Analysis of damage causing hazard processes on a torrent fan - scale model tests of the Schnannerbach Torrent channel and its entry to the receiving water

Bernhard GEMS[1,*], Michael STURM[1], Arthur VOGL[2], Christian WEBER[2] and Markus AUFLEGER[1]

[1] Unit of Hydraulic Engineering, University of Innsbruck (Technikerstrasse 13, 6020 Innsbruck, Austria)

[2] Austrian Service for Torrent and Avalanche Control, Imst regional headquarters (Langgasse 88, 6460 Imst, Austria)

*Corresponding author. E-mail: bernhard.gems@uibk.ac.at

The work presented within this paper deals with experimental modelling of torrential hazard processes on an Alpine torrent catchment's fan. A morphodynamic scale model (1:30) is set up to analyze damage causing processes in the lined trench at the fan and in the confluence zone with the receiving water. Fluviatile flow regimes covering bed-load fractions up to 12 % are considered. For model validation, a reconstruction of the disastrous 2005-flood-event is accomplished. Critical impact conditions, causing overloading of the confluence, regressive aggradation and lateral overtopping along the lined trench and the clogging of a bridge, are identified. Further, with the knowledge of the critical impact patterns for the current state situation, protective effects of river engineering measures, such as the implementation of groins and bed ramps in the receiving water or flood walls and the removal of the bed sills in the torrent, are analysed. The work points out the protective effects of a typical layout of a torrent channel at the fan, entering the receiving water, and illustrates potential for enhancements.

Key words: torrent, fan apex, bed-load transport, confluence, physical scale model

1. INTRODUCTION AND CASE STUDY SITUATION

The structural design of rigid torrent channels at the torrential fan is of basic importance for sufficient protection of adjoining settlement and infrastructure against torrential hazards. In case of floods, specific sediment transport processes in the channel, such as the transport capacity of the receiving water or rather regressive sedimentation starting at the entry to the receiving water and spreading towards upstream, are of great influence for the torrent channel capacity, the hydraulic characteristics and, thus, for the risk of overbank sedimentation. According to specific research in this field, the main parameters for a sufficiently dimensioned torrent channel are the gradient and the longitudinal profile of the channel, its surface roughness, the intersection angle at the junction with the receiving water, the bed levels at the junction point and the general hydraulic/morphodynamic conditions in the receiving water [e.g. *Hunzinger and Zarn*, 1996; *Hübl et al.*, 2002; *Hübl and Moser*, 2004; *Gems et al.*, 2014]. Their impact was observable during a couple of torrential flood events in recent years in the Alpine region [e.g. *Hübl et al.*, 2004; *Hübl et al.*, 2005; *Rudolf-Miklau et al.*, 2006; *Drexel*, 2011; *Pussnig*, 2013]. Apart from this influencing parameters, the characteristics of the impacting hazard processes, leading to floods with a purely fluviatile sediment transport behavior, to debris floods or rather to debris flows [*Hübl and Kaitna*, 2010; *Rickenmann*, 2014], further influence the potential hazard process pattern on the fan apex significantly.

The work presented within this paper pays particular attention to the analysis of fluviatile hazard processes on a torrent's fan, typically situated in the Austrian Alps. An existing channel layout at the lower alluvial and its entry to the receiving water are analysed within a morphodynamic scale model test. With regard to a best possible avoidance of overbank sedimentation in future, the current state situation is further optimized.

Fig. 1 Fan apex of the Schnannerbach Torrent 1970 and after the 2005-flood-event

The Schnannerbach Torrent as a tributary of the Rosanna River is situated in the Tyrolean Limestone Alps. Mainly exposed to the south, the catchment covers an area of 6.3 km^2, ranging from 1,120 m.a.s.l. at the entry to the receiving water up to 2,889 m.a.s.l.

The torrent is supplied with sediment from highly yielding, steep screes in the upper catchment part. In the lower reach, the torrent flows through a gorge section before passing the settlement area on the fan apex. Due to the characteristics of the sedimentary rock and the sparse forest vegetation in the catchment, large amounts of weathered products reach the trunk torrent. It represents a large portion of the sediment potentially available for remobilization. The hazard potential of the Schnannerbach catchment is mainly related to advective precipitation events with medium and high intensities, causing continuous sediment discharges and featuring a fluviatile, rather than debris, flow regime [*Rudolf-Miklau et al.*, 2006]. Material, which is activated during floods and partially deposited on the fan apex, is mostly small-grained and shows a comparatively uniform grain size distribution [*Sommer and Lauffer*, 1982; *Luzian et al.*, 2002; *Hübl et al.*, 2003; *Rudolf-Miklau et al.*, 2006; *Chiari*, 2008]. According *Rudolf-Miklau et al.* [2006], the 150-years flood peak (HQ_{150}) of the Schnannerbach Torrent amounts to 30 m^{3}s^{-1} (considering also the bed-load fraction). The maximum expected sediment load under design flood conditions is thereby estimated to 35,000 m³ or rather 5,555 m^{3}km^{-2}.

As a consequence of settlement development and the occurrence of some damaging torrential hazard events in the last couple of decades (**Fig. 1**), the torrent this day passes the settlement area within a lined trench, which is characterized by a sequence of artificial steps and pools and gradients between 8 % and 13 % (**Fig. 1**). Towards the entry to the Rosanna, the gradient decreases to 6.5 %. The confluence has an almost orthogonal shape; the entry features a drop in the bed levels with a height of about 1.5 m, depending on the bed level in the Rosanna River. Further on, upstream of the gorge in the lower catchment, an arch dam was built in order to ensure the deposition of a substantial fraction of the inbounding bed-load in case of torrential floods (**Fig. 1, right**).

However, it is apparent from **Fig. 1, right**, that the implemented torrent defense works cannot provide perfect protection against torrential hazards: During the 2005-flood-event, roughly 13,000 m^3 of sediment were detained by the arch dam, whereas 20,000-25,000 m^3 reached the fan apex and were deposited in the channel and the adjoining settlement area. About 10,000 m^3 entered the receiving water. The massive flooding and overbank sedimentation was thereby mainly induced by a regressive sedimentation process in the lined trench, starting at the entry to the Rosanna River.

The mentioned amounts of sediment were estimated by *Chiari* [2008] in the course of a reconstruction analysis of the flood event in August 2005. Assuming a continuous loading pattern during the entire flood hydrograph (a constant bed-load fraction), this leads to bed-load fractions of about 3 % at the fan apex of the Schnannerbach Torrent. As subsequently mentioned, preliminary tests in laboratory showed, that clearly higher bed-load fractions are required to induce regressive aggradation processes in the confluence zone, overbank flooding and sedimentation along the lined trench (**Fig. 6**). Accordingly, for the experimental analysis, the aforementioned sedigraph at the Schnannerbach catchment outlet was modified (**Fig. 6**).

2. MORPHODYNAMIC SCALE MODEL

Fig. 2 shows a sketch of the morphodynamic scale model, covering 275 m of the Schnannerbach channel and about 210 m of the receiving water course (Rosanna River). The scale is 1:30; the model conforms to Froude similarity. The channel structure is placed in a basin consisting of standard steel-aluminium elements. In the range of the Schnannerbach Torrent, the basin is set on a wooden substructure. Channel walls and sills, slopes, flood walls, the bridge structure and as well overbank terrain represent immobile structures within the model construction. They are built with rigid PVC and foamed polystyrene elements. Each element is patterned with a surface roughness corresponding to the prototype conditions.

The pools in the lined trench and as well the channel bed of the Rosanna River represent a mobile bed. For the channel bed characteristics and as well the bed-load input from the Schnannerbach catchment, quartz sand is used in a mixture that correlates with the prototype characteristics. The minimum grain size in the model is chosen to be 0.5 mm. The limit of 0.5 mm or rather 1.5 cm in prototype scale is set in a manner that all the sediment smaller than this value is added to the next larger bed-load fraction. With this configuration and model scale, any influential scale effects are precluded.

Fig. 3 illustrates the grain size characteristics for experimental modelling. It is derived from field samples, collected after the 2005-flood-event in the Schnannerbach catchment and as well in two neighboring catchments with similar hydrological and morphodynamic characteristics. Accordingly for the scale model test, the d_{50} amounts to 0.04 m and the d_{90} is 0.35 m (prototype dimensions).

The scale model is charged with water and sediments independently from each other at both upstream model boundaries. There, the loading discharges can be controlled in an unsteady mode. The supply of sediment at the Schnannerbach boundary is done manually by use of a belt conveyor. No sediments are supplied at the Rosanna boundary since no appreciable input of bed-load from upstream was observed during the flood event in August 2005 and, thus, is to be expected during a torrential event in the Schnannerbach catchment.

At the downstream scale model boundary an outlet reservoir with a weir overflow is installed. The reservoir is set on four pressure transducers (HBM, K-HLCB2) which allow for a continuous weighting of bed-load accumulation and, further, the determination of the transport rates.

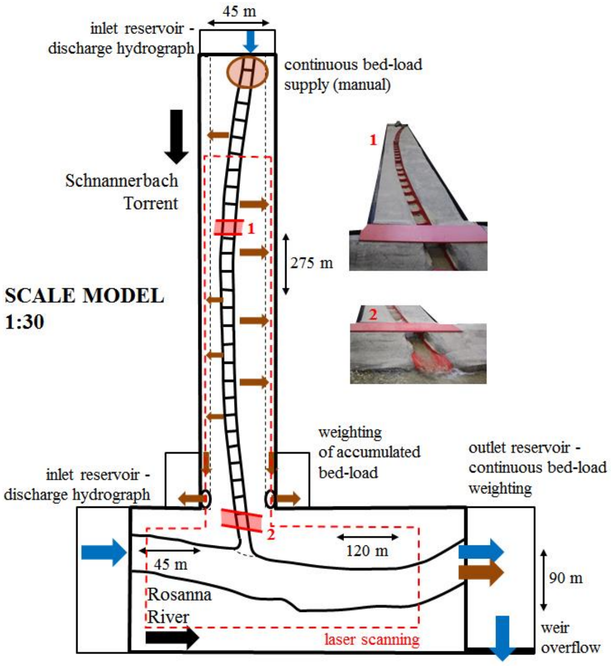

Fig. 2 Sketch of the morphodynamic model at the scale 1:30 (prototype dimensions)

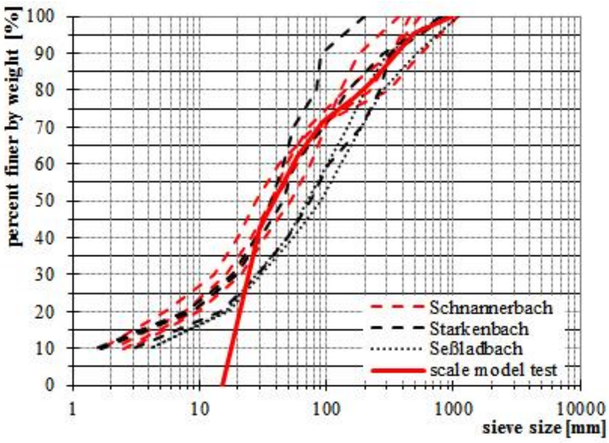

Fig. 3 Representative grains size characteristics in prototype dimensions

In case of overbank sedimentation along the lined trench, small (artificial) channels, running parallel to the Schnannerbach channel, collect the material and handle it to a small container on each side of the channel. With it, the fractions of sediment entering the settlement area and possibly causing substantial losses can be determined. Laser scanning is additionally done in the major part of the scale model in order to enable a complete balancing of the supplied bed-load and, primarily, to detect the deposition characteristics in the confluence zone.

3. TESTING PROGRAMME

The experimental analysis is basically structured in three conceptual steps; they are briefly described in **Fig. 4**. Firstly, a validation analysis in terms of a reconstruction of the disastrous 2005-flood-event is accomplished. Thereby, the impacting hydro- and sedigraphs are verified and, if necessary, adapted. Both, simulation data [*Chiari*, 2008] and as well observation data from the local residents in the village of Schnann are considered. With it, the model validation aims at a simulation of a realistic and typical hazard process pattern as occurred in August 2005 and, consequently, at the detection of critical spots and loadings patterns

Further, based on the findings from model validation, an optimization analysis focuses on the critical spots within the model extent, basically *(1)* the confluence zone and *(2)* the bridge crossing the Schnannerbach channel further upstream in the settlement area. Specific modification variants are analysed, each in terms of steady state simulations with the critical loading pattern (discharge and bed-load transport rate). According to the scheme illustrated in **Fig. 4**, they comprise of structural measures (a)-(e) in the Rosanna River in the confluence zone, modifications (f)-(h) of the Schnannerbach channel in the entry zone and as well adaptation measures (i)-(j) along the entire lined trench. Without the intention of anticipating the results of model validation, the main objectives of the optimization analysis can be briefly summarized as follows (the mentioned aspects surely influence one another):

- Increase of the Rosanna's transport capacity in the near range of the confluence zone in order to ensure the onward movement of sediments from the Schnannerbach Torrent;
- Avoidance or rather decrease of the regressive aggradation process in the lined trench;
- Increase of the transport capacity in the Schnannerbach channel, particularly in the near range of the upper bridge cross section;
- Avoidance of clogging of the bridges crossing the Schnannerbach channel;
- Best possible avoidance of overbank flooding and sedimentation along the lined trench;
- Compliance with legal regulations regarding the design flood water levels in the receiving water course.

Fig. 5 illustrates the most significant tested modification variants, both, in the confluence zone and along the lined trench.

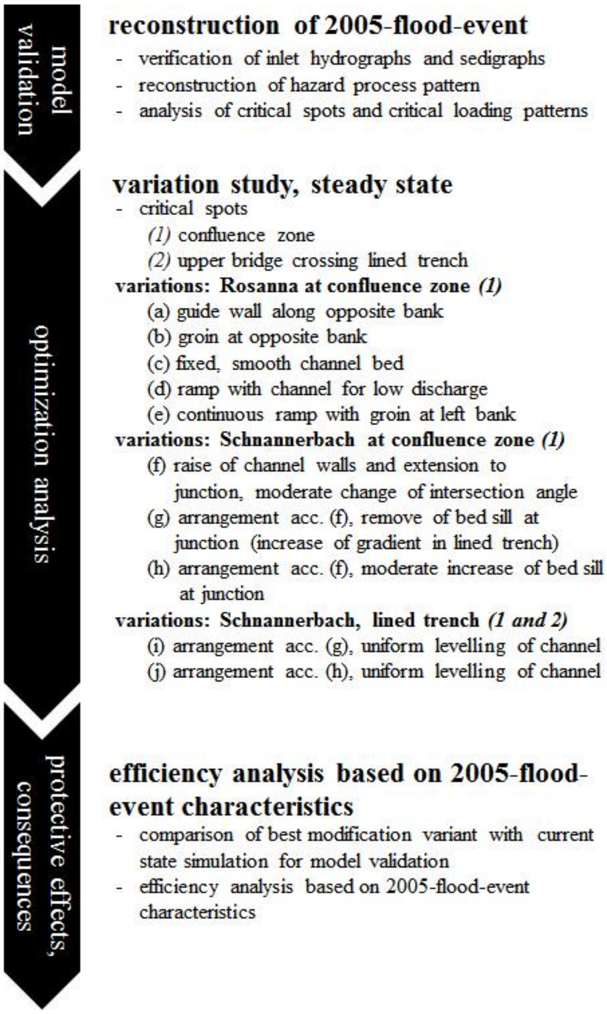

Fig. 4 Experimental analysis – testing programme

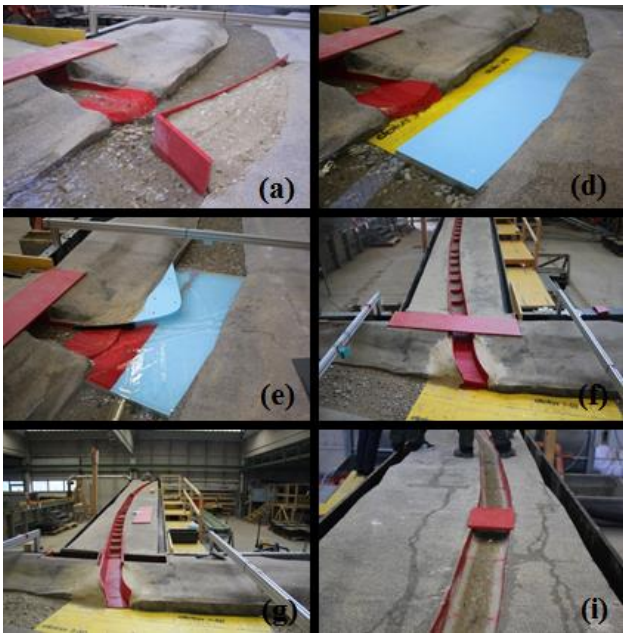

Fig. 5 Selected variants within optimization analysis

Variant (a) comprises a guide wall along the opposite bank of the Rosanna River in order to increase the transport rates at the entry of the Schnannerbach Torrent due to the channel constriction. The ramp in variant (d) aims at an increase of the channel gradient in the confluence zone. It does not extend beyond the entire channel width in order to ensure continuity for low and medium discharges in the Rosanna River.

Variant (e) comprises a ramp extending beyond the entire channel width and a groin situated at the left bank downstream of the entry. Within the modification variants (f) and (g), the entry zone of the lined trench is modified. The channel walls are raised and extended to the junction, the intersection angle at the entry is marginally changed and, within variant (g), the bed sill at the junction is removed in order to increase the gradient in the last section of the lined trench. Variant (i) includes the arrangements of variant (g) and, further, a uniform levelling of the Schnannerbach channel bed.

Those structural measures providing the best enhancement in terms of protection against torrential hazards and the mitigation of overbank flooding and sedimentation are finally tested on their efficiency. For it, the 2005-flood-event is again simulated and the results are compared to those from the model validation analysis.

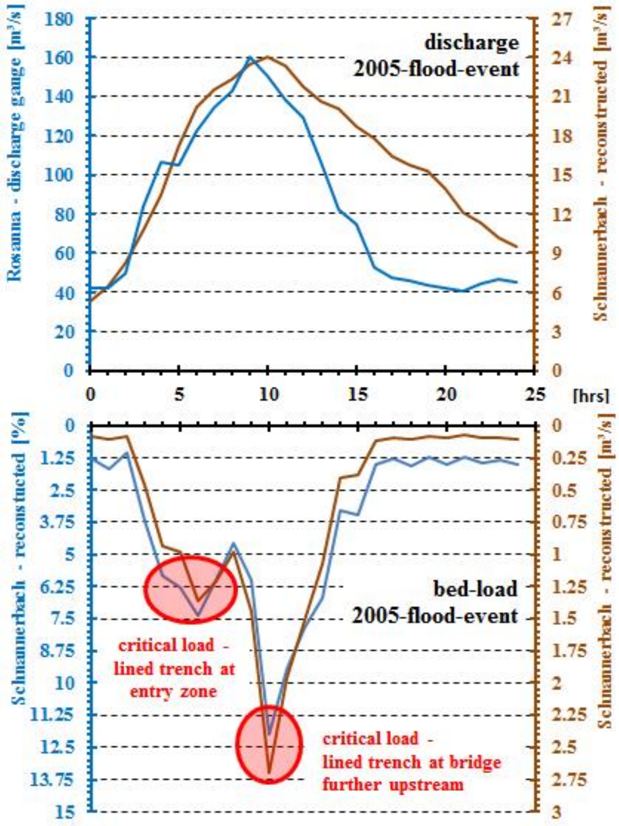

Fig. 6 Discharge hydrographs and sedigraph of the flood event in August 2005 (prototype dimensions)

4. RESULTS

Firstly, focusing on the reconstruction of the 2005-flood-event and thus on the model validation, **Fig. 6** illustrates the impacting discharge hydrographs and the sedigraph at the Schnannerbach model boundary. The hydrograph at the Rosanna River results from gauge measurements in proximity to the case study area. The hydrograph at the Schnannerbach torrent was derived by *Chiari* [2008] in the course of a morphodynamic reconstruction analysis of the torrential processes in August 2005 in the entire catchment.

Concerning the sedigraph at the Schnannerbach Torrent, the results from *Chiari* [2008] have been adapted: Preliminary experimental tests, carried out in a steady state mode with different discharges and bed-load fractions, revealed that the damage pattern shown in **Fig. 1** requires higher amounts of sediment. A fraction of roughly 6.5 % represents the critical load for the lined trench at the entry zone. Assuming HQ_5-conditions in the Rosanna River, such a quantity cannot be sufficiently moved onward in the Rosanna in the confluence zone. Consequently, the process of regressive aggradation in the lined trench occurs.

About one hour and 25 minutes (prototype dimensions) of simulation leads to overbank sedimentation upstream of the bridge there. If continuing the simulation clogging of the bridge appears, along with massive sedimentation in the adjoining flood plain. Due to the insufficient transport capacity in the receiving water, the entry zone of the lined trench means the critical spot of the channel being firstly overloaded. If not considering the influence of the entry zone towards upstream, the manageable bed-load fraction in the lined trench is about the double (12 %). To effect clogging of the upper bridge and overbank sedimentation in the adjoining settlement, both, bed-load fractions of about 12 % and the regressive aggradation from the entry zone towards upstream is required.

With the adapted sedigraph at the model input, a realistic damage pattern as documented in August 2005 (**Fig. 1**) occurs. Further, due to the consideration of information from local residents concerning the characteristics and the progress of the torrential event in August 2005, the critical spots and also the points in time of its first overloading are well reconstructed within the model validation.

Fig. 7 highlights snapshots during the validation experiment for the current state situation. The progressive deposition of sediments in the receiving water is evident. With an increasing duration of the experiment, regressive aggradation in the lined trench in the entry zone appears, leading to a first overloading of the channel after about 5 hrs of simulation (compare **Fig. 6**). Further, the bridge structure is clogging and all the incoming discharge and sediments either enters the artificial channels or gets deposited. Due to the subsequent decrease of the bed-load fractions (**Fig. 6**) the blockage gets flushed, before overbank sedimentation appears again due to the increasing impact conditions.

The situation in the lined trench further upstream is clearly affected by the processes in the entry zone. As long as the impacting bed-load fractions do not exceed the value of about 12 % and the process of regressive aggradation does not spread towards upstream to much, the channel structure copes well with the incoming discharge and sediment. However, in the latter case, the bed-load layer in the channel reaches the lower edge of the upper bridge and further leads to the clogging of the structure. The lowest snapshot in **Fig. 7** illustrates an overview of the situation at the end of the validation experiment for the current state situation. The simulation was stopped immediately after the clogging of the upper bridge structure.

Focusing on the optimization analysis, firstly the effects of the measures in the confluence zone are characterized: None of the variants (a)-(e) causes an significant increase of the transport capacities in the Rosanna River in order to cope with the sediments from the Schnannerbach Torrent and to prevent the process of regressive aggradation to some degree. This applies, although the tested river engineering measures mean a substantial modification of the natural water course; besides they lead to a significant raise in water levels upstream of the confluence.

The measures in the Schnannerbach Torrent, meaning the raise and extension of the channel walls and the change of the intersection angle (variant (f), **Fig. 4**), have a minor, but positive effect on the shape of the sediment deposition body in the confluence zone. Compared the current state situation it is more elongated, extends almost over the entire channel width and has slightly shifted towards downstream. The removal of the bed sill at the junction (variant (g), **Fig. 4**) enhances this effect since the incoming discharge and sediment enters the Rosanna River with greater energy. Concerning the beginning of the regressive aggradation process and the first occurrence of overbank sedimentation, modification variant (g) proves best.

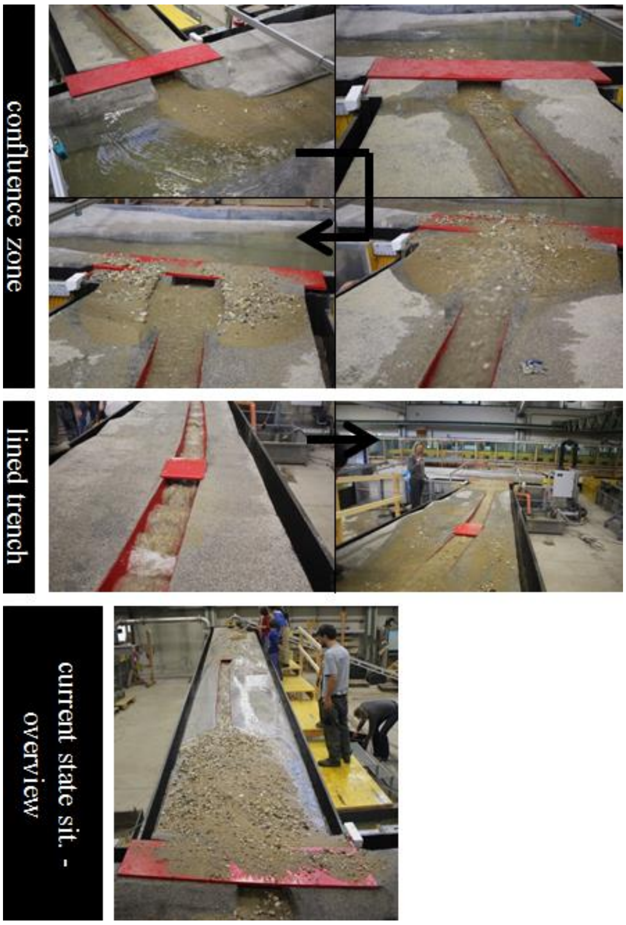

Fig. 7 Current state simulation results from experimental modelling

Within the lined trench, a uniform levelling of the channel bed and, with it, the non-availability of energy dissipation at the artificial steps does not improve the situation. Quite the contrary, with the arrangements of the variants (i) and (j), discharge and sediments reach the entry zone with considerably greater energy and further cause a more distinctive change in the flow and a more significant ponding effect of the receiving water respectively. Compared the situation of variant (g) the process of regressive aggradation initiates considerably earlier and also leads to overbank sedimentation earlier. Besides, an effect, that delays the beginning of regressive aggradation for the situation with artificial steps in the lined trench, is no longer effective with the variants (i) and (j): Wave formation, typically appearing in artificial open channels with step-pool-formations [*Premstaller*, 2006], develops in the lined trench and flushes the entry zone as long as the impacting bed-load fractions are rather low.

Fig. 8 highlights a comparison of the 2005-flood-event simulations for the current state situation and the favored modification variant (g).

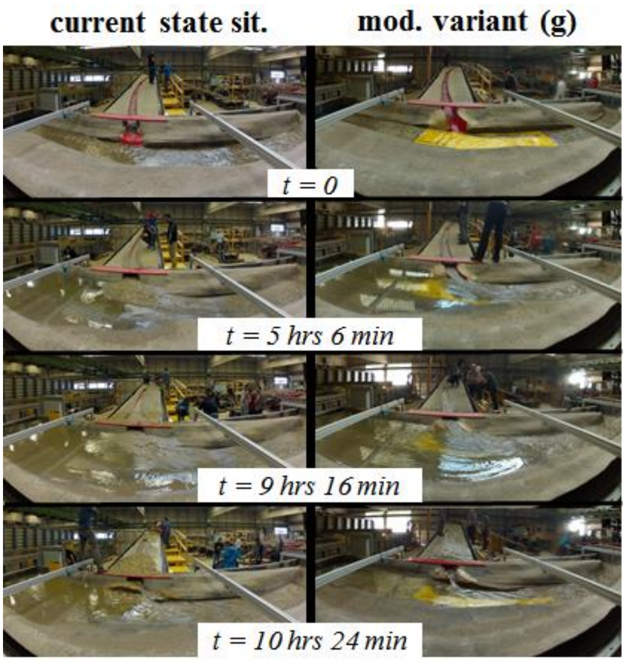

Fig. 8 Comparison of current state situation and modification variant (g) (prototype dimensions)

Overbank sedimentation starts at the lower bridge after about 5 hrs of simulation (prototype dimensions) for the current state situation. This is clearly delayed by more than 4 hrs with the applied modifications – inundation processes occur after 9 hrs and 16 min of simulation in this case. Snapshots at these points in time further reveal lower water levels in the Rosanna River upstream of the junction for variant (g). Clogging of the upper bridge, occurring after 10 hrs and 24 min of simulation for the current state situation, is no longer a problem if considering the modifications.

Fig. 9 illustrates the accumulated bed-load at the input and the downstream model boundary, again both for the current state situation and modification variant (g). A total of 35,610 m³ reaches the fan apex of the Schnannerbach torrent over a period of about 10.5 hrs, whereas about 43 % (current state sit.) and 50 % (variant (g)) of it are deposited in the outlet reservoir (see **Fig. 2**). The remaining sediment is deposited in the lined trench and in the receiving water. The higher amount of sediment at the outlet for variant (g) results from the lower amount deposited on the flood plain and the improved conditions at the lower bridge in the lined trench. Regarding the accumulated bed-load impacting from the catchment, roughly 8,000 m³ reach the fan apex before inundation firstly appears for the current state situation. Considering the measures from modification variant (g), inundation begins at about 26,000 m³ of accumulated bed-load.

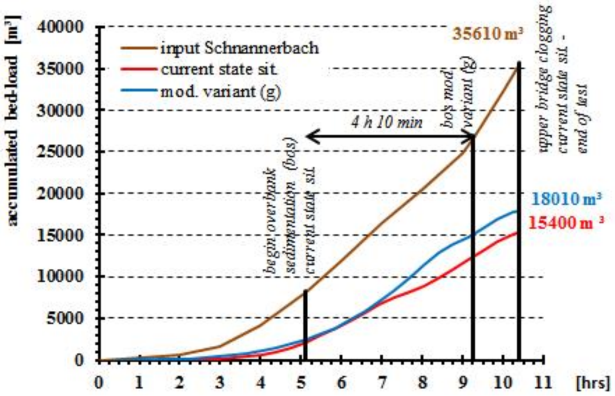

Fig. 9 Input of bed-load and accumulated bed-load at the downstream model boundary – comparison of current state situation and modification variant (g) (prototype dimensions)

5. CONCLUSIONS

The experimental modelling of the hazard processes in the Schnannerbach Torrent and the confluence with the receiving water lead to the following conclusions: Due to the too low gradient and thus transport capacities in the Rosanna River within the confluence zone, any engineering measures in the receiving water are not recommended. They do not prevent or constrain the massive deposition of sediments and the regressive sedimentation in the torrent channel significantly. Further, they cause a considerable damming up upstream of the junction and increase the flood risk there. The same holds for lateral measures in the lined trench such as the tested uniform levelling. Due to the characteristics of the entry zone, overbank sedimentation cannot be prevented, or at least delayed with it.

A positive effect is associated with local structural measures in the torrent channel in the entry zone. The raise and extent of the flood walls, the minor change of the intersection angle and as well the removal of the bed sill at the junction point considerable reduce the risk of overbank sedimentation along the torrent channel. For the specific case of the Schnannerbach Torrent, with rather low transport capacities in the receiving water, the removal of the bed sill seems to be very reasonable since there is not enough space for depositing all incoming sediment in order to fully prevent the process of regressive aggradation in the torrent channel.

Concerning the significance of the accomplished tests, it has to be pointed out, that the experimental analysis and thus the testing programme mainly focuses on the characteristics of the 2005-flood-event. For this specific impact pattern, protection of the adjoining settlement can be best possibly provided with the tested structural measures. In case of torrential hazard processes with larger discharges, higher bed-load fractions or even with the characteristics of a debris flood or flow, a great damage of the adjoining settlement still cannot be completely excluded. To some extent, this may represent an overload scenario. The present structural situation at the fan apex of the Schnannerbach Torrent, with a substantial part of the existing buildings being situated in the yellow and red torrent hazard zones, further on requires a prudent handling with the expectable hazard processes. This covers permanent monitoring in the catchment and at the fan apex, mobile protection measures if necessary (e.g. use of excavators to prevent bridge clogging) or emergency and evacuation procedures.

Besides, an integrated concept for protection against torrential hazards in the Schnannerbach catchment is currently managed by the Austrian Service for Torrent and Avalanche Control (Imst regional headquarters) and under preparation. It basically contains the modification suggests from experimental modelling but also includes the installation of inflatable weir structures in the openings of the retention dam further upstream in the catchment. With it, the retention or rather the dose effect at the dam can be permanently monitored and actively controlled and further coordinated with the situation on the fan apex. This concept will finally ensure the best possible protection against torrential hazards on the fan apex and also affects the excavation of sediments in the retention basin economically advantageous.

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