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Stéphane Lambert, B. Kister

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Analysis of Existing Rockfall Embankments of Switzerland (AERES)

Part B: Analysis of the collected data and comparison with up-to-date knowledge

Stéphane LAMBERT[1] and Bernd KISTER[2]

[1] Irstea, 2 rue de la papeterie, 38402 Saint Martin d'Hères cedex, France, + 33 4 76 76 27 94,
stephane.lambert@irtsea.fr
[2] Lucerne University of Applied Sciences and Arts, Technikumstrasse 21, CH – 6048 Horw, Switzerland.
Current position: kister - geotechnical engineering & research, Neckarsteinacher Str. 4 B,
D – Neckargemünd, +49 6223 71363, kister-ger@t-online.de

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Contractors
Lucerne University of Applied Sciences and Arts, CH-6048 Horw
Irstea, F-38402 Saint Martin d'Hères

Authors
Bernd Kister
Stéphane Lambert

FOEN support
Bernard Loup, Hazard Prevention Division
Arthur Sandri, Hazard Prevention Division

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- Part A: State of knowledge
- Part B: Analysis of the collected data and comparison with up-to-date knowledge
- Part C: Small-scale experiments

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Foreword

This document reports on the collection of data concerning RPE built in Switzerland and their analysis. It follows and makes implicit reference to the report entitled “Part A: state of knowledge”.

This collection was conducted during interviews with cantons and design companies concerned by this type of protective structure, with the aim of giving a global image of this structure park, in terms of dimensions and design, as well as providing pieces of information on the design methods in use in Switzerland nowadays.

The RPE inventory is not intended to be exhaustive but to be representative of the Swiss park. The study gathers exhaustive data concerning a large number of RPE and their design. The interviews revealed that the total number of RPEs in Switzerland by far exceeds 250 units. The data collection mainly focuses on more recent structures as older structures suffer from limited available documentation and very simple design. Consequently, restricting the study to newest ones is not detrimental to the aim of this study.

This report first describes the RPEs concerned by the data collection, before giving a brief overview of design approaches in use. Then, RPEs are analysed, in order to evaluate the current design practices with respect to impact strength. In this purpose, structures are compared one to each other. Basically, the aim of this comparison is to see to which extent the lack of well-established design rules leads to variability in the design of RPEs. The lack of well-established design rules should result in an inconsistency in the structure dimensions and possibly in apparently under-sized structures. Then, a simple and expedient assessment criterion, based on up-to-date knowledge, is proposed in order to evaluate the RPEs. Furthermore, the collected data are compared to criteria proposed by Kister (2015) based on small and half scale experiments. Last, the freeboard, if defined for the RPEs, had been compared to the target values given by the Austrian standard ONR 24810 (2013).

Content

1. Park description

1.1. Park considered

On total, the analysis is based on 68 embankments designed less than 20 years ago, except one built in the beginning of the 80's. 10% are still projects, but are considered in this study as it provides indications on the currently used design methods.

This sample is considered representative of existing embankments and provides a clear illustration of the design methods in use nowadays in the different cantons of Switzerland. More precisely, 13 cantons are concerned, with variable number of RPEs each (1 in BL, GL, OW and TI, 2 in JU and LU, 3 in VD, 4 in UR, 5 in NE and SZ, 10 in GR, 11 in BE and 22 in VS).

Some Swiss RPEs were also intended to intercept snow avalanches. The design of most of these structures was governed by snow avalanche containment criteria: these structures were not considered in the study.

The data were collected considering RPEs as continuous units. When two or more structures are located on the same site and result from the same design, these structures had been considered as different. In case the dimensions vary along its length, the tallest profile and corresponding design parameters are considered.

1.2. Dimension and shape

The RPEs are described based on data related to their shape and dimensions along their length (L) and cross sectional shape, as illustrated in Figure 1.

The dimensions of the RPEs considered in the analysis 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 (Figure 2). The average values are 155 m in length and 4.3 m in height respectively (Table 1). It is worth highlighting that the cumulative length of the 68 embankments exceeds 10 km.

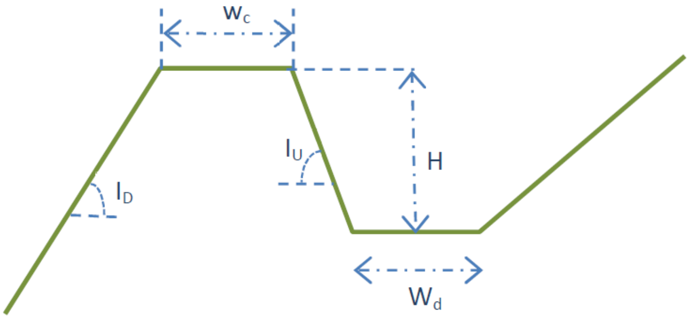

Figure 1 Definition of main data used for describing the cross section of the RPEs

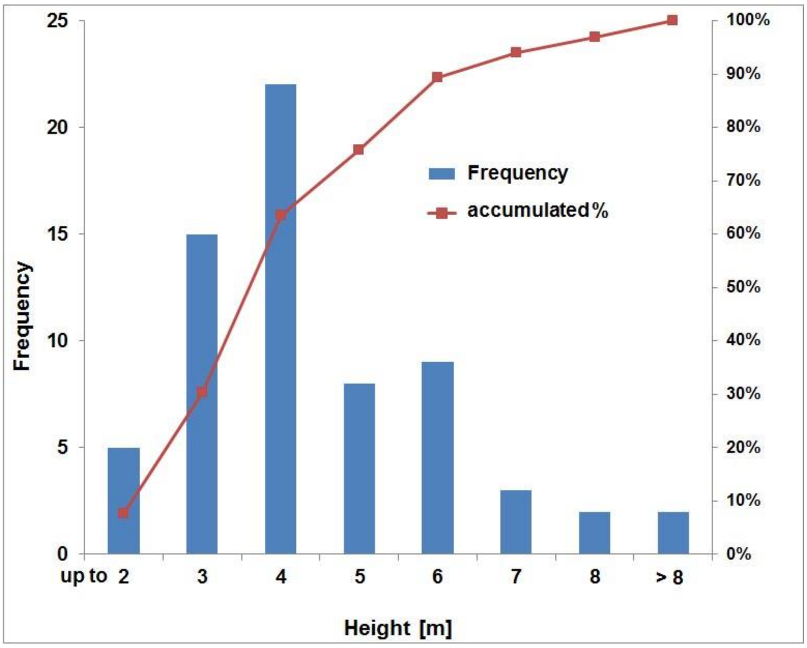

Figure 2 Bar chart of embankment height

Table 1 Minimum, maximum and average values for parameters describing the 68 RPEs

	W_c (m)	H (m)	L (m)	I_U (°)	I_D (°)	W_d (m)
Min.	1	1,5	15	33	33	0,5
Max.	8,6	13,2	700	87	80	14
Average	2,1	4,3	155	65	43	4

The vast majority of the RPEs is made of compacted soil, with a rockery facing at the uphill slope. About 30% of the RPEs exhibit a bi-linear uphill face with two different inclinations. The higher inclination corresponds to the lower part made of rockery. In such cases, an average inclination value was considered for I_U (Table 1). The motivations for such a design choice are:

(i) high inclination is required for stopping rolling blocks and thus mainly concerns the lower part of the uphill face and
(ii) soil close to the crest favour the energy dissipation and thus stopping blocks with high passing height, while avoiding downhill ejection of block or rockery fragments resulting from the impact on the rockery facing.

About 15% have their uphill face made of compacted soil (or debris) and consequently have lower uphill inclination values (down to 33°). Less than 10% of the RPEs include reinforcing elements (geogrid mainly, in the core or face only). About 20% of the RPEs have a downhill face with an inclination higher than 45°, obtained either with rockery or reinforced earth.

1.3. Intended structure capacity

The design with respect to the protection function of the 68 RPEs was conducted by 13 different companies.

In many cases, trajectory simulation results used for designing the structure were provided by another company than the design company. One or two of the following codes were used for this purpose: RockyFor3D, RofMod, RockFall (Dr Spang), CRSP, Ramms, RocPro, RocFall (rocscience). In some rare cases, no simulations were conducted. Half of the simulations include the RPE in the profile. More than 60% of the simulations were conducted using 2D models. When provided, the number of runs is most often less than 1000.

Table 2 Minimum, maximum and average values defining the impact loading by the block

	Weight (kN)	Velocity (m/s)	Kinetic energy (kJ)	Passing height (m)
Min	15	10	159	0
Max	1600	33,4	50000	6
Average	262	21,8	7478	2,2

These structures 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 (Table 2). 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 (Figure 3). 18% of the RPEs were designed for kinetic energies higher than 10 MJ.

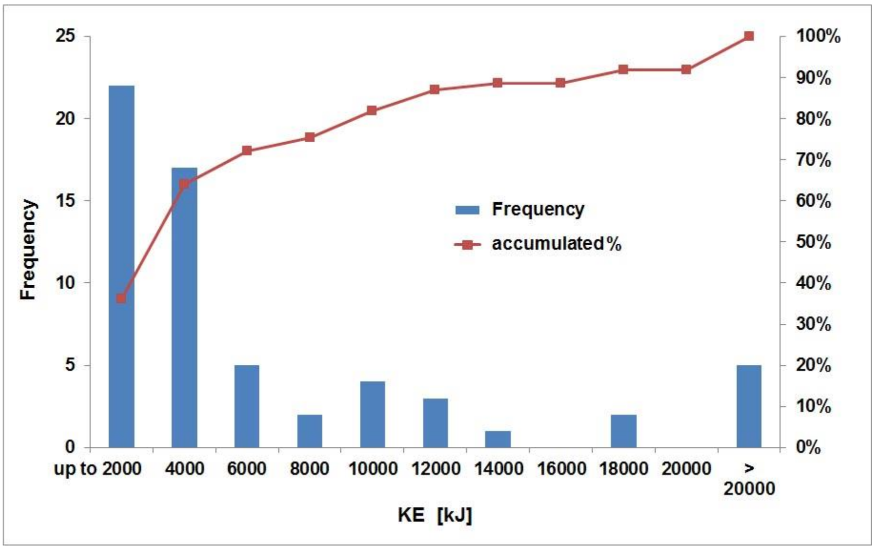

Figure 3 Bar chart of kinetic energy used for the design, total 61 embankments

2. Design methods overview

2.1. Design with respect to block trajectory control

The percentile used for defining the design values vary from 90 to 100%. Some cantons impose 95%. Besides, the accepted residual hazards (i.e. after RPE erection) vary according to the element at risk and return period of the event (30, 100 or 300 year return period). Significant percentages of blocks overpassing the RPE are sometimes accepted in case of a 300-year return period event. Last, construction cost is also a strong constraint, sometimes leading to the acceptance of a higher risk level (use of EconoMe).

The design with respect to block trajectory control mainly refers to the block passing height. Nevertheless, the analysis of the available reports concerning the 68 RPEs revealed that there was no unique definition of the block passing height from one company to the other. It sometimes concerns the block lower point, higher point or gravity centre, depending in particular on the trajectory simulation tool used. In addition, in many cases the considered definition is not explicitly indicated. Besides, in some cases, the passing height is obtained from simulations in the absence of RPE while in others its projected topography is considered. As a consequence, the collected data are biased and no conclusion may be derived.

The authors of this study recommend using the distance along the vertical axis from the toe of the uphill face of the RPE and the block gravity centre position as resulting from rockfall propagation simulations integrating the projected topography. This definition is consistent with the definition of the RPE height given in Figure 1.

While both the trajectory inclination and the block rotational velocity before the impact on the RPE face have been shown to affect the efficiency of the RPE in stopping the block, the corresponding values are very seldom provided.

There is also no consensus in terms of freeboard to consider, when indicated. The ratio of the freeboard to the block radius is extremely variable (0 to 1.2). The construction cost is often an argument for reducing the freeboard.

2.2. Structural design

Globally, the structural design of RPEs is empirical, based on the experience and habits of the design company. For instance, no information concerning the structural design is given for more than 60% of the 68 RPEs. On the other hand, some design companies have developed their own approach for designing embankments.

The impact loading was considered for the design of ten RPEs, four considering the recommendations provided by the Austrian standard (ONR 24810) and one considering the method proposed by Tissières (1999). Five were designed following the recommendations by FEDRO (2008), “Exposure of rock sheds due to rockfall”, for estimating the static equivalent force.

3. Analysis

In the absence of reliable, well established or recognized design method, the park is analysed based on three different approaches:

1. RPEs are compared one to each other, for tracking anomalous cases, based on the basic assumption that for a given energy the RPEs should have very similar dimensions.
2. Then a simple but pragmatic assessment criterion is used. The proposed criterion accounts for the main mechanisms occurring during the impact of the embankment by a block. It has been developed considering the existing real scale experiments data available in the literature.
3. Last, the structure park is evaluated based on criteria proposed by Kister (2015) after conducting small and half scale experiments.

The number of RPEs concerned by the different approaches depends on the availability of the necessary data. 54 and 47 RPEs out of the 68 were concerned by approaches (1, 2) and 3 respectively.

3.1. Cross-comparison

This comparison is conducted based on the idea that for similar impact cases the RPEs should exhibit similar dimensions. This assumption is acceptable for this structures park, as it is rather homogeneous in terms of structure type and constitutive materials.

Figure 4 gives the mid-height width of RPEs, sorted according to their height, together with the block kinetic energy these RPEs are supposed to resist. For a given class of structure dimensions, certain variability in block kinetic energy is observed. For example, the block kinetic energy for structure no.°28 is much higher than that for structure no.°1, of similar height and mid-height. This also holds for RPEs no.°14 and no.°29 compared to RPEs no.°57 and no.°58 respectively. As for RPEs with a height higher than 6 m, the block kinetic energy is very high for 4 RPEs compared to others while the difference in dimensions is not that pronounced (ID-Nos. 42, 43, 62 and 63).

Nevertheless, it is not possible at this stage to conclude on the proper design of these structures. The main conclusion is that there exists a discrepancy from one structure to the other. This may results from the lack of well established design rule.

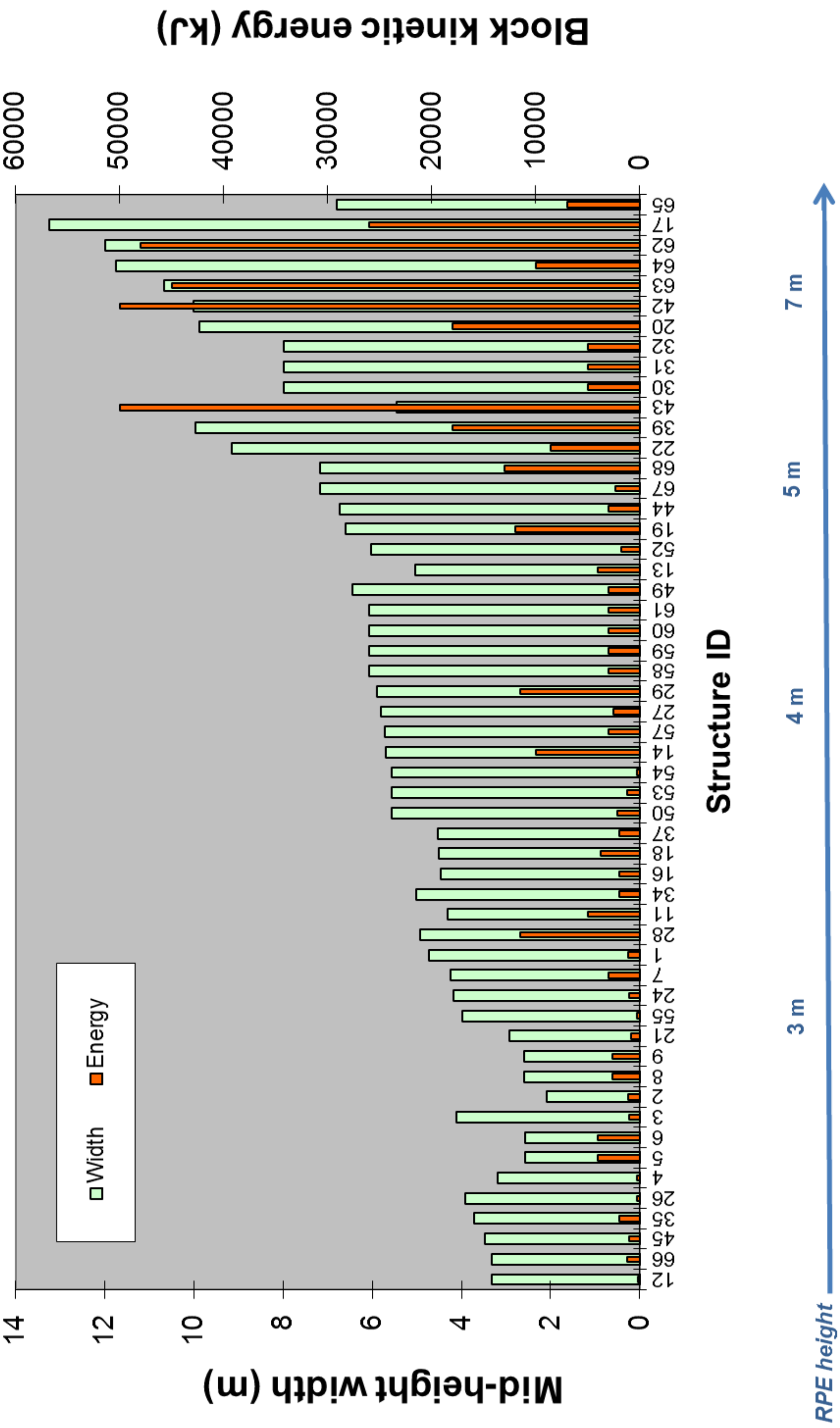

Figure 4 Comparison of RPEs based on their height and mid-height width

3.2. Real scale experiments based efficiency criterion

3.2.1. Criterion definition

A criterion considering real scale experiments data available in the literature is proposed in order to expediently assess the efficiency of a RPE in withstanding the impact by a block.

The ability of an embankment in resisting the block impact may be assessed based on its post-impact deformation and in particular on the displacement of the downhill face, opposite the impact. Indeed, the post-impact structure stability is strongly related to the displacement of this face. In case the impact energy exceeds the structure capacity the structure will be destroyed and the downhill face displacement will be very large.

Figure 5 plots the post-impact displacement values measured by different authors after conducting real-scale impact experiments involving block with energies in the 1000-5000 kJ range. The impacted structures were 3 to 4.2 m in height, 3 to 4.3 m in mid-height width with an uphill face inclination of 60 to 90°. Impacts were mainly located in the structure mid—height vicinity and the blocks had downward incident trajectories. Even if the global trend shows an increase in displacement with the block kinetic energy, a high scattering is observed.

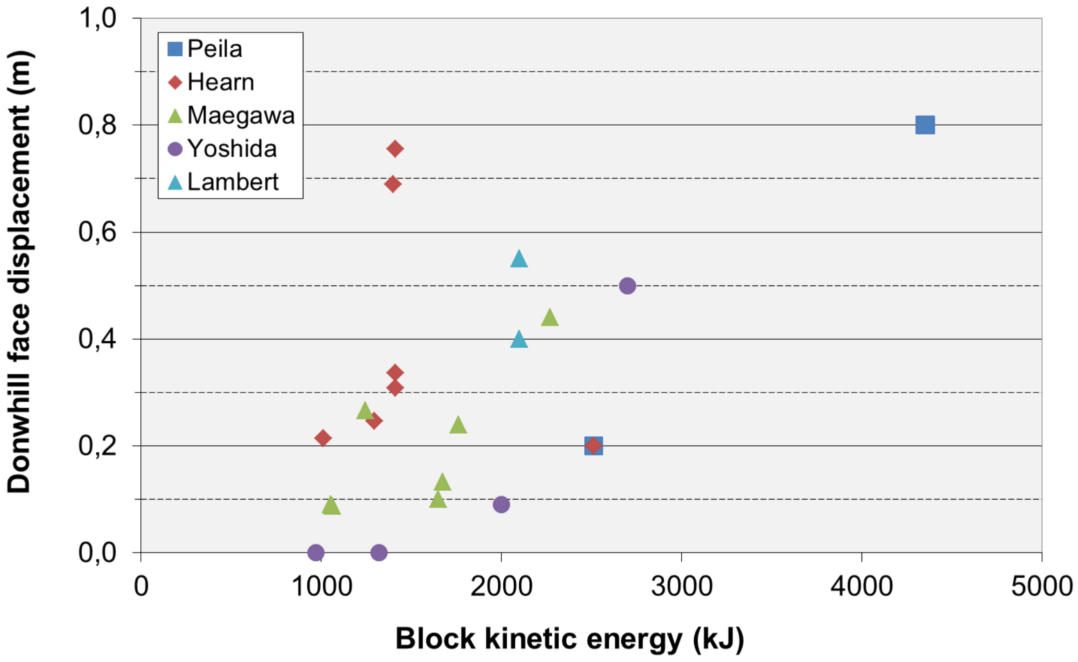

Figure 5 Post-impact downhill displacement measured after real scale experiments (for detailed information, see Table 3 of report “Part A: state of knowledge”)

The scattering is due to differences from one impacted structure to the other in terms of vertical cross sectional shape and dimensions, design and construction materials. The height ranged from 3 to 4.2 m and the mid-height width ranged from 3 to 4.3 m. Structures tested by Hearn were rectangular in cross section, with facings and core reinforced with timber and geotextile respectively. Peila tested reinforced structures with a trapezoidal cross sectional shape. Both faces were reinforced, allowing increasing the structure impact strength (Peila et al., 2002), in a ratio that can be estimated up to 2 from the small scale experiments conducted by Blovsky (2004). This explains why displacements are much smaller than for structures for which only the uphill face is reinforced. Data provided by Lambert et al. (to be published) concern rectangular in cross section sandwich structures made of gabion cages.

In spite of these differences, this data set provides a reliable and valuable basis for developing a simple and expedient RPE assessment criterion.

The criterion was developed with the aim of finding a simple relation between the downhill face displacement and the block kinetic energy. Due to the differences in structure dimensions and impact energy, the experimental results should be normalised. As for the block kinetic energy, it is proposed to normalize this parameter by the structure dimensions. Indeed, the block kinetic energy is transferred to the structure where it is dissipated mainly by compaction, but also by friction. The amplitude of both these dissipative mechanisms depends in particular on the structure dimensions: the smaller the structure, the smaller the dissipation. In an initial approach, the cross sectional area of the structure along the vertical axis may be considered as representative of the structure dimensions in the impact direction. As for the downhill displacement, it is proposed to normalize this parameter by the mid-height structure width, which is representative of the structure dimension in the impact direction, irrespective of the cross sectional structure shape.

Figure 6 shows the results presented in Figure 5 normalised by the structure cross sectional area and by the structure mid-height width. It can be seen that the displacement is higher than 25% of the structure width when the ratio of kinetic energy to cross section area exceeds 250 kJ/m². The 25% limit displacement value is in accordance with some methods proposed in the literature suggesting that above this limit, the structure is no longer stable after the impact.

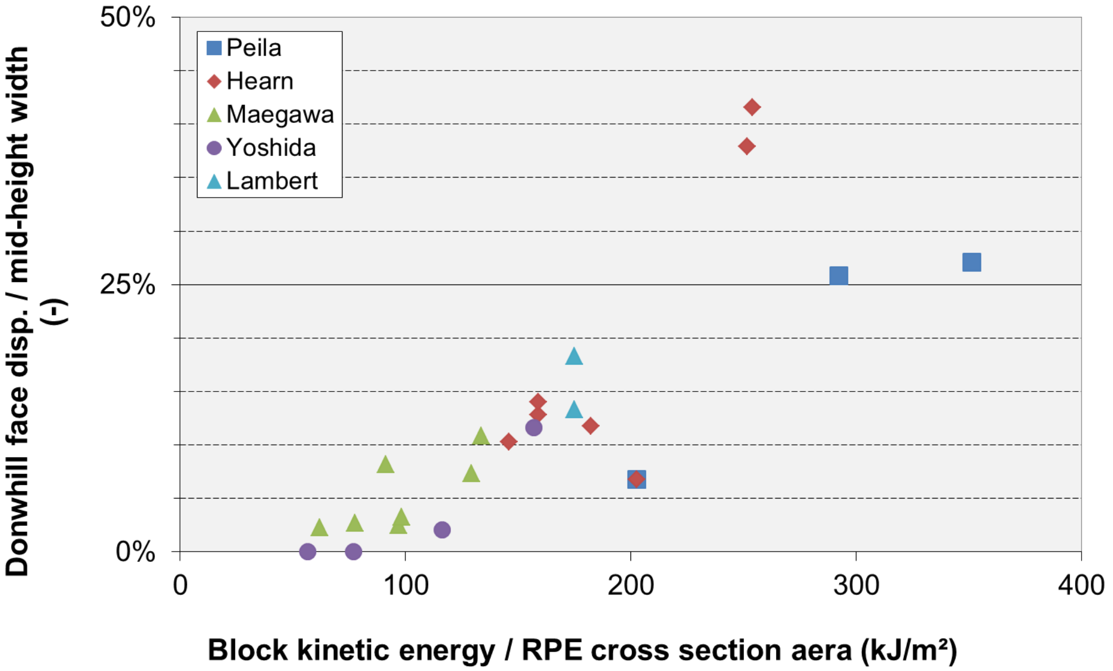

Figure 6 Relative downhill face displacement as a function of the ratio of the block kinetic energy to the RPE cross section area after real scale impact tests. (for detailed information, see Table 3 of report “Part A: state of knowledge”)

Considering this finding, the nominal structure capacity assessment criterion is defined as:

$$C_{25} = \frac{KE/A}{250}$$

where KE is the block kinetic energy (kJ), A is the structure cross section area along the vertical axis calculated from the ditch elevation (m²). A C_{25} value less than 1 indicates that the structure is able to withstand the block kinetic energy, considering that the maximum allowable downhill displacement is less than 25% the mid-height width.

Basically, this criterion means that above a value of 1, the kinetic energy of the boulder is in excess with respect to the embankment capacity in stopping the block while limiting the deformation to a given value.

The validity of this criterion, and in particular of the 250 threshold value, is related to the experimental conditions (structure design, block kinetic energy…). These conditions are:

- Reinforced structure;
- RPE with an height in the 3 - 4.2 m range, and a mid-height width in the 3 - 4.3 m range;
- Block with a 30° approx. downward incident trajectory;
- Impact point located at a significant distance from the crest (at least ¼ of the structure height).

The relevancy of this criterion may be questionable out of this validity domain. For example, an impact closer to the RPE crest or with an incident trajectory less than 30° would be more detrimental to the structure.

It can be observed that the 25% relative displacement value is a safe value. Indeed, results from Peila have shown that collapse occur for relative displacement higher than 40% in case of a structure reinforced on both faces.

Before applying this criterion to Swiss RPEs it has been applied to structures presented in the literature. In particular, some recent publications detail the design of existing structures, based on various methods, and with specific focus on the structural design with respect to block impact strength. Table 3 gives the C_{25} for RPEs described in 5 different publications. All the concerned structures are reinforced, with a height ranging from 5.4 to 10 m. None of the C_{25} values for these structures exceeds the threshold value of 1, suggesting this criterion is consistent with the different methods used for these specific structures.

Table 4 Application of the C_{25} criterion to RPEs detailed in the literature

Authors		Frenez et al., 2014	Lorentz et al., 2010	Grimod and Giachetti, 2013	Simmons et al., 2009	Rimoldi et al., 2008
Block kinetic energy	*MJ*	4	10	3	10	15
Structure height	*m*	5,4	6,5	10	8	10
Structure cross section	*m²*	22	44	88	50	76
C_{25}	-	**0,7**	**0,9**	**0,2**	**0,8**	**0,8**

Considering the data collected in the frame of this study, the main limitation with this criterion is the structure type. The vast majority of RPEs built in Switzerland are unreinforced ground compacted structures with a rockery facing. In such cases, larger downhill face displacements are expected, with relative values exceeding by far the 25% limit for the same kinetic energy. This means that a C_{25} much smaller than 1 should be adopted for unreinforced structures. As a consequence the limit value considered in the following is fixed to 0.5.
The criterion thus becomes: $KE < 125 * A$

Besides, the application of this criterion to this structure park faces the problem of data availability and reliability. For instance, the block incident angle is very seldom provided and the definition of the block passing height is extremely variable from one case to the other. As a consequence, two of the criteria defining the validity domain could not be checked.

3.2.2. Results

Figure 7 gives the C_{25} value of the 54 RPEs for which the required data are available. The analysis reveals that more than 42% of the RPEs have a C_{25} value less than 0.5 (23 RPEs) and thus may be considered able to withstand the impact by the block (Figure 7).

On the other hand, the C_{25} exceeds the value of 1 in 17 cases, among which 7 cases exceed the value of 2. It is worth highlighting that 2 out of these 7 critical cases could not be clearly identified after the cross comparison (ID-Nos. 5 and 6). On the contrary, the 4 tallest ones were identified (ID-Nos. 42, 43, 62 and 63). For these later cases, the C_{25} is used out of its validity domain in terms of RPE height, and impact point. For instance, in 2 cases the height is higher than 7 m and the free board is less than half the design block diameter (ID-Nos. 62 and 63). The damage potential to elements at risk of these high kinetic energy blocks justify conducting complementary analysis on these highly critical structures.

To a lesser extent, the proper design of RPEs having a C_{25} value between 0.5 and 2 should also be assessed.

Prior to any assessment of apparently critical structure, the relevance of using the C_{25} should be checked depending on the impact case vs. the experimental conditions. Second, the acceptability of the destruction of the RPE should be checked versus the return period of the event considered: destruction may be tolerated in case of a 300-year return period event but not for a 30-year one.

3.3. Small scale experiments based efficiency criterion

As a result of small and half scale tests with rotating blocks, Kister (2015) suggested criteria related to the efficiency of pure soil embankments in stopping a block, considering the risk of both structure punching through and over topping. Kister (2015) concluded from the experiments that in order to prevent from these risks, the structure should be such that the three following criterion should be fulfilled:

(i) The batter at the uphill slope should be at least 60°.
(ii) The thickness of the crest, w_c in Figure 8, should be 1.2 times the design block diameter.
(iii) At the impact point the thickness of the embankment should be 3 times the block diameter.

Following these three statements a cross section for an embankment can be constructed graphically. This cross section is shown in Figure 8.

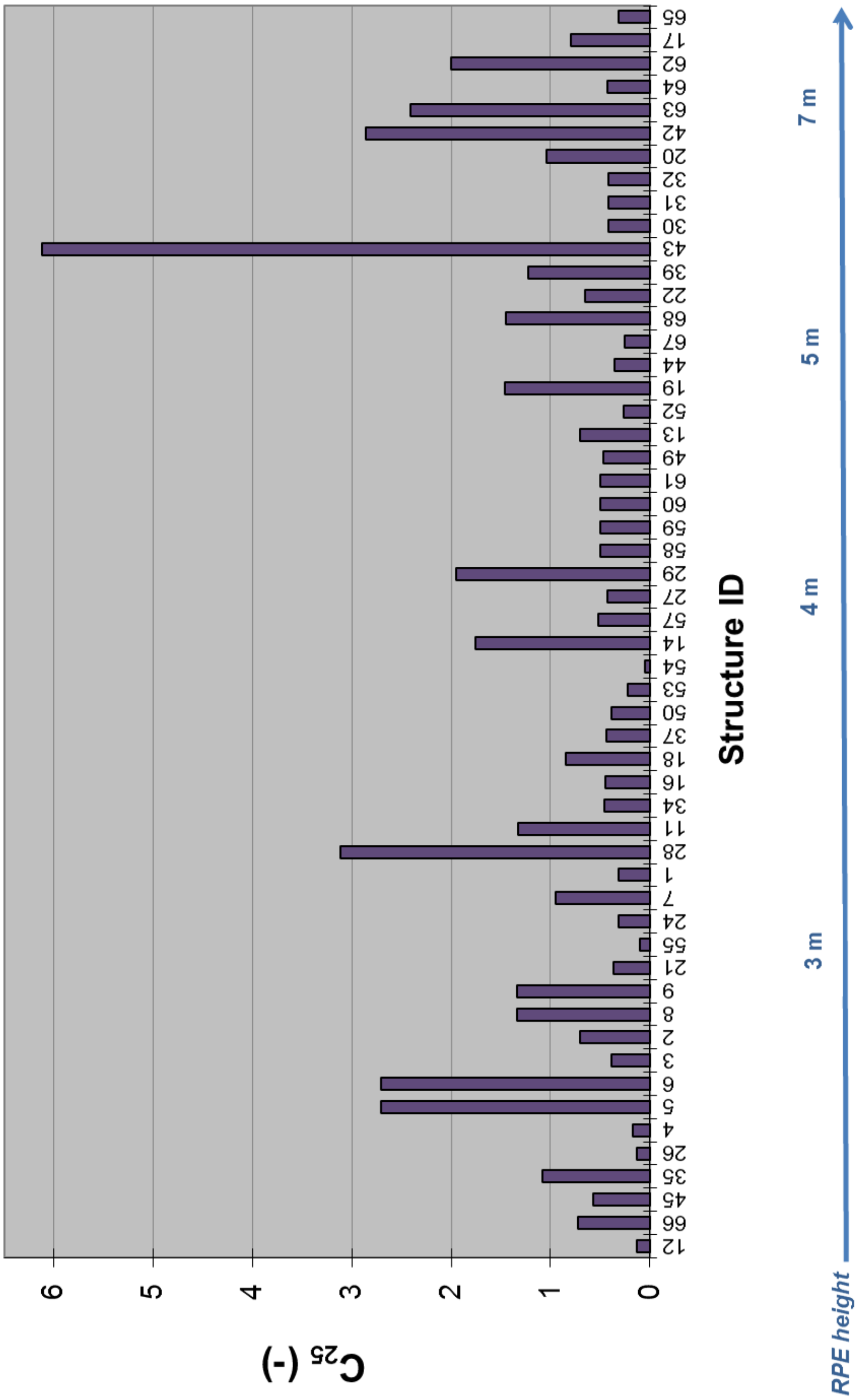

Figure 7 Application of the C_{25} efficiency criterion to RPEs

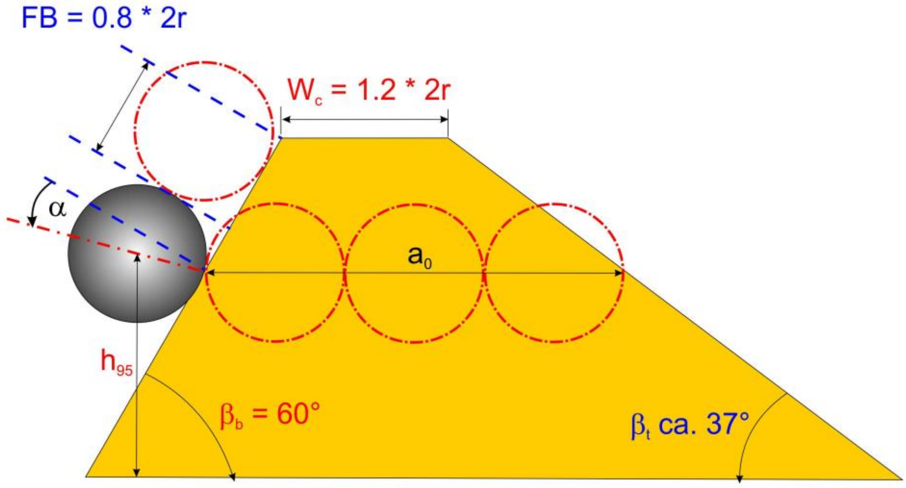

Figure 8 Cross section graphically constructed taking into account the three conditions given by Kister (2015)

For embankments with rockery criterion (i) is generally fulfilled. The criterion (ii) could be checked for 51 embankments where data of crest thickness as well as data of block volume or mass was available. The block diameter was calculated assuming that the block shape was a sphere. In the end, this criterion is fulfilled for 14 RPEs (Figure 9).

9 RPEs have a crest width-to-block diameter value less than 0.5. These are the most critical as most of the experiments with this ratio led to structure punching, in particular for a rotating block with an impact close to the crest. These 9 most critical RPEs have in common a relatively small crest width value (1 to 1.5 m). The concerned cases may be classified in two configurations:

- RPE height less than 3 m, exposed to a more or less rolling block with a diameter close to the structure height (typically 2.6 m) (ID-Nos. 1, 2 and 3)
- RPE taller than 3 m and exposed to a block with a high passing height with respect to the structure height so that the freeboard is less than 1 block radius (ID-Nos. 11, 62, 63, 64 and 68).

In both configurations, the structure width at the impact height is less than three times the block diameter. The block is thus faced by a relatively small volume of the RPE as opposition, favoring punching of the RPE.

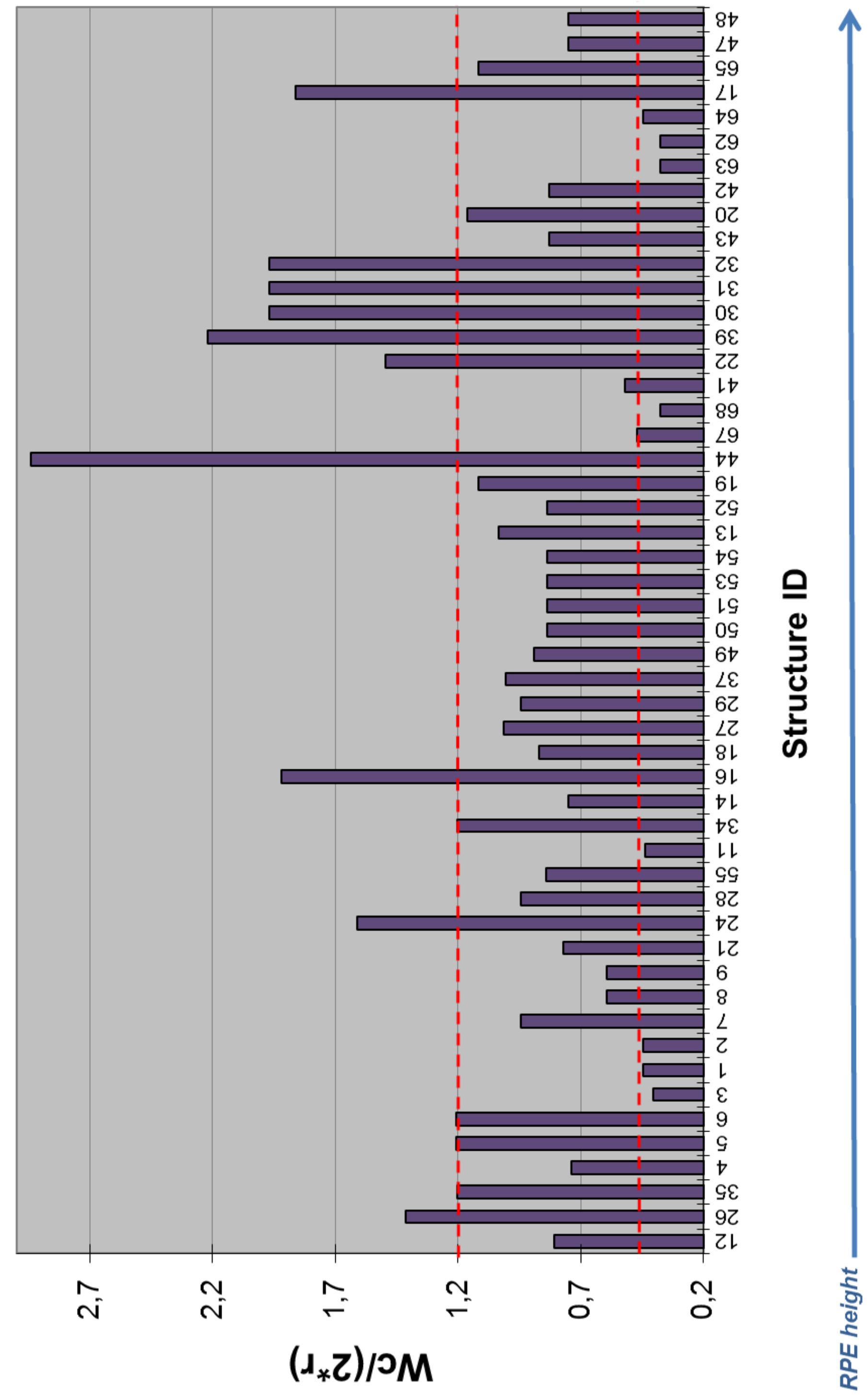

Figure 9 *Ratio of crest width to block size with limit values according to the approach proposed by Kister (2015)*

3.4. Discussion

The previous sections aimed at addressing the structural efficiency in resisting the impact by the block. Two approaches have been proposed to provide an expedient tool for roughly assessing the efficiency of the RPE from data related to the block and to the structure dimensions. These two approaches were developed based on different experimental data sets, and consequently have their own limitations and validity domains, in particular in terms of structure type. These two approaches may be considered complementary and, as a consequence, it is proposed to use these two approaches in parallel.

Among the 47 RPEs for which available data allow conducting these two approaches in parallel, 23 meet the C_{25} criterion (50%) and 14 meet the crest width-to-block ratio (30%), but only 6 meet both criteria (13%). Conversely, for 16 RPEs the two criteria are not met (34%). More notably, 12 RPEs are highly critical (C25 > 2 and crest width-to-block ratio < 0.5) for one of the two criterion (26%) and 2 are highly critical for both (4%). Considering that these criteria are based on different approaches with their own limitations, particular focus should be placed on this set of critical structures. For theses cases, further investigations may be conducted.

The functional efficiency of the RPEs is only addressed by the last approach. Basically, the functional efficiency is related to the uphill face inclination and to the freeboard.

3.5. Freeboard criterion according to ONR 24810

As already mentioned above, the functional efficiency of a RPE in case of an impact load is not only a question of the stability of the construction itself. The second scenario which has to be taken into account is the surmounting of a RPE by a block while the embankment will not be punched through and the damage is of minor extent. This part of functional efficiency is called fitness for purpose of a structure and has also to be taken into account for the design of a RPE. The Austrian standard ONR 24810 (2013) tries to solve this problem by defining different values for the freeboard depending on the construction type, the embankment's uphill slope inclination and the type of the facing (see part A of the report). As the minimum value defined in ONR 24810 the freeboard should be larger than one block diameter.

A freeboard had been listed in the available documents for 20 of the 68 embankments, this is about 30%. The freeboard dimension varies between 0.3 and 2.7 m and is shown in Figure 10.

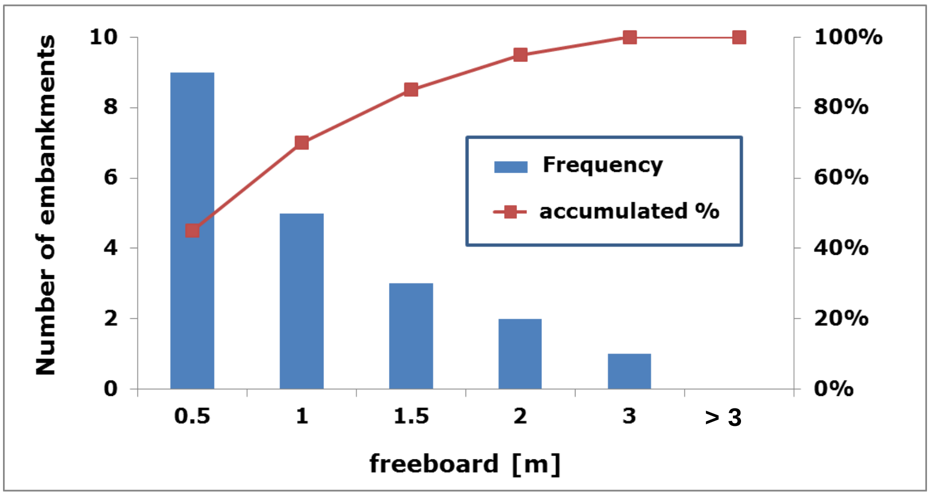

Figure 10 *Bar chart of freeboard used in the design of the RPEs*

Only for 11 of these 20 RPEs also the block diameter was given respectively could be calculated from the available data. Not one of these 11 RPEs fulfills the minimum value defined in ONR 24810. For 7 of the RPEs (8, 9, 10, 50, 51, 52, 53 and 54) the ratio of freeboard to block diameter was less than 0.25. For the design of RPE no. 3 and no. 22 the freeboard was chosen to be approximately the half block diameter. Only the part of RPE no. 2 with a batter of 70° and reinforcement comes up with a ratio freeboard to block diameter of 0.89 and therefore reaches approximately the minimum value of ONR 24810.

3.6. Post-construction events

Up to now only a few post-construction events had been recorded for the 68 embankments. Moreover the quality of the collected data differs widely. In most cases the block size is recorded and for a few examples a survey of the impact marks on the slope had been done. But an estimation concerning block energy or block velocity is missing.

In none of the recorded examples an embankment was punched through by a block. And in most cases the damage was relatively low and could be repaired with minor effort. On the other hand there exist examples, where a pure soil embankment had been surmounted by a block. This occurred for a trajectory perpendicular to the RPE axis as well as for a trajectory with an acute angle to the RPE axis.

No surmounting of an embankment with rockery at the uphill slope has been reported up to now. Only in one event a rock chip was released during the impact onto the rockery and it was able to surmount the RPE.

Figure 11 *Damage of a RPE with rockery at the uphill side after block impact (Tiefbauamt Graubünden)*

4. Conclusion

The analysis of the collected data allows drawing some conclusions regarding both the design methods in use and the Swiss structure park.

As for the design methods, the first remark concerns the difference in the definitions of the input parameter required for the design of RPEs. It has been shown that there was no consensus on the way to interpret and use the trajectory simulations results. In particular, the statistical estimator is extremely variable from one case to the other for both the block passing height and the kinetic energy (percentile). It is stressed that high percentile values requires high number of trajectory simulations to give relevant values, and more precisely high number of blocks passing the point where the passing height or kinetic energy is computed.
The second remarks concern basic geometrical definitions of the structure height and block passing height in particular. The different definitions observed introduce ambiguity that is detrimental to the structure design.
As an additional remark concerning the input parameters, the authors would recommend to promote conducting trajectory simulations accounting for the structure in the slope profile (2D or 3D) in order to provide relevant passing heights and kinetic energies of the block just before reaching the RPE. Nevertheless, it is reminded that most of the trajectory tools are not appropriate for simulating the rebound on the RPE face.

The consultation of the design reports revealed that a vast majority of RPEs in Switzerland are soil compacted structures with rockery uphill facing. The design of the structure height, including a freeboard, is extremely variable from one case to the other. Also, a limited number of RPEs were designed accounting for the dynamic loading, mainly considering the Austrian standard (ONR 24810). As a result of the absence of unique design method with respect to impact strength, a significant scattering is observed in the structure park in terms of structure dimensions for a given block kinetic energy.

In this context, the structure park was assessed with respect to the impact strength of the RPEs considering two approaches specifically developed for this purpose.
This expedient assessment method was applied to the structure park drawing the attention on 1/3 of the park that may not resist the impact by the design block. Based on this, further and detailed structure evaluations are suggested.

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