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Rockfall, a “wanted” circular

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Abstract

Rockfall is a common phenomenon in steep rock slopes. To eliminate or to reduce resulting risks, modern rockfall barriers are available offering high energy dissipation capacities. For their design, detailed knowledge of the conditions for rockfall generation is necessary. This includes its prerequisites as slope inclination and existence of unstable material on the surface, rockfall generation and triggering as well as its path. First, rockfall is defined and described. The causes behind the generation of unstable material on a slope surface are explained. Different triggering mechanisms are enumerated. The initial mode of motion of a rockfall after it was triggered is described as well as the subsequent modes. Decisive parameters for the occurrence of the different modes of motion are described. Velocity, kinetic energy and reach of a rockfall are explained.

Introduction

Rockfall is a threat to many traffic lines, technical installations and residence areas in mountainous regions all over the world (Fig. 1). In times of decreasing public acceptance of the consequences of natural risks authorities are busy with risk assessment and mitigation programmes, whereas law courts are gradually leaving their long-applied practice of classifying rockfall as “force majeure”.

Originating from steep inaccessible rock faces, resulting from local instabilities randomly distributed over large source areas, randomly occurring and attributed with high destructive potential rock fall is a real threat, difficult to predict and generally not to eliminate by local measures. Thus rock fall-prone areas had been avoided as residence areas for many centuries. Traffic lines through mountainous terrain and alpine installations had to live with rock fall risks so long. But ground became steadily more expensive and housing and industrial areas expanded into risky zones, cable cars needed big installations for car parking and machinery and they all wanted to be protected against natural risks including rock fall. It is not amazing; therefore, that industry and engineering science made big efforts in developing rockfall mitigation measures within the last 50 years.

The first rockfall protection structures were earth dams, galleries and rigid walls like rail and tie walls (Fig. 2). The breakthrough came in 1958 when Swiss cable producer GEOBRUGG installed the first rockfall barrier at Brunnen, Switzerland, consisting of flexible wire rope nets. By their invention extended objects like settlements and traffic lines could be protected by barriers without the necessity of eliminating all those local instabilities in the source areas. Long deceleration distances allowed for high kinetic energies to be dissipated, resulting in relative small forces within the system. Since 1984 the energy dissipation capacity of rockfall barriers made of steel wire nets increased by a factor of 12, based on intensive 1 : 1 field tests. Actually the European Organization for Technical Approval is on a good way to establish rules for certification tests as the Swiss already did by their Guideline for the Approval of Rockfall Protection kits in 1999. By these tests systems will become comparable and the statement of the system's fitness for use guarantees a minimum safety level. Due to their low energy dissipation capacity rigid structures didn't represent the state of the art any longer.

At the same time powerful rockfall simulation programmes have been developed. Thus the basic requirements for any engineering design – known forces and known resistances – became available. Nevertheless, risk assessment requires profound knowledge of mechanisms behind the generation of instabilities near the surface as well as of the different causes triggering rockfall events.

Characteristics of Rockfall

There is no generally accepted definition of rockfall. JOHN & SPANG (1997) and HEIERLI (1985) classify according to the volume of the involved rock. SAEFL distincts 3 different classes of rockfall

- Small rockfall ("Steinschlag") up to diameters < 2 m^3,
- Medium rockfall ("Blockschlag") with a diameter > 2 m^3,
- Big rockfall ("Felssturz") < 1 million m^3.

SPANG (1997) suggested to use kinetic energy of the block as classification criterion. There are differences on the number of blocks involved, too. For the purpose of this publication rockfall is defined as a natural process during which single stones, pebbles or/and boulders lose their original base and roll, slide, fall or bounce down a slope. Mostly they trigger further (secondary) rockfall along their path.

Rockfall is characterized by its

- Geometry;
- Mass;

- Transnational and rotational velocity;
- Total kinetic energy.

The number of blocks involved and the strength of the rock material are interesting, too. Geometry and mass of a rockfall may be constant between start and end, velocity and kinetic energy vary along the path.

The existence of rock fall risks depends on several prerequisites:

- Slope geometry; slope inclination > 1:1.5 (vertical to horizontal), the critical angle depends on the geometry of the block and on the slope surface (SPANG & SÖNSER, 1995);
- Unstable material on the slope surface;
- Triggering mechanisms;
- Total kinetic energy.

The slope surface is characterized by its geometry and strength, including surface roughness, rolling resistance and kinetic damping. Vegetation influences the paths and energy of a rockfall depending on its strength and distance, too. These parameters decide on the mode of motion and if a block comes to rest or gets accelerated. Seldom a rockfall keeps its initial mode of motion until it comes to rest, phases of rolling and bouncing may alternate as well as sections of deceleration and acceleration between start and end point. A block may also find a preliminary stable position within the slope, for example behind a tree, and continue after the tree is broken by a storm.

Generation of Instabilities

Unstable rock material on artificial slopes originates from the excavation process. Mechanical excavation by ripping or by hydraulic excavators with or without hydraulic hammers will always result in loose rock on the surface. Even pre-splitting and cushion blasting cannot avoid a loosened zone behind the excavation surface. Cleaning the face after excavation is mandatory, whether or not it really removes all the unstable material is doubtful. Covering the surface by wire mesh or on flatter slopes by topsoil and vegetation is usually the safer alternative. Even if all the unstable material should have been removed for the moment, weathering and other natural processes will do their best to accumulate it again.

In natural slopes a lot of processes lead to the generation of unstable material on the surface, i.e.:

- Unfavorable joint pattern (provoking the identical failure mechanisms as they also determine global stability of rock slopes);
- Weathering (chemical, physical, biological weathering) (Fig. 3);

- Failure by stress concentrations (especially in active fault zones and landslides); (see Paznaun)

- Stress relief;

- Erosion;

- Denudation;

- Storms.

Unfavorable joint pattern result in planar or wedge sliding, toppling and buckling as is well known from global stability of rock slopes. Because of incomplete separation a slope may be stable in spite of this joint pattern, but the degree of separation increases near the surface by stress relief and weathering thus resulting in surficial instabilities. Erosion removes the fines and accumulates the coarser material on the surface; storms uproot trees and expose soil and coarse material formerly protected by the roots to erosion. Weathering results in undercutting of competent strata by removal of softer ones, in loosening the locking of joints, in displacements due to frost and root pressure, insolation results in temperature induced stress failures. Some rocks contain unstable minerals under atmospheric conditions and decay reducing rock strength; others change into others with increasing volume and destroy the minerals compound.

Triggering

Rockfall can be triggered by a wide range of causes, from vibrations due to blasting and earthquakes, insolation, freezing and thawing, stress-induced failures and man-made actions to erosion and joint water pressures. The latter two relate to rainfall as the main topic of this conference. In the subtropical climate with occasionally heavy rainfall due to hurricanes rockfall triggering by high precipitation has a decisive influence on rockfall frequency. In most of Europe many different causes behind rockfall exist, especially in the alpine regions, making it difficult to separate their influence. This lecture, therefore, relates to experiences gained in Mexico during Hurricane Pauline (SPANG; 2003) as well as experiences from Hong Kong where in both cases steep slopes meet with occasionally extreme precipitation.

- High precipitation either in connection with erosion and/or denudation or together with the generation of transient joint water pressures as described by TERZAGHI & PECK (1961). Denudation and erosion happen mainly in steep slopes with scarce or no vegetation and coarse material within a fine soil matrix MAUNSELL, 1998). Increasing contents of clay minerals reduce the sensitivity of a soil to erosion.

- A report of the Süddeutsche Zeitung dated 23.08.2001 contains a photograph of a rock boulder with a volume of 15 m^3 falling on a Hokaido road during the Pabuk hurricane in August 2001. Such correlations between high precipitation and rockfall activities can be deduced from WONG (1996). He presents appropriate data for 1996 from Hong Kong.

- Because freezing and thawing is not relevant to the subtropical climate of Hong Kong, and the earthquakes in 1995 had maximum magnitudes of 3.1 and their dates did not coincide with the dates of high precipitation, only gravity, joint water pressure and subtropical weathering are left as causes for the reported rockfall.

  Climate allows for growth of vegetation throughout the year. The influence of gravity and weathering should lead to a constant rockfall activity throughout the year. Extraordinary rockfall activities during high precipitation should be linked to joint water pressures, erosion and denudation.

Fig. 4 allows for the following conclusions:

- In 1995 37 rockfalls were reported to the Hong Kong Geotechnical Department (GEO). 12 had a volume up to 1 m³, 12 a volume between 1 and 5 m³, 3 a volume between 5 and 10 and 6 a volume between 10 and 400 m³. For 4 rockfall events the volume is not reported.
- During January to June, and in September, November and December with precipitations of less than 220 mm, only 3 rockfalls were reported.
- 92 % of the rockfalls occurred in July, August and October with precipitations between 480 and 1080 mm.
- About 70 % of the rockfalls (25 events) occurred in August with a precipitation of 1080 mm (for comparison: July 650 mm, October 480 mm).
- Within the months with the high monthly precipitation rates rockfall intensity is linked to distinct heavy rainfalls. During the strongest rain from 12th to 13th August with a precipitation of 326 mm including the decreasing precipitation of Aug., 14th, 15 rockfalls were reported. The rainfall of Aug. 3rd with a precipitation of 187 had caused 8 rockfalls. These two strongest rainfall events caused 62 % of the annual rockfall history of the territory.
- According to Fig. 5 a critical precipitation exists at 220 mm/month and 122mm/24 hours, beyond which rockfall activity sharply increases.
- An indication of the rate of regeneration of instabilities is given by the fact that the rainfall of October 5th to 6th with a precipitation of 258 mm/24 hours provoked 2 rockfalls only, whereas the rainfall of August 2nd to 3rd at the beginning of the rainy season caused 8, despite its considerably lower precipitation of 187 mm/24 h. Without the heavy rainfall of August 2nd to 3rd, the rainfall of August 12th to 13th would have caused a much higher number of rockfalls than it actually did.
- Another correlation exists between the quantity of precipitation and the volume of rockfall. Rockfall volume increases with increasing quantity of precipitation.
- One would assume that the intensity within the heavy rainfalls has an influence on the rockfall activity, too, but this cannot be deduced from WONG's data. The rainfall of August 12th to 13th shows the maximum values of the 1, 2, 5, 12 and 24 hours precipitations.

- Rockfall intensity shows an obvious postponement to rainfall. The bigger the volume, the longer is the postponement. Thus the biggest and the third-biggest rockfall with volumes of 400 resp. 40 m^3 did not happen earlier than on August 14th, whereas the 4 rockfall events of Aug. 12th didn't exceed 5 m^3. Obviously this is due to the velocity of infiltration and the time needed to build up sufficiently high heads. It might also be understood as an indication to different mechanisms of triggering smaller and bigger volumes. This theory fits the experiences on the relation between rainfall and deep-seated landslides.

The main conclusions are:

- Heavy rainfalls are an important trigger for rockfall.
- Increasing precipitation results in increasing rockfall intensity.
- Increasing precipitation results in increasing volumes of rockfall.
- The absolute number of rockfall events depends on the time distance from the previous rainfall and the difference in rainfall intensity as well as on the regeneration rate of instabilities on the surface.
- Smaller rockfall occurs during rainfalls, big ones towards the end or slightly after.

From Wong's (1996) rainfall and mass movement statistics for the year 1995 in Hong Kong it can be learnt that not only the relative and absolute quantity of precipitation of subsequent events is decisive for the amount of mass movements they trigger, but also the time elapsing between them. Obviously an event with the same high precipitation as its predecessor will trigger less mass movements if it follows closely instead of a relatively long time after. There is no linear regression between damages and precipitation. Therefore the pure comparison of hourly rates or total precipitation will not be sufficient to assess their effects. Unfortunately, no statistical data to analyze the relations between return period, precipitation rates and damages were available at the time of this analysis.

GAFFNEY & BAKER (2000) report on rockfall problems in Pennsylvania caused by erosion of fine soils with a resulting coarse block layer on the surface. This problem is well known from Hong Kong, too, for example from the Tuen Moon highway-widening project (PINCHES & SMALLWOOD, 2000). Similar connections are known from the years 1889, 1910,1951, 1999 and 2000 having been characterized by wet winters and late snow melts in the European Alps resulting in a extraordinary number of rockfall, landslides and debris flows.

Storms may trigger rockfall either by uprooting trees with boulders laying behind or, more frequently, by uprooting trees exposing the topsoil between the roots to erosion. In Germany storm "Wiebke" devastated large areas, uprooting whole forests. As a consequence famous German Alp Road near Innzell in Bavaria had to be protected against rockfall originating from the loss of buttress of a lot of boulders and by erosion of the exposed soils.

Forestry works were the main reason behind a huge rockfall mitigation programme for a Federal highway near Berchtesgaden (GEBAUER et al., 1990) in Bavaria, when large boulders fell onto the road during cutting of trees within a steep rocky mountain slope. HEIERLI (1979) reports on a rockfall impacting on his house having been triggered by excavations for a forest road situated uphill.

Vibrations from earthquakes are well known as trigger for mass movements including rockfall. SÖNSER (2000) reports on a big number of rockfall events following the 2000 earthquake on Iceland. The magnitude had been 6.

Vibrations from blasting: WONG & PANG (1995) give an approach to assess the influence of blasting vibrations on the stability of rock slopes, based on peak particle velocity. This approach can be applied to rock blocks, too, and gives a good impression on triggering of rockfall by blasting. Obviously, the effect of rock fragmentation behind the excavated slope surface on rockfall generation is much higher.

Gravity itself can trigger rockfall if decreasing strength results in a safety factor < 1.

Running water (erosion) is identified by SANDERSEN et al. (2001) as one potential trigger behind rockfall.

Freezing joint water may open up joints and thus lead to an unstable position of the block. Freezing and thawing loosen a rock mass and reduce its strength until it falls below unity.

Roots are able to penetrate into any small joint. By their growth they exert a considerable pressure on the joint walls. According to WUNDERLICH (1968) this pressure can reach up to 150 kPa. Thus they are able to expand the joint opening. If this deformation leads towards a critical position, the affected block may become unstable and finally be pushed downhill.

Stress relief can be the cause behind rockfall, too. By erosion of valleys as well as by deep excavations the state of stress at the new surface is changed from a three-axial to a bi-axial state. Resulting deformations lead to an expansion of the rock mass towards the new surface and to the opening of pre-existing joints (WOLTERS, 1969, GERBER & SCHEIDEGGER, 1965 and MÜLLER, 1963, 178). This expansion itself can lead to instability on the slope surface (Fig. 7).

If a rock outcrop is undercut, **stress concentrations** arise at its throat. These stress concentrations may lead to failures and subsequently to rockfall (Fig. 8).

Since several years average temperatures in the European Alps rise and lead to a shift of the permafrost border to greater altitudes. Thus rock faces thaw after having been frozen for a long time. The result is a lot of additional rockfall. Famous and once frequently used mountain trails are now too dangerous as for example the Grand Couloir at the ascent from Chamonix to the summit of Mont Blanc.

Rockfall in mountainous regions is known to have its peak intensities in autumn, spring and summer time when the sun begins to warm up the rock faces. This phenomenon is due to the joint expanding and rock breaking effect of freezing and thawing (SANDERSEN et al., 2001).

MÜLLER (1963) reports on the effect of repeated loading and unloading by temperature and moisture. SPANG (1976) describes reversible deformations by temperature on a rock tower at Chicoasen damsite in Chiapas, Mexico. These deformations result in opening and closing of joints, the gradual sliding down of stones within the joints and their gradual widening until a critical state is reached.

Near Berchtesgaden in Bavaria a narrow mountain road climbs up to the Kehlstein at 1800 m asl. The road is closed during wintertime because of avalanches. A lot of blocks fall down during this time and get stuck in the snow. During snow melting most of these rocks become unstable again and lead to rockfall.

Rockfall bouncing down a slope most frequently impacts on other blocks. By these impacts parts of the traveling and/ or of the hit block may break apart and start traveling by themselves. Thus a bouncing block initiates secondary rockfall.

Popping off and decay of the original block are common phenomena, especially popping off from fast rotating blocks may lead to unexpected, very high flight paths.

Rockfall is often the forerunner of big landslides, as reported by WIECZOREK et al. (1995). Thus it is mandatory to analyze the causes behind a rockfall very thoroughly.

Rockfall Paths

Triggering leads to the primary mode of motion. This primary mode can be:
HOEK & BRAY (1977), SANDERSEN et al. (2001).

- Free falling;
- Toppling (PINCHES & SMALLWOOD, 2000);
- Sliding;
- Rolling.

If the block doesn't come to rest, the subsequent modes of motions are:

- Free falling,
- Bouncing;
- Rolling and
- Sliding.

Assuming rigid blocks velocity depends on rolling resistance due to elastic and plastic deformation of the slope surface. Rolling on a smooth rock surface must result in a very small rolling resistance, rolling on a soft soil in a high one. Elastic and plastic deformation of the ground is behind damping, too. According to the original NEWTON concept the tangential part of the velocity keeps preserved, only the normal part is reduced by the following normal damping ε

$$\varepsilon = \frac{(v_2 - v_1)}{(v_2' - v_1')}$$

The ideal conditions of Newton's model of impacting rigid bodies are not given in the case of rotating rock blocks impacting on a deformable surface. Therefore a tangential damping had to be introduced, representing the effects of a short sliding phase during impact including elastic and plastic deformation of the ground. This tangential factor of damping governs the change in tangential translational velocity as well as the change in the angular velocity.

According to RITCHIE (1963) the mode of motion depends on the slope inclination as the only factor. This might be right for smooth slope surfaces. In nature slope surfaces are characterized by changes in inclination, steps and asperities, whose influence on rockfall paths is outsizing that of the inclination.

Potential energy is calculated by the formula

$$E_{pot} = m \cdot g \cdot h$$

Speaking about kinetic energy, mostly translational kinetic energy is meant. Calculations as well as field observations show that the energy stored in rotation can be as high as about one third of the translational energy. Therefore not only the translational part of the kinetic energy of a rockfall should be determined according to the following formula.

$$E_{tot} = \frac{1}{2} m v^2 + I \omega^2$$

It is not only the kinetic energy of a block describing its effect on a sensitive object, but the velocity, too. Velocity depends on the mode of motion and on the energy losses along the path. Of course the highest velocities result from free falling. BUWAL bases its tests on velocities up to 27 m/s observed in nature, describes velocities up to 40 m/s. SAFL gives velocities between 5 and 30 m/s. Rockfall from the 260 m high vertical cliffs at Chapmans Peak Drive near Cape Town could reach a translational velocity up to 68 m/s. A study by SPANG (2003) showed a negligible influence of air resistance even in the range of this velocity. There is no proof of a practically important critical or limit velocity.

Energy losses depend on the mode of motion and the adequate parameters, since free falling potential energy is nearly completely transformed into kinetic energy. Air resistance can be neglected. Rolling is governed by rolling resistance, sliding by sliding friction and bouncing by normal and tangential damping. Mostly more than 50 % of the potential energy is dissipated by these processes.

The flatter a slope is and the smoother its surface, the closer will rockfall clinch to the surface and the lower bounce heights will be. Berms being not wide enough to stop rockfall act as 'ski jump' and lead to wide and high bounces. The maximum width of a bounce occurs if the angle of impact is 45° not taking into account damping and spin.

Bounce heights and widths can either be measured in the field by mapping impacts on the surface and on trees or other obstacles, by rockfall tests with high-speed cameras or by rockfall simulation.

Asperities on the slope surface force a rolling rockfall to bounce, if their size is big enough. Thus rolling resistance is replaced by damping. Asperities can be defined by their frequency and amplitude. Single asperities should be mapped by surveying. Asperities are generally randomly distributed on a slope surface. Thus they can be modeled by statistical means. Steep asperities of a magnitude to the order of the rockfall occurring on debris cones may stop it. This is the reason of the gradation frequently observed on debris cones.

Sometimes it is decisive whether or not a sensitive object is within the range of rockfall. To test the range would require protecting the object first, Mapping of former rockfalls doesn't give a reliable answer in all cases. Two other possibilities exist: Rockfall simulation or a concept derived from landslide and avalanche research. The concept was originally published by SCHEIDEGGER (1973). Since its base is purely empirical, it should be used for pre-design only.

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Figures

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fig2_ahlburg1870.jpg

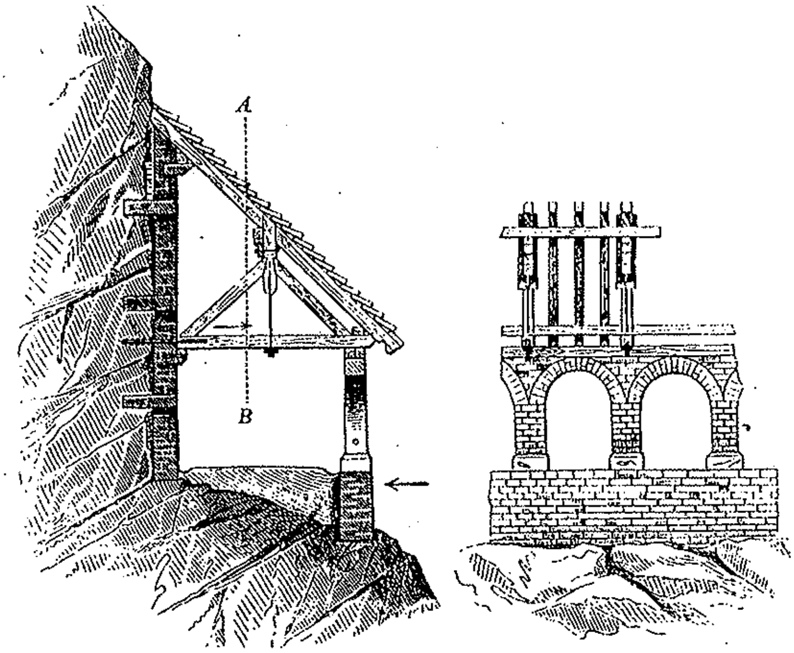
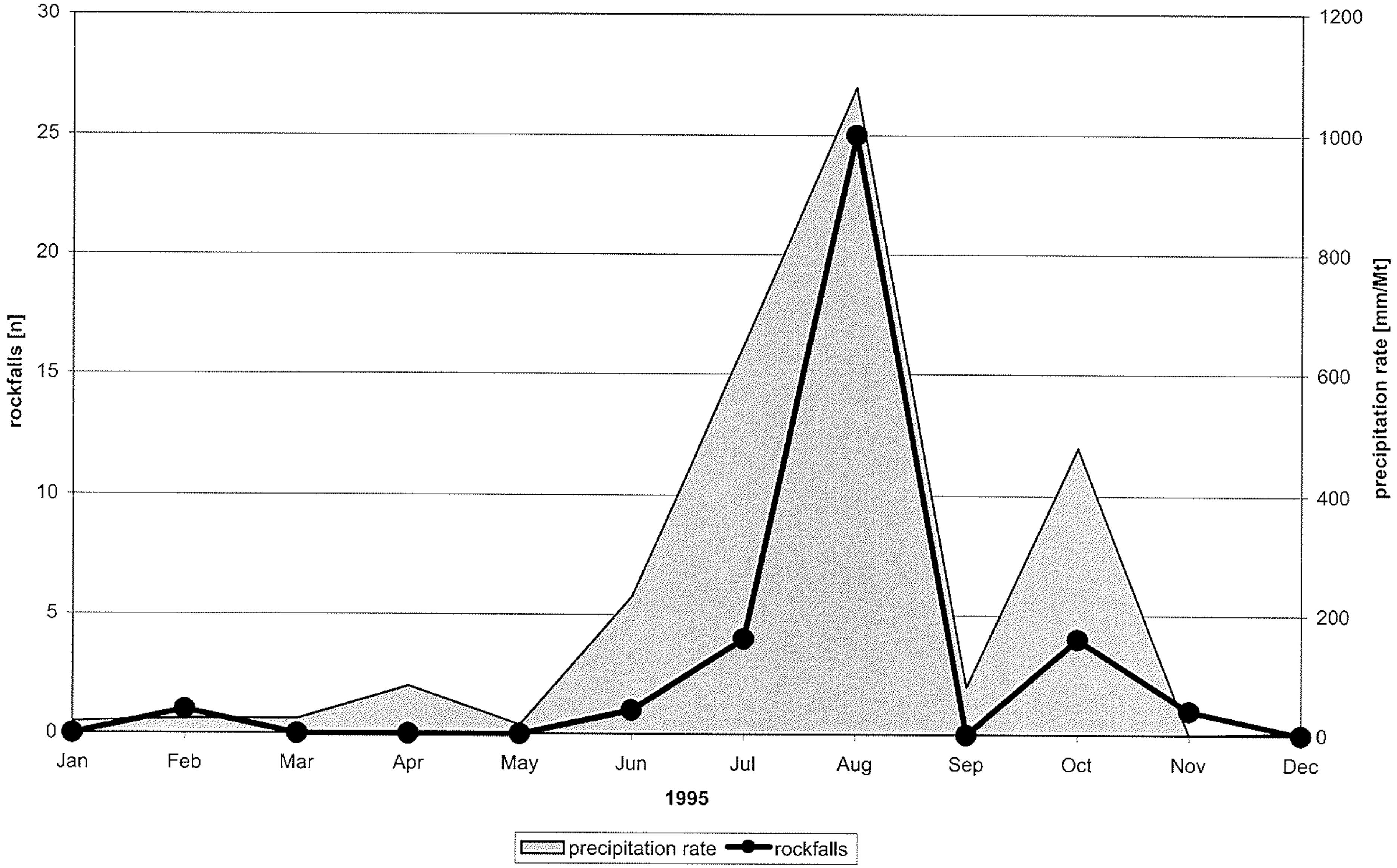


fig3_kilimandjaro.jpg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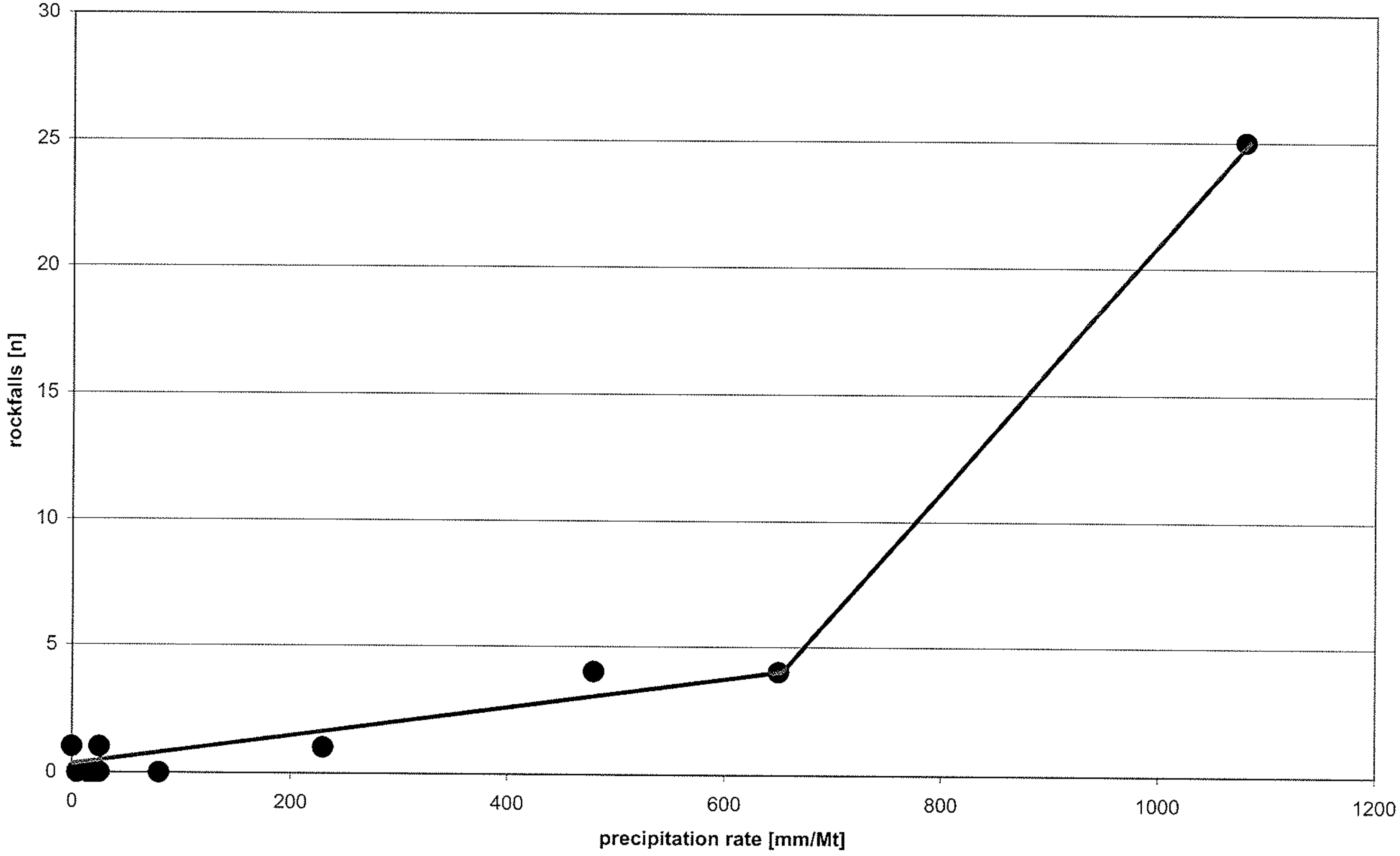
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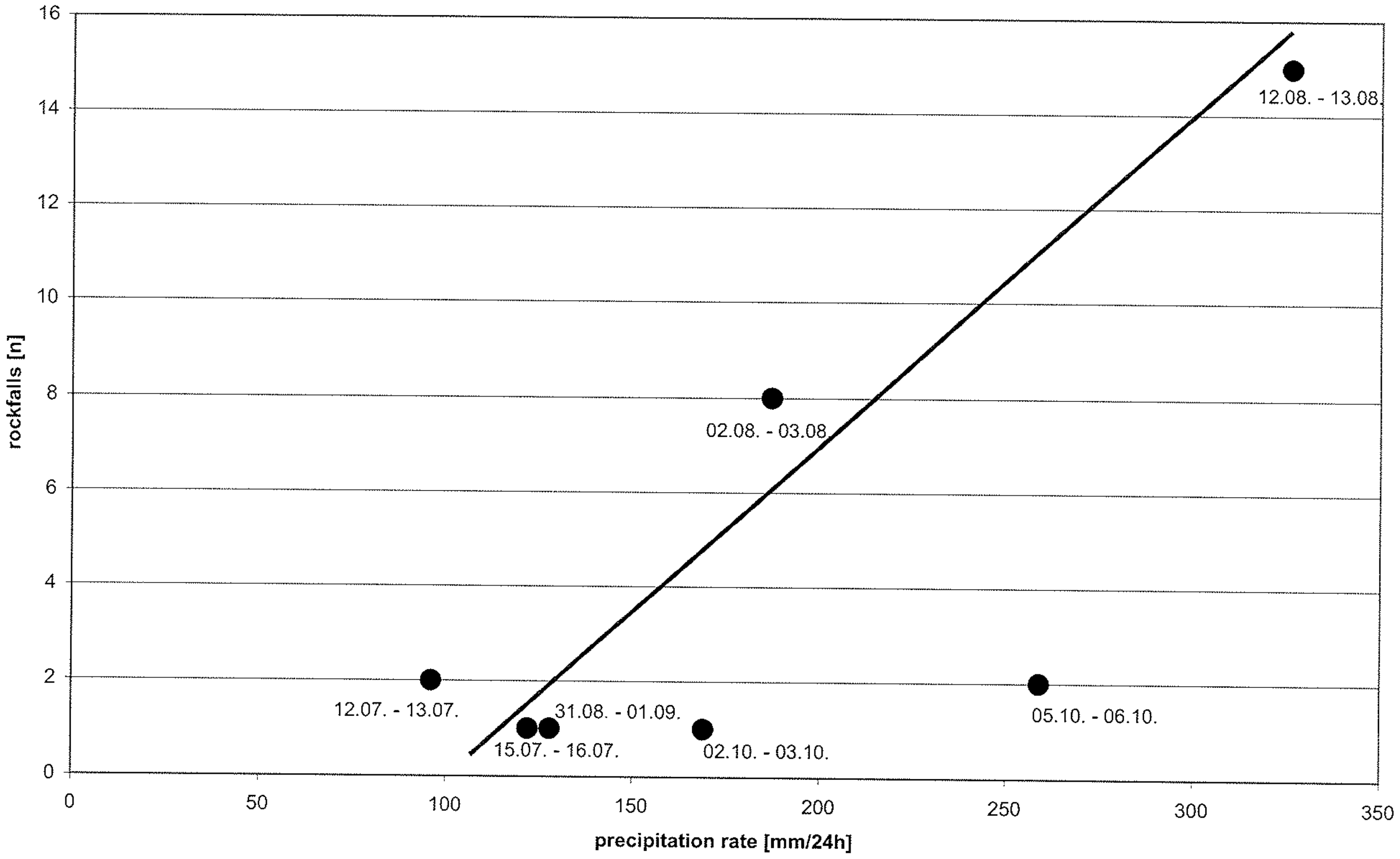
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fig7_kehlsteinroad.jpg

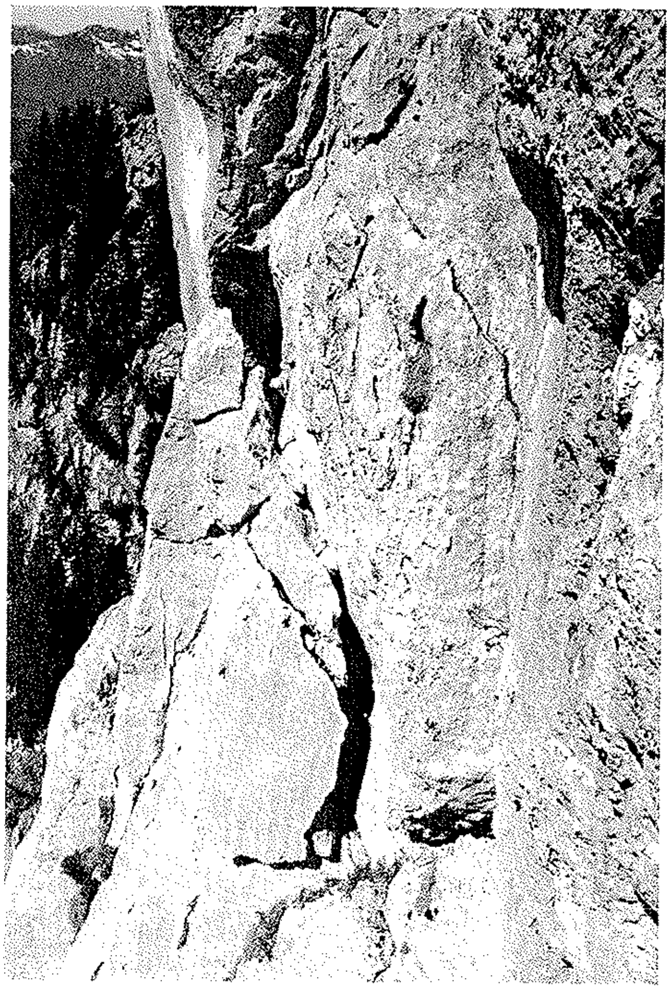

fig8_stressrelief.jpg