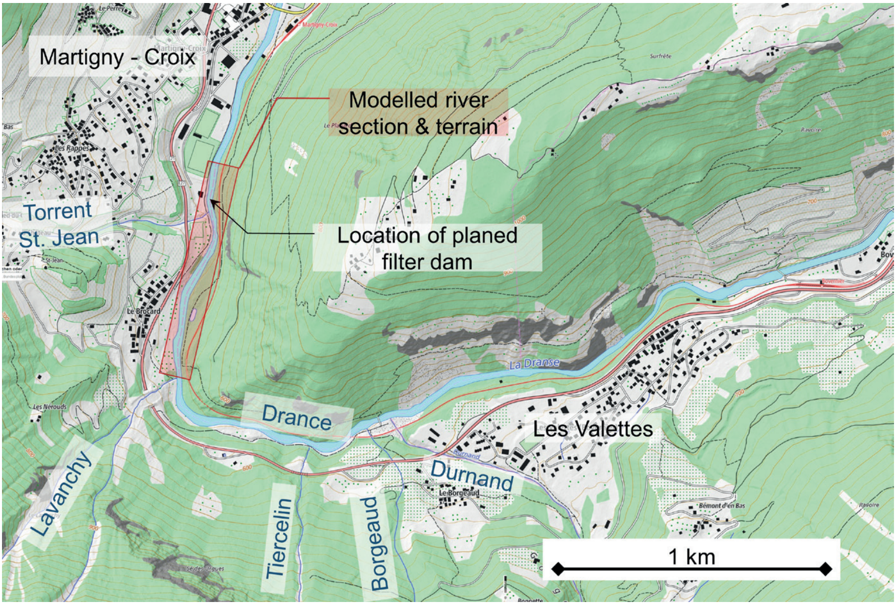

Figure 1: Map of the region of interest, indicating the modelled river reach. Reproduced with the authorization of Swisstopo JA100120.

METHODS

Hydrological, geomorphological framework

The river has been reproduced on an 850 m long reach with bed slopes varying between 2.4 % and 3.1 %. The part upstream of the sediment control dam is about 600 m long and includes the inflows of the Lavanchy and St. Jean Torrents. The downstream part serves for the analysis of energy dissipation. The range of discharges tested in the experiments is shown in Table 1, where Qd denotes the design discharge for clogging of the orifice.

Table 1: Range of discharges analyzed in the experiments in m³/s at prototype dimensions. Qd denotes the design discharge of opening clogging.

Q_{mean}	Q_d	HQ 2.33	HQ 5	HQ 10	HQ 20	HQ 50	HQ 100	HQ 300	HQ 500 (EHQ)
10	30	86	105	119	130	175	230	280	345

Two different grain size distributions are applied in order to account for the differences between the coarser channel bed and the finer sediment supply of debris flow from the lateral torrents. The bed mixture is characterized by D30 = 29 mm, D50 = 92 mm and D90 = 435 mm, where the mean diameter is Dm = 165 mm. The supply mixture is characterized by D30 = 25 mm, D50 = 43 mm and D90 = 156 mm, where the mean diameter is Dm = 75 mm.

Driftwood

Since the catchment area of the Drance is partially covered by alpine forests, driftwood is likely to occur during floods. The blockage of hydraulic structures like the filter check dam and the bridges through the town of Martigny during floods have to be avoided. The behavior of driftwood and retention measures is studied by injecting piles of wood at the model entrance with different structural setups. The driftwood samples consist of 15 trunks of 10 m of length, 10 trunks of 15 m of length and 2 rootstocks.

Scaling and model setup

The model has a geometric scale of 1:42 and is about 21 m long and 2.8 m wide. In order to promote the participation of local stakeholders and the inhabitants of Martigny, the model was built in the neighborhood of the future establishment site. The geometric scale was chosen due to spatial limitations (upper size limit) and the respect of Froude and sediment transport similarities (lower size limit).

The model is shown on Figure 2 with the upstream and downstream basins for water storage of 0.75 m³ and 4 m³ respectively, the two pumps and the chutes for the lateral torrents.

Figure 2: View of the model with the lateral torrents, the supply pumps as well as the upstream and downstream water storage basins.

The transported sediments, supplied at the upstream end of the channel, are captured in industrial filter bags which are suspended in the downstream basin.

Layout of the filter check dam

The initial configuration of the filter check dam implies two 10 m wide standard crest spillways, a stilling basin furnished with 1.5 m large blocks and a 4 m large central pile for the placement of a sluice gate covering the 4 m wide orifice of the filter check dam (prototype dimensions). The shape of the stilling basin is orientated at the standard design of a stilling basin. As the structure will be located in a right hand curve of about 24°, the crest axis of the spillways is inclined by 12° with respect to the upstream river axis for guiding the flow towards the downstream river axis.

The geometry of the orifice is crucial because a too large opening will lead to excessive sediment transit during floods, i.e. self-flushing, offering therefore insufficient protection downstream. A too small opening on the contrary will retain too much sediments, leading to early or even permanent backfilling of the retention volume. The elements of the structure, described in Figure 3, were designed for a 100-year flood.

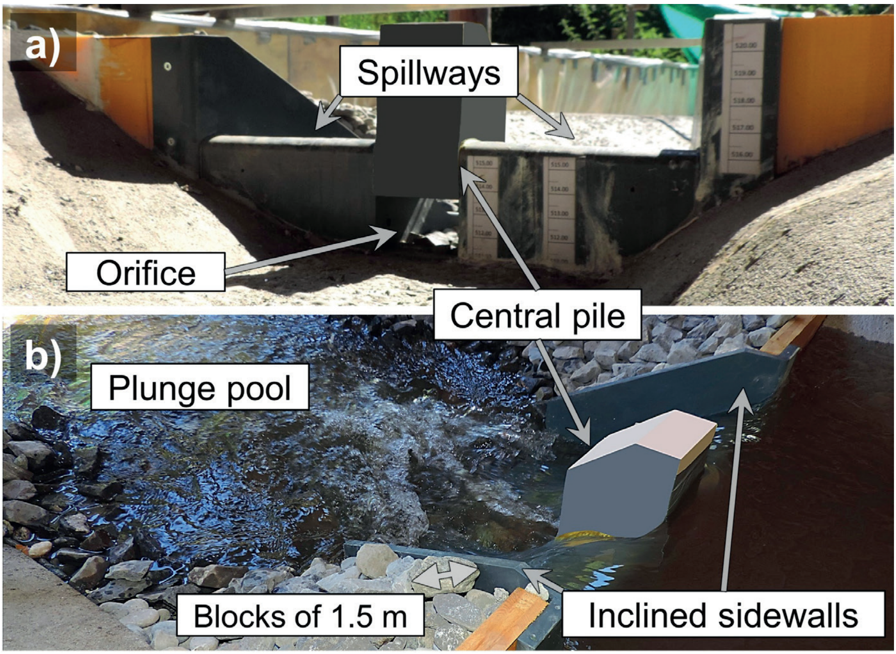

Figure 3: Elements of the filter check dam: opening, central pile, crest spillways and stilling basin with 1.5 m large blocks (prototype dimension): a) dry model from upstream and b) lateral view during a 100-year flood.

The effects of the structure on energy dissipation were analyzed with respect to the central pile (placed / suppressed), the implementation of a sluice gate in front of the orifice for the flushing control (opened / closed), the shape and length of the stilling basin (standard stilling basin / pear-shaped) and sediment transit through the filter check dam.

Measurements

The water level was recorded by means of ten ultrasonic probes and the water discharges were controlled individually for each pump by two flow meters. The sediment output was measured at the end of each experiment by means of an industrial scale. Video and picture documentation was constituted to highlight dynamic processes like the behavior of driftwood, the development of flow patterns and the sediment transport.

Scenarios

Combined with modifications of the layout, different discharge scenarios and solid transport events were studied. The whole range of discharges according to Table 1 was tested for the initial layout configuration with large central pile and standard-shaped stilling basin, under steady flow conditions without bedload. The focus of interest is the behavior of the structure in case of ordinary flow conditions (about 10 m^3/s), frequent floods i.e. HQ 2.33 with 86 m^3/s, 100-year flood with 230 m^3/s and extreme flood event with 345 m^3/s which comply with 0.87 l/s, 7.52 l/s, 20.12 l/s and 30.18 l/s at model scale, respectively.

For the 100-year and the extreme flood scenarios, the functioning of the structure must be guaranteed for ordinary bedload transport as well as with debris flow from the lateral torrents. The hydrograph and the corresponding sediment curve which apply for a 100-year flood event are shown in Figure 4.

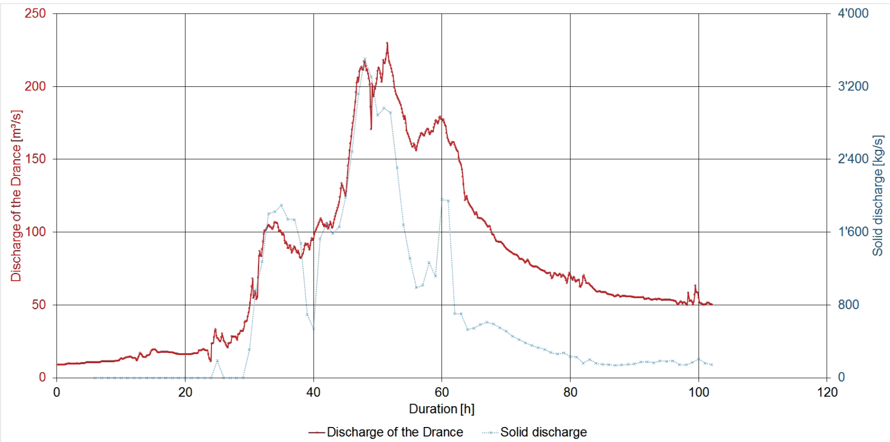

Figure 4: Showcase hydrograph and sediment curve of a 100-year flood, based on the flood from the year 2000.

The sediment curve is based on the evaluation of bedload from the results of a 1D numerical simulation with Gesmat code at the model entrance. The peak of the solid discharge is about 3.5 t/s, which correspond to about 18.5 kg/min at model scale.

RESULTS

Hydraulic control and sluice gate

The hydraulic effects of the structure for the initial configuration with central pile and active orifice were studied experimentally and theoretically by means of a stage-discharge relation. The small width of the orifice (less than 50 % of the river width) imposes backwater for nearby all discharge conditions.

Central Pile and Driftwood

The central pile influences the backwater and induces driftwood clogging on the right bank spillway in 10 % of the tests. The presence of the pile has only minor effects on energy dissipation in the stilling basin. Initially, flow deflectors were foreseen for deviating the flow towards the left river bank directly upstream of the filter check dam, where the driftwood was intended to be retained in case of floods, according to Schmocker and Weitbrecht (2013). The authors propose to install vertical piles between the main channel bed and the river banks longitudinally to the river axis in an outer river bend, where vertically oriented vortices occur during floods and push the driftwood towards the outer bank. Thus, the driftwood can be trapped behind the barrier of piles. In the present case, due to the influence of backwater, the solution with flow deflectors cannot establish the suggested flow conditions. Another promising position for a pile structure was identified in an outer right hand bend about 350 to 450 meters upstream of the filter dam. Here, driftwood can be retained, but only if the pile structure also crosses the river axis.

Stilling basin

The key parameter for the evaluation of the efficiency of the stilling basin is the energy dissipation by means of water surface level and flow velocity measurements upstream and downstream of the stilling basin. The initial shape according to a “standard” stilling basin had the poorest performance in terms of energy losses. The energy dissipation was improved by adapting the geometry of the stilling basin to a pear-shape with the narrowing towards the downstream direction. Further improvements were achieved by increasing the depth of the basin by about 1.5 m and elongating the stilling basin by about 10 m in prototype dimensions. As the structure is situated in a right hand bend, the energy dissipation was even more pronounced by applying an asymmetric deepening of about 1 m more along the right river bank, as this measure makes the velocity profile more uniform at the downstream end of the stilling basin. The stages of improvement of the energy dissipation are illustrated in Figure 5, based on the energy head of a 100-year flood.

The experiments have shown that the 1.5 m large boulders are mobilized during floods, thus requiring stabilization measures.

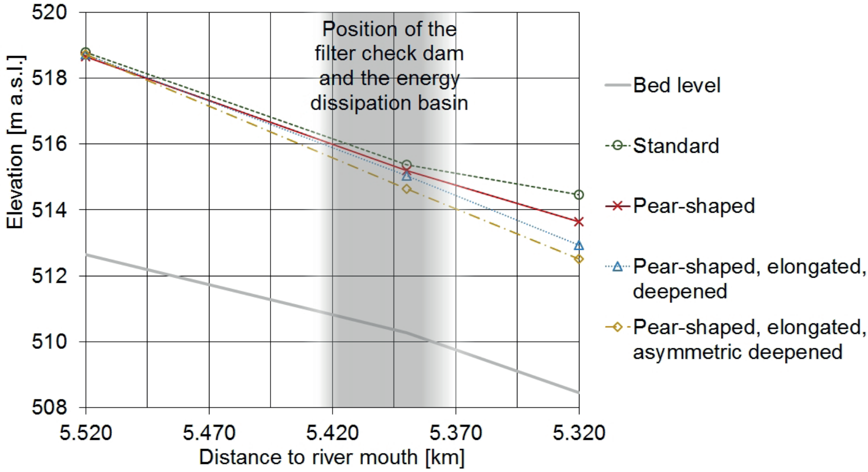

Figure 5: Improvement of the stilling basin by adapting the shape, pool depth, length and 183 symmetry with respect to the longitudinal river axis based on the energy head during a 100- 184 year flood (HQ100).

Sediment Transfer

The sediment transfer through the filter check dam, notably the opening, is strongly linked to the flow pattern along the structure which was analyzed by injecting tracer color. The observations are documented in Figure 6 for a discharge of 30 m³/s.

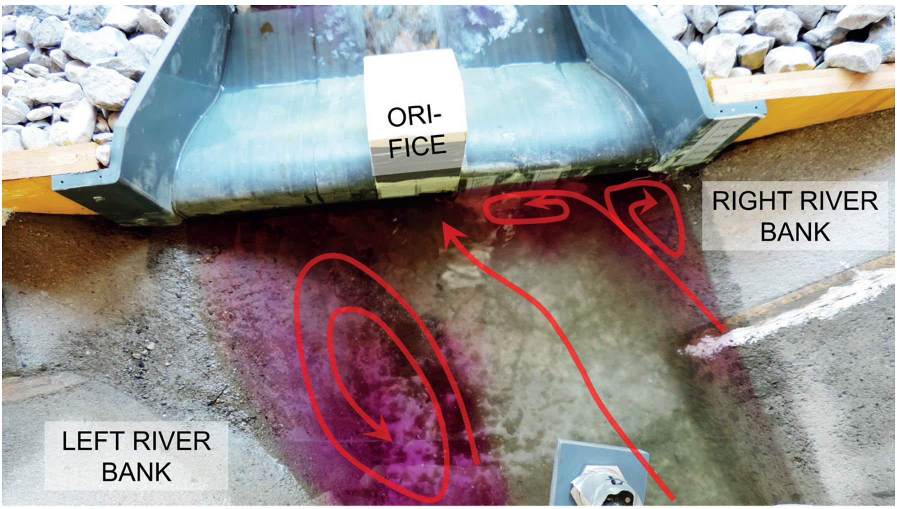

Figure 6: Flow pattern upstream of the filter check dam for a discharge of about 30 m³/s.

Within the range of the tested discharges (minimum 10 m³/s), a quiet water zone established at all discharges upstream of the dam towards the left river bank. As shown in Figure 6, sediment deposits at the outer bound of the recirculation zone close the main current.
The behavior of the structure during floods was studied by reproducing the hydrograph of Figure 4 by incremental steps and without closing the weir. The experiment was stopped at the flood peak for the analysis of the depositions. A large part of the sediment was retained upstream of the filter dam with a deposition slope of about 0.7 %. However, about 1/3 of the injected sediment passed the structure and was captured in the sediment bag. In prototype dimensions, about 20’000 m³ of sediments would have been directed towards the town of Martigny.

CONCLUSIONS

The initial layout of the filter check dam included standard spillways and a stilling basin designed for a 100-year flood (HQ_{100}) with a 4 m large central pile and orifice. The design of the basin was experimentally improved stepwise by adaptations of its shape, the length and the depth. An additional improvement was achieved by increasing the pool depth asymmetrically along the right bank, as the structure is situated in a right hand bend.
The experiments have shown that about 2/3 of the sediments are retained by the structure during a 100-year flood. The rest can be safely transported through the channelized section in the town of Martigny.

The actual design of the orifice probably requires a control measure, i.e. a sluice gate to avoid self-flushing in the falling limb of a flood event. Alternative remedy measures are conceivable, like the installation of vertical poles or horizontal beams in shape of a mechanical barrier upstream of the orifice. This alternative will be examined on the model too.
Driftwood is partially blocked when the central pile applies. However, a retention zone about 350 m to 450 m upstream of the filter check dam was identified for the installation of a driftwood retention device.

Many of the existing open check dams were designed based on the own experience of the responsible engineer (Armanini and Larcher, 2001). For safety reasons, it was considered that it is more convenient for the filter check dam at the Drance River to design a narrow opening with a gate. However, the installation and the handling of a sluice gate during floods are critical issues. As an alternative, the enlargement of the opening with the implementation of a grid rack has to be considered but was not yet implemented in the framework of this study.

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