AUSTRIAN JOURNAL OF EARTH SCIENCES | VOLUME 102/2 | 61 - 68 | VIENNA | 2009

INTEGRATION OF LARGE DEEP-SEATED, CREEPING MASS MOVEMENTS IN A REGIONAL HAZARD MAP - AN APPROACH TO DETERMINATE IT'S PROBABILITY OF OCCURRENCE

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KEYWORDS

accelerating creep
mass movement
failure relation
material law
hazard map
monitoring

ABSTRACT

In the last two decades hazard maps (HM) have established as one of the major tools for risk assessment and urban planning in alpine regions. During this time, various efforts and methodical adjustments could be recognized that significantly supported reliability and applicability of HM. All those adjustments are based upon the fundamental Swiss system of geological hazard assessment and mitigation, the so called BUWAL, which is by now considered to be the main fundament for the elaboration of HM in alpine areas. One of the last problems that can be regarded as almost unsolved in terms of a local hazard zoning and elaboration of HM is the integration of large deep-seated and creeping mass movements (i.e. "Talzuschub", "Sackung") in these maps. The classification of hazard zones that are to be depicted by the HM according to BUWAL requires the assessment of "intensity" and "probability of occurrence" as basic information. But since intensity appears to be irrelevant for the classification of those phenomena (intensity is only determined by velocity [rate] as moving rock mass [volumina] and depth of surface of rupture always correspond to a "high"-grade intensity) and thus probability of occurrence is the main parameter for classification respective the BUWAL matrix, it becomes obvious, that existing methods have to be completed by different approaches. Sound research, published in various papers during the last decades, showed that almost every slope movement takes place in correspondence to the theories of "accelerating creep", no matter if one regards falls, topples, slides or a spreads in bedrock or soils. Thus, the application of mathematically based concepts of creep theory in combination with suitable codes of numerical modelling and targeted monitoring systems as fundament for data collection in addition to intensive geological field works seems to be such a different and promising approach for integrating large deep-seated and creeping mass movements in a regional HM. This article introduces the research project "Talzuschub Algund" that makes use of this multi-based concept, also discussing requirements, chances and constraints of the accelerating-creep-theories for elaboration of HM and time related forecasts / predictions in the sense of the BUWAL-matrix. The project was established in 2007 by the Office for Geology and Building Material Testing of the Autonomous Province of Bolzano in close cooperation with the Chair for Engineering Geology of the Technische Universität München.

Im Verlauf der letzten 20 Jahre haben sich Gefahrenzonenpläne (GZP) zu einem der wesentlichen Instrumente zur Bewertung von Naturgefahren und damit verbundenen Risiken sowie zur urbanistischen Planung in alpinen Regionen entwickelt. Während dieser Zeit erfolgten verschiedene Fortschritte und methodische Verfeinerungen, die Verlässlichkeit und Anwendbarkeit der GZP signifikant verbesserten. All diese Verfeinerungen basieren auf der fundamentalen Schweizer Methode zur Bewertung geologischer Gefahren und ihrer Abwehr, dem sog. BUWAL, das heute als wesentlichste Grundlage zur Ausarbeitung von GZP in alpinen Regionen angesehen wird. Eines der letzten Probleme, die im Zusammenhang mit lokaler Gefahrenzonierung und der Erstellung von GZP als nahezu ungelöst angesehen werden können, ist die Integration von großen, tiefgreifenden und kriechenden Massenbewegungen (d.h. "Talzuschüben", "(Groß-)Sackungen") in diese Kartenwerke. Die Klassifizierung von Gefahrenzonen, die durch den GZP gemäß BUWAL dargestellt werden sollen, erfordert die Bewertung von "Intensität" und "Eintrittswahrscheinlichkeit" (Wiederkehrhäufigkeit) als Grundinformationen. Da jedoch die Intensität für die Klassifizierung dieser Phänomen irrelevant erscheint (Intensität ist einzig durch die Geschwindigkeit (Bewegungsrate) bestimmt, da Kriechmasse [Volumen] und Tiefe der Bewegungsfläche immer der Intensität "hoch" entsprechen) und somit die Eintrittswahrscheinlichkeit das wesentliche Kriterium zur Klassifizierung unter Berücksichtigung der BUWAL-Matrix ist, wird offensichtlich, dass die existierenden Methoden durch alternative Ansätze ergänzt und vervollständigt werden müssen. Tiefgehende Forschungen, veröffentlicht in verschiedenen Aufsätzen während der letzten Jahrzehnte, zeigen, dass nahezu jede Hangbewegung in Übereinstimmung mit den Theorien des "beschleunigten Kriechens" abläuft – unabhängig davon, ob man Sturzphänomene, Kippungen, Rutschungen oder Driftphänomene in Festgestein und/oder Lockergestein betrachtet. Deswegen erscheint die Anwendung von mathematisch basierten Konzepten der Kriechtheorie in Verbindung mit geeigneten Codes der numerischen Modellierung und zielgerichteten Beobachtungssystemen zur Datensammlung, als Ergänzung zu intensiver geologischer Geländearbeit, als solch ein andersartiger und vielversprechender Ansatz für die Integration großer, tiefgreifender und kriechender Massenbewegungen in einen regionalen GZP. Dieser Beitrag stellt das Forschungsprojekt "Talzuschub Algund" vor, das dieses auf mehreren Säulen basierende Konzept anwendet und er diskutiert Erfordernisse, Möglichkeiten und Grenzen der Theo-

rien des beschleunigten Kriechens zur Ausarbeitung von GZP und zeitbezogenen Vorhersagen und Prognosen im Sinne der BUWAL-Matrix. Das Projekt wurde im Jahr 2007 ins Leben gerufen durch das Amt für Geologie und Baustoffprüfung der Autonomen Provinz Bozen, in enger Zusammenarbeit mit dem Lehrstuhl für Ingenieurgeologie der Technischen Universität München.

1. INTRODUCTION

In the last two decades hazard maps (HM) have been established as one of the major tools for risk assessment and urban planning in alpine regions. During this time, various efforts and methodical adjustments could be recognized that significantly supported reliability and applicability of hazard maps. All those adjustments are based upon the fundamental Swiss system of geological hazard assessment and mitigation, the so called BUWAL (1997, 1998 and 1999), which is by now broadly accepted and considered to be the main fundament for the elaboration of hazard maps in alpine areas. One of the last problems that can be regarded as almost unsolved in terms of local hazard zoning and elaboration of a regional hazard maps is the integration of large deep-seated and creeping mass movements (i. e. “Talzuschub”, “Sackung”). Since terminology varies to a large extend in international scientific literature, this paper applies the terms “compound sagging” (acc. Hutchinson, 1988) or “complex rock flow” (acc. Varnes, 1978) for complex large deep-seated, creeping mass movements like the one presented below.

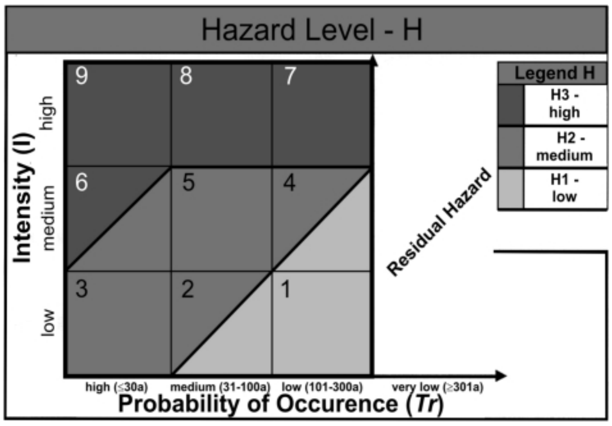

FIGURE 1: BUWAL-Matrix for classification of hazard levels that are to be depicted in a HM (from A.P.Bz 2007, modified).

2. PROJECT “TALZUSCHUB ALGUND”

In 2007 the Autonomous Province of Bolzano started the graduated elaboration of hazard maps for all municipalities belonging to the territory of South Tyrol. These hazard maps have to be compiled in accordance to the official guidelines (A.P.Bz, 2007) that refer to the approved principles and publications of BUWAL.

Almost each municipality north of a geographical line from the Swiss border near Glurns via Meran and Sterzing to the northeast corner of South Tyrol (Ahrntal) is affected by the geological phenomenon of compound sagging / complex rock flow. The classification of hazard zones that are to be depicted by the hazard map requires the assessment of “intensity” and “probability of occurrence” as basic information (Fig. 1). Therefore the Office for Geology and Building Material Testing (Office in charge for all geological aspects of HM in South Tyrol) is now forced to provide a reliable and applicable method for the integration of complex large deep-seated, creeping mass movements in the municipal hazard maps. Dealing with an integration of this geological phenomenon, one is faced with two major problems in contrast to other phenomena like rock falls, slides, debris flows, etc. These problems are:

- large variations in activity over very long periods of time, clear acceleration only towards failure,
- therefore distinct time-dependence of intensity,
- intensity is only determined by velocity (rate) as moving rock mass (volumina) and depth of surface of rupture always correspond to a “high”-grade intensity and thus appear to be irrelevant for classification,
- probability of occurence is the main parameter for classification respective the BUWAL matrix,
- impossibility of mitigation (reducing hazard) – necessity to reduce vulnerability and exposure (risk assessment and risk mitigation).

Considering these general conditions, it becomes obvious that integration of compound saggings / complex rock flows is a big task for persons in charge for the elaboration affected hazard map. They are forced to investigate the relevant area in a manner that

- reveals internal structures of the creeping rock mass and allows separation of homogeneous (and more or less independent) units,
- shows possible interactions between these single units of the mass movement,
- permits definition of movement thresholds for defined scenarios like damage/loss of houses, infrastructures, danger to traffic, etc.,
- enables prediction for probability of occurence and failure forecast, respectively,

FIGURE 2: Location of project area “Talzuschub Algund”.

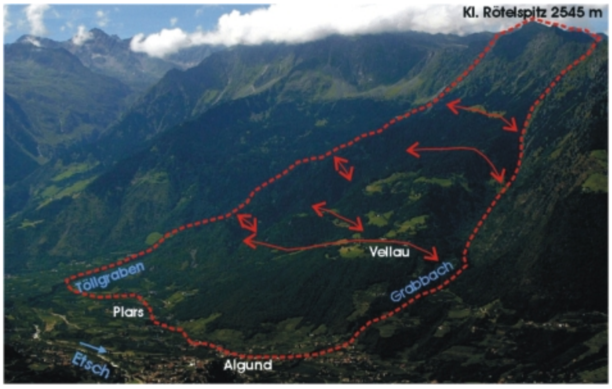

Figure 3: View of mass movement “Talzuschub Algund”, with red dashed line indicating rock mass affected by the creeping movements and solid red lines indicating major scarps/trenches related to the sagging/complex rock flow (see also Figure 4).

- detects all processes and phenomena directly linked to the large moving rock mass, i. e. (proceeding) disintegration of the rock mass, rock fall, toppling, debris flow.

To meet all those special needs corresponding to the area wide elaboration of hazard maps in South Tyrol, the Office for Geology and Building Material Testing of the Autonomous Province of Bolzano established several research projects dealing with compound saggings / complex rock flows. One of those is the research project “Talzuschub Algund”, established in 2007 in close cooperation with the Chair for Engineering Geology of the Technische Universität München.

3. “Talzuschub Algund” – framework

The compound sagging / complex rock flow of Algund is situated in South Tyrol, about 10 km west of Meran (figure 2). The large deep-seated mass movement ranges from the crest/ ridge at “Rötelspitz” (2545 m a. s. l.) down to the Etsch valley and the villages of Vellau, Plars and Algund at about 400 m a. s. l. It is laterally confined by the brooks of “Töllgraben” (west) and “Grabbach” (east, figure 3).

The slope is built up predominantly by gneiss (ortho- and paragneiss) and to a much less extend by mica schists and amphibolites. The metamorphic rocks belong to the Texel Unit and are thus part of the Austroalpine Unit. Metamorphic ages are alpine within the area presented here (Spalla, 1993). The Texel Unit was formerly considered to be part of the “Ötztalmasse”. The local grade of alpine metamorphism is medium to high grade (amphibolite to eclogite facies at some places). During the Oligocene (Alpine orogenesis) dykes with andesitic intrusions were formed as a consequence of the intense tectonic activity. Today, large areas of the slope are covered by quaternary deposits. These are glacial till, detritus from rock fall and debris flows and alluvial sediments from the local brooks and the Etsch river (see Fig. 4 for geological map).

Since till deposits could be found in large scarps/trenches of the mass movement, field work for the project could prove that the sagging / complex rock flow of Algund and Vellau was active already before the last ice age (i. e. pre-Würmian). The rock mass is extensively disintegrated and jointed. Large morphologic structures that can be related to the movements have developed. Those are scarps, trenches (at some places similar to a “graben”), transverse ridges and (due to field observations active) cracks (fig. 5 and 6). The crown/main scarp and the toe of the movement can be identified easily in the field (fig. 3 and 4). Several surfaces of rupture have to be assumed and investigated (fig. 5) and local focuses of creeping movements can be distinguished from parts with generally minor activity or displacements. The largest features related to the creeping rock mass are scarps, trenches and holes / depressions of up to ca. 1500 m extend parallel to the slope and ca. 150 to 200 m perpendicular to the slope (spreading displacements, sagging, see also fig. 4). These large gaping structures reach depths up to ca. 40 m, according to

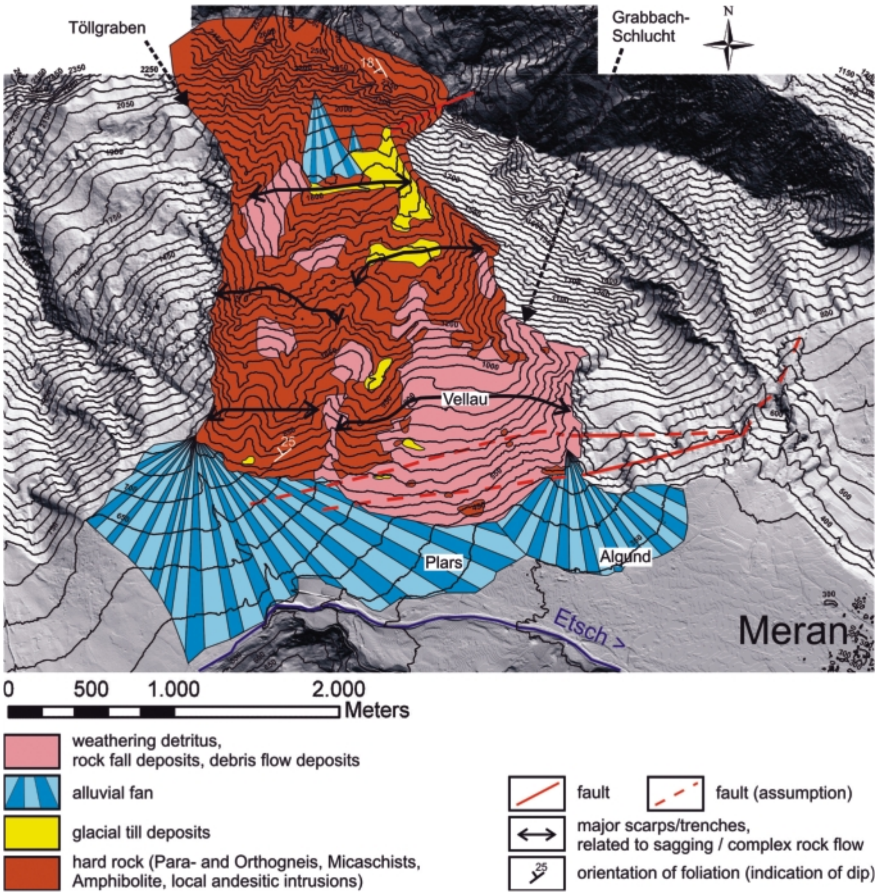

Figure 4: Simplified geologic map of the project area between "Töllgraben" and "Grabbach".

field measurements.

Usually, the causes of deep seated creeping mass movements can be directly linked to geology, hydrology and geomorphology of the slope affected. This also applies for the Algund mass movement.

From the geomorphological point of view - in combination with rock mechanical aspects – the creeping slope is by now still very steep and has probably not reached its mechanically stable equilibrium. The upper outcrops of rupture planes also show significant indications of an orientation steep downslope. So the movements will not finally stop unless either a locally stable slope angle is reached due to the flattening in the course of the compound sagging/complex rock flow or the movement is blocked (for example by reaching the opposite slope of the valley below ground level).

As figures 4, 5, 7 and 8 show, the orientation of the metamorphic rocks' foliation varies in the project area. Two main trends can be found at the relevant slope: in the crest region and the upper parts of the slope cleavage planes are dipping downslope whereas in the lower and middle parts of the slope it dips into the slope. This enables sliding directed to the valley on cleavage planes in the upper parts of the slope and a combination of spreading and sliding movements in the middle and lower parts where foliation enables spreading and sliding is supported by joint sets. Movements induced and supported by foliation are furthermore eased if already moderate weathering has changed mechanical conditions on the cleavage planes. This may happen easily and to a large extend as deep disintegration of the local rocks is intense and cleavage planes usually are coated by medium to coarse grained and thick layers of mica.

The local hydrogeologic situation should also be regarded at least in a short basic outline for understanding the characteristics of the complex sagging/rock flow of Algund. The Etsch valley around Meran is the region in South Tyrol with the most intensive annual precipitations with an average of about 1000-1200 mm/year. Apart from the two lateral brooks of Grabbach and Töllgraben no permanent superficial waterflow can be observed in the project area and no springs crop out. The water immediately runs off in the highly jointed and fractured rocks where large extends and depths have to be assumed for vertical joints due to the creeping movements. But on the other hand significant parts of the slope are covered by wood - mainly consisting of spruce and larch. These trees typically have shallow roots and therefore need to reach groundwater within about 2 m below ground surface. So the conclusion seems to be evident that high water pressures can be built up in vertical joints of the creeping rock mass and locally provoke seasonal movements and changes in rate.

One of the characteristics of large deep-seated creeping mass movements is that other hazardous processes like rock fall, debris flow and shallow slides are significantly increased in the area affected due to the intensive disintegration of the entire rock mass that builds up the instable slope. These processes can be considered to be "linked" or “combined” processes with respect to the compound sagging/complex rock flow (Fig. 9). Of course, they also have to be taken into account for the elaboration of the local HM. Linked processes have to be assessed separately in accordance with the BUWAL matrix that provides approved and applicable criteria for classification with regard to each linked process' intensity and probability of occurrence. So, a HM depicting an area affected by large deep-

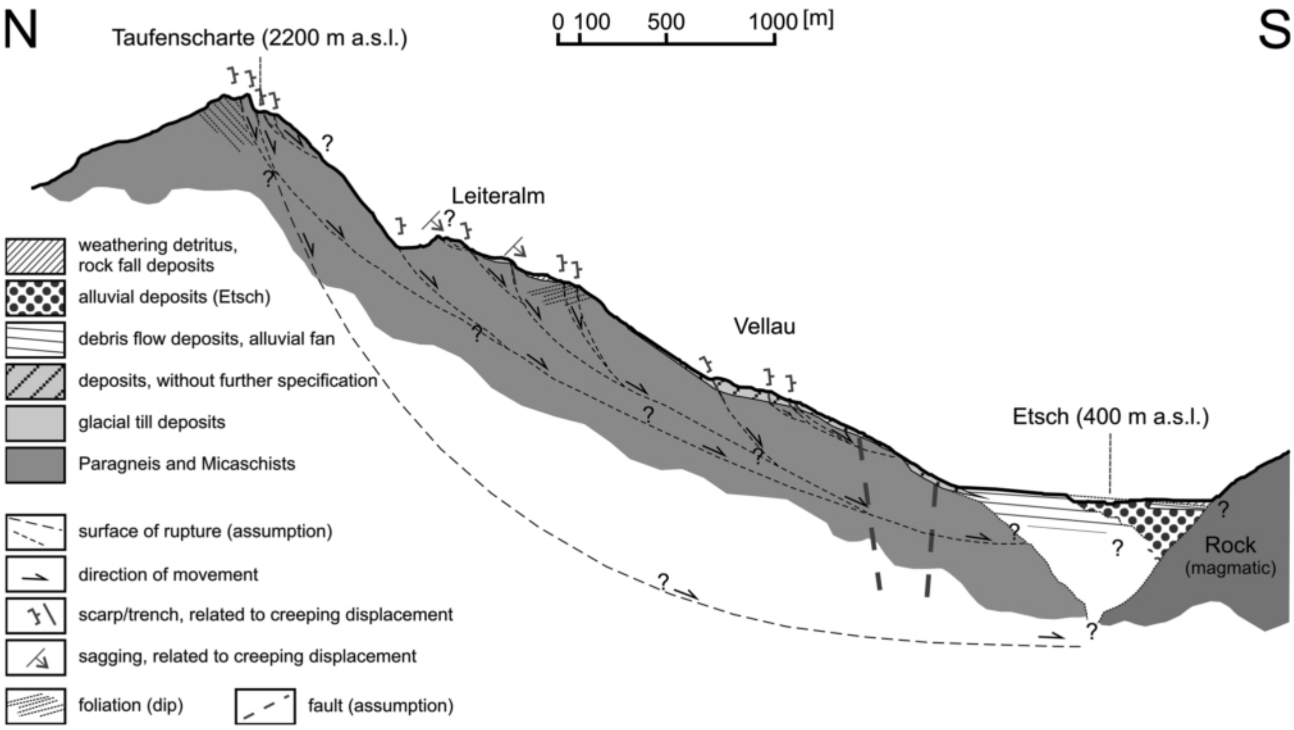

Figure 5: Characteristic cross section of “Talzuschub Algund”, ranging north to south from the ridge area via Vellau to Etsch valley near Algund.

seated mass movements finally has to display two types of local hazard zones – those ones related to the linked processes with "manageable" extend and on the other hand those ones related to the compound sagging / rock flow proceeding "in the background".

The following concept for the assessment of the Algund mass movement in terms of a reliable hazard maps is bases on

- detailed field work (geologic and geomorphologic mapping),
- petrografic analysis,
- rock mechanics laboratory tests,
- application of suitable rock mass classification (GSI acc. Hoek, 1997; Marinos, 2000),
- development and realization of a detailed monitoring concept.

Figure 6: Tension crack, gaping with extent of more than 35 m.

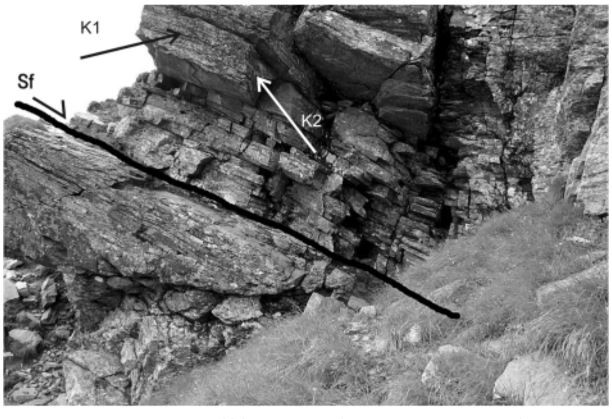

Figure 7: Foliation (Sf, black line) in the upper part of the mass movement, dipping downslope, enabling in combination with two orthogonal vertical joint sets (K1 and K2) sliding on cleavage planes; Picture taken from behind the ridge.

4. From monitoring to hazard maps (HM)

Based on the intense geologic field works and the further research described above, a detailed monitoring system has to be projected and installed at the slope affected by the sagging / complex rock slide of Algund. This research enables to determine focuses, i. e. places that show a significantly increased number of prominent features and structures related to the creeping mass movement or places with a high exposition/ vulnerability with respect to the sagging/ complex rock flow and its linked processes and phenomena.

The data gained by monitoring systems have to allow or support

- determination of all relevant surfaces of rupture (depth and extension),
- determination of separated, possibly interacting units within the sagging/complex rock flow,
- numerical modelling of the mass movement by use of suitable codes like UDEC or FLAC,
- elaboration of sections of particular creep curves that are suitable for application of appropriate creep theory and failure relations for time related forecasts/ predictions in the sense of the BUWAL-matrix (see following paragraph).

It has to be emphasized, that the problem of classifying a large deep-seated creeping mass movement in view of ist probability of occurrence (as required for a hazard map) can only be solved by applying well established and mathematically based theories and methods for failure prediction of creeping rocks (and soils respectively). For this type of mass movement both numerical modelling and failure prediction based on mathematical analysis of creep curves can only be carried out on an adequate level if monitoring lasts for at least three to four years (Crosta, 2003).

5. Applicable concepts of creep theory

Sound research, published in various papers during the last decades, showed that almost every slope movement takes place in correspondence to the theories of “accelerating creep”, no matter if one regards rock falls, topples, slides or a spreads in bedrock or soils. This statement corresponds also to the broad experience the Office for Geology and Building Material Testing gained by monitoring slope movements and slope failures all over South Tyrol.

Complete creep curves can be divided in three stages (Emery, 1978, fig. 10). Those are “primary” creep after instantaneous elastic response (I), “secondary” or “steady state” creep (II, can last for enormous periods of time) and “tertiary” or “accelerating” creep (III) that leads to material failure and slope failure, respectively, in terms of mass movements.

The observed creep curves may vary in dimensions of velocity, time and acceleration or due to seasonal or meteorological influences but the basic pattern always remains valid

(Crosta, 2003, fig. 11).

In other words: the art of integrating compound saggings / complex rockslides like “Algund” in a regional hazard map is the art of determining their actual position(s) on their particular creep curve(s) and to predict the curve’s shape towards failure. Based on the broadly established relations / laws of Saito (1966, 1980) and Fukuzono (1985) a material failure relation, introduced by Voight (1988), provides a powerful tool for very well approximated failure time calculations of mass movements. Ist general application and its constraints were demonstrated in several publications (e. g. Tilling, 1988; Voight, 1989; Cornelius, 1993; Crosta, 2003). In the following a very short introduction in Voight’s (1988, 1989) concept is given, as it appears to be fundamental for dealing with saggings/complex rock flows in view of a regional hazard maps. With this concept rate changes are related to rates during accelerating creep by the materials failure relation as

$$\ddot{\Omega} = A\dot{\Omega}^{\alpha} \qquad (1)$$

Ω is a measurable quantity like displacement / strain. The dots refer to differentiation with respect to time – i. e. one dot stands for velocity/rate, two dots for acceleration/rate change. A and α are dimensionless constants and can be derived from a given dataset (monitoring data, rate vs. time) as

$$\dot{\Omega} = \left[A(1-\alpha)(t-t_0) + \dot{\Omega}_0^{(1-\alpha)}\right]^{1/(1-\alpha)} \qquad (2)$$

Eq. (2) is the solution with respect to rates for general cases $\alpha \neq 1$, with initial (start monitoring) time and rate t_0 and Ω_0. It allows to calculate failure time t_f with single-differentiated Ω_f (rate at tf) as

$$t_f = \frac{\Omega_f^{(1-\alpha)} - \Omega_0^{(1-\alpha)}}{A * (1-\alpha)} + t_0 \qquad (3)$$

Voight (1988) states that time to failure can be ascertained graphically by drawing reciprocal rate curves (t-$\dot{\Omega}^{-1}$graph). The intersection of the resulting graph with time axis can be taken as t_f (figures 11 and 12).

The curves displayed by figures 10 and 12 are ideal ones, of course. And a common reflex in Geology is to state immediately that "nature can not be described or calculated by mathematics and formulas" and that there are too many natural effects influencing the mass movement and the rock mechanical conditions. In general that is true, for sure. But as publications of the last seven to eight years (e. g. Crosta, 2003) showed, geological and meteorological influences on the creeping rock mass have an significant impact on the detailed shape of the associated creep curves without changing the general development of the creep curves. And the key point for application of creep curves and creep theory for hazard assessment is the analysis of the curves' general development, heading towards time of failure – i.e. intersection with axis of abscissae for reciprocal rate curves or increasing vs. infinite for directly drawn diagrams (see also last two paragraphs at the end of this paper). Such an "real" creep curve, influenced by natural imponderabilities is shown in figure 11.

Main influences on creeping behaviour of moving rockmas-

Figure 8: Foliation (Sf, black line) in the lower part of the mass movement, dipping into the slope, enabling spreading between cleavage planes due to gravitation/tension forces at the steep slope; in combination with orthogonal joint pattern (K1 and K2) creeping movement is eased.

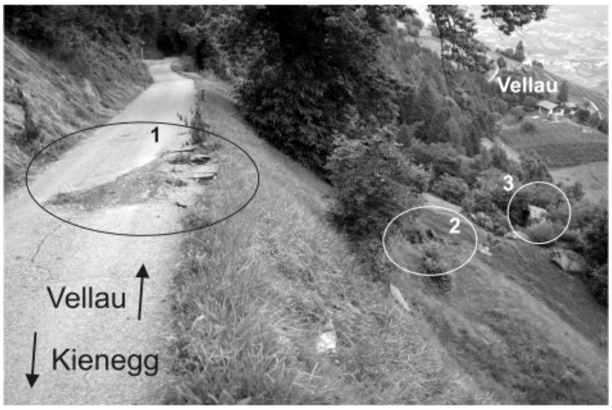

Figure 9: Example for increased activity of other hazards (“combined” processes) in the area of deep seated creeping mass movements: rock fall event on local road between Vellau and Kienegg in June 2008; Severe damages on the road (1) caused by a Gneiss block of about 1.5 m^3 (3) that was stopped in a hedge after hitting the slope one more time (2); one of five rock falls of large dimension that affected the slope around Vellau in June 2008.

ses for the area of Algund are hydrologic ones (changes in precipitation, melting of snow), slope variations due to rock fall events and earthquakes up to magnitude 5-6 that have to be considered for the area around Meran.

Figure 11 also shows that it is absolutely essential to run monitoring systems for adequate periods of time - as a rule more than 3-4 years. Otherwise data can be misinterpreted dramatically or trends that are significant despite seasonal changes and influences on creeping behaviour can not be recognized and analysed.

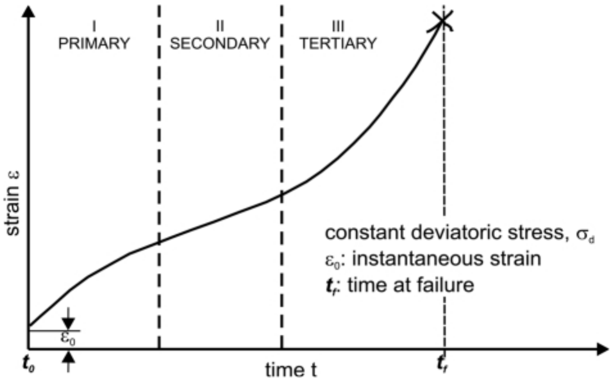

FIGURE 10: Ideal creep curve showing creep behaviour in different stages (Emery, 1978, modified).

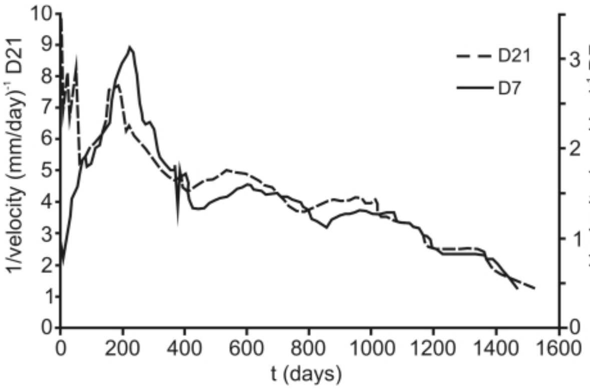

FIGURE 11: Creep-curve, influenced by seasonal changes in hydrological conditions (Crosta, 2003, modified).

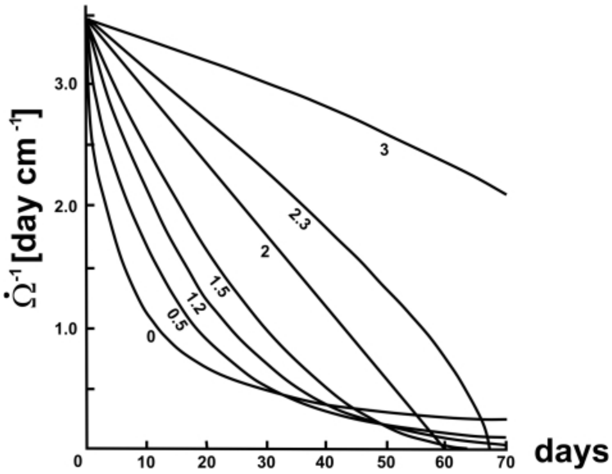

FIGURE 12: Typical reciprocal rate curves, illustrating sensitivity and difficulties resulting from calculated α (Voight, 1988, modified).

As figure 12 indicates, the curvature of the reciprocal rate curves is controlled by α. Results are linear for $\alpha = 2$, concave for $\alpha < 2$ and convex for $\alpha > 2$. This is one of the most dangerous effects for applying this concept in view of creeping mass movements since research of the authors named above proved that α typically ranges between 1.6 and 2.2 for rocks (Cornelius, 1993; Crosta; 2003) and single values may fall outside this limits. So t_f easily might be undervalued for $\alpha < 2$ and overvalued for $\alpha > 2$ which is both a serious threat to a reasonable forecast in view of a reliable HM. The method depends to a large extend on sophisticated calculations and statistical fits of α.

Cruden (1987) stated the reliability of Saito-based forecast-methods for slope failure and threshold definitions (q.v. Crosta, 2003) for time scales of about 6 months and thus their fitting to the temporal specifications of HM matching the BUWAL-matrix. This is due to the fact that prediction of failure in terms of a HM and the BUWAL-matrix respectively does not require statements that are accurate within hours or days. One always has to be conscious of the large time scale a HM deals with as categories of time are 30 years, 100 years and 300 years. So the main information that has to be given for the assessment of a deep-seated creeping mass movement in view of the local HM is when failure of the rock mass or single parts of it has to be expected according to its creep curve and the current stadium of creep the movements can be related to (primary, secondary or tertiary). It seems to be applicable to consider primary creep to be related to "very low" to "low" probability of occurrence of failure in accordance with the BUWAL-matrix whereas secondary creep can be related to "low" to "medium" probability of occurrence and tertiary creep has to be linked with "high" probability of failure-occurrence.

This entire concept has one major precondition. It has to be impossible, that the mass movement assessed is able to develop in a catastrophic manner, i.e. directly from primary creep to acceleration (tertiary creep) or with an secondary stadium of creep that lasts only for an exceptionally short period of time. The mass movement's correspondence to a roughly typical ("perfect") creep curve within the geological and seasonal constraints discussed above and thus the fulfilment of this major precondition can not be cleared only by monitoring. Sound geologic field work is the only basis for dealing with the question of an possibly exceptional behaviour of the mass movement or ist single units. So it becomes obvious that neither of the applied methods can be used for assessing compound saggings / rock flows exclusively but it should be possible to develop a reliable and broadly accepted local HM for areas affected by these mass movements by combination of all methods applicable for the geologists in charge – "traditional" field work and laboratory analysis, reflection of local rock mechanics and hydrology, monitoring and finally application of numerical codes for simulations of the complex process and mathematically based approximations as discussed in this paper.

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Received: 9. June 2009
Accepted: 9. November 2009

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