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Review of the mechanisms of debris-flow impact against barriers

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Abstract

Our limited understanding of the mechanisms pertaining to the force exerted by debris flows on barriers makes it difficult to ascertain whether a design is inadequate, adequate, or over-designed. The main scientific challenge is because flow-type landslides impacting a rigid barrier is rarely captured in the field, and no systematic, physical experimental data is available to reveal the impact mechanisms. An important consideration in flow-structure interaction is that the impact dynamics can differ radically depending on the composition of the flow. Currently, no framework exists that can characterize the impact behavior for a wide range of flow compositions. This review paper examines recent works on debris-flow structure interactions and the limitations of commonly used approaches to estimate the impact load for the design of barriers. Key challenges faced in this area and outlook for further research are discussed.

Keywords: Debris flows, barriers, impact mechanisms, flow compositions,

1. Background

The Association of Geohazard Professionals (AGHP) is an industry association that was created in 2013 to support the development of standards, specifications, and best practices for the design and implementation of geohazard-related technologies and products; and to provide education to the geohazard community. The AGHP Debris Flow and Steep Creek Hazards Mitigation Committee (Committee) was formed in 2017 and currently includes members from North America, Asia, and Europe. The first committee workshop was held on June 3, 2018 in Canmore Alberta, Canada and included a discussion of the wide range of design guidelines that are available. The Committee recognized that design practices for debris-flow mitigation structures vary between different world regions, and some aspects of practice are not well described in the existing guidelines. This paper is a collective effort by AGHP members and focuses specifically on current understanding of debris-flow impact mechanism against barriers.

Steep creek flows made of mixtures of soil, rock and water, surge downslope at high velocities. These flows include floods, hyper-concentrated flows, debris flows, and rock avalanches (Hungr et al., 2014). To mitigate these hazardous flows, rigid barriers (e.g., Takahashi, 2014) and flexible barriers (e.g., DeNatale et al., 1999; Wendeler, 2008; Bugnion et al., 2012) are commonly installed in the predicted flow paths. Correspondingly, a reliable estimate of impact load is required to design these barriers. However, current design approaches for estimating impact loads relies heavily on empiricism and do not explicitly consider the composition of the flow, including the particle size and the ratio of solids

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to fluids. Such approaches make it difficult to ascertain whether a barrier design is robust, inadequate, or over-designed.

Our present knowledge in this area is deficient for three main reasons. First, debris flows impacting structures are rarely captured in the field. Second, debris flows are scale-dependent phenomena (Iverson, 1997; Zhou and Ng, 2010). More specifically, small-scale physical experiments (e.g., Canelli et al., 2012; Scheidl et al., 2013) cannot holistically model the absolute stress state in a granular assembly, the timescale for pore pressure dissipation, and the degree of viscous shearing observed in prototype flows (Iverson, 2015). To capture the granular and fluid stresses in real flows more holistically, centrifuge model tests (Bowman et al., 2010) or large-scale physical experiments are necessary (Iverson, 2015). Third, depending on flow composition, specifically the ratio of solids to fluids (Iverson, 1997; Iverson and George, 2014) and particle size (Faug, 2015; Song, 2016; Song et al., 2017a and 2017b), the impact dynamics of debris flows can vary drastically. A framework that characterizes the impact mechanism of debris flows by considering a wide range of flow compositions—solid-fluid interaction and particle size effects—is necessary to make reliable estimations of the impact load.

2. Impact Models

Current opportunities for advancing our understanding of the impact mechanism of debris flows are reflected in international guidelines (VanDine, 1996; MLR, 2006; NILIM, 2007; Kwan, 2012). An estimate of impact force exerted by debris flows, assuming continuum-like behavior, is based on force equilibrium in hydrostatic models and momentum conservation in hydrodynamic models. Another type of loading that needs to be considered is discrete loading, which is created by short duration impulses from large particles (Ng et al., 2018). Existing approaches for estimating loading are discussed below.

2.1. Continuum loading

Continuum-based approaches adopt empirical coefficients to account for various uncertainties, including unknown impact mechanisms and flow composition. For example, the momentum-based equation for estimating impact (Hungr et al., 1984; Kwan, 2012; Volkwein et al., 2014) is given as follows:

$$F = \alpha \rho v^2 h w \tag{1}$$

where α is the empirical pressure coefficient, ρ is the bulk density, v is the impact velocity, h is the flow thickness and w is the channel width. Clearly, flow composition is not explicitly considered in equation 1, and α accounts for the complexity of variables involved in natural geological material and natural settings. To highlight the empiricism of equation 1, a literature review shows that α values are not consistent (Table 1). For example, α of 3.5 is recommended for less viscous flows and 1.0 to 5.3 for more viscous flows (Scotton and Deganutti, 1997). Thurber Consultants Ltd. (1984) recommended α value of 3 to 5 for flow compositions in Austria and Switzerland. Kwan (2012) recommended α values from 2.0 to 2.5, depending on the type of structural countermeasure. Sovilla et al. (2016) demonstrates that the dimensions of the structure also fundamentally influence the impact pressure. Clearly, a scientifically based approach is urgently required to characterize the impact behavior for a wide range of debris flows.

Table 1. Summary of hydrodynamic models for estimating debris flow impact on a rigid barrier

Pressure coefficient (α)	**Reference**
α = 1.0	VanDine (1996)
α = 3.0 to 5.0	Zhang (1993)
α = 1.0 for circular structure α = 1.3 for rectangular structure α = 1.5 for square structure	MLR (2004)
α = 2.5 to 3.0	Lo (2000), Kwan (2012)
α = 2.0	Vagnon and Segalini (2016)
α = 1.5 to 5.5	Canelli et al., (2012)
α = 2.0 to 4.0	Hübl and Holzinger (2003)
α = 1.0	NILIM (2007)
α = 1.0	SWCB (2005)

Ancey and Bain (2015), Faug (2015), Ashwood and Hungr (2016), and Song (2016) all suggest that to more appropriately characterize impact, both static and dynamic loading must be explicitly considered as follows:

$$F = 0.5k\rho g(\beta h)^2 w + \alpha' \rho v^2 hw \quad (2)$$

where α' is the coefficient for dynamic effect only, k is the coefficient for static effect only, and β is the ratio between the height of the static deposit and flow thickness before impact. Song et al. (2017b) further characterized the pressure coefficient to represent both dynamic and static loading with clearer physical meaning as portrayed by the following relationship:

$$\alpha = \frac{\kappa' \beta^2}{2} \frac{1}{F_r^2} + \alpha' \quad (3)$$

where F_r is the Froude number ($v/\sqrt{gh}$). The F_r is characterised by the ratio of inertial to gravitational forces of flow-type landslides in an open channel flow (Hübl et al., 2009; Choi et al., 2015a).

2.2. Discrete loading

Discrete loading is generated from large particles entrained in debris flows. These particles exert a concentrated impulse that can destroy structures in the flow path. To capture discrete loads exerted by these large particles, the Hertz equation is often used in design guidelines (Lo, 2000; NILIM, 2007; Swiss Federal Road Authority, 2008). The impact force calculated based on the Hertz contact theory (Johnson, 1985) assumes an elastic impact scenario which is given as follows:

$$F = \frac{4E}{3} R^{\frac{1}{2}} (x)^{\frac{3}{5}} \quad (4)$$

where E is the effective modulus of elasticity, which is given as $1/E = (1 - {\nu_1}^2)/E_1 + (1 - {\nu_2}^2)/E_2$ (subscripts 1 and 2 denote parameters relating to the barrier and boulder, respectively) and ν is the Poisson's ratio. R is the equivalent radius, which is given as $1/R = 1/R_1 + 1/R_2$, (R_1, R_2 are the radius of curvature of contacting bodies) and x is the deformation, which is given as follows:

$$x = \frac{15mv^2}{16ER^{\frac{1}{2}}} \quad (5)$$

where, m is the mass of boulder and v is the impact velocity.

Kwan (2012) introduced a modified version of Eqn. 4 for design to estimate the impact force between a granite boulder and a reinforced concrete rigid barrier. The equation is given as follows:

$$F = K_c 4000 v^{1.2} R^2 \quad (6)$$

where, K_c is a load-reduction factor, v is the velocity of the boulder and R is the radius of the boulder.

A fully elastic solution is generally believed to be over conservative (Hungr et al., 1984; Lo, 2000; Sun et al., 2005). Therefore, a load-reduction factor K_c was introduced. This factor is empirical and recommended values vary in the literature (Table 2). Equation 6 is for a single boulder and an equation that can capture the mechanics of a cluster of boulders impacting a surface simultaneously remains a crucial scientific challenge that needs to be addressed.

Table 2. Summary of Hertz equations for estimating boulder impact load on rigid barrier

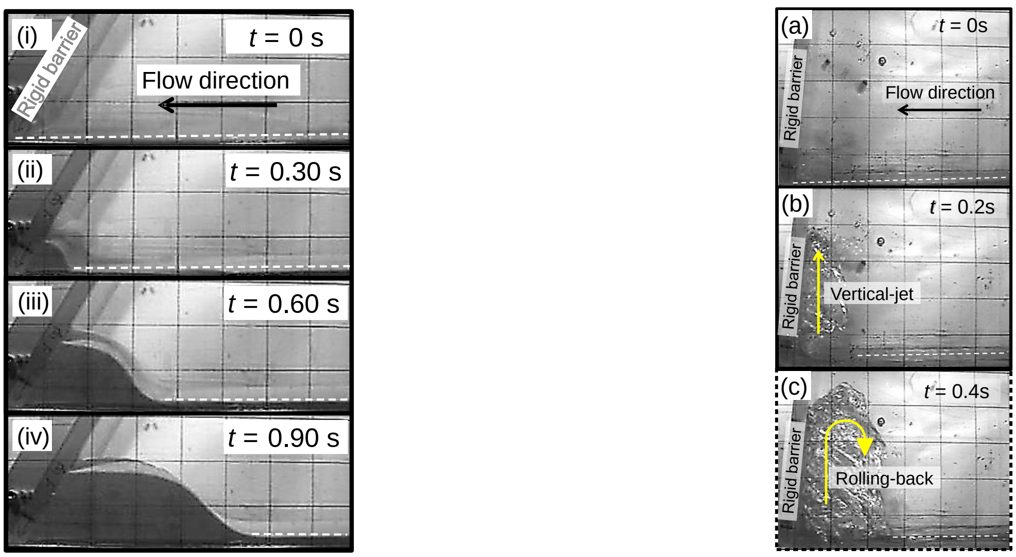
Load reduction factor Kc	Reference
K_c = 0.1	Lo (2000)
K_c < 0.1	NILIM (2007)
0.2 < K_c < 0.5	SWCB (2005)

3. Impact Mechanisms

Equation 2 is convenient for engineering design, but fails to explicitly capture the key mechanisms of impact observed in physical experiments. These key mechanisms include the accumulation of static deposits called ‘dead zones’ (Chanut et al., 2010; Faug et al., 2009, 2011, 2012 and 2015; Choi et al., 2017), the pile-up of highly frictional flows (Koo et al., 2016) or the vertical-jet-like behavior of viscous flows (Choi et al., 2015a). Physical experiments have demonstrated that the impact mechanism strongly influences the impact load, and consequently the load distribution along a structure (Song et al., 2017a). As such, more details pertaining to impact mechanisms in two most extreme types of geophysical flows: dry granular flow and water flow are discussed below.

3.1. Pileup and vertical-jet mechanisms

To illustrate how the impact mechanism is governed by flow composition, let us consider two of the most extreme types of geophysical flows, specifically dry granular flow and water, impacting a rigid barrier. A dry granular flow is highly frictional with air as the interstitial fluid, which has a low viscosity and plays a relatively insignificant role in regulating the flow dynamics. Instead, frictional and inertial grain stresses dominate. Choi et al., (2015a) demonstrated that when a dry granular flow composed of Leighton Buzzard (LB) fraction C sand with uniform grain diameters of about 0.6 mm, impacts a rigid barrier, a pileup mechanism develops (Fig. 1a).



(a) (b)

Fig. 1 (a) Observed pileup impact mechanism for supercritical dry sand impacting an orthogonal barrier (b) Observed vertical-jet mechanism for supercritical water flow impacting a vertical barrier installed along a channel inclined at 5º (redrawn from Choi et al., 2015a)

This mechanism exhibits a rapid attenuation of flow kinetic energy from the high degree of enduring frictional contacts between grains and their boundaries. Furthermore, a granular material with angular grains, such as sand, exhibits a high degree of bulk compressibility, assuming fragmentation does not occur. This feature is controlled by the changes in void ratio from elastic shear distortions of angular grain contacts (Iverson, 2015). High compressibility leads to bulk deformation during impact through shearing between grains, which is a very effective dissipater of flow kinetic energy compared to viscous shearing contributed by the interstitial fluid (Choi et al., 2015b). The properties of dry sand therefore inherently limit accretion along the free surface upon impacting a barrier. Instead, bulk deformation, for F_r within the transitional range (Faug, 2015), leads to the development of a granular bore that propagates or piles-up along the upstream direction in the channel.

Compared to dry granular flow, water exhibits a vertical-jet mechanism upon impact if the initial F_r conditions are supercritical (Armanini, 1997; Choi et al., 2015a). This impact mechanism is characterized by the redirection of flow vertically along the barrier (Fig. 1b). A vertical-jet mechanism develops because the inertia of the flow is significantly larger than the restoring gravitational field, which is responsible for 'pulling' the flow towards the channel. The obvious transfer of flow momentum in the vertical direction for water, compared to dry sand, is because less flow kinetic energy is lost during the impact process. The energy loss is only limited to viscous shearing of the fluid and shearing along its boundaries (Choi et al., 2015b). The effects of viscous shearing in the dissipation of flow kinetic energy is less significant compared to enduring frictional-grain stresses in dry sand. Furthermore, water, has a relatively low bulk compressibility compared to that of dry sand. This lower bulk compressibility promotes run-up upon impact in the only unconfined boundary within a channel, and that is the free surface. By contrast, dry granular flow can compress along the slope-parallel direction during impact and can also pileup towards the free surface of the channel.

Aside from the flow composition, the dynamics of channelized flow, specifically the F_r before impact also strongly influences the resulting impact mechanism (c.f., equation 3). Physical model tests have already demonstrated that water in supercritical flows exhibit a vertical-jet mechanism. By contrast, water in subcritical flow exhibits a reflective-wave mechanism upon impacting a rigid barrier. This mechanism can be characterized by limited transfer of momentum along the vertical direction or free-surface of the channel, the flow impacts the barriers and is allowed to reflect back upstream. Any disturbance to the flow in the channel, such as the barrier, will transfer energy as a wave. The flow inertia for subcritical flows is less than the restoring gravitational field. Therefore, a reflective-wave mechanism is exhibited for subcritical flows. For granular flows, the F_r of the flow before impact strongly influences whether gravitational or inertial effects are dominant (Faug, 2015; Sovilla et al., 2016).

4. Flow composition effects on dynamic response

4.1. Solid-fluid interaction

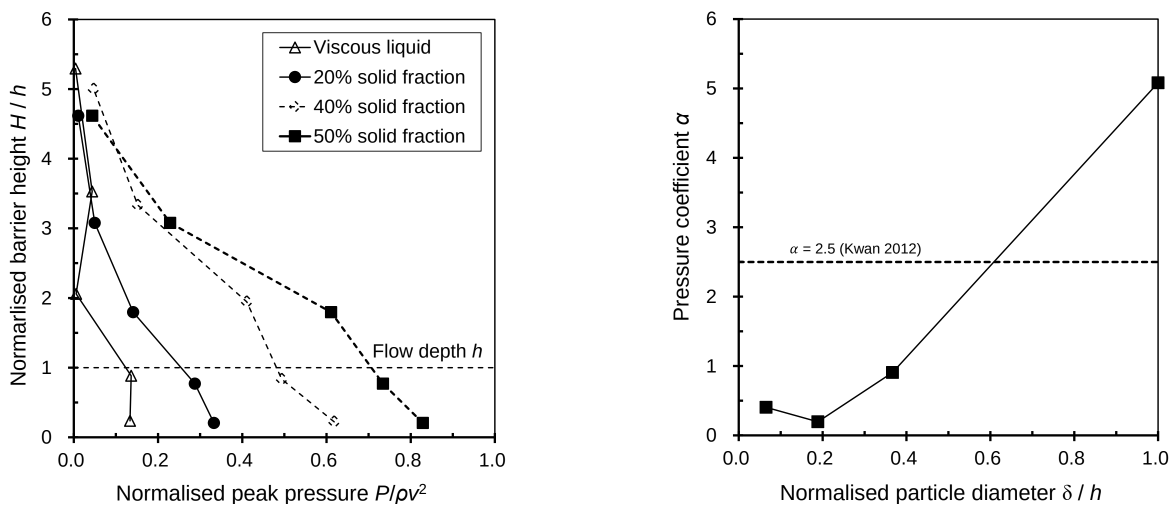
The complex flow dynamics of debris flows are governed by the interaction between the solid and the fluid phases. Solid-fluid interactions control the changes in the pore fluid pressure, which in turn regulates the Coulomb friction within and at the boundaries of a landslide (McArdell et al., 2007; Iverson and George, 2014; George and Iverson, 2014). The degree of interaction between the solid and fluid phases in the flow can be represented by the solid fraction, or the proportion of solids to fluids by volume (Cui et al., 2015). Flows with a higher solid fraction more readily dissipate flow energy by shearing between grains (Choi et al., 2015b).

Although a great foundation has been established for the structural response of different types of barriers (DeNatale et al., 1999; Wendeler et al., 2006; 2007; Kwan et al., 2014), there remains a knowledge gap on how different flow types can result in very different impact loads. To remedy this gap in the literature, Ng et al., (2016a; 2016b) and Song et al., (2017a; 2017b) carried out a set of centrifuge tests to model the impact mechanisms of debris flows, dry sand and viscous flows, with varying flow composition, on rigid and flexible barriers. Depending on the flow composition, the impact behavior differed drastically. For dry granular flows, the dissipation of the flow kinetic energy was significantly enhanced via stress-dependent friction, unlike viscous flows, which dissipated the flow kinetic energy less readily.

As discussed, a dead zone is useful for attenuating the impact load on an obstacle or barrier, but it can also contribute to the overall load acting on a structure. Song et al., (2017b) carried out a series of centrifuge experiments modelling the impact of two-phase flows on a rigid barrier. In these experiments, the solid fraction was progressively increased from 0 to 0.5. As expected, as the solid fraction increased, particle image velocimetry analysis (White et al., 2003) showed large dead zones. The larger the dead zone observed, the higher the resulting peak impact load measured on the barrier. These findings confirmed that the impact process for two-phase flows is as much a dynamic process as it is a static process. The higher the solid-fraction in the flow, the more pronounced the dead zones. These deposits in turn augment the overall load acting on the orthogonally-configured barrier (Fig. 2a).

4.2. Influence of particle size

Another important feature that adds to the complexity of investigating the impact mechanisms of debris flows is the effects of particle size. Song (2016), Song et al., (2017b), and Song et al., (2018) demonstrated that as the particle size increases, more discrete loads with higher magnitudes are generated. The impact dynamics resulting from large glass spheres differ significantly from dry sand or a two-phase mixture, with the same equivalent volume and F_r conditions before impact. Dry sand exhibits a progressive loading pattern to its static state without an obvious dynamic peak or sharp impulses. The two-phase mixture, however, exhibits a continuous loading behavior, which reaches its peak load before softening towards a static state. The two-phase mixture is fluidized and takes a longer time to reach a static state because of a lack of shear resistance in the flow. Clearly, a comparison of the different flow types highlight the distinct loading pattern exerted by a cluster of large particles compared to dry sand and two-phase flows.



(a) (b)

Fig. 2 (a) Influence of solid fraction on dynamic response of rigid barrier (redrawn from Song et al., 2017b) (b) Effects of particle size on dynamic response of rigid barrier (redrawn from Song et al., 2018)

A comparison of the loading time-histories with existing impact models show that both the dry sand and two-phase mixture are bounded by the superposition of both equations 2 and 3. However, the cluster of glass sphere, resembling a bouldery flow, generates sharp impulses that exceed the superposition of equations 2 and 3. These results indicate that the entrainment of large and hard inclusions in debris flows warrants consideration in the design of structural countermeasures, to safeguard against local damage.

To further investigate the effects of particle size, the performance of the hydrodynamic approach, based on different normalized particle sizes was investigated (Song, 2016). The peak loads were compared (Fig. 2b), and results showed that continuum-based mechanics (equation 3) fail to capture sharp impulse loads at a normalized particle size of 22 mm, based on the recommended dynamic coefficient of 2.5 (Kwan, 2012). Although a solution for capturing the impulse loads for a cluster of large particles was not provided, test results help to evaluate the current impact models for discerning the effects of particle size. A crucial challenge remains to account for impulse loads from a cluster of large particles and to distinguish what particle size is generating impulses that cannot be captured using continuum mechanics (equation 3).

Sharp impulses can be attenuated by increasing the contact time between a particle and a surface. Depending on overall stiffness of a structure, the effects of particle size can diminish. For instance, flexible barriers were originally adopted for capturing rock fall and have been adopted for resisting debris flows in the past decade (Kwan et al., 2014). Another approach for attenuating sharp impulses is to install cushioning materials in front of rigid barriers to diminish these loads (Ng et al., 2017).

5. Summary

Examination of the current state of research on the impact mechanisms of debris flows is presented in this paper. This study highlights the importance of considering the composition of a debris flow to assess the resulting dynamic response and impact mechanisms induced on a rigid barrier. Some key aspects from this review paper is summarized as follows:

1) The effects of the particle size are manifested in the inertial grain stresses of the flow during impact. As the particle size increases, the debris-flow transitions from contact-dominated (continuum) to inertial-dominated (discrete) grain stresses. The larger the particle size, the higher the magnitude and number of sharp impulses that are induced on a barrier.
2) The effects of solid-fluid interaction, specifically the ratio of solids to fluids dictates the force exerted on a barrier.

The higher the solid fraction, the more predominant grain-contact stresses are, thereby inducing higher static loads on the barrier during impact.

3) The flow type governs the mechanism of impact on rigid barriers. Granular flow, which consist of angular grains, readily dissipate flow kinetic energy through enduring shear contacts between grains and deformation from its high bulk compressibility. By contrast, inviscid flow does not readily dissipate flow kinetic energy from internal viscous shearing and viscous shearing along its boundaries. The ratio of inertial to gravitational forces before impact dictate the impact mechanism. These mechanisms are critical for discerning the design load and distribution on barriers.

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