# Experimental study of the variability of sediment transport processes under outburst flood conditions in mountain streams

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## EXPERIMENTAL STUDY OF THE VARIABILITY OF SEDIMENT TRANSPORT PROCESSES UNDER OUTBURST FLOOD CONDITIONS IN MOUNTAIN STREAMS

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| **Author Comments:** | |
| **Response to Reviewers:** | Dear reviewers,<br><br>Thank you for your comments on this paper, which have helped me identifying weaknesses of the previous version.<br>I have notably included a discussion on other flume experiments to explain that, even if they technically are very similar to our own, differ in terms of objectives, and in that sense, are quite original and inevitably prospective (see notably the new introduction to the METHODS section).<br>This also stressed the necessity to explain better the specific features and related scientific challenges of outburst floods. I have tried to improve the paper that way. I notably tried to evidence that we focus more on triggering conditions than on flow propagation.<br>I also tried to evidence the specific challenge for practitionners dealing with potential outburst floods.<br>Parts which have been modified: abstract, introduction, methods, and conclusion.<br><br>Best regards<br>Dominique Laigle |

# EXPERIMENTAL STUDY OF THE VARIABILITY OF SEDIMENT TRANSPORT PROCESSES UNDER OUTBURST FLOOD CONDITIONS IN MOUNTAIN STREAMS

## ABSTRACT

To date, little is known on the features of sediment transport processes that can be triggered by an outburst flood for given field conditions. We present the results of 94 experiments carried out in a 5.0 m-long, 0.2 m-wide flume, mimicking the conditions of outburst floods on steep slopes, where water is suddenly released upstream of an erodible bed constituted of sand. Investigated slope gradients cover the range 1.7 to 38.0 %. Flow features are qualitatively analysed using pictures taken by video cameras. We emphasize analysis of the flow front features, and internal shear inside the flow. At gentle slope, the wave propagation is mainly constituted of water with limited sediment transport. When increasing the slope, a series of processes are evidenced, and lead to very concentrated rapid mass flows. We try to classify the observed flows in reference to well-known field phenomena. We finally suggest a continuum of sediment transport processes from bedload to debris flows.

## INTRODUCTION

Outburst floods in mountain areas result from many initiation processes like, for instance, the breaching of morainic or ice dams in glacial context when a periglacial lake has formed under the effect of climate change, or the sudden melting of huge quantities of ice, notably in volcanic context. They also result from the breaching of a natural dam, often following the clogging of a valley floor by a lateral landslide. They may also result from the collapse of a man-made dam whose number has drastically increased in Alpine environment over the last decades under the increasing need of water resources available for snow-making.

Outburst floods are, by nature, very unsteady flows generally propagating as a wave of water and sediment. Their intensity, notably in terms of peak discharge, is generally much higher than that of hydrological floods likely to occur in a given mountain stream catchment. It may even sometimes affect areas where no hydrological floods could occur. In Alpine environment, the presence of steep slopes and loose sediment, combined with the specific features of outburst floods can lead to very intense erosion and sediment transport processes, even catastrophic debris flows (e.g. Schuster, 2000 ; Laigle & Bardou, 2022).

To date, little is known on the features of sediment transport processes that can actually be triggered by an outburst flood for given field conditions. For the point of view of practitioners in charge of hazard

assessment and risk mitigation, such lack of knowledge leads to uncertainty on the kind of phenomena to be dealt with, and potentially to the risk of choosing inappropriate tools and methods.

The general objective of the present work is to try to reduce the uncertainty mentioned above. More precisely, we aim at prospectively analysing the features of sediment transport processes triggered by the sudden release of pure water upstream of a reach of erodible material. This work is carried out in controlled conditions in a laboratory flume and aims at establishing a typology of flow features, as well as evidencing the role played by parameters such as the slope gradient or the volume of water released.

## METHODS

Sediment transport processes have very often been studied in laboratory flumes, and the related scientific literature is abundant. However, a large majority of these experiments were carried out under conditions of constant or slowly varying input water discharge. Hence, not fully coherent with the very unsteady flows we aim to address. A famous example of experimental facility used to study flows triggered in dam-break conditions is the USGS debris-flow flume, notably presented by Major (1997). However, in these experiments, a mixture of water and sediment, and not only water, is released. Hence, once again not fully coherent with the study of sediment scouring and entrainment by clear water that we aim to address. To our knowledge, Spinewine & Zeck (2007), among other publications from this research team, have presented the most advanced experimental and modelling work on the propagation of dam-break waves on a moveable bed. However, their flume experiments were carried out only in flat or very gentle slope gradient flumes. Finally, we made the choice to adopt the same principle as the experiments by Spinewine & Zeck (2007), but to investigate a large range of slope gradients.

Our experiments are carried out in a 5 m-long and 0.2 m-wide flume (Figure 1) equipped with lateral glass walls. The flume is supported by a metallic structure that makes it possible to easily adjust the slope gradient from 0. % to 51.8 %. A tank with a capacity up to 0.35 $m^3$ is directly connected to the upstream extremity of the flume by a sluice gate. This sluice gate can be quickly opened, thanks to a pneumatic actuator, to release the water initially stored in the tank. A 0.08 m-thick layer of sand is deposited uniformly on the flume bottom over a 0.03 m-thick plastic grating to avoid sliding of the sand once the flume is inclined. A small vertical plate, 0.08 m high, is also placed at the downstream extremity of the flume to avoid sliding of the sand. A sill, parallel to the flume bed, is placed immediately below the sluice gate to avoid the possible direct impact of sub-vertical flows coming out of the tank. A tank located downstream collects water and sediment exiting the flume. We use some

63 calibrated sand with a size ranging from 0.5 to 2 mm. Additional analysis revealed that 16 % of this
64 sand is finer than 0.5 mm.

65 The set of devices used to characterize the flows is composed of ultrasonic distancemeters, the
66 downstream tank in which the sand exiting the flume is collected, and later dried and weighted, and 4
67 video cameras. Only qualitative observations carried out with these video cameras are presented
68 hereafter. 3 video cameras are located laterally and take pictures through the lateral glass walls. 1
69 video camera is located above the axis of the flume pointing downwards.

70

71 Figure 1 Sketch of the experimental device.

72 Considering the classical similitude based on the Froude number, these experiments can be reasonably
73 interpreted in the field considering a 1/25 geometric scale.

74 RESULTS AND DISCUSSION

75 94 experiments were carried out on 16 slope gradient values ranging roughly from 1.7 to 38. %, and
76 volume of water released ranging from 12. to 58. liters.

77 Experiments show common features independently of the slope gradient and volume of water
78 released:

79 - As the water is suddenly released from the upper tank, the propagation systematically exhibits
80 a wave front. However, the features of this front strongly vary from one experiment to
81 another, according to the quantity of sediment entrained.
82 - Considering the sediment transport, each experiment exhibits erosion of the mobile bed
83 upstream of the flume, followed by sediment transport, and then deposition of the sediment
84 downstream. The location of these two latter processes varies with the slope gradient and
85 volume of water released. Large quantities of sediment may exit the flume, and are then
86 collected in the downstream tank.

87 We analyze hereafter the evolution of the flow features versus the imposed experimental conditions,
88 which are mainly the flume gradient and volume of water released. The flow front features appeared
89 particularly relevant for this analysis. Their variability is illustrated in Figures 2 and 3. Additionally, the
90 variability of the internal shear inside the flow is illustrated in Figure 4.

On gentle slope (Figure 2-A, 5.12 %), the maximum flow thickness is 3 cm, and the mean velocity about 0.75 m/s. Only the water propagation can be visually identified. The sediment transport remains limited in an active layer located below the water layer. This can be seen for instance in Figure 4-A.

On Figure 2-B (8.55 %), the maximum flow thickness is 3 cm, and the mean velocity is about 0.5 m/s. The features of the propagation are similar to the latter, except the presence of a clearly visible cord of sediment, about 4 cm wide and 2 cm thick, located at the tip of the wave.

On Figure 2-C (20.88 %), the maximum flow thickness is 4 cm, and the mean velocity is about 0.35 m/s. A sediment front, about 3 to 4 cm thick, is present at the wave tip, but its volume remains limited (yellow arrow shows the length). This front is unstable in time and space. It takes the form of fingers where the sediment is pushed by the flow for a few seconds and then stops. Subsequently, the flow diverges and forms another finger with a different position along the flume width.

Figure 2 Shape of the flow front with slope gradient and volume of water released respectively: A/ 5.12 % - 58. l, B/ 8.55 % - 58. l, C/ 20.88 % - 26. l.

On Figure 3-A (24.56 %), the maximum flow thickness is 4.5 cm, and the velocity is about 0.26 m/s. Processes are somewhat similar to those observed in Figure 2-C, except that the volume of the sediment front is larger, and its instability in time and space has slightly reduced, compared to the latter. Sometimes, the water may overflow the sediment front.

On Figure 3-B (36.24 %), the maximum flow thickness is 8 cm, and the mean velocity is about 0.26 m/s. Most of the sediment is mobilized in a mass flow, with a long front (yellow arrow shows the length), up to 8 cm thick, which occupies the whole flume width. Furthermore, the front tip is followed by some visually homogeneous mixture of water and sediment, which is sheared over the whole flow thickness (Figure 4-B). The flow appears quite stable in time and space when compared to the flows presented so far.

On Figure 3-C (34.0 %), the maximum flow thickness is 3.5 cm, and the velocity is less than 0.1 m/s. In this case, conditions are similar to Figure 3-B, except for the volume of water released, which is less important. At the beginning of the experiment, a large front has formed as in the previous case, and stopped in the flume. Under the effect of the water still circulating inside the sediment mass, the front has slowly dislocated. Figure 3-C shows the front after dislocation.

Figure 3 Shape of the flow front with slope gradient and volume released respectively: A/ 24.56 % - 27. l, B/ 36.24 % - 28. l, C/ 34. % - 12. l, dislocation of the front.

Figure 4 shows the thickness (yellow arrow) and features of flows seen through the lateral walls. Except at the front tip, the flows previously presented in Figure 2 and Figure 3-A show features similar to Figure 4-A, with a basal layer of active sediment transport underneath a layer of almost clear water. The flow thickness varies according to the imposed experimental conditions, though. The thick sheared zone of visually homogeneous material presented in Figure 4-B appears as typical of mass flows and has been observed in a limited number of our experiments related to conditions given in Figure 3-B.

Figure 4 Thickness of the sheared zone with slope gradient and volume released respectively: A/ 28.33 % - 20. l, B/ 36.24 % – 28. l.

On slopes ranging from about 30. to 36. % were sometimes observed some kind of transitional flows where, within the same experiment, features of flows presented in Figure 3-A (non-homogeneous flow, with separate movements of water and sediment, as in all previous figures) and Figure 3-B (homogeneous mass flow), even Figure 3-C, could be observed alternatively.

Even though the previous presentation shows that the slope gradient greatly influences the features of our experimental flows and favor the development of mass flows, it must be noticed that each individual feature has showed up progressively. For instance, an unsteady front was sometimes observed in conditions where some mass flow was observed in a previous experiment, or dislocation was sometimes observed at relatively gentle slope. Consequently, it is quite difficult to establish a typology of flows with well-bounded categories. Only a fuzzy classification (not presented here) was possible, based on consideration and combination of several individual features (e.g. volume or stability of the front, material internal shear). This leads us to think that the different phenomena we have observed should be seen as a continuous evolution determined by a series of individual processes.

Our series of observations leads us to try to connect the features of our experimental flows to features of well-known field processes of sediment transport in mountain streams. We notably notice that, on gentle slope, our experimental flows look very similar to classical bedload transport. On slopes of the order of 30. to 36. %, many features related to debris flows (e.g. large and highly concentrated mass

flow showing internal shear) are present. According to the remarks of the last paragraph, any attempt to connect our experimental observations to categories of field phenomena can only lead to a tentative classification. Anyhow, we suggest the following classification based on the range of slope gradients that we investigated experimentally:

- [1.70 % ; 20.88 %]: bedload transport ;
- [20.88 % ; 28.32 %]: hyperconcentrated flow (e.g. Pierson, 2005)
- [28.32 % ; 36.24 %]: debris flow (e.g. Takahashi, 2014, Laigle & Bardou, 2022)

Inside these large domains, sub-domains can be identified showing slightly different features, which also seem influenced by the volume of water released:

- [8.55 % ; 20.88 %]: intense bedload transport
- [30.26 % ; 36.24 %]: immature debris flow (e.g. Takahashi, 2014)
- dislocation: over a large range of slope gradients

## CONCLUSIONS

Outburst floods in mountain areas result from many initiation processes, and are very unsteady flows generally propagating as a wave of water and sediment. Little is known on the features of sediment transport processes that can actually be triggered by an outburst flood for given field conditions, and for practitioners in charge of hazard assessment and risk mitigation, such lack of knowledge leads to uncertainty on the kind of phenomena to be dealt with. In order to try to reduce such uncertainty, we have carried out laboratory experiments mimicking the effect of outburst floods. The main objective of the present work was to study the variability of flow features under conditions of sudden release of water upstream of an erodible streambed, and their evolution versus series of factors including notably the slope gradient.

The 94 laboratory experiments we carried out have shown a large variability of flow features, ranging from rather diluted diphasic bedload transport to very concentrated, apparently monophasic, mass flows. These experiments have also evidenced a series of intermediate phenomena where instability in time and space is very often present. We have shown that, depending upon the slope gradient, our experimental flows showed features similar to phenomena classically observed in steep mountain streams, and described in the related scientific literature. We have evidenced the important role played by the slope gradient in the progressive evolution of flow features towards mass flows. However, it was not possible to establish a well-bounded typology of phenomena based uniquely upon

consideration of the slope gradient, and other parameters will require further investigation. Indeed, the global flow features appear as the result of a combination of individual processes, some of them becoming dominant according to the experimental conditions. This suggests a continuous evolution, and the existence of transitions between the rather well-known field phenomena – bedload, hyperconcentrated flows, debris flows - as they are defined in the current scientific literature.

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Figure 1



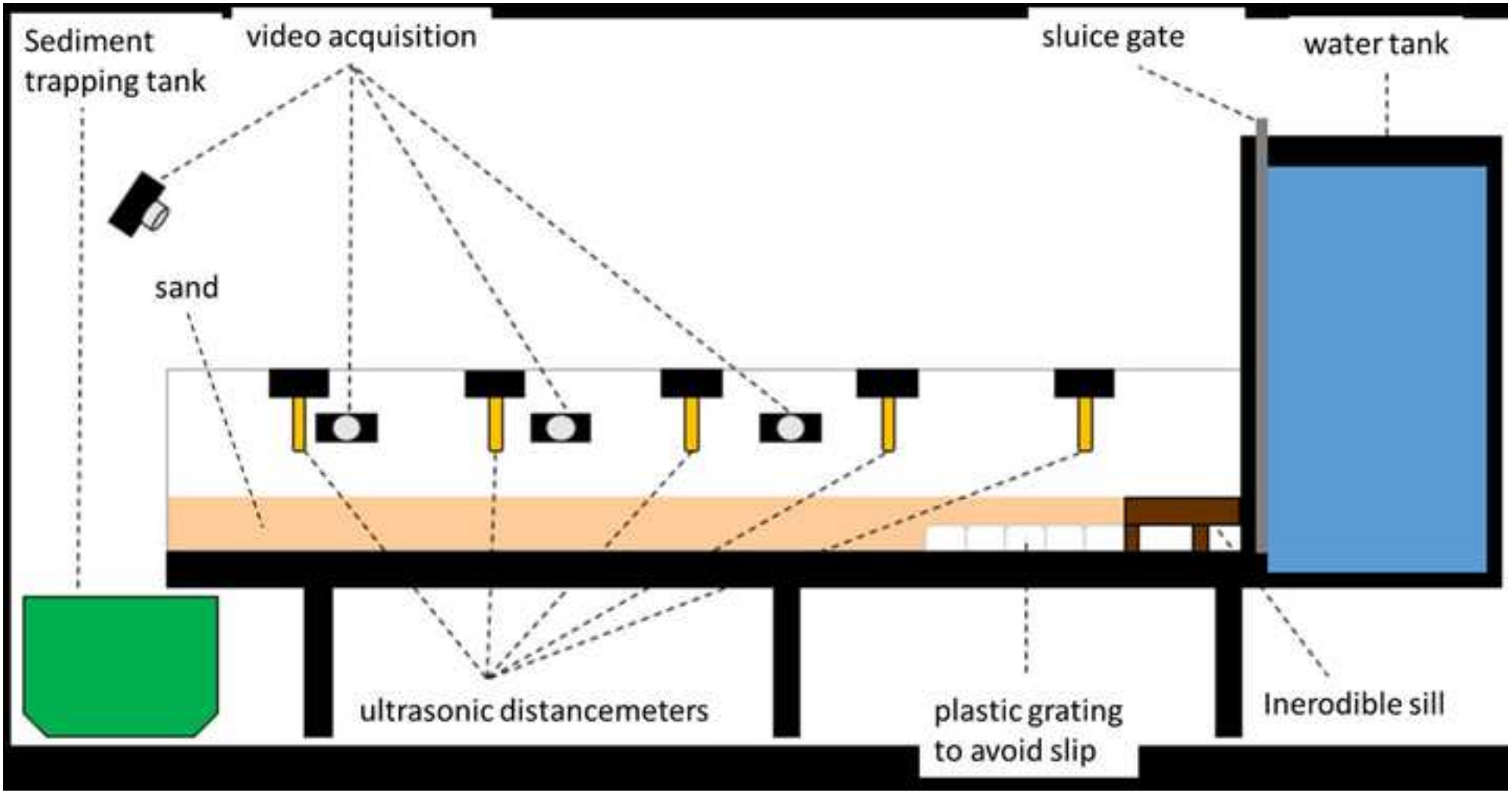

Figure 2



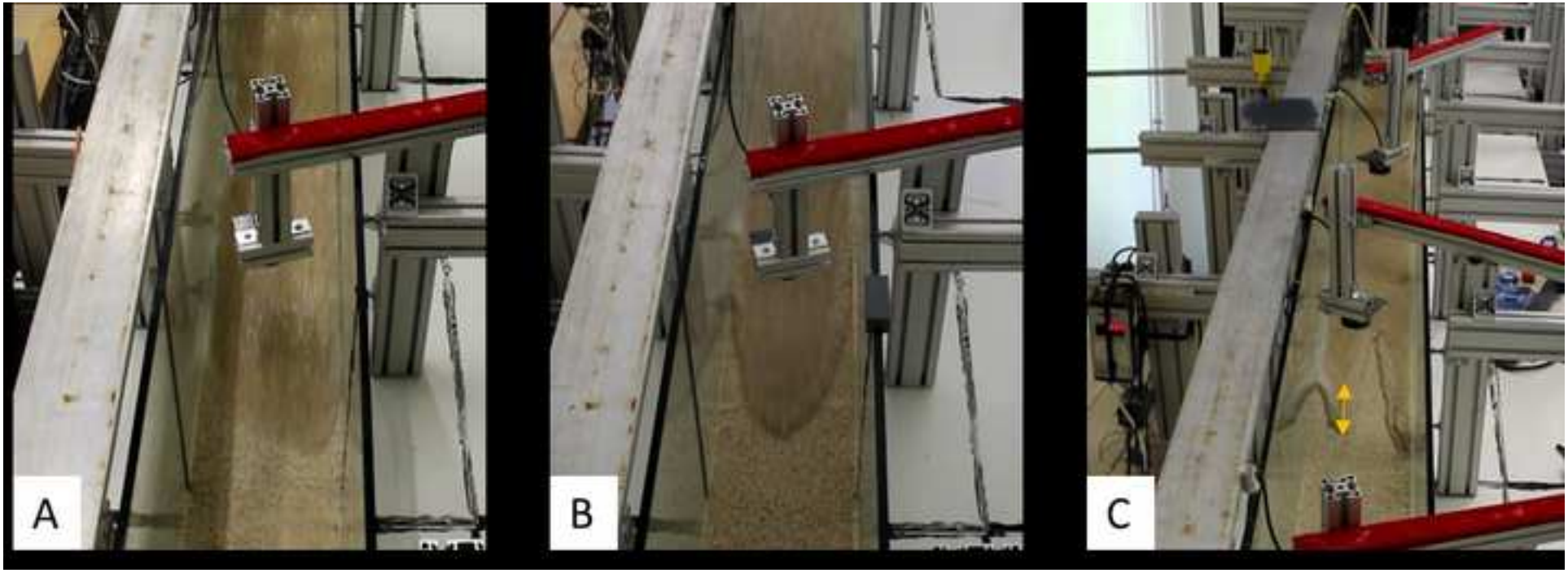

Figure 3

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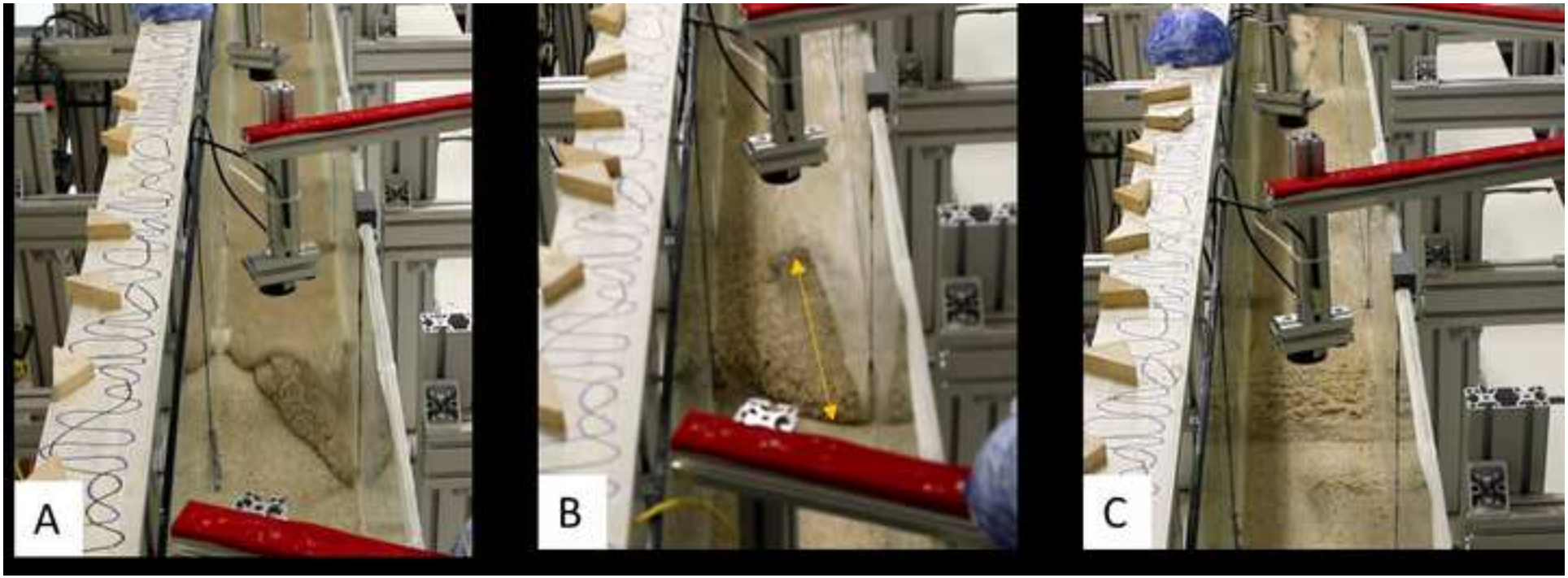

Figure 4

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