Movement studies to forecast the time of breaking off of ice and rock masses

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Abstract

The prediction of the time of breaking off of unstable ice or rock masses can be important if settlements or other fixed features (roads, railway etc.) exist within the potential hazard zones. Two such events happened recently in Switzerland. The first one was an icefall from a hanging glacier situated on the west-facing slope of Eiger (Bernese Alps). A large icefall has the potential to impinge on tourist facilities located in the immediate vicinity of the Jungfraujoch-railway Station Eigergletscher. The second case concerns a rock destabilisation which occured from a rock wall in the vicinity of Jungfraujoch. This unstable rock mass threatened the exit of a tunnel used by tourists leaving the Jungfraujoch railway Station. In both cases, movement surveys were undertaken soon after the first signs of a destabilisation. An almost perfect regularity by which such unstable masses accelerate prior to the time of breaking off could be recognised. The time of failure can be predicted quite accurately by extrapolation of the deformation-time function, which has been approximated by a hyperbola.

l Introduction

Although large icefalls from steep glaciers or large rock falls in the Alps are rare, the consequences of such events can be dramatic. Often they are restricted to inhabited and remote areas. Sometimes this is not the case. The main objective is then to look for means by which damage to property can be reduced and loss of life avoided. While the most important factors responsible for the destabilisation of large ice or rock masses are known in principle, the complex feedback mechanisms influencing the relationship between these factors make an accurate assessment of the stability of ice or rock masses

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difficult. Furthermore, direct measurements on such glaciers or rock walls remains a difficult and dangerous task. The distribution and development of crevasses and, more generally, the flow pattern can help to delineate an acutely unstable ice mass. Aerial photographs combined with photogrammetric investigations are very useful to recognise potential ice falls. Major rock falls are usually preceded by a noisy opening of joints accompanied by increased debris fall activity. The deformations prior to the main breaking off are much smaller in rock falls than in ice falls and a precise terrestrial survey (geodetic, joint opening, extensometers etc) of the unstable rock masses is necessary.

A warning by an expert is difficult to use for hazard mitigation unless it includes a forecast of the time of final rupture. At present the most promising approach for such a prediction is the regularity by which certain large ice or rock masses accelerate for a long time prior to the instant when the avalanche begins. In the case of a hanging glacier on the Weisshorn (Valais, Swiss Alps), the village of Randa was severely damaged in 1819 by a very large combined snow and ice avalanche. This led to a detailed study in 1972/73 of a seemingly threatening Situation. A volume of approximately $5xl0^6$ m^3 of ice was accelerating in a characteristic way on a slope of about 45°.

2 The Weisshorn case study

In 1972 the formation of a prominent crevasse on the hanging glacier on the Weisshorn gave cause for alarm, leading to movement surveys at the surface of the hanging glacier. A hyperbolic law has been found to fit best the data on change of velocity with time (Flotron, 1977; Röthlisberger, 1977). The following hyperbolic function:

$$u = u_0 + a\ (X - t)^n \qquad (1)$$

(« is the velocity at time *t;* the other parameters are constants) was used to interpolate the measurements at different times *t*. Based on 20 measurements from 1970 and February 1973, the predicted time of breaking off r_ = 4th September 1973 ± 40 days was obtained (with n = -l, a = 1420 cm and u_0 = 3.0 ± 0.5 cm day"^{1}). The failure occurred on August 19th, which was within the forecasted time interval. Figure l illustrates these results.

3 Recent movement studies on hanging glaciers and rock masses

In the following we present two recent cases where the time of breaking off was predicted successfully. The first case concerns a hanging glacier and the second one a rock fall. The breaking off forecast, that means the determination of t_, was performed by the integrated form of equation (1) (for n = -l):

$$s = s_0 + u_0\, t - a \ln(t\_ - t), \qquad (2)$$

where s is the displacement at time t since the beginning of the instability. Because equation (2) is nonlinear in the parameters, a nonlinear fitting method was used (Householder reflexion and Bevington regression). The advantage of using equation (2) instead of (1) for determining $t\_$ is that the measured displacements s_i, at time t_i can be directly used for the fitting procedure. This is not the case when equation (1) is used, since the velocity u_j has first to be determined from the s_j measurements. In that case the corresponding time t_j to a velocity u_j is not clearly defined.

3.1 Case study Eiger

A hanging glacier situated on the west-facing slope of Eiger (Bernese Alps, Switzerland) regularly releases chunks of ice at the glacier front. A large icefall (more than lOO'OOO m^3) has the potential to impinge on tourist facilities located in the immediate vicinity of the Eigergletscher railway Station. Il is therefore essential that an icefall event will be predicted accurately such that the endangered area can be closed off and, if necessary, evacuated in time. In March 1990 a large crevasse behind the glacier front was observed by the Jungfraujoch railway security personnel. Three stakes with prisms, were installed on the unstable glacier part and regularly surveyed from the Station Eigergletscher by electronic distance measurements. On the base of 13 measured positions s the forecasted time foi breaking off r_ was August 17th ± 6 days. On August 20 (1990) 100'OOOm^3 of ice breacked off and the consecutive avalanche stopped some 200m south-east from the railway Station. This event occurred well inside the predicted time interval. In figure 2 the fitted hyperbolic function and the 13 measured displacements *(s)* between March 16 and July 11 1990 are shown.

3.2 Case study Jungfraujoch

Jungfraujoch (3500m asl) can easily be reached by the Jungfrau railway. Up to lO'OOO people/day enjoy Jungfraujoch and the surrounding tourist facilities. A tunnel allows the visitors to reach the Jungfraufirn glacier from the railway Station. The tunnel end at the glacier is exposed to debris and rock falls. In summer 1990, fresh vertical cracks were observed in the rock wall above the tunnel exit. The unstable rock mass was surveyed and joint openings were measured. During the following winter the displacements decreased and in early summer 1991, when melt water intruded the joint System, the displacements increased again.

To survey the unstable body more precisely, two electronic extensometers crossing the dominant crack were installed in July 1991. Clear deformations were measured with one extensometer in the first weeks. As soon as the deformation rate u reached 0.1 mm/day, the exit to the glacier was closed for safety reasons (August 8th 1991). A new tunnel with a save exit to the glacier was constructed to provide safer tourist access. At the end of August 1991 displacement rates above the old exit were still increasing (see Fig. 3) and on October first at 3:30pm some 3'000-5'000 m^3 rock material fell on the glacier. Although the displacements were very small, the precise measurements helped to forecast this event and guaranteed the safety of the visitors.

In the period 2.5 months prior to the rupture, more than 130 extensometer readings were performed. The final acceleration phase of the unstable rock started at the beginning of August 1991. Starting with the measurement on August 12th (day 0) *t„* was calculated with equation (2). On September 23lh the calculated *t_* was only 1.5 days before failure occurred (Fig. 3). Figure 4 demonstrates the improvement of the forecast with the readings approaching the time of breaking off. In the final two weeks preceding the rupture, the forecast was better than ±4 days. The last reading was taken only two hours before the actual rupture. By that time (Fig. 4) *t„* was 22 hours after the event. This suggests that the final acceleration phase is not well represented by the proposed hyperbolic function.

4 Conclusions and perspectives

The limitation of this forecast method lies as much in the short-term irregularities äs in the extreme difficulty of obtaining sufficiently accurate data without interruption. The time of breaking off t_ in equation (1) or (2) arises when *u* —> *infinite*. In reality we expect the ice or rock mass to fall for *t* < *t*_. But there is a lack of experience on the critical velocity and acceleration that is reached immediately before final rupture. The results presented here were obtained by choosing *n* = -l in equation (2). More experience, especially immediately before final breaking, is necessary to verify this value. A detailed analysis of the velocity-time function from other well documented breaking off events, especially in the final acceleration phase, would give more insight into the open questions. The physical explanation of the proposed hyperbolic law is another open question. Using a finite element computational model for the analysis of stress and flow in a two-dimensional model of an ice mass breaking off from a cliff, Iken (1977) has shown that a stepwise crack extension alternating with viscous flow leads to the observed form of the velocity-time relationship. In the case of rock falls, the process is different. It is therefore possible that another type of law is more appropriate for rock falls.

There are other possibilities of preventive measures. However, none of them are completely satisfactory. The most certain consists of avoiding the danger zone altogether. There is a basic rule applicable especially to important ice falls, that if a particular one has occured once, it will happen again in a similar way. Unfortunately our records do not extend sufficiently far back to allow us to depend on this rule very often.

References

Flotron, A. (1977). Movement studies on hanging glaciers in relaüon with an ice avalanche. *Journal of Glaciology*, 19 (81):671-672.

Iken, A. (1977). Movement of a large ice mass before breaking off. *Journal of Gladology*, 19 (81):565-605.

Röthlisberger, H. (1977). Ice avalanches. *Journal of Glaciology*, 19 (81):669-671.

Röthlisberger, H. (1981). Eislawinen und Ausbrüche von Gletscherseen. In *P. Kasser (Ed.), Gletscher und Klima - glacier et climat, Jahrbuch der Schweizerischen Naturforschenden Gesellschaft, wissenschaftlicher Teil 1978,* pages 170-212. Birkhäuser Verlag Basel, Boston, Stuttgart.

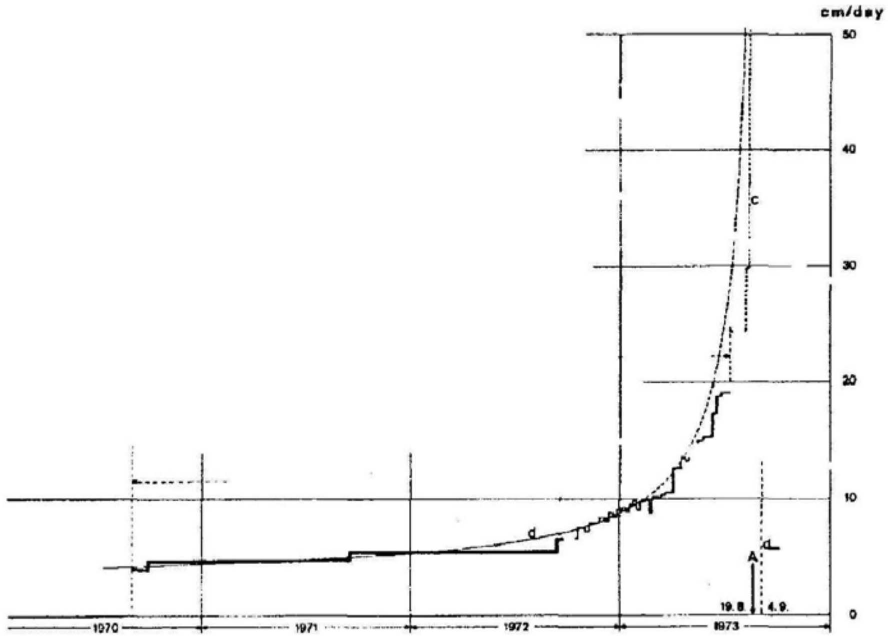
Figure Captions

Figure 1: Measured velocities *u* on the hanging glacier Weisshorn and hyperbolic function *u(t)* (after Röthlisberger, 1981).

Figure 2: Eiger ice fall: Measured positions *s* (circles) and the obtained hyperbolic function. The vertical dotted line shows the calculated t_ and the vertical dashed line the observed breaking off time (day 0 corresponds to March 16, 1990).

Figure 3: Jungfraujoch rock fall: Measured displacement (circles, crosses) *s* äs a function of time and calculated hyperbolic function (day 0 corresponds to August 12, 1991). Measurements represented by circles were used for the fitting procedure.

Figure 4: Time difference between forecasted and observed breaking off äs a function of time approaching final breakage (the dashed lines show the observed break off time).



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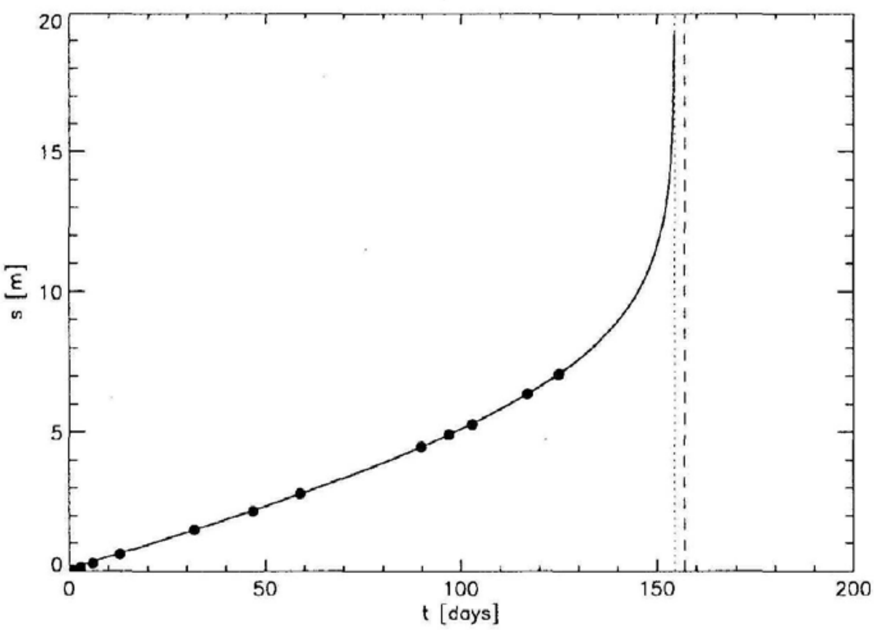

Figure 2:

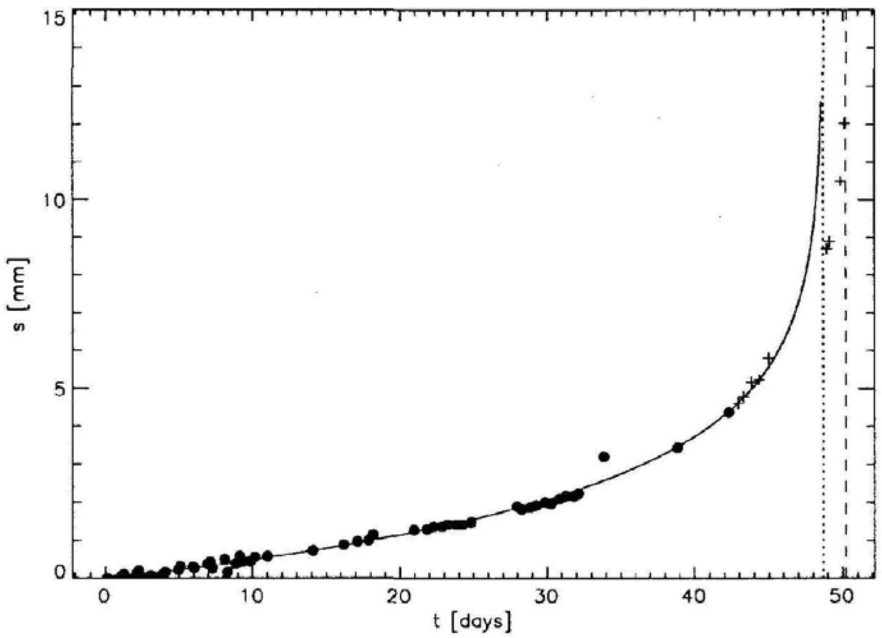

Figure 3:

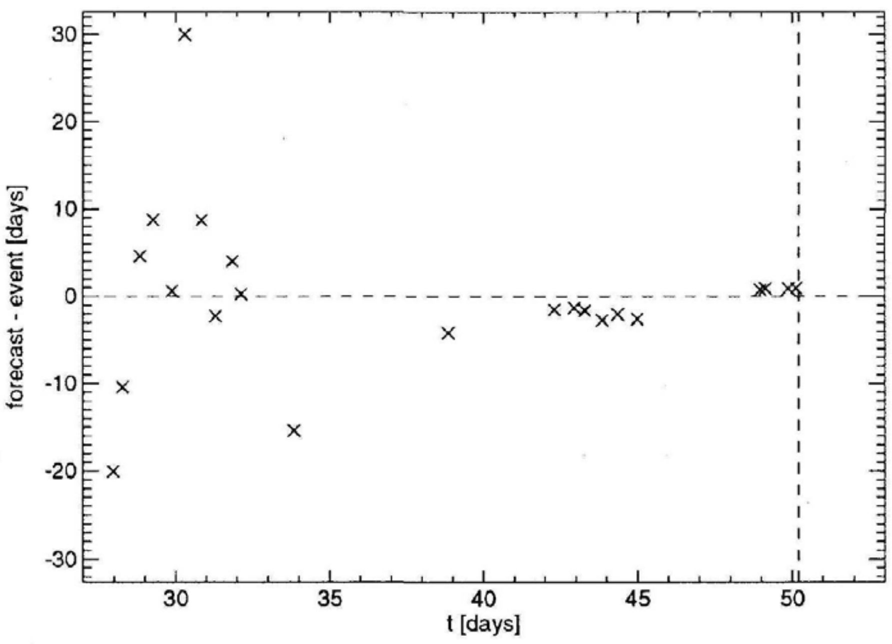

Figure 4: