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Estimating the impact forces of rock avalanches on protective structures

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ABSTRACT: Climate change is contributing to an increased frequency and intensity of gravitational mass movements, including rock avalanches, landslides, and debris flows, which pose significant threats to settlements and critical infrastructure in alpine regions. Mitigation of these hazards often relies on the implementation of protective structures such as barriers, embankments, and deflection systems. The effective design of such structures requires a precise understanding of the physical processes and forces involved during impact events. However, direct measurements of impacts generated by large-scale mass movements are highly challenging due to the extreme forces involved, which frequently exceed the capacity of available instrumentation. Consequently, controlled small-scale model tests have become an essential approach for investigating these processes. Over recent decades, several research institutions across different countries have conducted experimental model tests to simulate and analyse the interactions between moving masses and protective structures under reproducible conditions. At the University of Innsbruck, a dedicated experimental facility enables systematic testing of various types of protective structures under simulated gravitational mass movement impacts. These tests allow for the assessment of dynamic load patterns, energy dissipation mechanisms, and structural deformation behaviour. The resulting datasets provide critical empirical input for the development of physically-based impact models, which in turn support improved design guidelines and enhance the reliability of protective measures. This research contributes to advancing hazard mitigation strategies in mountainous environments, ultimately supporting climate adaptation efforts and increasing the resilience of alpine communities and infrastructure to gravitational mass movement hazards.

KEYWORDS: Rock avalanche, Impact force, Protective structure.

1 INTRODUCTION

Cost-intensive protective structures are usually built to protect against flow-like mass movements. For the design of these structures, the impact must be determined as accurately as possible. Standards and regulations exist in Austria for debris flows (ÖNORM B 4800:2025) and for snow avalanche (ÖNORM B 4801:2024). For gravitational mass movements, such as rock avalanches, there are no standardised or regulations. Many authors e.g., (Ashwood and Hungr 2016, Ho, Koo, Kwan 2018, Ng, et al. 2017, Bugnion, et al. 2012) have published studies on the impacts on structures due to gravitational mass processes. These design recommendations often consider the static impact (p_{stat}) separately from the dynamic impact (p_{dyn}). The static impact can be calculated using Equation (1) and is based on the earth pressure theory using the factor (K).

$$p_{stat} = K \cdot h_{st} \cdot \rho \cdot g \tag{1}$$

The dynamic impact is generally based on the conservation of momentum and can be calculated with Equation (2).

$$p_{dyn} = \alpha \cdot \rho \cdot v^2 \tag{2}$$

In Equation (1) and Equation (2), (ρ) denotes the density, (g) the gravity (v) the velocity of the granular mass, (K) the earth pressure coefficient, (h_{st}) the static height of the granular mass in front of the barrier and (α) an empirical parameter. If the area of impact is considered, the forces (F_{stat}) and (F_{dyn}) can be determined from the pressures.

According to (ÖNORM B 4800:2025), the dynamic impact force (F_{dyn}) is expected to be greater than the static impact force (F_{stat}). This means that the dynamic impact force (F_{dyn}) is decisive for the dimensioning. Subsequently, the determination of the empirical factor (α) becomes important. In (Poudyal, et al. 2019), the recommended values for the empirical parameter (α) were published from different authors. Values for (α) in the range of 1.0 to 5.0 are recommended. Depending on the approach, the impact force (F_{dyn}) can therefore be 5 times higher. The published factors for the empirical factor (α) are primarily recommended for the impacts of debris flows.

As noted previously, in the case of gravitational mass movements such as rock avalanches, no standardized regulations or empirically derived parameters exist for estimating the impact forces acting on protective structures. Figure 1 illustrates the impact process, depicting the dynamic parameters of the moving granular mass, the resulting pressure on the protective barriers (example shown with a flexible net system), and the corresponding acting height.

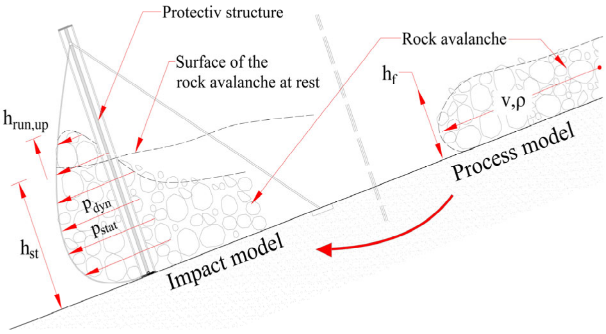

Figure 1. Representation of the rock avalanche for the process model and the impact model. The parameters of the impact model with velocity (v), density (**ρ**), and flow height (h_f). The parameters of the impact model with dynamic impact pressure (p_{dyn}) and static load pressure (p_{stat}), deposition height (h_{st}), and the height of the run up ($h_{run,up}$) from (Berger et al. 2024).

For this reason, extensive model tests were carried out at the University of Innsbruck to observe and measure the impact process resulting from dry granular masses on a barrier. For the model tests, the impacts on different types of barriers were examined.

2 METHODS

The model test at the University of Innsbruck consists of a reservoir, a flume base, side walls and different types of barriers. In general, the model test is made of galvanised steel. The side walls are made of acrylic glass. The flume base is approx. 3.2 m long and 0.325 m wide. Through the opening of the gate, the test material accelerates and collides with the different types of barriers at the end of the flume. With the model test of the University of Innsbruck, tests were carried out with inclinations (θ) between 20° and 40°. Higher inclinations result in higher velocities of the granular mass. The individual components of the model test are shown in Figure 2.

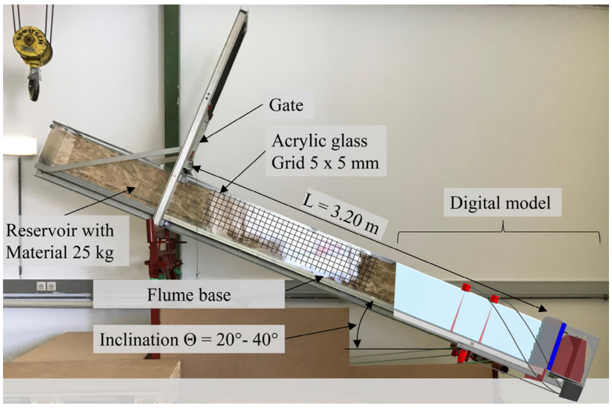

Figure 2. Combination of the digital and photo model of the small-scale laboratory experiment at the University of Innsbruck from (Berger et al. 2024).

By using different types of barriers, the influence of the barrier stiffness can be investigated. A steel plate was used as a rigid barrier. Three different materials (Net I, Net II and Net III) were used as flexible barriers. Net I have the stiffest behaviour. Net III has the most flexible behaviour. The embankment was constructed with a geogrid-reinforced net. The tree barrier Types can be shown in Figure 3.

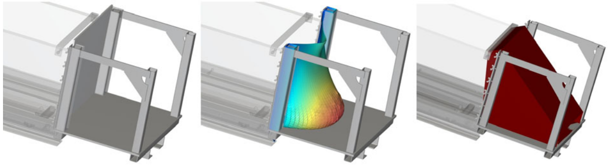

Figure 3. Illustration of the different types of barriers; left, rigid barrier consisting of a steel plate; middle, flexible barrier in the deformed position; right, reinforced embankment construction. All barrier types were fixed to the slide from (Berger et al. 2024).

For each model test, 25 kg of material were used. The test material used was sand, a mixture of sand and gravel (ratio 1:1), steel spheres and glass spheres. The steel and glass spheres have a diameter of 2 mm. The grain size distribution for the test material can be seen in Figure 4.

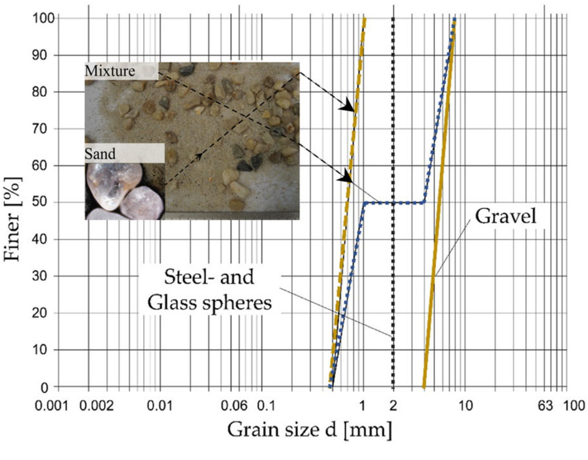

Figure 4. Grain size distribution of the test material, sand, gravel, the mixture and glass spheres, including an illustration of the grain shape.

The focus of the model tests from the University of Innsbruck is mainly on dry granular flow-like mass movements with high velocities, which occur during rock avalanches. The grain shape of the sand and gravel particles reflects a natural material. The model test series with steel spheres will not occur in nature in this way, but due to their geometrical almost perfect spherical structure and due to their high density, they are ideal for determining an upper bound of the impact force. By using different test material and by varying the inclination of the flume base in the model test, a deeper understanding of the movement of gravitational mass movements is gained. This forms a basis for the dimensioning of protective structures due to the impact of granular mass movements. Two optical distance lasers (Baumer OM70-L0600.HV0350) allow the measurement of the flow height and the velocity of the front of the granular mass. The force time impact on the barrier was measured using the load cell (HBM U10M/1,25KN). The entire test procedure was recorded with a total of 3 video cameras. In addition, the video recordings were used to determine the velocity of the granular mass using the software Kinovea. The front of the granular mass was marked in each frame, from the beginning to the end. As a result, the velocity over the entire process duration could be determined.

3 RESULTS AND DISCUSSION

The results of all model tests were published in (Hofmann and Berger, 2022, Berger, 2023 and Hofmann and Berger, 2023). In total, approximately 200 model tests were carried out. For the interpretations and conclusions from these tests, only the measurement results of the natural test material (sand and mixture) are used. Figure 5 shows the force – time diagram with a constant inclination (θ) of 30.2 ° for different types of barriers.

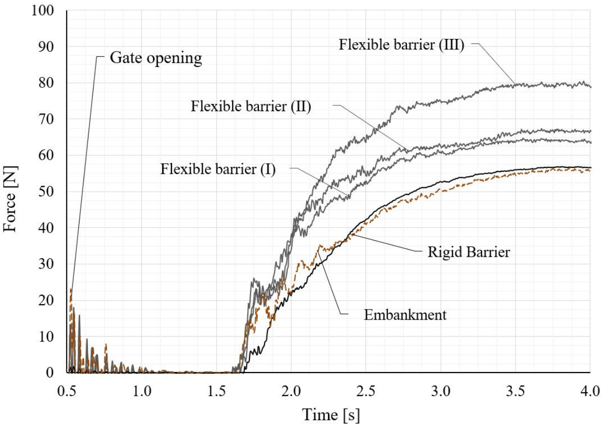

Figure 5. Force - time diagram for the rigid barrier, three different flexible barriers and the embankment.

The following findings result from the investigations with the model test of the University of Innsbruck and the natural test material (sand and mixture):

- When the earth pressure coefficient K_0 is used for K in Equation (1), the resulting static force F_{stat} is systematically underestimated. This highlights the need for appropriate calibration of K.
- Model tests with a flume base inclination of less than 38.8° (corresponding to velocities $v \leq 5.5$ m/s) show negligible differences between the measured static force F_{stat} and dynamic force F_{dyn} At these lower velocities, dynamic amplification effects are minimal. The conversion of model parameters to real-scale values can be done according to (Berger and Hofmann, 2022).

- The velocity v within the moving granular mass is not uniform; internal shear and particle interactions result in significant velocity gradients, which influence both the impact duration and the distribution of forces on protective structures.
- Increasing the flexibility of a barrier generally leads to higher measured impact forces from the granular mass (see Figure 5). This greater force in flexible barriers arises primarily from system deflection: the more a barrier deforms, the more material is retained within its structure during impact. This retained mass continues to exert pressure, resulting in an increased overall force. In contrast, rigid barriers tend to shed material onto the ground surface, with only the leading front of the flow exerting force.
- This conclusion applies specifically to impacts involving substantial volumes of granular material, such as rock avalanches. It should not be generalized to isolated rockfall events or impacts involving small amounts of material, where the flexibility of the structure generally reduces the impact forces.
- A greater amount of material also results in a longer impact duration on the protective structure compared to a single-block impact during a rockfall event. In such cases, structural flexibility does not have the same damping effect.

The mass movement of a rock avalanche shows a highly turbulent behaviour, which makes it very difficult to determine a representative velocity (see Figure 6). For the model test, the three video recordings and the measured values from the distance lasers can be used to determine the velocity.

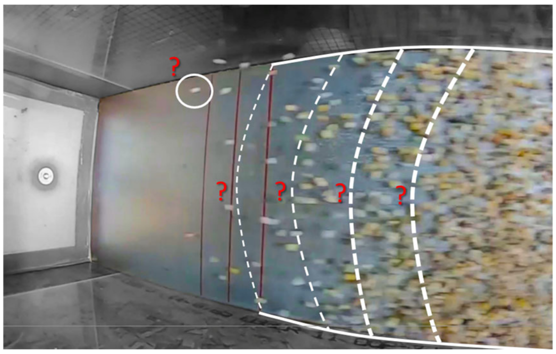

Figure 6. Snapshot from the video recording capturing the granular mass prior to impact with the barrier. The leading front of the granular mass lacks a distinct, well-defined boundary.

For real rock avalanches, it is only possible to estimate the velocity. Furthermore, the measurement results of the model tests, analogous to (Poudyal, et al. 2019), do not allow to determine a unique empirical parameter (α) for rock avalanches. Rather, the evaluations of the model tests show that it is necessary to create a design concept that is not influenced by the velocity (v) but considers the type of barrier.

4 CONCLUSIONS

Based on the findings of the model tests from the University of Innsbruck, an alternative design model was developed in (Hofmann and Berger 2023, Berger and Hofmann, 2024). This design model first determines the static impact (F_{stat}) based on the creep theory and a dimensionless factor ζ_s (see Equation 3 and Fig. 7).

$$F_{stat} = F_{g,red} \cdot \zeta_s \tag{3}$$

- $F_{g,red}$ = static force obtained from the adapted creep pressure theory (see Figure 6);
- ζ_s = static coefficient independent of the barrier type = 1.0 to 1.5;

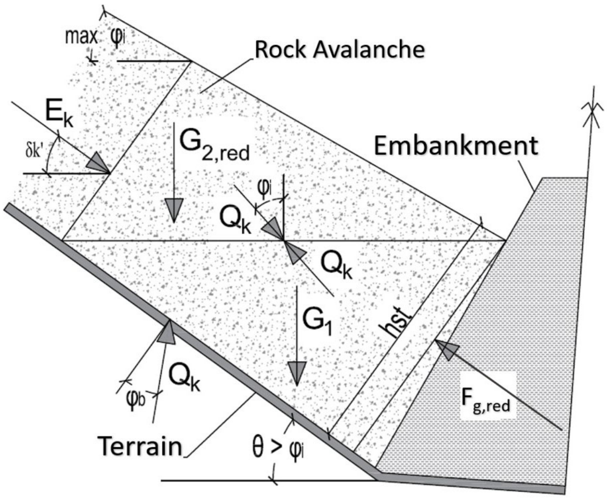

Figure 7. Force vectors of the creep pressure ($F_{g,red}$) (parallel to the transport plane) using the partial sliding bodies and considering the angle of bottom friction (φ_b) from (Hofmann and Berger, 2023).

The dynamic impact force (F_{dyn}) in Equation (4) can be calculated with the static force (F_{stat}) and the dimensionless factor (ζ_d). The dimensionless factor (ζ_d) considers the type of barrier. The upper bound of the dynamic coefficient (ζ_d) range, which varies with the barrier type, is obtained from back-calculation from the model test. Using the maximum value ensures that none of the test results exceed the force predicted by Equation (4).

$$F_{dyn} = F_{stat} \cdot \zeta_d \tag{4}$$

- ζ_d = dynamic coefficient depending on the type of barrier;
- ζ_d = 1.0 to 1.06 for embankment;
- ζ_d = 1.0 to 1.15 for rigid barrier;
- ζ_d = 1.0 to 1.30 for flexible barrier;

The advantages of the design model according to (Hofmann and Berger 2022) with Equation (3) and Equation (4) are in particular that the velocity (v) of the granular mass is not required for the determination of the impact. In contrast to the empirical dimensionless factor (α) of Equation (1) and Equation (2), the factors (ζ_s) and (ζ_d) of Equation (3) and Equation (4) have small ranges. If $\zeta_s = 1.5$ is used, no result from the model test gives a higher value for (F_{stat}) than calculated with Equation (3). In addition, Equation (4) considers the different types of protective structures.

With the model experiment of the University of Innsbruck, various studies are being investigated in relation to rock avalanches. In addition to the model tests, numerical calculations are carried out to record the measurement results in more detail.

In addition, with the numerical calculations, scaling effects between model tests and real events can be investigated (Berger and Hofmann 2022). In addition to developing a design model for the impact of rock avalanches on barriers of various types, the experimental results from the model tests provide valuable data for calibrating parameters in numerical simulations. (Berger and Hofmann, 2022) initially performed numerical back-calculations of the impact forces on a rigid barrier caused by idealized spherical steel particles, employing the Discrete Element Method (DEM) to replicate the physical interactions at the particle scale. Building upon this, subsequent simulations by (Berger et al. 2024) modelled the behaviour of a granular mixture impacting a flexible barrier using a fully three-dimensional DEM approach.

The calibration parameters obtained from these detailed numerical simulations serve as essential inputs for accurately representing material–structure interactions in numerical impact models. This calibrated numerical framework enables more reliable and precise simulations of real-world impact scenarios on protective structures, thereby supporting improved design and assessment of mitigation measures against gravitational mass movements such as rock avalanches.

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