4 ROCKFALLS

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4.1 INTRODUCTION

In order to assess the technical possibilities of individual rockfalls or catastrophic falls of large rock masses, it is first necessary to briefly define which types of phenomena will be considered, as well as their intensity and probability of occurrence. According to a generally admitted classification, the generic term *landslides* includes all gravity induced movements of a soil or a rock mass along a slope (WP/WLI 1990). Five major mechanisms can be distinguished:

fall topple slide flow spread.

The major characteristic for rockfalls is the suddenness of their occurrence, associated with the high particle velocity. Block velocities of 20 to 40 m/s are commonly observed on landslide sites.

Rockfalls consist of free falling blocks of different sizes which are usually detached from a steep rock wall or a cliff, after an initial block *toppling* (block overturning) or a *local slide*, associated with gravity, water pressure in the joints or adjacent block thrust. The block movement also includes bouncing, rolling and sliding with rock block fragmentation during slope impact (Fig. 4.1).

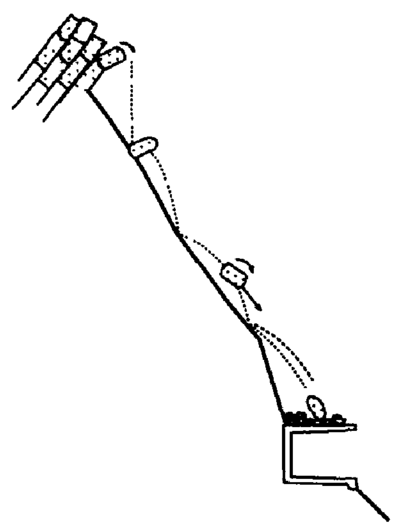

Fig.4.1 Different particle positions during a rockfall.

In Switzerland, an important research programme called *Matterock* has been accomplished recently (Rouiller et al 1998). It deals with the study of the structural pattern of the cliff, confronted with the local topography and with the assessment of the probability that a rockfall can occur, for a given volume and shape.

Rock block *fall analysis methods* are used in order to predict the block path and the block energy during movement (Giani 1992). A block detached from a rock face may have the following types of movement during flight: free falling, bouncing, rolling, or sliding. Analytical procedures for the mathematical description of the rockfall phenomenon, that consider the geometrical and mechanical characteristics, have been set up by several researchers in the last twenty years. The analytical formulations can be divided into two categories: rigorous methods and lumped mass methods. In the *rigorous method analysis*, the size and shape of the blocks are assumed to be known "a priori" and all the block movements, including those involving the block rotation, are considered. In the *lumped mass method*, however, the single block is considered to be a simple point of mass m and velocity v. Therefore, the rotational moments are not taken into account.

When focusing on the relation between the dangerous natural phenomenon and the man-made structures to be protected (buildings, roads, lifelines), it is worth noting that the disaster resilient infrastructures have to be designed mainly in the *slope* exposed to rockfalls, because no relevant protection can be taken in the source area, except some attents of local stabilisation in the cliff zone. This is often hard to attain and dangerous to modify.

4.2 ROCKFALL RESILIENT INFRASTRUCTURE

4.2.1 Stabilisation methods

The modification of the cliff geometry by drilling and blasting is an hazardous solution, associated with difficulties in *controlling* the fall of the blasted rock itself as well as in *assessing* the stability of the remaining rock masses.

However, the face of the cliff can be protected by bolting and shotcreting in order to reduce the rate of weakening of the rock mass or of the weathering process. The *remedial works* are not easy to execute and their effectiveness difficult to quantify by means of stability analyses or visual observations.

4.2.2 Protecting measures (Fig. 4.2)

The *design* of protecting measures involves the evaluation of the rockfall characteristics and the slope geometry (Descoeudres 1997). Rockfall modelling allows the designer to compute the maximum possible length of the path of a flying block, the distances between the bounces, the elevation of the block trajectory above ground, the velocities and the energy assumed by the block at any time of the movement. In situ observations of past rockfall damages allows calibration of the model.

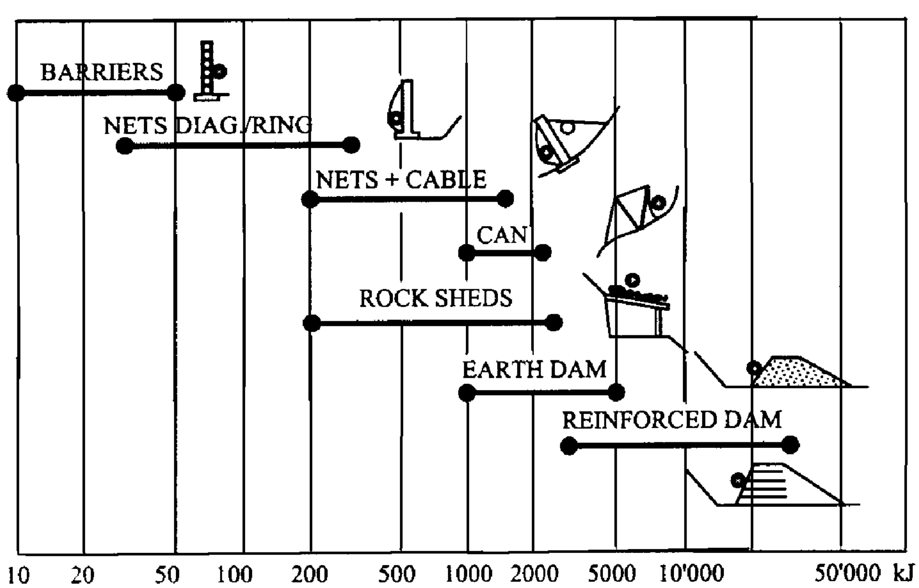

Fig. 4.2 Energy dissipated by different protection structures.

Modification of slope geometry

The creation of benches or ditches in a slope to stop falling blocks can be effective. The position of the *benches* is designed by simulating a large number of rockfalls in a computer model where the benches are incorporated. The rock exposed on the plane of the beams can be covered with uncompacted rockfill or earthmaterial to absorb a large part of the impact energy.

Slope *ditches* are used to catch the blocks after a fall to prevent rolling or to change the block movement from falling to rolling. Rockfall modelling can also be applied for the best ditch positioning and for the ditch geometry design (depth and width).

Barriers and wire net systems

Rail walls and other *stiff barriers* are often used, either individually or in combination with ditches. Their capacity of energy absorption is low. The kinetic energy of deformation is about 10 to 50 kNm or kJ.

Flexible wire net systems, supported by hinged steel posts, have been extensively developed during the last ten years. A detailed description is given in section 4.3. The energy absorbing capacity has been improved from about 250 kJ in the 1980ies to more than 2'000 kJ nowadays with ring net constructions.

Rock Sheds

Rockfall shelters are usually concrete structures covered on the roof by an absorbing material such as soil backfill used as a shock absorbing cushion. These protecting structures are expensive but efficient, and consequently used in areas with serious rockfall problems. A detailed description and design approach is given in section 4.4.

Reinforced earth retaining structures

Earthdams, often reinforced at the upstream-impact slope with strip / sheet metallic or wire elements, can absorb the largest kinetic energies of falling rocks, up to 30'000 kJ. The impacts of blocks of about 20 to 30 tons with velocities of 30 to 40 m/s create important deformations in the earth dam. A periodic control of the works is therefore required. Reparations are possible after a major event.

4.3 WIRE NET ROCKFALL BARRIERS

4.3.1 Introduction

For the last ten years, flexible wire net systems have become an integral part in the protection against rockfall. These modern structures consist of steel wire nets supported by hinged steel posts, which are tied back by wire ropes that contain rope brakes (Fig.4.3).

In order to stop a rock, the maximum kinetic energy of the rock has to be smaller than the energy absorbing capacity of the rockfall barrier. For the last ten years, this energy absorbing capacity has been considerably improved by the use of more sophisticated structural components and structural alterations. In 1985, rocks with a kinetic energy of about 250 kJ could be stopped; nowadays, ring net constructions capable of withstanding more than 2000 kJ are possible (Gerber and Haller 1997). These results could not have been achieved without co-operation between industrial firms and research institutes. This applies particularly to the testing of structural components and complete systems. Rockfall barriers have been tested in different countries (e.g. USA, Japan, Taiwan, China, France, Italy, Switzerland) and world-wide contacts between researchers are quite close. In Switzerland, extensive full-scale testing has been carried out by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) and two industrial firms, one of the latter having a world-wide reputation for its flexible rockfall barriers. In the following, some major results will be presented.

Fig.4.3 Rockfall Barrier with Brake Rings and Strain Gauges.

4.3.2 Full-Scale Testing of Rockfall Barriers

The testing site at Beckenried in Switzerland is characterised by a fairly stable rock surface with a slope angle of about 45°. In the first tests (Test Series 1) a cable crane was used to move the rocks up to the top of the slope from where they were set into motion, accelerated down the slope and - after several impacts with the ground - ended in the barrier, which was to be tested. Due to this set-up, the energies acting onto the barrier differed considerably. All the same, in 1990 a first important step in the development of rockfall barriers was reached, namely, the improvement in energy absorbing capacity from about 250 kJ to about 400 kJ. This was, so to say, the birth of the highly flexible type of rockfall barrier, internationally employed ever since.

The aim then was to obtain higher values of a rock's kinetic energy and, accordingly, of the barrier's energy absorbing capacity. To this purpose, a new cable crane was installed. In Test Series 2, the rocks remained suspended from the cable crane during part of its downward motion, were released in full flight some distance above the barrier and hit the ground prior to rolling or bouncing into it. The impact velocities were mostly lower than 20 ms^{-1}. In Test Series 3, the rocks were aimed directly from the downward moving cable crane at the rockfall barrier with a given velocity of about 26.5 ms^{-1}. This set-up made it possible to not only calculate the energy of a rock in advance, but also to hit specific points of the barrier quite accurately. In 1992 Test Series 3 raised the energy level to about 1000 kJ (Gerber and Böll 1993) and by the end of 1997, 2000 kJ could be absorbed.

Comparing international results, it is essential to stress the fact, that all the maximum values of impact energy mentioned in the context with our tests, were fully absorbed by the rockfall barriers themselves. That means, that no ground contact occurred during the deceleration phase of the rock in the net, and that the systems suffered no damage.