Rockfall Barriers - Design and Practice in Europe

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ABSTRACT: Within this paper, the present European approach to rockfall risk management is described. A definition of rockfall is given. Geotechnical investigations and input data are described. Differences in rockfall generation and triggering between Hong Kong and Europe are dealt with. Modern rockfall simulation as a means to define risks, protection requirements, dynamic loading and height of potential structures and selection of appropriate placement is presented. Technical possibilities of rockfall barriers and their actual limits are presented. Safety concepts based on probabilistic approaches are proposed. System testing requirements are discussed. The state of standardization in Europe is presented. Remarks on shortcomings and comments on actual developments are given. Finally an outlook into further developments is given.

INTRODUCTION

Because of its topography and dense population Europe has a lot of settlements and traffic lines situated in highlands and mountain ranges. It is the common goal of geologists and engineers to protect these facilities against avalanches, mudflows, slides and rockfall. Because of some spectacular accidents and the decreasing risk acceptance of the public new efforts were made in natural hazard mitigation and risk management since the seventies. Now, systematic mapping of natural terrain for risks assessment is required by law in Austria, France and Switzerland. Relevant legislations in other European countries are in progress. The German Railways have introduced a risk rating system of their own for all their earthworks and rock features along their 28.000 km of tracks. In rockfall mitigation, considerable progress has been made. To meet the new requirements, new design methods have been developed. New or improved barrier systems and a high safety standard become available in the market. Technical development in this area is still on-going.

DEFINITIONS

Rockfall is defined here as movement of single rocks or small groups of rocks, the size of pebbles or boulders or even bigger in free falling, sliding, rolling or toppling with subsequent bouncing or ongoing sliding/rolling. Deep seated instabilities, leading to typical rock slides are not covered by this definition. It has proved not practicable to include volumes or energies in this definition, because volume without velocity (kinetic energy) is not significant and kinetic energy itself may vary widely during the rockfall process, so that a rockfall may change classes several times on its way down a slope. Thus no reasonable limitation of size/energy can be given.

Risk is defined according to HINZEN (1996) as the product of probability and expected damage (Fig. 1).

Fig. 1: House at See, Austria, completely destroyed by a 30 m³ monolithic rockfall in 1995.

CAUSES BEHIND ROCKFALL

There are two groups of causes behind rockfall, depending on their size/location:

- Adverse joint patterns, insufficient strengths and water pressures in joints, which may cause failure by conventional deep seated rock mechanics failure modes.
- Mechanisms related to or near the surface of rock faces. There are considerable differences between Hong Kong and Europe because of their different climate.
  In Northern and Central Europe freezing and thawing is the main cause behind rockfall, followed by vegetation root pressure, in Southern Europe insolation and vegetation root pressure prevail. In Hong Kong water pressure in joints and surface erosion caused by heavy rainstorms may be the main causes, followed by root action and weathering.

DESIGN PHILOSOPHY

The present European planning procedure in rockfall mitigation can be summarised by the following general guidelines.

- Carry out **systematic mapping** on the slope to identify risk areas.
- **Avoid such areas** wherever possible, for example by moving intended structures to safe areas.

- If this is not feasible, **risk mitigation** is **required**.
- In selecting mitigation measures, **avoid ecological impacts**.
- Where this is not feasible, **minimize and compensate for ecological impacts**.
- **Avoid bulky systems**, prefer linear structures.
- **Use** preferably inconspicuous, light, **transparent structures** with high specific strengths.
- **Select economic solutions** (low construction cost, short construction time, long lifetime, low maintenance requirements, but high safety).

These guidelines lead to the following design steps.

- **Detailed geotechnical mapping** (size, volume and location of unstable rocks, features prone to cause rockfall, average and maximum size of boulders, parameters of slope surface) as first step of the design of all mitigation measures (for details see SPANG & SÖNSER, 1995).
- **Risk assessment** using rockfall simulation programs, like ROCKFALL.
- **Definition of design parameters**, especially of dynamic loading, geometry of barriers/ditches, dams, galleries etc., together with the selection/optimization of their locality based on rockfall simulation.
- **Selection of appropriate structures** mainly according to the required energy dissipation.
- **Optimization of dimensions** by use of probabilistic safety concepts.

Details will be given below.

GEOTECHNICAL MAPPING – WHAT IS IT GOOD FOR?

- Identification of the geological situation, including joint pattern and water regime.
- Identification of the rock mechanics qualities of the exposed material.
- Identification of unstable zones near or on the surface and their qualities.
- Establishing further input data for risk assessment.

GEOTECHNICAL MAPPING – WHAT BASE IS REQUIRED?

In most cases terrestrial or aerial photos will be used as appropriate base for mapping rock exposures. Aerial photos mostly are taken from helicopters, by oblique views; terrestrial photos from opposite sites. Conventional topographic maps are less adequate for steep slopes, because of their mode of projection. Additionally, sections showing profiles are required.

GEOTECHNICAL MAPPING – HOW IS IT DONE?

It is done by conventional geological and geotechnical mapping techniques, supported by photo documentation etc. In most cases it will be executed by mountaineering, because of the inaccessibility and steepness of the outcrops. Data are established by

- Direct visual stability evaluation of the outcrop's surface;
- Measurements by special transits, rules and tapes;
- Guessing parameters in the field by experience as far as they cannot be measured directly;
- Mapping traces of previous rockfalls (markings on trees, impacts on surface);
- Execution of in situ rockfall tests.

This Mapping should only be carried out by experienced specialists.

RISK ASSESSMENT

Risk assessment is done in several steps, by different approaches.

- **Global stability analysis**; it refers to deep seated problems of statical instability, dealt with by HOEK & BRAY (1981); based mainly on joint pattern analysis and subsequent statical calculations.
- **Local stability analysis**; this is mainly done during geotechnical mapping by visual evaluation; local instability refers to surface and surface near unstable zones; typical objects are loose rocks on the ground surface; ordinary rock mechanics stability analysis procedures (see above) mostly are not applicable; mechanical stability analyses by calculations are not economic, because of the generally small size and great number of unstable rock pieces.
- **Determination of the range of rockfalls** by use of rockfall simulation programs. By this step endangered objects are identified.
- **Determination of impact energies** and bounce heights at the protected zones where the endangered objects lie.
- **Sensitivity analysis** of the risk level; it is related to the damage which can be caused by rockfall, considering the dynamic resistance/energy dissipation capability, value of the endangered object, etc. There is – for example – a considerable difference between the sensitivity of a railway line, a road and houses. For ecample busy highways and side roads would require different safety factors by economic reasons.

At least the latter three steps should be supported by probabilistic analyses. This refers to the frequency of impacts, the probability of different magnitudes of kinetic energy as well as impact heights, which may have a decisive influence on the following step as well as on the magnitude of the resulting risk.

SELECTION OF MITIGATION MEASURES

According to the topography of the terrain above the endangered zones and kinetic energy and bounce height distributions along the slope profile obtained from rockfall simulation, the kind of protective measure(s) is preselected. Additionally non technical boundary conditions like land property, access etc. usually have to be considered, too. The two basic possibilities are

- divert, or
- stop rockfall.

Diversion is done by galleries, stopping can be done by a wide variety of structures, mainly depending on the required energy dissipation. Energies > 2,500 kJ require earth dams/ditches; energies < 2,500 kJ can be dissipated by barriers of different materials, where rigid steel, wood and concrete structures are nearly completely replaced now by flexible wire rope nets of different types and strengths. Fig. 2 shows the result of a geotechnical risk analysis and the recommended mitigation measures.

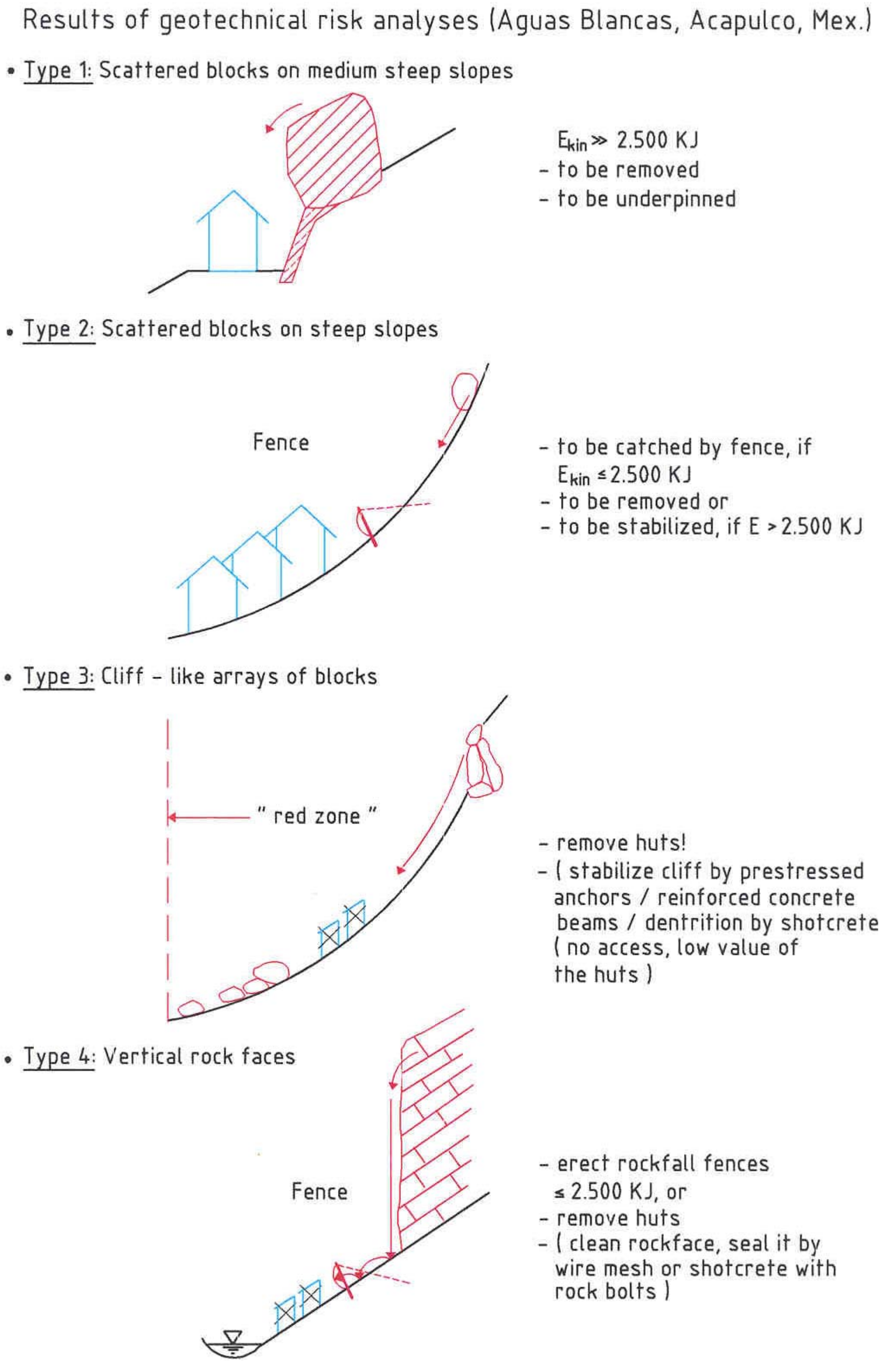


Fig. 2: Results of a geotechnical risk analysis and recommended mitigation measures for a slope above Acapulco, Mexico.

Between about 100 and 2,500 kJ the required tool to dissipate the impact energy are elements which can transform kinetic energy into heat (break elements) or into plastic or elastic deformation (steel tubes, springs etc.). The advantage of flexible structures is based on the fact that work on a system is defined as the product of force and displacement, **W = F · s**; for constant work, small displacements (rigid system) must lead to high forces, whereas large displacements (flexible system) allow for small forces within the system. Fig. 3 shows an attempt to combine a rigid steel barrier with elastic elements.

Fig. 3: Rockfall barrier built of steel beams and old tires at Matsubarako, Nagano Pref., Japan.

Final position(s), number, kind and dimensions of barriers are fixed by further simulations. Fig. 4 shows the result of a rockfall simulation by „Rockfall“. The results can be exported to CAD-systems for the production of detailed working drawings for construction. Because of the above, bidding has to be based on the required length, height and energy dissipation and other additional requirements like maximum displacement, corrosion protection, colour etc. Energy dissipation of the system which the manufacturers offer, has to be proven by tests and guaranteed by them, a detailed description of a system within the bill of quantities is therefore not possible.

The procedure can be summarised as follows:

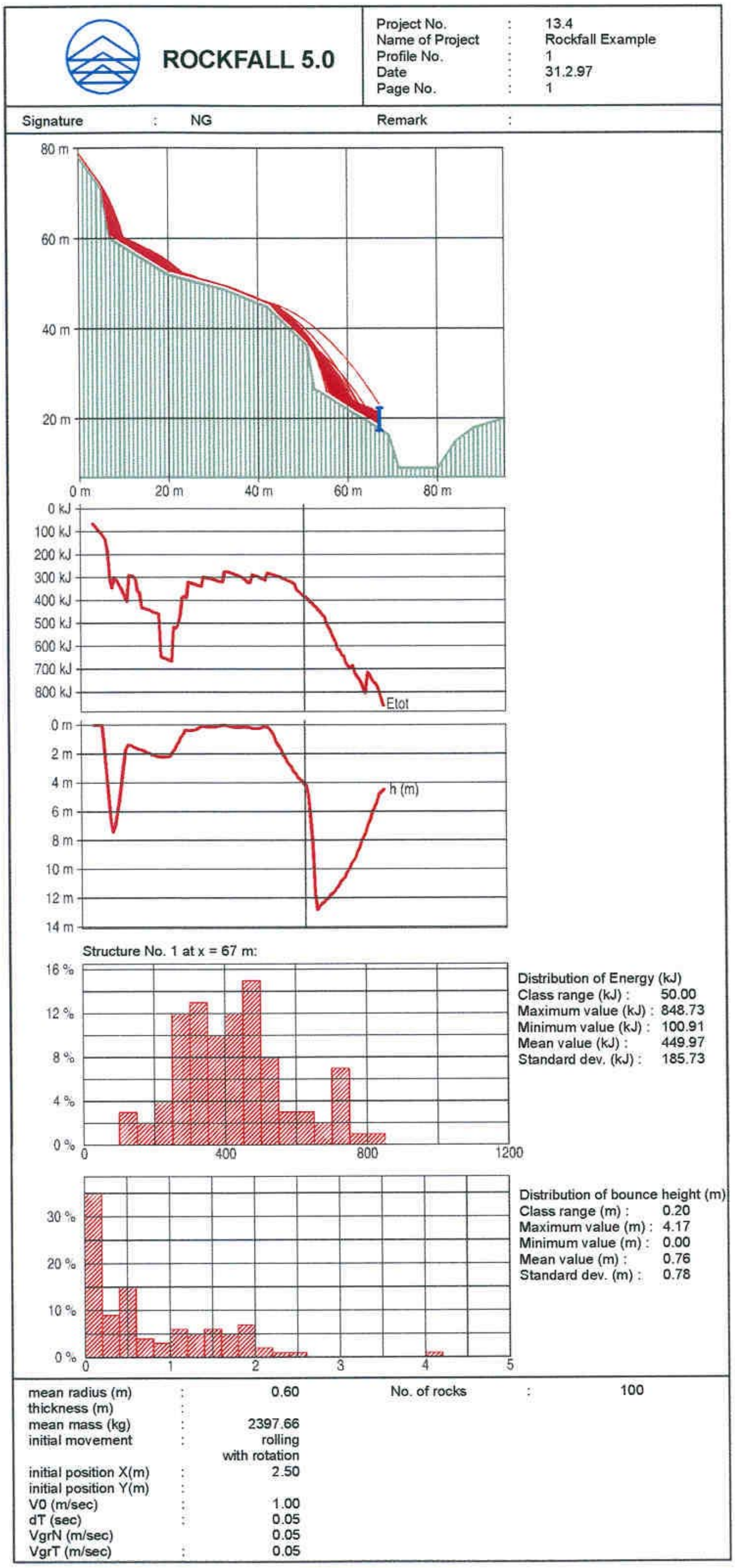
- Determination of the distribution of kinetic energy and bounce heights along representative slope profiles using rockfall simulation.
- Pre-selection of type, position(s) and geometry of protective structures and test these selections by additional runs.
- Change selections, if necessary.
- Final simulation with fixed geometries, positions etc. leads to confirmation of the adequacy of the selection. If not, go back to previous step.

STATE OF STANDARDIZATION

Actually there exists no standard for rockfall barriers in Europe or elsewhere. Planning and inplementation are based on personal experience and knowledge and are not fixed by written recommendations or official rules. The lack of standards is due to the youth and limitation of the market, as well as of the number of manufacturers.

It has to be stressed that a standard engineering approach to dimension rockfall barriers and their parts does not exist at the moment. The energy dissipation capacity of the different structures/products is known only by more or less extensive/systematic tests. Fig. 5 shows tests on rail and tie walls at Egerkingen. Besides very simple cases (rail and tie walls) there are also no structural calculation procedures at present.

Fig. 5: Rockfall tests on a rail- and tie wall near Egerkingen, Switzerland, 1992.



ROCKFALL 5.0

Project No. : 13.4
Name of Project : Rockfall Example
Profile No. : 1
Date : 31.2.97
Page No. : 1

Signature : NG
Remark :

Structure No. 1 at x = 67 m:

Distribution of Energy (kJ)
Class range (kJ) : 50.00
Maximum value (kJ) : 848.73
Minimum value (kJ) : 100.91
Mean value (kJ) : 449.97
Standard dev. (kJ) : 185.73

Distribution of bounce height (m)
Class range (m) : 0.20
Maximum value (m) : 4.17
Minimum value (m) : 0.00
Mean value (m) : 0.76
Standard dev. (m) : 0.78

mean radius (m) : 0.60
thickness (m) :
mean mass (kg) : 2397.66
initial movement : rolling with rotation
initial position X(m) : 2.50
initial position Y(m) :
V0 (m/sec) : 1.00
dT (sec) : 0.05
VgrN (m/sec) : 0.05
VgrT (m/sec) : 0.05

No. of rocks : 100

rockfall simulation with 100 rocks

profile and rockfall paths

envelope curve of kinetic energy

envelope curve of bounce height

distribution of energy on rockfall fence at x=67 m

distribution of bounce height on rockfall fence at x=67 m

general data

Fig. 4: Results of a rockfall simulation by „Rockfall“, for a railway cut near Moutier, Switzerland.

FIELD TESTS

Field tests are usually executed as free falling tests, direct launch tests, (up to now also without spin, indirect launch tests with spin, but scarely executed). In most tests rock hits the centre of the panel, no systematic tests were known up to now, where all potential target points, including the outer edges of the panels, had been tested under different impact angles. Also only very limited numbers of tests have been carried out with measuring devices for accelerations and deformations and the data are not published.

SAFETY CONCEPTS

A barrier may fail by two different failure modes:

- **Geometrical failure** – the structure is jumped over, because its height is insufficent;
- **Structural failure** – the structure is not strong enough to withstand the impact.

With reference to STOCKER (1997) there are 3 different possibilities to define safety factors against these failure modes.

- **Safety factors as a lump sum** on the load (structural safety) and on the bounce height (geometrical safety). This is the old fashioned way. By applying usual factors of 1.5 to 2.0 this procedure can lead to cases, where the kinetic energy at the barrier is bigger than the potential energy at the original location. Obviously this procedure leads to unrealistic, very conservative and uneconomic solutions.
- **Application of partial safety factors** on all input data, for example on the rock volume, rock density, friction angles, damping etc. Following STOCKER (1997) this usual approach leads to physically meaningless input data and to the multiplication of safety factors, which results in a total safety of unknown magnitude, it may lead to ultra-conservative solutions too.
- **Probabilistic approach**, using a random number generator to vary all input data during rockfall simulation as it is the case with „ROCKFALL“; all input data are given by their mean values and by their range, considering the uncertainty of their determination (SPANG & SÖNSER, 1995). By a sufficient number of rocks the rockfall simulation delivers energy and bounce height distributions at the barrier positions, where each value corresponds to a certain probability. To determine the design values, a certain probability of their occurence has to be selected. It is recommended to use as many rocks as is necessary to come to identical maximum values for two consecutive calculations with the same input data, but different numbers of rocks (depends on the slope profile and the range of input data) and to select probabilities between 5 and 2 %.

This procedure was suggested by the Swiss Ministry of Ecology, Traffic, Energy and Communication in 1998 for the dimensioning of rockfall protection galleries. A probability of 7 $*10^{-4}$ (one event amongst 1,500) is proposed as design base. This suggestion may lead to an unsafe design, because it doesn’t take frequency and lifetime into consideration. The probability P_1 of a rockfall with a certain energy within a certain number of rockfalls alone is not a sufficient base for decisions. The number of events per year must be considered too. This number can be taken from field observations or from guess work. The probability of a design rockfall within 80 or 100 years can be determined by multiplication of the probability P_1 and the number of events per lifetime. This procedure is recommended as appropriate, although there is a lack of definitions of tolerable probabilities up to now. It shall be eliminated soon by the actual discussion on probabilistic safety concepts within the engineering community. Further refinement could be added by considering the probability of a hit on the endangered object, if this is moving as traffic on a road or trains.

By the way, this approach is similar to that one used for dimensioning sewers – not the biggest event is the design base, but an event with a defined return period. This approach includes – of course - a statistical risk, that the barrier may fail, but this is inherent in every engineering structure. Only relative degrees of safety do exist.

CONCLUSIONS

Present rockfall mitigation in Europe is technically based on 3 main pillars:

- Thorough geotechnical mapping;
- Use of sophisticated rockfall simulation programs;
- Use of flexible barriers for energies up to 2,500 kJ.

This concept is also valid for the specific situation of Hong Kong.

This author has engaged in rockfall mitigation for more than 20 years. It is his strong belief that further progress in this field can only be archieved by

- Improving the geotechnical input;
- Application of probabilistic safety concepts;
- Design of realistic test procedures combined with adequate instrumentation and scientific evaluation of the results;
- Development of mathematical approaches to understand the dynamics of rockfall barriers.
- Development of technical standards for planning, construction, testing and maintenance – most preferably at the international level.

This task is too big for single any individual researchers – it is recommended to set up an international team of engineers, physicists and mathematicians for this task. This author would be happy to join!

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