Laboratory experiments to analyse the influence of bridge profiles on debris-flow impact forces

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Abstract. Debris-flow impact plays a significant role in the failure of bridges in mountainous areas posing a risk to human life and leading to high reconstruction costs. The aim of this study is to measure and quantify the frontal impact forces of debris flows on bridge superstructures based on laboratory experiments with a special regard to the comparison of two different bridge profiles and the presence / absence of a bridge pier. To this end, we conducted 20 experiments, measuring the frontal impact forces on the bridge superstructure with two 3-axis force sensors at the abutments of the miniature bridge. We found that the type of the superstructure does have an influence on the magnitude of the frontal impact forces.

1 Introduction

Mountainous areas exhibit a greater density of bridges than flat regions due to their topography and mobility requirements. At the same time, bridges in higher altitudes are exposed to various dangers such as flash floods, fluvial sediment transport processes, debris floods and debris flows. A glance at the statistics of bridge failure in the US shows that debris flows alone cause 3.33 % of bridge collapses. If debris-flow impacts are added to general collisions, both sum up to over 15 % contribution to bridge failure [1].

Besides posing a threat to human life, frequent destruction of bridges also entails the need for frequent reconstruction, which consecutively leads to high financial expenditures. Since there is evidence that endangered areas prone to debris-flow events are likely to increase as a consequence of climate change as well as spatial development [2], the topic of debris-flow impact investigation is also relevant for the future safety of infrastructure elements.

The influence of debris flows on bridge piers has already been analysed in the past [3] – [6] whereas mechanisms and consequences of debris-flow impact on bridge superstructures remain unclear. Debris-flow impacts on masonry arch bridges have been studied before, however, the investigations were based on a separate examination of impact forces and the behaviour of the structure [7].

We hypothesize that frontal impact forces play a considerable role in bridge failure caused by debris-flow impacts. We also conjecture that the type of the bridge superstructure, specifically the bridge profile has an influence on the occurring forces. We aim to measure and quantify the forces exerted on different bridge profiles during debris-flow impact based on small scale experiments. Additionally, we investigate the influence of a bridge pier on the acting forces.

2 Methods

The experimental setup (1 in Figure 1) consists of a semi-circular channel with a length of 4 m and a diameter of 0.3 m. The channel is inclined at 20 ° and the experiments feature a scale of 1:30. The debris-flow material is released from a rectangular starting box in a dam-break scenario. Travelling down the flume, the material forms a typical debris-flow habitus (granular head, more liquid body and tail) before hitting the miniature bridge profile (2 in Figure 1) at the end of the flume.

Fig. 1. Experimental setup total (1) and detailed view of the miniature bridge mounted on a steel frame (2)

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This study features two miniature bridge profiles: the solid slab profile (1 in Figure 2) and the trough profile (2 in Figure 2). Both profiles have a total length of 0.33 m and a width of 0.4 m normal to the direction of the flow. The solid slab profile features cantilevers with a length of 0.05 m to both sides in and against the flow direction. The total height of the solid slab profile is 0.02 m. The trough profile has no cantilevers and a total height of 0.06 m, which results in an impact area three times as large as that of the solid slab. The miniature bridge profiles were fabricated of cement and are mounted on a steel frame that is decoupled from the flume to avoid the influence of vibrations of the channel. The bridge pier is made of wood. It is not force-locked with the bridge profile (3 in Figure 2) and it can be easily removed (4 in Figure 2).

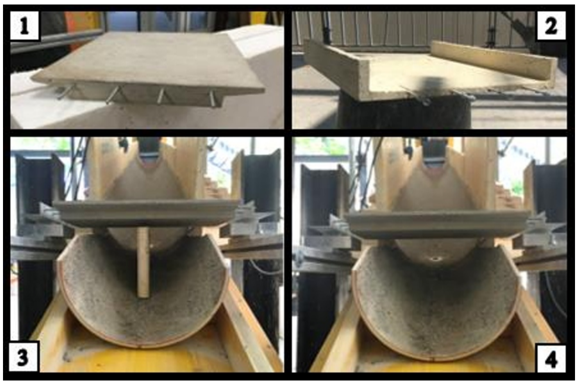

Fig. 2. Solid slab profile (1), trough profile (2), setup with pier (3) and setup without pier (4)

The debris-flow mixtures are based on previously conducted experiments [8], [9]. The total mass is kept constant at 50 kg and corresponds to a granular debris flow. The solid-fluid-ratio in terms of volume is 65:35 %.

A total of 20 experiments were carried out. There were five replicates in each setup: solid slab, solid slab with pier, trough, trough with pier.

Flow heights are measured at three locations with Baumer OADM 20I6480/S14F laser distance sensors. The flow velocity is estimated based on the passage time of the debris-flow front between the laser sensors 1 and 2 [9]. Additionally, pore water pressures are gauged with Keller 25Y piezoresistive pressure transmitters [10] below the laser sensors. The impact forces are measured with 3-axis force sensors (ME K3D120) at the left and right abutment of the bridge.

The signals are amplified by means of a Quantum MX1601B datalogger from HBM and postprocessed with the corresponding software Catman V5.3.2. 2400 Hz was chosen as basic measurement frequency. The logged signals were processed by applying a Butterworth lowpass filter, the cut-off frequency to differentiate the impact of single particles from the bulk impact was set at 10 Hz based on the consideration of flow velocities and the maximum grain diameter.

To compare the frontal impact forces of the four setups, we first acquired the maxima of the filtered forces in the horizontal (y) and vertical (z) direction (see 2 in Figure 1) by summing the forces of the left and the right sensor in each timestep and then reading out the maximum values F_{max,y_i} and F_{max,z_i} for each replicate i. The resulting maximum frontal impact force F_i was calculated with the following equation (1).

$$F_i = \sqrt{{F_{max,y_i}}^2 + {F_{max,z_i}}^2} \qquad (1)$$

The setup with the solid slab profile is set to be the base case. To enable an efficient comparison of the setups, all values were related to the median of the maximum frontal impact force of the solid slab $\widetilde{F_{\mathrm{bc}}}$ or base case (A) (eq. 2), yielding the dimensionless related frontal impact force F_{ri}, which will be analysed in more depth in next section.

$$F_{ri} = F_i / \widetilde{F_{bc}} \qquad (2)$$

3 Results and Discussion

Figure 3 shows the results within boxplots of the related frontal impact forces F_{ri} grouped by the investigated four setups: base case (A), base case + pier (B), trough (C) and trough + pier (D). Each group consists of five replicates, yielding a total of $n = 20$.

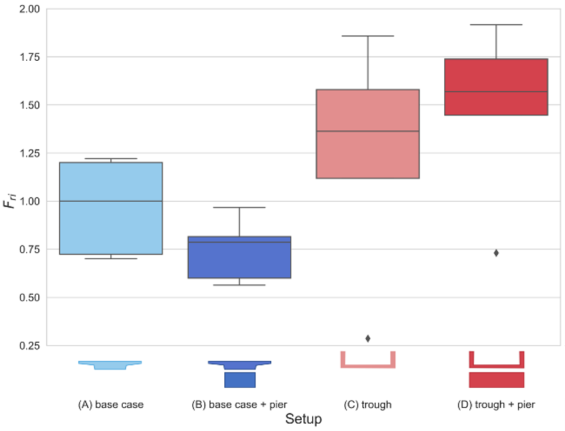

Fig. 3. Boxplots of related frontal impact force F_{ri} for the setups base case (A), base case + pier (B), trough (C) and trough + pier (D). $n_{total} = 20$, $n_{Setup} = 5$

We found that the median F_{ri} in setup (B) is about one quarter smaller compared to the base case (A). We assume that the pier in setup (B) influences the debris-flow dynamics in a way that material is dammed which reduces the flow velocity resulting in lower frontal impact forces. The comparison between (A) and (C) shows that the related forces for (C) exceed the forces in (A) by more than a quarter. Thus, we conclude that the profile of the superstructure has an influence on the magnitude of the frontal impact forces, which could be explained by the extent of the impact area.

The presence of the pier results in lower forces for the full slab bridge (B) and higher forces for the trough bridge profile (D). We suggest that this is caused by the absence of a cantilever at the trough profile, provoking a higher damming effect.

If we compare the pier-setups (B) and (D), we can see that the forces in (D) are much greater than in (B).

Again, this might be due to the impact area, which is larger for the trough profile.

4 Conclusion and Outlook

After conducting and evaluating 20 experiments with two different profiles and with and without a bridge pier, we can summarize that the forces are greater with the trough bridge setups (C) and (D) than with the base case setups (A) and (B). This may be attributable to the impact area. Furthermore, the pier seems to have an influence on the frontal impact forces, but the direction of the influence may depend on the profile as well as the position of the pier in relation to the bridge superstructure.

We plan to extend the test series to a total of five profiles in order to investigate the influence of the profiles even more closely. In addition, further tests may be carried out in the future to study not only the frontal impact forces, but also other potential force components such as uplift or frictional forces.

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