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Risk Analyses and Risk Management - Slope Instabilities in Alpine Environments

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RISK ANALYSES AND RISK MANAGEMENT – SLOPE INSTABILITIES IN ALPINE ENVIRONMENTS

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Abstract

Two prominent deep-seated gravitational slope deformations in the Eastern Alps (Tyrol, Austria) have been activated in the last seven years and pose serious threats to the densely populated valleys. Based on multidisciplinary field investigations, different hazard scenarios of slope failures have been evaluated for risk management processes. These event scenarios, which are characterised by strongly varying volumes of the failing slide masses as well as by different probabilities of occurrence, and varying disintegration factors control different accumulation and damage scenarios. Finally, these evaluations and risk analyses aimed to define "design events", i.e. which scenarios are relevant for the dimensioning of mitigation measures. The main aim is to sustainably enable further land use, in comparison to the overall geohazard risks that are also present at several other sites in Tyrol (Austria).

Introduction

Slope instabilities have always been a serious threat to alpine environments, especially in steep and narrow valleys such as the Inn valley and its main tributary valleys (Tyrol, Austria), where some of the largest mass movements in the Alps cluster spatially. Recently some of them affected areas of settlement and infrastructure and, thus, attracted increased attention even of the general public. To investigate the involved processes and the risk potential of natural hazards such as floods, debris flows and landslides, the alpS competence centre for natural geohazards was established in 2001 in Innsbruck. The results of a multidisciplinary research project on several fossil and active mass movements in Tyrol (e.g. Chwatal et al., 2005; Zangerl et al., 2006) and the surroundings indicate that slope instabilities are controlled by the complex interplay of lithological, structural and morphological parameters, subcritical fracture propagation, seismic activity and fluctuations of the groundwater flow (Prager et al., in preparation). Concerning the legal aspects, geohazards and especially the topic "instable slopes" have been fixed in the "Alpen-Konvention, Protokoll Bodenschutz"(Convention on the Protection of the Alps, Protocol on Soil Protection), which is the basis of a checklist introduced by the Geological Department of the Tyrolean Government (Heissel et al., 2004).

Statistical approaches to the recurrence intervals and timing of slope collapses are commonly based on frequency-magnitude relations of dated events in a specific region (e.g. Perret et al., 2006, and references therein). Concerning the Eastern Alps, probabilistic analyses are lacking, because not enough dating for specific regional sites is available yet. So far, all available dating data have been compiled for the first time and comprise at present more than 100 dated mass movements (landslides and debris flows), but of those only 20 dated rockfalls and rockslides are situated in Tyrol (Prager et al., in preparation). However, this compilation yielded crucial information about large-scale systems, i.e. the temporal and spatial distribution of Holocene mass movements in the Eastern Alps, but not about the future behaviour of a site-specific slope where no failures have been observed in the geological past. Therefore, the semi-quantitative analysis of different failure scenarios is a crucial aspect of landslide risk management and will be exemplified in two case studies in the Eastern Alps (Tyrol, Austria).

Case study 1: the Eiblschrofen rockfall

Slope failures

The Eiblschrofen rockfall originated from a steep mountain slope (Figure 1) right above the old mining town of Schwaz. The well-exposed scarp area is made up of competent Devonian dolomites, which border on incompetent Palaeozoic schists upslope and a Triassic succession downslope. These units have been polyphase and heteroaxial folded and faulted. Active faulting along the adjacent Inn valley fault-system is indicated by increased seismic activity, with earthquakes ranking among the strongest ever documented in Austria (Drimmel, 1980). However, the structures of the Eiblschrofen massif are characterised by a complex network of differentially orientated brittle discontinuities. Coalescence of bedding and fracture planes led to substantial slope instabilities. In addition, the dolomitic bedrock units have been intensively mined, in medieval times because of their substantial silver-ore content, in modern times because of the increasing demand for calcareous resources. The mining activity ended abruptly in summer 1999, when several 10,000 m^3 of rock masses failed at the steep scarp walls (see Figure 2). As a first consequence, homes and local businesses were evacuated. Subsequently, further rockfall events occurred in August 1999 and continued significantly until 2001.

Measures

Immediately after these rockfall events the first risk management processes were started. Two large retention dams, approx. 25 m and 15m high and with a retention volume of 130,000 m^3 and 80.000m^3, were constructed in small valleys that provide discharge systems from the scarp area down to the valley bottom. To minimize the risk acceptable for the construction teams, a multi-sensor monitoring network, comprising detailed field surveys, optic and acoustic observation by guards, laser scanners, GPS systems and microseismic measurements, was installed permanently (Bayer et al., 2000; Scheikl et. al., 2000). These monitoring systems have objectively and subjectively increased the factor of safety for the settlement areas. In recent years, there has been an increasing demand to evaluate the risks for the areas beneath the rockfall scarps and for the possibility of future land use downslope of the dams.

Risk analysis

The risk analysis aims to evaluate (i) the slope kinematics and different hazard scenarios by selecting and setting up a monitoring concept, (ii) the consequences, i.e. possible damage scenarios, of the different event scenarios, and (iii) the hazard potential of the rockfall area in comparison to other regions in Tyrol. According to the structural model of the scarp area, the future Eiblschrofen slope kinematics will most probably be characterised by toppling processes and by smaller rockfall events and differential rockslides (see Figure 1). Thus, based on different scenarios, a semi-quantitative risk analysis and an event tree (see Figure 2) have been established as follows:

- Different “failure scenarios” are predisposed and controlled by the lithological - structural settings and have been elaborated by an expert team for rock mechanics (GFM, 2001). The volumes of the failing rock masses vary between approx. 835,000 m^3 (scenario 1: differential toppling and sagging to creeping processes of the topmost bedrock units) to nearly 4.5 mill. m^3 for the worst case scenario (scenario 5: failure and sliding of the whole Eiblschrofen massif).
- To evaluate different “accumulation scenarios”, the potentially failing rock mass volumes have been compared with different debris volumes that can be retained by the dams. The retention potential of the dams depends on the accumulation geometries of the failing rock masses, i.e. whether the majority accumulates upslope or shows a greater runout and reaches the dams. Three accumulation scenarios have been numerically evaluated by the 3D-application of georeferenced digital elevation models (Marschallinger and Stejskal, 2000).

- Finally, three possible "damage scenarios" have been elaborated: (a) the occurrence of excess "stray boulders", which may individually bounce and overflow the dams, (b) the overfilling of the retention space of the dams, so that even bigger volumes of rockfall debris can overflow the barriers and (c) the damage and break of the dams, a less probable worst case scenario that was not the aim of this risk analysis.

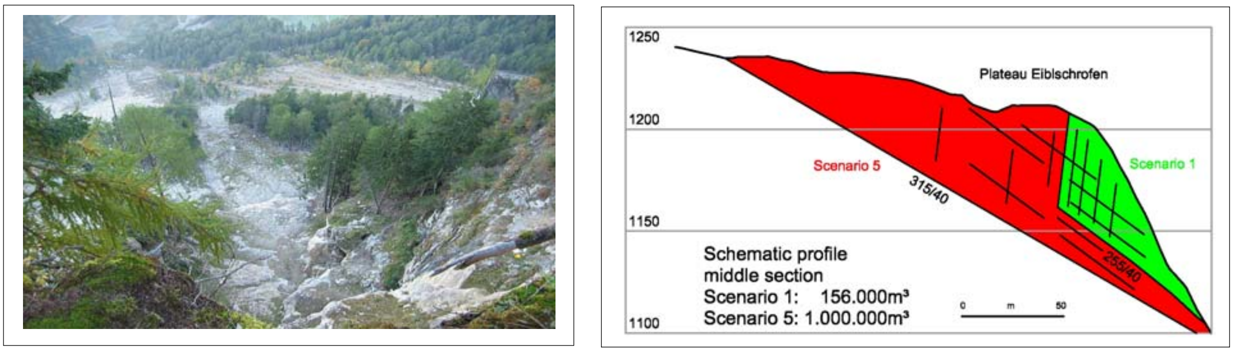


Figure 1: Downslope view of parts of the scarp area (left) and schematic comparison of failure scenarios 1 and 5.

Risk management approach

According to the different rockfall failure scenarios, the following topics have been elaborated: (1) the database and (2) the controlling parameters of the individual scenarios, (3) the warning signals and, above all, (4) a comparison to other case studies and regions. The application of probabilistic methods to the Eiblschrofen was not satisfactory, because (i) there are not enough case studies of dated mass movements in the adjacent areas to enable longer-termed (geological periods) statistics, (ii) site-specific data concerning rockfall frequency and magnitudes are not available and (iii) the setting here is quite unique because of the intensive mining activities for centuries. However, there is no geological evidence, e.g. mass movement deposits or fluvial backwater deposits, which indicate significant rockfall events from the Eiblschrofen after the withdrawal of the Pleistocene glaciers (here at approx. 15,000 yrs BP).

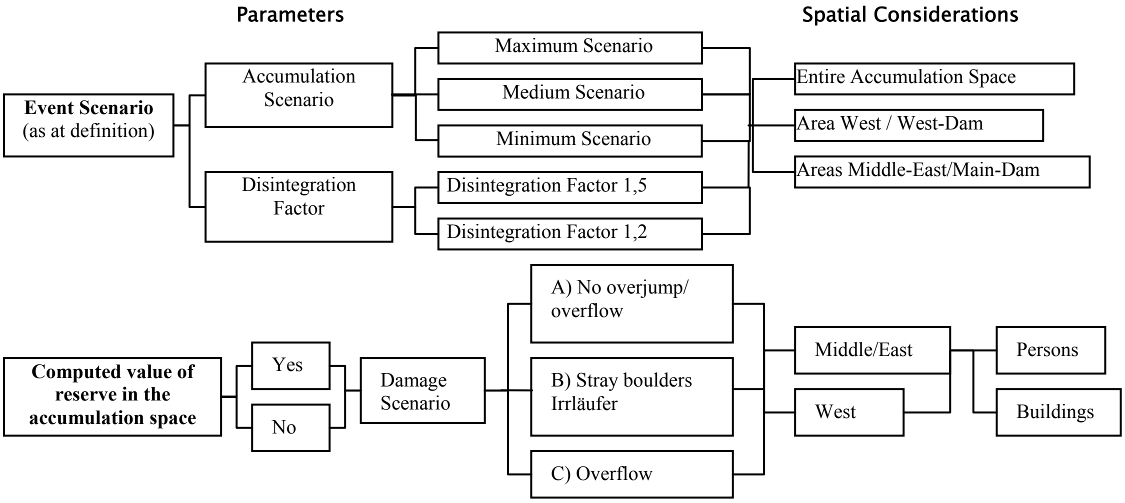
As an approach, the accumulation scenarios have been compared with the volumes of the possible failure scenarios, also considering a branching of the rock fall masses and a runout between the two dams. Dynamic disintegration and spread of the rockfall debris has been calculated for different disintegration factors of 1.2 and 1.5. These values are plausible, because seismic measurements at the prominent Köfels and Lesachriegel mass movement deposits (both Austria) yielded mean porosities of approx. 23% and 31% respectively (Brückl, 2001). Based on this, the retention space of the dams is sufficient for nearly all failure- and accumulation-scenarios, especially concerning the most probable failure scenarios 1 to 3 (Table 1).

	Residual retention space [m^3] at:		
Failure Scenario	Min. Acc. Scenario	Medium Acc. Scenario	Max. Acc. Scenario
1	1,054,500	2,504,500	5,124,500
2	360,000	1,810,000	4,430,000
3	*-348,000*	1,102,000	3,722,000
4	*-1,005,000*	445,000	3,065,000
5	*-2,584,500*	*-1,134,500*	1,485,500

Table 1: Comparison of the remaining retention spaces in different failure scenarios (1 to 5), and their associated accumulation scenarios (minimum, medium and maximum case).

Negative, numbers in red indicate that the available accommodation space of the retention dams will be entirely filled and, occasionally, be overflowed by the failing rock masses.

With regard to established concepts of progressive failure, smaller rockfall events (scenarios 1 and 2) are assumed to precede large ones (failure scenarios 3, 4 and 5). An expert group in geotechnics, which has been investigating the Eiblschrofen area for nearly 7 years, has made an assessment of the relative probabilities. The basis of the risk estimations was the assessment of potential failure scenarios, where the slope may fail partially or totally. These scenarios have been quantified from "10" (i.e. very probable) to "0" (i.e. impossible) and put into graphs as an event tree (Figure 2). For the assessment of the most probable event (failure scenario 1) it should be noticed that even the magnitude of this scenario is more than 5 times larger than that of all alarm thresholds considered during the previous monitoring. So far, the maximum failure event that has been considered in the existing alarm plans comprises a failing rock mass volume of only approx. 150,000 m^3.
Therefore, the probability of the scenario 1 has to be seen in comparison to the other, clearly larger events, especially with regard to those events, which are assumed to overflow the dams or even damage these barriers. It is obvious that, compared to events much larger than all events ever witnessed yet (i.e. failure events 1 and 2), the failure scenarios 3, 4 and 5 are extremely unlikely to occur. Even for the event 3 very unfavourable parameters of both failure and subsequent run-out are necessary to overflow the barriers. A damage scenario that cannot be excluded even in the smaller failure scenarios is the occurrence of individually bouncing "stray" boulders, which are characterised by rather unpredictably flight paths. In general, a certain residual risk that individual rockfall boulders may randomly fail sometimes and somewhere, will always remain in Alpine residential, economic and recreation areas.



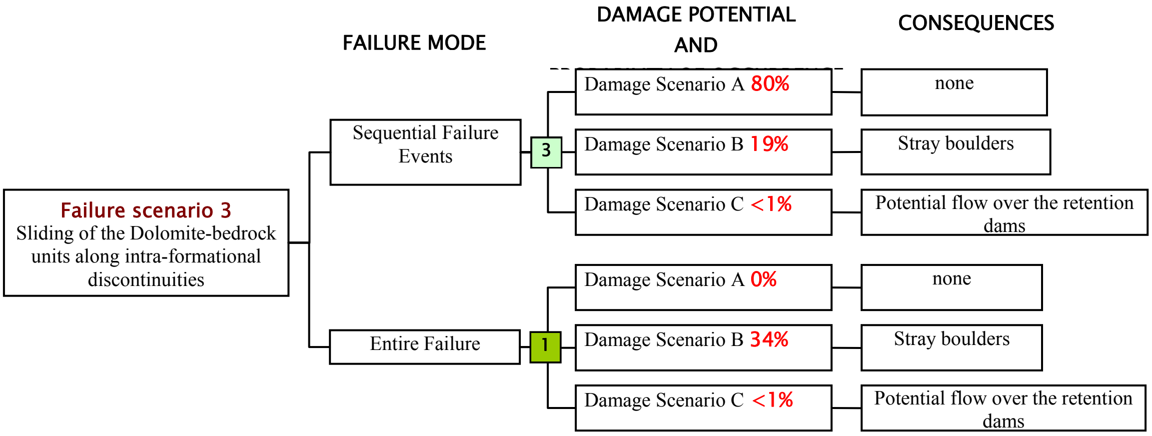


Figure 2: Example of an event tree (referring to event scenario 3).

Conclusions

- All event scenarios have been evaluated as theoretically possible scenarios, with none of them having occurred yet.
- Regarding the site-specific geological and kinematic parameters of slope movements, the size of the design event was defined by an expert team. Five main scenarios for potential slope failure events have been elaborated, where the failing rock mass volumes vary from 835,000 to over 4 mill. m^3.
- Based on the available data, the probable failure scenarios 1 to 3 are medium-sized events and thus will not overfill the dams. These will be overflowed only if very strong disintegration of the failing rock masses causes excess accumulation volumes; otherwise enough retention space is provided by the protection dams.
- Sufficient warning time is ensured by the application of permanent monitoring systems (GPS, microseismic measurements and site inspections).
- Worst-case scenarios, where the failure shifts upslope and mobilizes increased rock mass volumes (scenarios 3, 4 and 5) are probably associated with preceding smaller events, i.e. the failure of more superficial rock units; thus, in combination with the monitoring network these precursory events can be used as an indication to start evacuations.
- Potential major events have the character of catastrophes, which are yet not covered by any state-of-the-art methods, neither technically nor legally. Comparable and even larger risk situations are present at some other slopes in Tyrol, too. But in contrast to the Eiblschrofen massif, these are not yet monitored on a regular basis.

Case study 2: the creeping slope “Zintlwald”

Slope failure

In August 2005 exceptionally heavy rainfalls caused severe flooding and activations of landslides in Tyrol, in southern Bavaria and in parts of eastern Switzerland. However, the slope movements at the Eiblschrofen massif did not attract increased attention. In contrast, near the city of Landeck (western Tyrol), the intensive rainfalls raised the water level of the Rosanna river and (re-) activated parts of one of the largest mass movements in Tyrol. The well-known landslide “Zintlwald” (Figure 3) often caused problems to the infrastructure and thus had already been investigated in previous studies. Slowly creeping slope movements (referred to as "Talzuschub"), have been known formerly (e.g. Poleschinski, 2004), measuring medium creeping rates of approx. 1 cm/year at a pipe bridge of a hydropower plant.

The landslide is part of the polyphase and heteroaxial deformed Landecker Quarzphyllite Zone, where incompetent bed rock units border on competent successions of the Northern Calcareous Alps in the North and the Silvretta basement unit in the South (Brandner, 1980). Causing significant deformation of the steeply inclined rock units, several brittle fracture systems have enabled substantial fluvio-glacial erosion and related undercutting of the Zintlwald slope toe by valley deepening. Thus, in the course of the 2005 flood event, a landside area of approx. 25,000 m² has been (re-)activated and destroyed a power plant, parts of the main road and the railway connections between Austria and Switzerland. Most likely, the landslide acceleration was triggered by substantial fluvial erosion of the over-steepened slope toe. In addition, local accelerations, i.e. slope-type debris flows, may be attributed to an increased water saturation of the topmost succession of the disintegrated landslide masses.

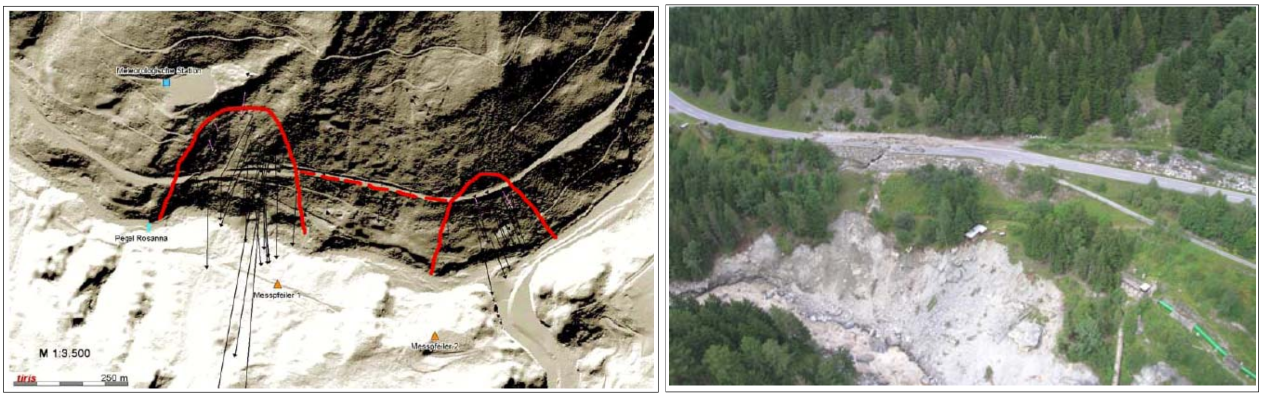


Figure 3: Parts of the deep-seated mass movement “Zintlwald” showing areas with increased slope-deformation (left) and fluvial erosion of the slope-toe (right) (Poscher and Mattle, 2006).

Measures

To evaluate the risk potential, several geological, geotechnical and hydrogeological surveys and measurements (geodesy, seismics) have been carried out and will continue in 2006, comprising core drilling campaigns. At present, these investigations show the following (Poscher and Mattle, 2006):

- The Zintlwald landslide is a large-scale and deep-seated “Talzuschub”, where the significantly moving sliding masses currently affect an area of about 30 km^2 and comprise at least 5 million m^3.
- Downslope from the scarp areas (max. elevation 1900 masl) the rock masses are disintegrated by continuing creeping processes, which are also indicated by an unsmooth morphology with characteristic pull-apart trenches.
- Some zones are characterised by higher seismic velocities than adjacent areas, indicating the occurrence of less disintegrated phyllitic rock units within a relative finer-grained matrix.
- The basal sliding zone is not a subplanar or concave plane, but an intensively undulating zone; therefore, the thickness of the disintegrated rock mass extends up to more than 150 m but varies intensively spatially.
- Based on this and on geodetic measurements, the thicker successions of the sliding mass correlate well with areas of increased slope deformation.
- In general, slope kinematics is characterised by three different types of movements, which vary strongly spatially: (i) the majority of the creeping slope is characterised by very slow velocities in the cm range per year, (ii) partial sections feature increased velocities of a few cm/d and (iii) some of the topmost sections downslope move as slope-type debris flows and show remarkably high velocities of up to 1.3 m/d.

Risk analysis and risk management

The evaluation of different slope parameters indicates:

- Increased movements of parts of the creeping slope are possible and may cause serious threats due to their sudden occurrence and because they probably can dam the fluvial discharge system (i.e. the Rosanna river, at approx. 900 m asl).
- Because any erosion of these backwater damming landslide barriers may cause flash floods in the downstream regions, detailed alarm plans have been set up.
- Accelerated slope deformations are most likely to occur during the snowmelt in spring, especially when superposed by increased precipitation.
- An activation of the entire Zintlwald landslide, i.e. comprising several tens of km^2, has been evaluated as a not very realistic scenario.

Conclusion (as at March 2006)

Based on compiled field and monitoring data

- The huge creeping slope of Zintlwald can be subdivided into kinematically different slope sections, i.e. different hazard zones. The topmost successions near the slope toe (comprising a thickness of about 10 m) can rapidly move as slope-type debris flows. Remarkably high deformations rates of up to 1.3 m per day have been registered.
- The high slide velocities and future accelerations of the creeping masses are probably governed by the seasons and the weather by (i) fluvial erosion of the slope toe due to increased discharges and (ii) varying amounts of water saturation of the slide debris.
- Major risks for the traffic routes can be recognised by the monitoring network.
- Erosion of the locally steep riverbanks has not been judged as a severe threat to the inhabitants downstream of the landslide area.
- The majority of the investigated slope is characterised by very low deformation rates and does not yield any evidence of accelerating movements. A catastrophic failure of the entire creeping slope is not expected yet.
- The major risks comprise catastrophic accelerations of larger parts of the landslide. Comparable worst case scenarios might already occurred previously in the Holocene and cannot be excluded in the future. But such catastrophes are commonly indicated by precursory events, i.e. slope-type debris flows and/or fluvial erosion processes at the slope toe. Therefore, enough warning time will be available.
- Detailed field observations and geodetic measurements have shown that the monitoring allows adequate reaction (i.e. road and railway closures and, in the worst case, an evacuation of the population downstream of the hazard site).

Final remarks

With regard to all geological and geotechnical parameters, different failure-, accumulation- and damage-scenarios have been evaluated for both the Eiblschrofen rockfall and the Zintlwald landslide. Site-specific design events were defined by expert teams and provide thresholds for alarm and evacuation measures. Concerning the spatial land-use planning and safety of major traffic routes no events larger than the design events have been considered thus far. However, future tendencies of different failure scenarios can be recognized in time by applying state-of-the-art monitoring systems. As a result, the naturally occurring “basic geohazards” in Alpine valleys require fundamental multidisciplinary evaluations to sustainable apply socio-economic risk management processes.

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