Literature-based Expedient Criterion for Assessing the Impact Strength of Switzerland's Rockfall Protection Embankment Inventory

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This article proposes an expedient criterion for assessing the ability of any type of rockfall protection embankment in resisting the impact by the rock block. The approach consists in comparing the design kinetic energy of the block to the embankment dimensions. The embankment is deemed impact resistant if the block kinetic energy is such that the downhill face displacement remains below a threshold value. A differentiation is made between reinforced and non-reinforced embankment. This criterion was developed considering the available literature concerning real-scale impact experiments conducted on embankments. It was then applied to 54 well described embankments built in Switzerland. Even if the Swiss inventory appears globally well designed with respect to impact strength, this criterion draws the attention on 6 potentially highly critical embankments.

Key words: rockfall, embankment, impact, assessment, criterion

1. INTRODUCTION

Rockfall protection embankments (RPE) are massive civil engineering structures built in elevation with respect to the soil in the aim of arresting or deviating rockfall with kinetic energies up to 150 MJ (**Fig. 1**). RPEs are generally built from soil or other granular materials, sometimes compacted, sometimes including reinforcements. The uphill face may be made of different materials: soil, rockery, gabions or recycled-tires, for example.

The design of RPEs normally addresses both their ability in controlling the rock block trajectory and their mechanical stability. As for this latter facet, the challenging issue is the response of the structure to the impact by a block of given mass and velocity. This complex question has motivated various research works since the 90's, based on real-scale experiments, small-scale experiments or numerical modeling (for references and synthesis, see [*Lambert and Bourrier, 2013*] or [*Lambert and Kister, 2017a*]). These works progressively contributed to the development of design rules with respect to embankment impact strength, as proposed only recently (e.g. [*ONR, 2013*]).

In some countries of the Alpine arch (France, Switzerland, Italy in particular) large structure inventories exists, mainly with public ownership. Such structure inventories are heterogeneous in terms of construction date, structure technology, constitutive materials, dimensions, and designed capacity. In fact, most of existing RPEs had been designed with minimum or no consideration for the impact load resulting from the block interception.

In such a context, questions concerning the efficiency of existing RPEs may rise, in particular when dealing with risk management revising natural risk prevention plans. In such cases, it is not affordable to use complex methods to assess the efficiency of embankments. This article introduces an expedient criterion for assessing the impact strength of RPEs. The criterion is based on data from real-scale experiments available in the literature and conducted by different research teams. It aims at helping public authorities in assessing their inventory. It is here applied to Swiss RPEs.

Fig. 1 Example of a 7m-tall reinforced embankment protecting a road (S. Lambert)

This work is part of the research project entitled "Analysis of Existing Rockfall Embankment of Switzerland" (AERES) commissioned and funded by the Federal Office for the Environment (FOEN). This project includes a detailed state-of-the-art ([*Lambert and Kister, 2017a*]), the analysis of the inventory ([*Lambert and Kister, 2017b*]), small scale experiments on rockery facing embankments ([*Kister and Lambert, 2017*]) and an analysis of post-construction events. This article gives a condensed version of these documents for what concerns the expedient criterion and its application to the embankments built in Switzerland.

2. THE SWISS EMBANKMENT INVENTORY

A recently conducted survey showed that the number of RPEs in the different cantons of Switzerland by far exceeds 250 units [*Lambert and Kister, 2017b*]. This inventory mainly consists of compacted earth/soil structures, with a rockery facing. A minority consists of earth-reinforced structures. Even if the very first ones were built in the beginning of the 80's, most of them were built less than 10 years ago. During this survey, the available technical documentation appeared very poor in some cases. At the end, only 54 embankments were sufficiently well described to be considered in this study. These constructions were less than 20 years old.

The 54 structures were designed by different companies, using different approaches and design tools for both defining the design event (rock block trajectory, velocity and mass) and designing the embankment. As for this latter facet, only 10 embankments were designed in an attempt to account for the dynamic loading among which 4 considered the recommendations given by [*ONR, 2013*], and 4 based on the recommendations established by [*FEDRO, 2008*] for computing the impact force acting on sheds.

The dimensions of these 54 RPEs range between 15 and 700 m in length and 1.5 and 13 m in height. Approximately 64% of the embankments have a height of 4 m or less, but only approximately 6% have a height larger than 7 m. The average values are 155 m in length and 4.3 m in height respectively.

These 54 RPEs were designed considering reference blocks with a weight and a kinetic energy in very wide ranges: 15 to 1600 kN and 160 kJ to 50 MJ, respectively. About 40% and 64% of the embankments have been designed for stopping blocks with a kinetic energy less than or equal to 2000 and 4000 kJ respectively. 18% of the embankments were designed for kinetic energies higher than 10 MJ.

Fig. 2 cross-compares the embankments by providing the project block kinetic energy, considered for the design, and the structure mid-height width, for structures ordered according to their height. It can be seen that for similar structure dimensions (width and height) embankments were designed for intercepting blocks with kinetic energy over wide ranges (see examples in the red rectangles). This suggests that either some structures are undersized or others are oversized.

Of course, this comparison is conducted without any reference to the location where the embankment is built, neither to the design companies concerned. The aim here is rather to globally evaluate the relevance of the embankment design in general, and considering that there are lacks in the design recommendations.

3. EXPEDIENT CRITERION FOR IMPACT STRENGHT ASSESSMENT

The criterion was developed with the aim of finding a simple relation between the embankments characteristics and its ability in resisting the impact by the block. The parameters describing the embankment were voluntarily kept simple so that this criterion could be applied for a very large panel of embankment types. It was also motivated by the fact that available data concerning some existing structures are very limited.

This criterion was developed based on the current state of knowledge concerning the impact strength of embankments.

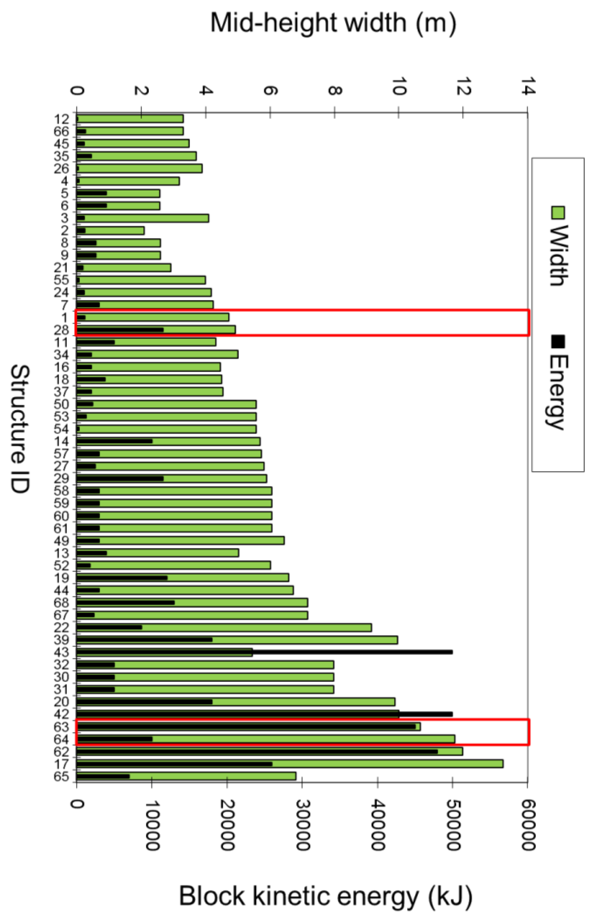

Fig. 2 Cross-comparison of the embankments considered in this study. Mid-height width and design block kinetic energies for embankments ordered according to their height. Red rectangles: see text for explanation.

3.1 State of knowledge

Different studies have addressed the response of embankments to impact, involving real-scale experiments, small scale experiments or numerical modeling (review in [*Lambert and Bourrier*, *2013*]). The proposed criterion was developed emphasizing data from real-scale experiments, as providing concrete evidences concerning real structures.

The literature provides detailed data related to 5 studies involving real-scale experiments with block kinetic energies beyond 1000 kJ. Studies with lower kinetic energies were not considered as leading to limited structure deformation, far from structure collapse. **Fig. 3** shows the 5 reinforced structures concerned by the studies involving real-scale experiments. Their cross sections were either rectangular or trapezoidal, with height ranging between 3 and 4.2 m. At mid-height, the embankment width ranged from 3 to 4.3 m. It must be noted that for some of these studies, there were some differences between the tested structures, but of minor importance compared to the differences between the different studies.

Among the impact experiments conducted on these RPEs, only those carried out in similar impact conditions had been 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 block incident trajectory was also considered. In most of the cases, the trajectory was oriented downward with a 30° inclination approximately. **Table 1** gives the structure dimensions, test conditions and measurements related to the 20 tests considered. The maximum block kinetic energy involved was 4350 kJ. The residual deformation on the uphill and downhill faces (i.e. exposed to impact and opposite to impact, respectively), when available, are the only data describing the embankment response to impact.

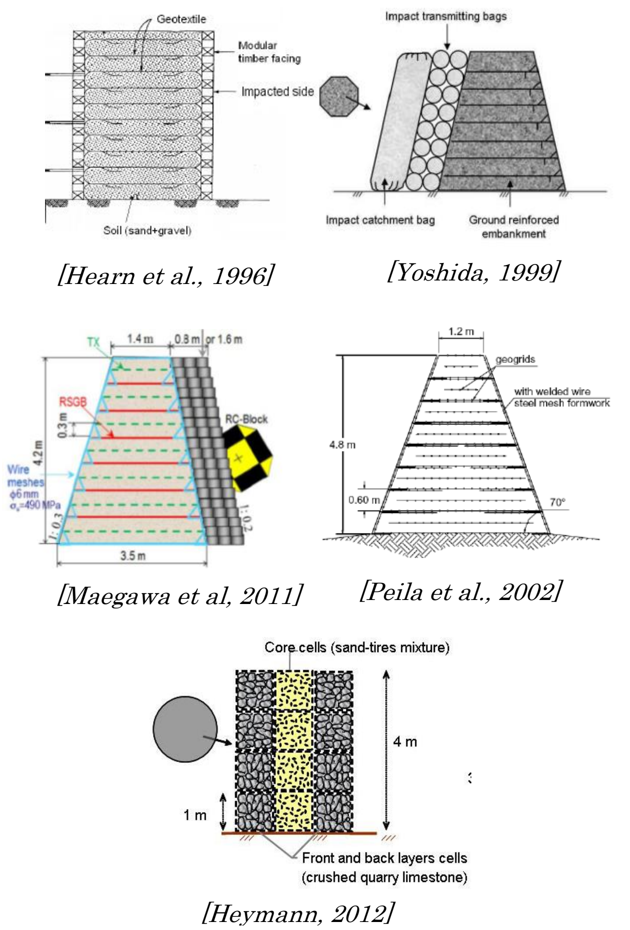

Fig. 3 Embankments subjected to real-scale impact experiments by different authors

Table 1 Data related to real-scale experiments considered in this study

Source	Structure Height (m)	Structure Thickness (crest/base) (m)	Impact energy (kJ)	Deformation Uphill-face (m)	Deformation Downhill-face (m)
Hearn et al., 1995	3.05	1.82/1.82	1010	0.6	0.21
	3.05	1.82/1.82	1400	0.9	0.7
	3.05	1.82/1.82	1410	-	0.76
	3.7	2.4/2.4	1410	-	0.34
	3.7	2.4/2.4	1300	-	0.25
	3.7	2.4/2.4	1410	-	0.34
Peila et al., 2002	4.2	0.9/5	2500	0.6	0.23
	4.2	0.9/5	4350	1	0.9
Yoshida, 1999	4	3.3/5.3	970	0.22	0
	4	3.3/5.3	2000	-	0.09
	4	3.3/5.3	2700	-	0.5
Maegawa et al., 1991	4.2	2.2/4.3	1060	1.13	0.09
	4.2	2.2/4.3	1240	1.57	0.27
	4.2	2.2/4.3	1760	1.73	0.24
	4.2	3/5.1	1050	1.44	0.09
	4.2	3/5.1	1650	0.76	0.1
	4.2	3/5.1	1670	1.8	0.13
	4.2	3/5.1	2270	1.9	0.44
Lambert	4	3/3	2200	1.4	0.55
	4	3/3	2200	0.9	0.4

3.2 Impact response of embankments

Behind the differences in structure types and test conditions, these experiments globally provide a trustworthy source of results for understanding the embankment impact response ([*Lambert and Bourrier, 2013*] or [*Lambert and Kister, 2017a*]). The analysis of the embankment response reveals that, among other mechanisms, the impact by the block first induces compaction and crushing of coarse materials close to the impacted area. Then, it progressively induces displacement of part of the embankment, with friction along shear planes. Basically, the higher the kinetic energy, the larger is the RPE deformation and consequently the downhill face displacement (**Fig. 4**). And finally, if the block kinetic energy is in excess with respect to the RPE nominal capacity, collapse is reached as a result of a large downhill face displacement. In the end, the downhill face displacement appears to be a good indicator of the impact response of the embankment: the higher this displacement and the closer to collapse, whatever the amplitude of the various mechanisms involved in this structure deformation.

In order to account for the differences in dimensions of the tested embankments, it is proposed to normalize the downhill face displacement by the structure mid-height width, which is representative of the embankment width opposed to the block penetration.

The block kinetic energy is also normalized by the area of the structure cross-section, which is considered here representative of the mass of the embankment associated to the impact. This approach is consistent with the fact that the larger the structure, the higher the required block kinetic energy for reaching a same embankment deformation [*Hearn et al.* 1996].

Fig. 5 presents the normalised results received from the real-scale experiments on the structures presented in **Fig. 3**. It shows a rather linear relationship between the relative downhill face displacement and the normalised kinetic energy.

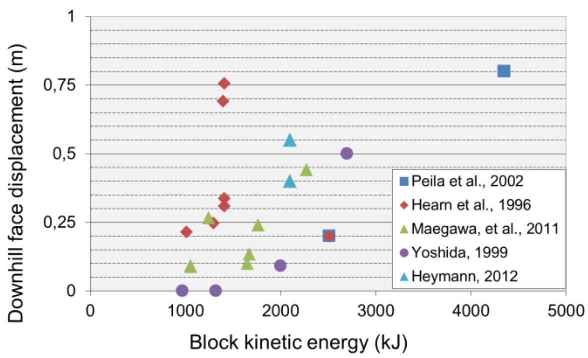

Fig. 4 Results from the real-scale experiments presented in **Fig. 3** and **Table 1**.

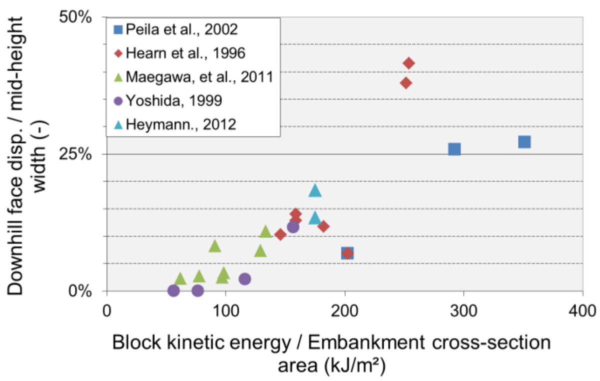

Fig. 5 Normalised results of **Fig. 4**

3.3 Criterion

The results presented in **Fig. 5** show that below a normalised kinetic energy of 250 kJ/m², the downhill displacement remains on a level less than 25% of the structure width. The 25% threshold for the downhill face displacement is considered as a relevant limit beyond which the structure may not be stable anymore. It is in line with previously proposed threshold values proposed in the literature in relation with analytical methods [e.g. *Ronco et al.*, 2009].

This practically implies that the downhill face displacement of an impacted embankment is acceptable if:

$$\frac{KE}{A} < 250$$

where KE is the block kinetic energy (kJ) and A is the structure cross-section area along the vertical axis calculated from the ditch elevation (m²).

Based on this finding, it is proposed to consider that an embankment is impact resistant if $E'_{25}<1$, with:

$$E'_{25} = \frac{KE}{250 * A}$$

E'_{25} is a normalized block kinetic energy, where the subscript 25 refers to the ratio of accepted downhill face displacement with respect to the structure width (here 25%).

The validity domain of this criterion is conditional on the experimental conditions. With respect to the embankment, the criterion is valid for reinforced structures, with height in the 3-4.2 m range and a mid-height width in the 3-4.3 m range. With respect to the loading, the criterion is valid for a block diameter typically half the embankment height, with an incident downward trajectory inclined by 30° approx. with respect to the horizontal axis, having a kinetic energy in the 1-5 MJ range and leading to an impact point close to the embankment mid-height, and thus at a sufficient distance from the crest. Out of this domain, the criterion validity may be altered.

4. APPLICATION TO THE SWISS EMBANKMENT INVENTORY

4.1 Inventory evaluation

The proposed expedient criterion was applied to the 54 previously mentioned embankments (**Fig. 6**). In this figure, the embankments are ordered according to their height, with result bars in violet for non-reinforced structures and yellow bars for reinforced structures (4 out of 54).

As for the reinforced embankments, E'_{25} slightly exceed the value of 1 in 2 cases. Exceeding a value of 1 is not detrimental for a reinforced structure: it indicates that a large downhill face displacement takes place, not necessarily implying an impending collapse. Indeed, the experiments conducted by Peila et al. (2002) showed that a reinforced embankment was able to survive two successive impacts with a E'_{25} exceeding 1. The 2 other reinforced embankments meet the requirement.

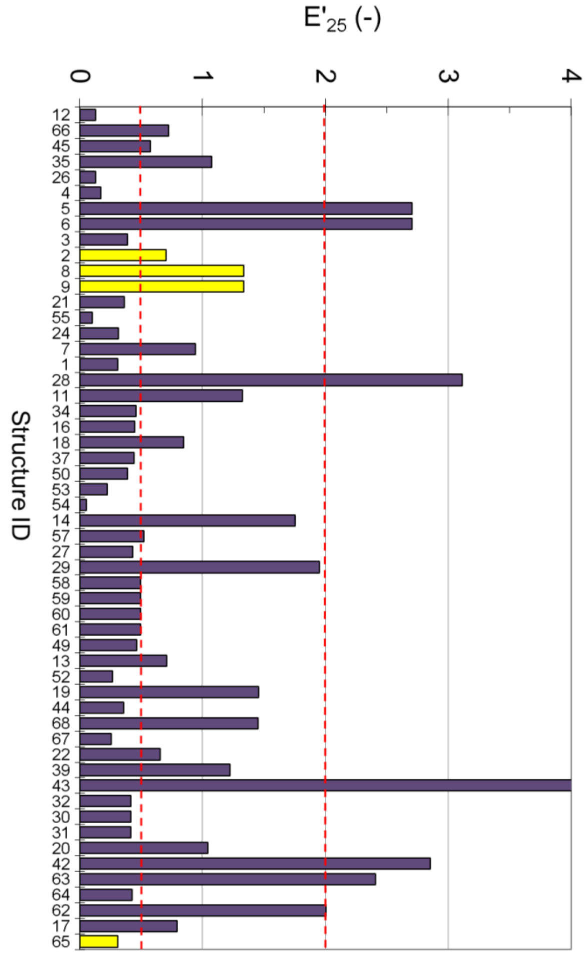

Fig. 6 Embankment inventory evaluation (violet and yellow for non reinforced and reinforced embankments resp. (see the text for explanations about dotted lines)

As for non-reinforced structures, the validity of the criterion is questionable. Indeed, for such embankments, the downhill face displacement is much higher than for a reinforced embankment impacted by a block of same kinetic energy. Considering the results from the literature [*Peila et al.*, 2002][*Brandl and Blovsky*, 2004] it is proposed to account for this lower impact strength by dividing the acceptable downhill face displacement by 2, such that the criterion becomes $E'_{25}<0.5$. 27 non-reinforced embankments meet this specific requirement out of 50. On the opposite, in 6 cases E'_{25} exceeds the value of 2, which is considered highly critical for unreinforced RPEs. In 2 out of these 6 cases, the criterion is applied within its validity domain in terms of embankment height, mid-height width and block kinetic energy. In the 4 remaining cases, at least one condition is not fulfilled with respect to the validity domain.

On total, for 17 non-reinforced embankments out of 50 E'_{25} is within the 0.5-2 range, which is critical but to a lesser extent.

At the end, applying the criterion on this inventory draws the attention on about 10% of highly critical cases (6 non reinforced embankments). To a lesser extent, about 35% of the embankments exceed the criterion (17 non reinforced embankments and 2 reinforced ones). Finally, around 60% of the inventory meets the criterion.

4.2 Discussion

On the whole, it is a noticeable good point that more than 50% of the embankments meet the criterion while less than 20% were designed with consideration for the dynamic loading by the rock block. Analysing more specifically the E'_{25} value for embankments for which the impact was considered in the design process, it appears that using [*ONR, 2013*] led to slightly more efficient structures in resisting the impact than [*FEDRO, 2008*]. Nevertheless, only 1 out of the 8 structures concerned by these designs meets the E'_{25}-based criterion.

For embankments for which the criterion is not met, complementary analysis could be conducted to assess their impact strength based on deeper investigations and calculations. Nevertheless, some practical limitations rose applying this criterion. These limitations relate to the available information with respect to each case and its quality. First, the definition of the embankment height is not unique. Depending on the case, this value may be measured along the vertical axis or along the embankment face, as a difference between the crest elevation and either the ditch elevation or the natural ground elevation. Second, the definition of the impact height is also not unique: in some cases, the block lower point is considered while in other it is the gravity centre. More generally, questions in relation with parameters related to the rock block trajectory raise. Indeed, the impact height and the block trajectory inclination are not always provided by the documentation while these two parameters clearly influence the response of the embankment. For instance, the embankment deformation resulting from an impact close to its toe will be limited. On the contrary, an impact close to the crest, or by a block with a sub-horizontal incident trajectory will be more detrimental to the embankment safety. In the absence of these data, the criterion was applied considering that these unknown parameters met the validity domain requirements. For this reason, it is recommended that, prior to any further assessment of apparently critical structure, the relevance of using the E'_{25}-based criterion should be checked depending on the impact case vs. the experimental conditions.

5. CONCLUSIONS

In order to assess the efficiency of large structure inventories an expedient criterion for the impact strength of rockfall protection embankments has been developed based on data from real-scale experiments available in the literature. This expedient criterion basically relates the displacement of the downhill face of the embankment, which results from the impact by the rock block, to the impact energy. This criterion is voluntarily kept simple to be applied to a wide variety of existing structures.

This criterion was applied to a sample of 54 well documented embankments built in Switzerland during the last 20 years. In spite of the fact that their design seldom accounts for the dynamic loading, about 60 % of the embankments appear to be impact resistant. On the opposite, the attention of owners is drawn on 10% of the structures for which impact strength is highly questionable.

Even if easy and convenient to use, it is not recommended to use this criterion for design of new structures.

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