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Efficiency assessment of existing rockfall protection embankments based on an impact strength criterion

Stéphane Lambert[a,*], Bernd Kister[b,1]

[a] Université Grenoble Alpes, Irstea, UR ETGR, Centre de Grenoble, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France
[b] Lucerne University, Neckarsteinacher Str. 4 B, D – 69151 Neckargemünd, Germany

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ABSTRACT

This article first proposes a literature-based criterion for evaluating the capacity of protection embankments in resisting rockfall-induced impacts. The criterion is intended to help stakeholders and public authorities expediently evaluate the strength of existing embankments. It is intentionally kept simple so that it can be applied to any type of embankment and even in those lacking design documentation. The criterion was developed based on available data from real-scale impact experiments conducted worldwide on various types of embankments. It relates the embankment downhill face deformation to the block-incident kinetic energy, differentiating reinforced and non-reinforced embankments. This criterion is then applied to a set of ninety-eight embankments built in France and Switzerland. While the dynamic loading was seldom considered for their design, it appears that > 50% of these embankments meet the criterion. This held evaluation, more importantly serves to identify the nearly one-third of this set for which the application of this criterion suggests an excessive downhill deformation, inviting further investigations with respect to their impact strength and performance expectations

1. Introduction

Natural hazards in Alpine areas are of major concern to urban planners, transportation operators and managers. Similarly as in other areas, the development of transport corridors and the increase in population results in a rising risk exposure, while in a global context of growing aversion to risk. Besides, the projected influence of global warming on the occurrence and intensity of natural gravity driven events such as debris flows, snow avalanches and rockfall questions the efficiency of existing risk management strategies and mitigation measures. Rockfall constitutes the most frequent and widespread natural threat to human environment in Alpine areas, with events and sometimes fatalities at any season and any altitude.

Rockfall protection embankments are massive earthworks built to deviate or to arrest rock blocks on their route down to the elements at risk (Fig. 1). Embankments have in particular been used for decades in Europe where first structures date back to the 1950s. While initially made from compacted ground, successive technological developments have led to a wide variety of structure types and geometries, involving various materials such as rockery, geosynthetics, recycled tyres or gabion cages (Peila, 2011; Lambert and Bourrier, 2013). The design of these passive protection structures, in particular, addresses the ability of the structure in satisfactorily controlling the block trajectory as well as in resisting the impact force by the rockfall. For both these design facets, research conducted during the last two decades have led to advances in understanding of their function and design (e.g. Ronco et al., 2009; Lambert et al., 2013; ONR 24810, 2013). In particular, the necessity for better design methods for embankments with respect to block impact resistance has motivated various research efforts based on experimental and numerical analyses (see a review in Lambert and Kister, 2017a). Nevertheless, none of this research work widely benefit commonly used design methods, with the exception of the recent Austrian standard (ONR 24810, 2013). This standard, however, is based on small-scale experiments. Additionally, most of existing analytical methods proposed in the literature have been shown to be unreliable, even if easy to use (Kister and Fontana, 2011; Lambert and Kister, 2017a).

In some countries of the Alps, large rockfall protection embankment inventories exist. Inventories recently conducted by the authors suggest that their number exceeds 300 units in both France and Switzerland (Lambert, 2012; Lambert and Kister, 2017b). These embankments protect elements at risks such as housing, roads and railways. Similarly as in other alpine areas, most of them are owned by public authorities. The Swiss and French embankment collections consist of a wide variety

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[*] Corresponding author.
E-mail address: stephane.lambert@irstea.fr (S. Lambert).
[1] In the past: Lucerne University of Applied Sciences and Arts, CH – 6048 Horw, Switzerland.

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Fig. 1. Example of a 7 m-tall reinforced embankment protecting a road (La Grave, France) and of a small rockery-facing embankment protecting a house (Soazza, Switzerland) (pictures: S. Lambert).

of structures in terms of construction date, type, dimensions and design approach. The available documentation concerning their design appears to be extremely variable depending on the construction date, in particular. In such contexts, public authorities face the question of the efficiency of existing embankments in resisting impact by rockfall, as for instance when revising hazard maps or natural risk prevention plans.

This article proposes an expedient criterion for evaluating the impact strength of existing rockfall protection embankments. This criterion is based on the state of knowledge and notably aims at helping public authorities conduct structure analysis for identifying potentially undersized embankments. This is of particular interest when dealing with structures of uncertain characteristics or nominal capacity and when a specific study of each embankment is not affordable.

The article is structured as follows. First, the criterion is introduced, examined and discussed based on the state of knowledge concerning the impact response of embankments. To this aim, data related to real-scale experiments are considered. Then the criterion is applied to two large structure collections, the French and Swiss ones. The confrontation of these embankments to the criterion allows for addressing the global efficiency of these collections while highlighting the limitations in this expedient approach. In conclusion, the proposed impact-strength criterion appears simple and useful, in particular in view of identifying potentially inefficient rockfall protection embankments in resisting the impact. These possibly critical cases can then be investigated in more details with more sophisticated methods.

1.1. Impact-strength criterion

The criterion aims at evaluating the ability of embankments in resisting the dynamic loading resulting from the impact by the rockfall. It was developed based on the current state of knowledge concerning the dynamic response of embankments to impact. It was voluntarily kept simple to be applied to a wide variety of embankments even when the available documentation regarding both the built structure and the design event is sparse.

1.1.1. State of knowledge

Various studies have addressed the response of embankments to impact, involving real-scale experiments, small-scale experiments or numerical modelling (Lambert and Bourrier, 2013; Lambert and Kister, 2017a). Small-scale experiments constitute a cost-saving alternative to real-scale experiments, in particular with the aim of conducting parametric studies. Even if results obtained from small-scale experiments are of great qualitative value, questions related to scaling issues and the extrapolation to the real-scale arise. This is particularly true for small-scale tests under gravity, and less for centrifuge tests. As for research involving numerical modelling, results may be biased by limitations in the numerical method used, or by simplifications and assumptions made for modelling the structure and loading. Consequently, the criterion proposed herein was developed emphasising real-scale experiments, as providing concrete and indisputable evidence concerning the response of embankments to impact by a rock block.

The literature review presented by Lambert and Kister (2017a) indicates that among the published studies involving real-scale impact experiments, five provides detailed data related to tests with block kinetic energies beyond 1000 kJ. Studies concerning impact experiments involving kinetic energies < 1000 kJ were not considered as leading to limited structure deformation, far from structure collapse.

Fig. 2 shows that these five studies concerned embankment differing by their shape, dimensions and constitutive materials. The embankment cross section was either rectangular or trapezoidal, with a height ranging between 3 and 4.2 m. At mid-height, the embankment width ranged from 3 to 4.3 m. All the structures were reinforced, except for one test of the series conducted by Peila et al. (2002). It must be noted that among these studies, some investigated the response of structures with slightly different characteristics. Nevertheless, these differences were judged to be of minor importance compared to the differences between the structures concerned by the different studies.

Among the impact experiments conducted on these structures, only the ones carried out in similar impact conditions were considered. These conditions were defined as a single block of kinetic energy higher than 1000 kJ impacting the embankment close to its mid-height. The impact conditions are also described by an approximately 25–30° downward block-incident trajectory, a block diameter typically half the structure height and a maximum kinetic energy of approx. 4.5 MJ.

Table 1 Real-scale impact experiments with block kinetic energies higher than 1000 kJ. gives the structure dimensions, test conditions and measurements related to the 21 tests considered. The maximum kinetic energy involved was 4350 kJ. The residual deformation on the uphill face (exposed to impact) and downhill face, when available, are the only data related to the embankment response to impact. With the exception of the study by Heymann (2012), none of these studies provides data related to the structure real time response.

Notwithstanding the differences in structure types and test conditions, these experiments globally provide a trustworthy source of results for understanding the embankment impact response. Complemented with observations from small-scale experiments and numerical simulation results, the process of embankment collapse from rockfall impact was described by Lambert and Bourrier (2013) as a three-phase process (Fig. 4). During the first phase, a compression wave travels from the impacted area towards the downhill face of the embankment. During the second phase, the embankment moves globally. The last phase corresponds to the progressive structure collapse, as a result of an excessive downhill face displacement. During this three-phase process, different mechanisms appear with time: impact wave propagation, large strains and deformation, energy dissipation by compaction and