Optimized Rockfall Protection by „ROCKFALL“

Protection optimée contre la chute de pierres en usant le logiciel „ROCKFALL“

Optimierter Steinschlagschutz mit dem Programm „ROCKFALL“

R. M. Spang
Geoplan Dr. Spang GmbH, Geotechnical Consultants, Witten, Germany

Th. Sönser
Federal Ministry of Agriculture and Forestry, Foresttechnical Service in Torrent & Avalanche Control, Innsbruck, Austria

ABSTRACT: In the past rockfall mitigation was based on experience only. Generally neither rockfall paths nor energy dissipation capabilities of structures were known. By extensive in situ rockfall tests this shortcoming could be overcome during the last years. Energy dissipation capability of structures is well known now and will be still increased by future developments. This article summarizes test results on various structure types and tries to classify structures according to their energy dissipation capability. Meantime also rockfall simulation is feasible thus delivering rockfall paths and energies for dimensioning. A summary of these programs is given. „ROCKFALL“ was developed since 1979 to support design work for many rockfall mitigation projects. The program and its input data are described. Some general aspects of crucial input data are discussed. Especially normal and tangential damping are dealt with. Problems to establish input data led to the development of back calculation methods with different degrees of sophistication. Two examples show typical applications and capabilities of rockfall computer simulation using ROCKFALL. Finally future needs in development and research are discussed.

RESUME: Il y a quelques ans la protection contre la chute de pierres eté fondée seulement sur l’expérience. La capacité d’ absorption d’ énergie n’ etait pas connue comme aussi l’ énergie des pierres était inconnue. Par des nombreux essais de champs la capacité d’absorption d’ énergie de les types différents de constructions protégeantes est bien connue maintenant. Dans cet article premierèment les séries des essais les plus importantes sont demontrées. Les constructions protégeantes sont classifiées selon leur capacité d’ absorption d’ énergie. Par le development des logiciels de simulation de chute de pierres on peut calculer maintenant les hauteurs des sauts et les énergies cinématiques le long des profiles de pente. Dans cet article certains logiciels de simulation de chute de pierres sont demontrés, leur caractéristiques sont élaborées. Dans la deuxième part de cet article le logiciel de simulation de chute de pierres „Rockfall“ est presenté et appliqué, que l' auteur premier a developpé depuis 1979. Les demandes aux données sont décrites. Des problemes speciaux de la sélection des quelques de cettes dates sont discutés. En détail, la résistance au roulement, la géométrie des pierres et l' atténuation normale et tangente sont presentées. Pour la définition des données des méthodes différentes de la calculation arrière des chutes de pierres et des essais de champs sont usés. A la base de deux examples actuelles les applications typiques du logiciel „Rockfall" sont demontrées. A la fin la nécessité des investigations scientifiques et des developpments en future sont expliqués.

ZUSAMMENFASSUNG: Bis vor wenigen Jahren beruhte der Steinschlagschutz ausschließlich auf Erfahrung, nachdem weder das Energieaufnahmevermögen von Steinschlagschutzbauwerken, noch die in der Trasse ankommenden Energien bekannt waren. Durch umfangreiche Steinschlagversuche ist inzwischen das Energieaufnahmevermögen der verschiedensten Bauwerkstypen hinreichend bekannt. Die wichtigsten Versuchsreihen werden dargestellt und charakterisiert. Steinschlagschutzbauwerke werden nach ihrem Energieaufnahmevermögen klassifiziert. Durch Entwicklung leistungsfähiger Steinschlagsimulationsprogramme können inzwischen auch Sprunghöhen und kinetische Energien entlang von Hangprofilen berechnet werden. Eine Reihe von publizierten Steinschlagsimulationsprogrammen werden dargestellt, ihre Charakteriska werden herausgearbeitet. Im zweiten Teil des Beitrags wird das Steinschlagsimulationsprogramm „ROCKFALL" vorgestellt und verwendet. Die Anforderungen an die Eingangsdaten werden beschrieben. Spezielle Probleme der Festlegung verschiedener dieser Eingangsdaten werden diskutiert. Speziell wird auf die Rollreibung, die Geometrie des Steinschlags und auf die normale und tangentiale Dämpfung eingegangen. Probleme bei der Festlegung von Eingangsdaten führten zu verschiedenen Methoden der Rückrechnung von Steinschlagversuchen und natürlichen Steinschlägen, auf die im weiteren eingegangen wird. Anhand von zwei aktuellen Beispielen werden typische Anwendungen des Steinschlagsimulationsprogramms ROCKFALL dargestellt. Schließlich wird auf notwendige zukünftige Forschungs- und Entwicklungsaktivitäten eingegangen.

Introduction: Decreasing acceptance of natural risks by the public and increasing acceptance of personal health risks especially in extreme sports are one of the most prominent features of the outgoing 20th century. Desaster prevention therefore became one of the most important aspects of public interest in geotechnical engineering. Not any natural risk like earthquakes, tsunamis, volcanic eruptions, floods and landslides can be so simply foreseen and prevented as small scaled rockfall. It is not amazing therefore that due to intensive theoretical and practical investigations during the past 20 years a state of the art was reached where rockfall mitigation became a common subject in rockslope engineering practice. The main problems of geotechnical slope surface stability analysis, determination of potential rockfall paths and dimensioning of retaining structures as for their required height and energy absorption capacity are widely solved. The initial step in this development was the execution of in situ rockfall tests mostly by manufacturers for improvement of their retaining structures design. Table 1 gives a general idea of the most important ones.

Tabelle 1

Mostly single rocks were released, kinetic energies went up to 1.200 kJ. Only two test sites exposed soils, the other tests were executed on rock surfaces. Attention shall be payed to the fact that not all of the tests led to angular velocities and therefore to realistic test results. This is the case for all free falling tests and tests where rock was thrown into the structure by mere translation.

From these tests modern retaining structures could be developed and improved. As shown by table 2 a wide range of energy absorption between 20 and 2.300 kJ is available now. Systems with even higher energy absorption capacity are under development. 5.000 kJ might be expected for the next few years.

Tabelle 2

Table 2: Classification of retaining systems according to energy dissipation

Figure 1

Figure 1: Fundamental rockfall retaining structures dimensioning and positioning problems; E = energy absorption capacity; h = required structure height; 1 - 3 possible locations.

Inspite of these approven possibilities of rockfall mitigation the problem of selecting the appropriate system and its height for a certain location remained, as is shown in principle by figure 1. Its solution required adequate progress in rockfall simulation resp. in the calculation of rockfall paths. A summary of different approaches to rockfall simulation is given by table 3. In general they are based on the laws of motion and reduce rockfall to a mass point. Only few of them consider angular velocity; only one calculates rockfall paths in three dimensions. Mostly spheres and cylinders are considered. There are important differences regarding user's convenience, data input and output, graphic possibilities and parameter variation.

Tabelle 3

Within this publication an actual version 3.0 of SPANG's (1988) Rockfall Simulation Program in used. Main improvements are since then:

- Visual basic instead of Fortran 77
- Windows surface

- Automatic parameter variation of all slope quality parameters but general slope geometry with up to 1.000 rocks/run
- Consideration of cylinders/disks
- Roughness angle to simulate uneven irregular slope surfaces
- Graphic screen/printer/plotter output of slope geometry and rockfall paths
- Graphic output of energy and height distribution along slope profile.

Input data for ROCKFALL: Table 4 gives a list of main input data required by ROCKFALL.

Tabelle 4

Whereas most input data can be determined easily, four of them are really difficult to establish and no general accepted methods or orders of magnitude do exist. These factors are discussed below in detail.

Roughness Angle: Depending on usual survey techniques, economic reasons and number of data limits, continous surveying of slope surfaces is practically not available. Usually the slope surface is considered therefore as a polygonal sequence of linear sections, modelled as slices with vertical boundaries and linear surfaces with constant inclinations between them. It is known however from rockfall tests as well as from direct evidence that slope surfaces can be extremely uneven, and randomly ondulated. Thus simple computer simulation will show a boulder merely rolling down an inclined plane. Whereas a boulder will suffer a lot of impacts on asperities by travelling down a natural slope surface leading to bouncing. As the resulting energy transition is completely different the calculated path will be highly inappropriate and invalid. Therefore a roughness angle was introduced which is applied and varied by the program within a selected range, leading to randomly distributed impacts and interruptions of mere rolling or sliding. Because natural asperities are also randomly distributed as for their slope angles and positions, this procedure leads to realistic modelling of rockfall paths.

Adequate values are determined in the field along representative reference lines by conventional surveying. Measurements comprise base lengths and heights of asperities, resulting in medium/maximum inclinations.

Rolling Resistance: It is obvions that rolling resistance is important within generally gentle slopes or within slopes exposing gentle sections. Rolling resistance may also become important in slopes with high damping factors where bouncing fastly fade. If rockfall tests are executed, rolling resistance can be determined according to figure 7, if either speeds or times or „footprints“ are known.

Usual ranges of rolling resistance for different surface conditions can be taken from literature. Generally accepted values are shown in table 5. Rolling resistance can be determined by rockfall experiments to a satisfying degree of accuracy.

Tabelle 5

Normal damping: Normal damping or factor of restitution ε was first described by NEWTON (1686). According to him the factor of restitution governs the normal component of velocitiy after impact and can be defined as shown by Figure 2. Is is known that the restitution factor is depending on velocities and geometries of the colliding bodies. For rockfall analysis this aspect is generally neglected. The influence of this assumption is unknown.

Figure 2

Figure 2: Oblique excentric impact of a sphere with definition of the coefficient of resistution ε acc. to NEWTON for pure rolling along contact plane.

To give an idea of the realistic range of values of the factor of restitution, Table 6 shows laboratory values for different materials.

Tabelle 6

Using NEWTON's definition, values for rock to rock and rock to soil interactions must be expected to be very small. This was proven by intensive compaction tests by BEINE (1986). Figure 3 shows measurements of acceleration and velocity after impact of a 17 kg model mass in loose sand after free falling from 2.1 m. The impact velocity is 0.02 m/s. The resulting factor of restitution is about 0.003. It is conceeded that this value may range at the lowest limit of realistic values. Values of 0.5 and even higher, which are used for example by HOEK (1987), are obviously based on other definitions of the factor of restitution, they are therefore not comparable.

Figure 3

Figure 3: Velocity vs. time graph for impact of a 17 kg modelmass, diameter 0,15 m, after free falling from 2.1 m down to loose sand, acc. to BEINE (1986), derived from acceleration measurements.

Because free falling or rebound tests are difficult to be executed and laboratory tests for the determination of the factor of restitution are not applicable until now, rockfall tests and back analyses seem to be the only means to arrive at realistic values. These values should be low as stated above.

Tangential Damping: Free falling is one of the common starting modes of rockfall and bouncing is common in steep slopes. Besides in the rolling mode and in fewer cases in sliding, impacts are therefore governing energy balance and path of rockfall. According to the laws of motion a body changes its direction and its translational velocity and - if the impact is not central - its angular velocity during impact. Rockfall in general leads to excentric oblique impacts as shown by figure 2. The effect of angular velocity on rockfall path can be taken from figure 4.

Figure 4

Figure 4: Influence of angular velocity on rockfall path for $\varepsilon = 0.5$, DF = 1; a: without angular velocity, b: with angular velocity regarded.

Changes in direction and velocities are by theory governed exclusively by the above described factor of restitution and by friction between rockfall and slope surface. There is no additional tangential damping incorporated. Because most authors report on tangential damping, the factor was incorporated in ROCKFALL for comparison of results. It is seen, that tangential damping leads to steeper throws which don't seem to be realistic.

Geometry of Rockfall: In nature, rockfall will never be spherical or ellipsoidal, inspite of the fact that most (or all) published rockfall simulation programs are using spheres or ellipsoids. The effect on resulting paths might be practically negligible in bouncing, but differences become obvious in rolling. While a sphere will merely roll down an inclined plane, if friction is high enough, governed by rolling resistance, an angular block's velocity will be governed by corner/aerea/slope contacts and with growing angular velocity by corner/slope collisions, i. e. a transition to bouncing occurs (figure 5). This may be also facilitated by excentricities. Rolling resistance and damping effects in general will not have the same effects on path parameters, thus leading to different rockfall paths. To minimize these effects in simulation the above described roughness angle was completed by a distance factor. This factor leads to a randomly selected interruption of uniformly inclined slope sections in the rolling or sliding mode, forcing rockfall to bounce. Depending on the normal damping coefficient these bounces will be short and will soon be damped to zero or will become common for this section.

Figure 5

Figure 5: Rockfall geometry, kinds of motion and resulting paths; a: rolling of a sphere; b: sliding of a prism on even surface; c: rolling and d: bouncing of prisms.

Output: ROCKFALL's output consists of tables and graphs. Table 7 lists the most important output data and explains their meaning, figure 6 gives a typical graph. All input data can be printed also.

Tabelle 7

Figure 6 explains the use of ROCKFALL for positioning of structures and selection of structure type and height. The upper drawing shows the slope profile together with the single traces of rockfall; the drawing in the center shows the total energy distribution and the lower drawing the path height distribution along the slope profile. If, for example, a heavy rockfall structure with a height of 3 m is under discussion, figure 6 gives the positions where such a structure will be sufficient. At the same time it also shows optimal positions as for structure height and energy absorption capability. Also existing structures can be classified by comparison of required and available qualities.

Figure 6

Figure 6: Rockfall's output and its application for protection works selection and positioning.

Calibration Methods in Back Analysis: As explained above at least rolling resistance and restitution coefficient have to be established by back analysis of rockfalls, because the actually available experience is not reliable enough to take them from geotechnical mapping or index properties/index tests, as it will be desireable for the future. There exist several methods for the required calibration of input data from rockfall tests:

- „*Footprint Criterium*": i. e. variation of input data to get just the same paths („identical footprints") in calculation as observed in nature.
- *„Final reach/run time criterium"*: i. e. variation of input data to reach at the same final position where rockfall stopped or was stopped in nature/to reach at the same time rockfall was travelling between start and rest.
- „*Similarity Criterium*": i. e. variation of input data to reach at similar paths as natural rockfall exposes.

Figure 7 explains the resulting back analysis methods as:

- *Exact Tracing Method*, and
- *Limited Parameter Variation Methods*.

Their advantages and disadvantages are discussed below.

***Figure** 7*

Figure 7: General approaches to parameter calibration in back analysis; A: Exact tracing; B: Limited parameter variation methods.

At first sight Exact Tracing seems to be the more reliable procedure. In practice it may be like looking for the center of the most critical slip circle in slope stability analysis. Tracing can be applied, if the following conditions are fullfilled:

- Rockfall tests are feasible/available or natural rockfall occured.
- Footprints are clearly recognizeable or good video registration exists.
- Surveying is done with high accuracy i. e. with adequate distances of measuring points.
- Between independent paths of different rockfall tests/rockfall events only minor differences exist within the same profile.

These favorable conditions may occur not too often, because they are mostly linked to simple slope geometries, smooth slope surfaces and regular rockfall geometries. In every other cases the Limited Parameter Variation Methods will prove more adequate, because travel paths with their decisive rockfall - surface interactions are subject to chance and the resulting energy/height - distributions are randomly spaced within a specific range.

By the way Limited Parameter Variation is the only possible method in cases where tests are too dangerous and natural rockfall events are not adequately reported. Resulting uncertainties can be covered by defining a wider range of possible slope quality parameters and by executing an even greater number of simulations.

Examples: On November, 6th, 1993, a rockfall of about 300 to 500 m³ occured from the western slope of the Dristenschlag Mountain, near Karlsteg, Austria. The major part was stopped within a small gorge, from which flank it originated, a smaller part reached a federal road at the toe and blocked it. The block size was up to 20 m³ and more. The material consisted of gneiss of the central Tauern window.

Geotechnical mapping exposed a lot of instable situations and an ongoing danger for the road and a nearby resthouse.

ROCKFALL proved that short bounces were prevailing near the toe, but energies were beyond the capacity even of very heavy fences.

It was decided therefore to protect the road and the building by an earth dam with a steep hillside slope to prevent rocks from overrolling the crest. Figure 8 shows the general situation after rockfall had occured.

Figure 8

Figure 8: Rockfall at Karlsteg, Austria; general situation; western slope of the Dristenschlag Mountain with blocked road at the toe.

Figure 6 shows the result of a rockfall simulation for protection works at Stumm, Unterwald, Austria. A residence area was endangered by repeated rockfalls up to 2 m^3. The rocks consisted of hard quarzphyllite. The source area exposed a lot of instable situations, thus leading to the suggestion of building a rockfall fence just above the buildings, where the slope flatened. The main aspects from figure 6 are:

1) Locating a single fence at the toe is feasible, a very heavy fence with a energy absorption capacity of at least 2.000 kJ and a minimum height of 2 m is necessary.
2) If there is any access to the slope surface, a combination of a heavy fence at about x = 30 with an energy absorption of 1.500 kJ and a minimum height of 1 m and a second light fence at the toe would lead to a more economic solution.
3) The cheapest solution may be a sequence of light and very light fences above the steps just preventing rockfall from getting high speeds and energies.

The latter solutions would require additional runs, which are not shown in this paper. A final decision about the solution to be carried out was not taken until this paper was written.

Conclusions: For rockfall mitigation powerful design procedures and retaining structures have been developed within the last 10 to 20 years. There is no further need for guessing energy absorption capabilities and structure heights. Furthermore optimized positions can be located by rockfall simulation. Nevertheless there is a need in further research and development in some decisive points. These are:

- The effect of general rockfall geometries resp. block geometries should be clarified and modelled.

- From rockfall tests and from rockfall events data about relevant slope surface qualities, as rolling resistance and normal damping should be collected and ranges of realistic values should be established for different surface materials.
- Additionally laboratory and index tests should be developed for direct or indirect determination of these values.
- The 100 %-catchment-philosophy, which actually prevails, should be replaced by probabilistic safety concepts, based on energy vs slope length and height vs slope length distributions and risk analyses regarding also rockfall frequency and impact-on-structure probabilities.
- In addition to fockfall tests case histories on the behaviour of rockfall fences during real impacts should be collected. The authors would be very grateful for each such report.
- Development of energy absorption capabilities of fences should be enforced and energy absorption of earth dams should be tested. Earth dams obviously sustain even several times more energy input as fences ever will do.

All these measures will further improve risk assessment as well as improve safety against rockfall of our residence areas and traffic lines and help us to do this with greater economic efficiency.

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* Westfalenstraße 5 - 9, D-58455 Witten

** Liebeneggstraße 11, A-6020 Innsbruck

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