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Modelling flow-landslides impact against protection structures

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Abstract. Dynamic impact of flow-like landslides against protection structures calls for a sound understanding of the interaction mechanisms. In fact, despite a large variety of flow-landslides, there is also a significant availability of several types of protection works and many different modelling approaches, which have been customized to the specific classes of flow-landslides and protection structurers. Some remarks are reported below in a design-oriented engineering framework.

1 Introduction

Independent on the landslide type, the site-specific geo-environmental context and the triggering mechanisms always play a role. Among the most destructive gravity-driven mass movements there are flow-like landslides, which can be mainly grouped in two main classes: i) channelised and ii) unchannelised. The former ones are controlled by both slope morphology and soil properties, while the latter ones can be even more complex as the propagation path itself is the outcome of the propagation mechanisms. Another key issue concerns the presence (or not) of boulders and the amount of rock debris. In fact, the impact of boulders against protection structures is highly destructive. On the other hand, the propagation of so-called flowslides is typically related to the features of the landslide body formed by liquefied soils. Even more, the case of recurrent phenomena (e.g., annual or seasonal debris flows inside the same channel or ravine) must be distinguished by those cases of first-failure landslides, which occur and propagate only once in a given area.

The previous differences are fundamental for: i) the type of usable protection structures, ii) the landslide-structure interaction mechanisms.

2 Protection works and mechanisms

In many cases, the use of control works is one of the few landslide mitigation options usable to protect structures and infrastructures. Sometimes, the protection works are instead part of a more comprehensive landslide risk mitigation strategy including hazard/risk zoning, slope stabilization interventions and early warning systems.

Many of the mitigation measures are designed to intercept and contain landslide debris in order to provide protection to developments on slope or at hill toes. It entails landslide resisting barriers and debris straining structures. On the other hand, some of the mitigation measures regulate the landslide debris runout process e.g., impediments along landslide debris flow path which aim to achieve dissipation of debris kinetic energy and to promote deposition of landslide debris.

According to this rationale, landslide risk mitigation measures can be classified into two groups: i) flow control measures and ii) protection measures. The first group includes: transport channels, check dams, debris flow impediment and straining structures, grill structures, deflection structures, among others. the second group contains, for instance, debris-resisting barriers, debris retention basins, debris flow sheds. A complete description of those several options is available in the scientific literature, while some remarks are provided below especially with reference to the landslide-structure interaction mechanisms.

In fact, it is useful stressing that flow control measures are engineering works constructed on the landslide propagation path and they aim to regulate the landslide debris runout process. Particularly, those works are used to retard the rate of debris transportation and reduce the active volume of the landslide debris. Conversely, protection measures are usually constructed at hill toe, and they are expected to retain some/all the landslide debris and to prevent damages to development.

The landslide-structure interaction mechanisms are intimately related to the type and geometry of protection work. (1) For instance, transport channels must ensure the passage of debris surges down a pre-determined path, without blockage or overflowing (Hungr et al, 1987; Kang, 1996). (2) On the contrary, check dams allow stormwater flow, as well as drainage of water from the solid material entrapped behind the dam. (3) Interestingly, built as array of columns, the baffles are often used to spread the flow (Cosenza et al, 2006) or behind a debris-resisting barrier as a sacrificial structure to screen out boulders for design robustness (Kwan et al, 2018). (4) Debris-straining structures are measures with openings designed to trap stony landslide debris, including boulders, from a debris flow. Examples are slit-, cell-, or grid-structures. (5) On the contrary, “dewatering screens”, which are horizontal grill

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structures, allows the draining of the debris to slow it down and consequently promotes debris deposition through consolidation. (6) Deflection structures are used to divert debris flows away from the highly vulnerable areas towards a less steep topography, where the debris runout velocity reduces, and debris deposition is initiated. (7) Debris-resisting barriers are generally constructed near the distal end of a drainage line as a terminal barrier in order to minimize the run-up height and debris impact loading on the barrier. Rigid barriers (typically concrete dams or earthfill embankments) can resist high impact load from the debris. Flexible barriers are instead built using steel wire nets and are subject to large deformation when they intercept landslide debris. (8) Debris retention basins are usually constructed at the deposition zone where the ground profile is relatively gentle, and a sufficient area is available for debris flow to slow down and deposit.

3 Modelling approaches

Numerical modelling is the most used option to tackle the analysis of Landslide-Structure Interaction (LSI).

Examples of Discrete Element Method (DEM) are reported by Leonardi et al. (2016), Calvetti et al. (2017) and Shen et al. (2018) or continuum mechanics models based on Eulerian methods (Moriguchi et al. 2009), Lagrangian particle-based methods such as Smoothed-Particle Hydrodynamics (SPH) (e.g. Bui and Fukagawa 2013), Particle Finite Element Method (PFEM) (e.g. Idelsohn et al. 2006), Finite Element Method with Lagrangian integration points (FEMLIP) (e.g., Cuomo et al. 2013), Material Point Method (MPM), (Ceccato et al., 2018) or coupled Eulerian-Lagrangian methods (Jeong and Lee 2019).

Several other numerical methods exist since years (Rabczuk and Belytschko, 2004) and meshfree methods are becoming very popular. However, the solid-fluid hydro-mechanical coupling and the role of the interstitial fluid in the landslide-structure interaction have been considered only in recent times. For instance, the impact behaviour of saturated flows against rigid barriers was simulated through MPM analyses of centrifuge test results (Cuomo et al., 2021a).

Analytical models have been also used to investigate the LSI for various cases. Yong et al. (2019) proposed an analytical solution for estimating the sliding of a barrier under the impact of a boulder. In this case, the colliding bodies are both assumed as rigid, and the impact is studied through the elastic collision principles. However, such method cannot be applied for instance to the case of a flow-like landslide impacting a Deformable Geosynthetics-Reinforced Barrier (DGRB), i.e., an embankment made of coarse-grained soil layers reinforced by geogrids (Cuomo et al., 2020b). Li et al. (2021) proposed an analytical model to estimate the peak impact pressure that a debris flow exerts on a rigid barrier. Such model has the strength of being validated by data encompassing a wide range of distinct flow regimes, relative to real-scale observations of debris flows, small-scale experiments and recent coupled CFD-DEM simulations. Song et al. (2021) obtained an analytical model for evaluating the deflection of a flexible barrier (a net fixed to the ground) through the validation against experimental results of centrifuge tests. Ng et al. (2021) examined the case of dual barriers.

Recently, Cuomo et al. (2022) proposed an analytical model based on inelastic collision approach applied to a deformable landslide body impacting against a movable and deformable earthfill barrier; Di Perna et al. (2022) proposed an enriched empirical approach for impact loading and landslide energy release. Both approaches were calibrated and validated through Material Point Method simulations.

Nevertheless, landside physical modelling is still a valuable tool, and recent experiences in centrifuge or large flume facilities allow collecting meaningful insights about the landslide-structure interaction mechanisms, for instance for rigid and flexible barriers (Song et al., 2017; Choi et al., 2015).

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