Volume 1

Landslides and Engineered Slopes

Protecting Society through Improved Understanding

Editors: Erik Eberhardt, Corey Froese, Keith Turner and Serge Leroueil

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

Kinematics and internal deformation of a slow deep-seated rock slide in metamorphic rock (Niedergallmigg, Austria)

C. Zangerl & C. Prager
alpS-GmbH, Grabenweg 68, 6020 Innsbruck, Austria

W. Chwatal & E. Brückl
Institute of Geodesy and Geophysics, Vienna University of Technology,1040 Vienna, Austria

H. Kirschner, R. Brandner
Geology und Paleontology, University Innsbruck, 6020 Innsbruck, Austria

ABSTRACT: The slowly "creeping" deep-seated rock slide Niedergallmigg (Tyrol, Austria) comprises a volume of more than 400 million m^3 and a maximum thickness of more than 300 m. Results from geodetic surveys i.e. terrestrial and GPS methods show actual slope velocities ranging from 3 to 8 cm per year. The rock slide Niedergallmigg is located in phyllitic rock of the Landecker Quarzphyllite Zone and paragneissic rock as well as mica schists of the Silvretta Crystalline Complex. Post-glacially, the sliding mass moved more than 200 m which in turn caused considerable internal rock mass deformation i.e. fracturing, fragmentation and dilatation. In relation to the pre-failure topography the middle to upper part of the rock slide gained volume loss and at the toe the slope volume increased. GIS-based estimations show an enormous volume imbalance between the volume loss and accumulation areas. Given that the volume increase at the toe is nearly three times smaller than the volume loss at higher elevations considerable slope toe erosion by the river Inn has occurred post-glacially.

1 INTRODUCTION

Generally, the mechanisms and processes of slowly creeping rock slides that cause rock mass fragmentation, internal strains and the initial formation of failure and shear zones, respectively, are not yet understood in detail. Therefore new conceptual models focusing on these mechanical processes need to be established. The comprehensive analyses of rock slide geometries in relation to pre-failure slope topographies and of surface deformation monitoring as well as subsurface investigation data (e.g. boreholes, seismic surveys, inclinometers) help to obtain new fundamentals about these complex slope processes.

Frequently it is observed that deep-seated rock slide masses experiences considerable changes of its geometry. Numerous field observations at rock slides in metamorphic rock masses (e.g. schists, paragneisses, phyllites) show that the pre-failure rock slope topography is different than the actual one. A key feature of these slope geometries is a convex shaped i.e. bulge-like topography at the foot of the slope and a concave shaped i.e. subsidence-like topography in the middle to upper part. It is obvious that the newly formed slope geometries result from gravitational slope processes where internal deformation occurred within the rock mass of the slide. Cataclasis, shearing, fracturing and dilatation are the key deformation processes. Analyses of borehole core logs into deep-seated rock slides show that in comparison to the stable bedrock an increased number of brittle shear zones (i.e. fault gouges and breccias) and fractures occur (Bonzanigo et al. 2007, Zangerl et al. 2010). It is assumed that this increased discontinuity density develop from internal rock mass strains most likely during the initial i.e. first-time rock slide formation process. Subsequent strain localization will lead to discrete shear/creeping zone formation where most of slope deformation accumulates. At an advanced state of the slope the initially prevailing process of internal fragmentation and deformation reduces and sliding/creeping along discrete shear zones is getting more relevant. This is confirmed by actually measured inclinometers through active deep-seated rock slides where often sliding/creeping along one or several sliding zones is observed (Novarraz et al. 1996, Watson et al. 2007, Zangerl et al. 2010). In contrast, rock masses in between does not show appreciable deformation rates.

The implications of internal rock mass deformation processes on slope behaviour are manifold. Firstly, strain localization leads to the formation of one or several discrete sliding zones composed of fault breccias and gouges which control the creeping and strength behaviour (Zangerl et al. 2010). Secondly, internal rock mass strains can change the sliding mass geometry considerably and thus affect the in-situ stress condition along the active sliding

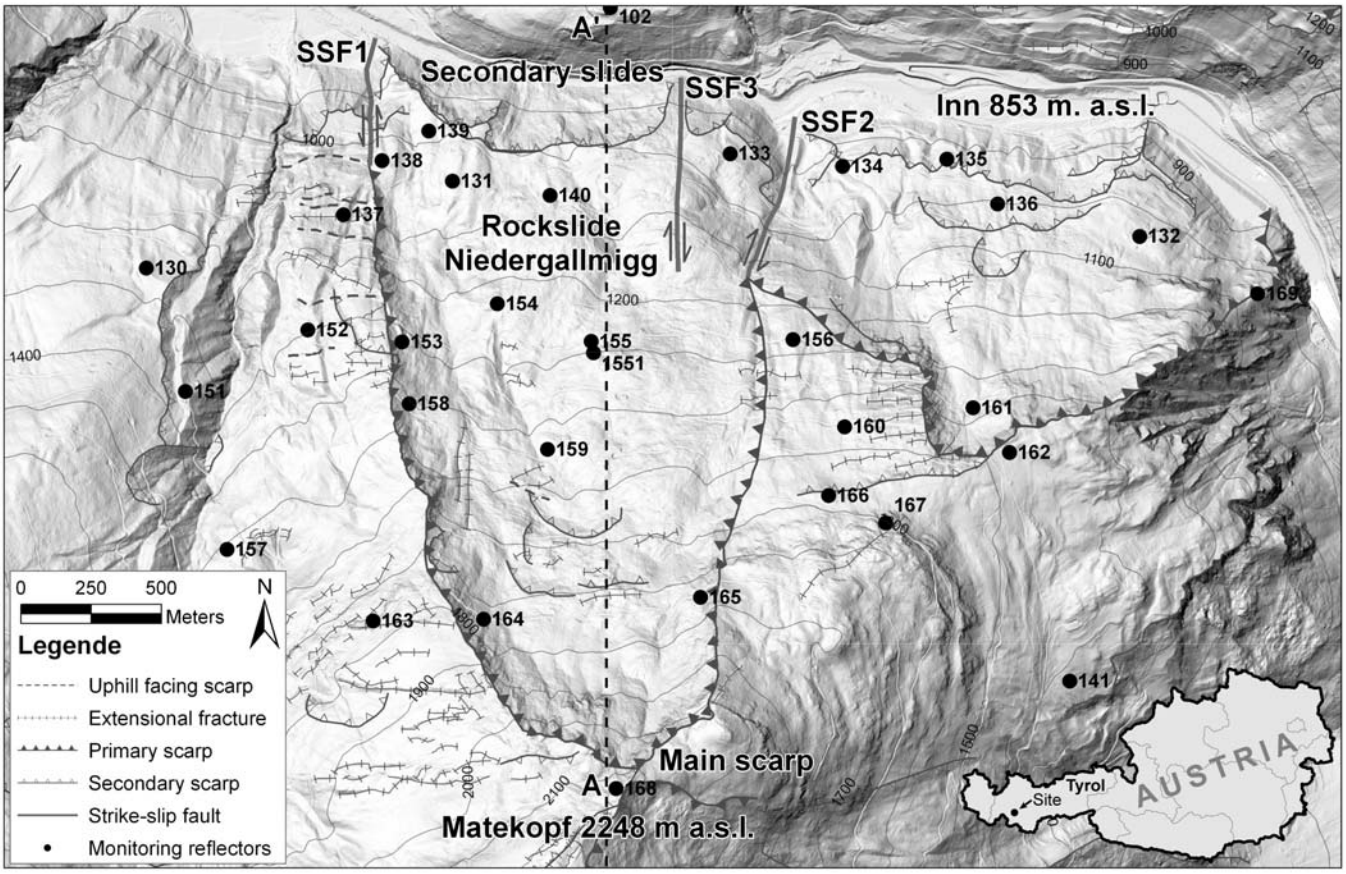


Figure 1. Hillshade map of the deep-seated rock slide system Niedergallmigg (Austria) showing primary and secondary scarps, strike-slip faults (SSF1, SSF2, SSF3), geodetic monitoring targets and the trace of the cross section A-A'.

zone(s). And thirdly, the internal deformation process causes rock cataclasis, fracturing and fragmentation which in turn weakens the strength and alters the hydrogeological characteristics of the rock mass. This in turn can favour the formation of secondary rock slides at the toe of large rock slide systems.

The complex interaction of the more than 300 m thick rock slide system Niedergallmigg (Austria) with the river Inn at the slope toe is a primary focus of this contribution. Rock slide volume balance analyses were performed in order to determine mass loss due to river erosion. Furthermore observations and analyses of the slope kinematics, geometrical slope changes and internal deformation processes are presented.

2 GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The slow rock slide system Niedergallmigg is located in Northern Tyrol, Austria (ETRS89 10°37'29" / 47°06'38"). It shows a difference in elevation between the toe and the main scarp of about 1400 m and a maximum E-W extension of almost 1500 m (Fig. 1). Morphological features, in particular the appearance of the head scarp at the Matekopf (2248 m.a.s.l), indicate a total displacement of the slide mass of more than 200 m. These large slope displacements caused the formation of a remarkable well shaped primary scarp which is traceable across the entire slope. The pre-failure mean slope angle is inclined about 30°.

Tectonically, the case study is situated within the Silvretta Crystalline Complex which comprises the upper part of the rock slide (Brandner 1980). The middle to lower part the slide is build up by rocks of the Landecker Quarzphyllite Zone. The main thrust fault between these two units is dipping flatly and outcrops at an elevation between 1500 to 1600 m.a.s.l. (Fig. 5). Hence paragneisses and schists of the Silvretta Crystalline were thrust on phyllitic gneisses, phyllites of the Landecker Quarzphyllite Zone. In the study area the NE-SW trending Engadine and the E-W trending Inn Valley Fault Zone are main structural lineaments in a strike-slip mode. Within tectonic units, polyphase deformation processes formed ductile and brittle structures that influence the rock mass strength and anisotropy. Nevertheless the orientation of the foliation of the rock masses is characterized by a flat to medium inclined dip angle to south and therefore was found to be unfavorable to promote slope failure and to generate a persistent failure plane.

Even though age dating of the Niedergallmigg rock slide was not performed so far a post glacial formation age of several thousand years is assumed.

3 SEISMIC INVESTIGATION

In order to explore the thickness and internal structure of the Niedergallmigg rockslide a 3-D refraction seismic survey was carried out (Fig. 3; Chwatal et al. 2006, Zangerl et al. 2009). Therefore 373 seismic stations were installed along 4 transverse profiles comprising a total length of 7.5 km and a geophone distance of 15-25 m. 41 shots were recorded simultaneously by all receivers. This geophone set up enabled 2-D analyses along the four profiles but also a 3-D inversion of the whole data set (inline and cross-line shots). The seismic data show a vertical gradient of the velocity for the sliding mass and a nearly constant velocity for the underlying in-situ bedrock.

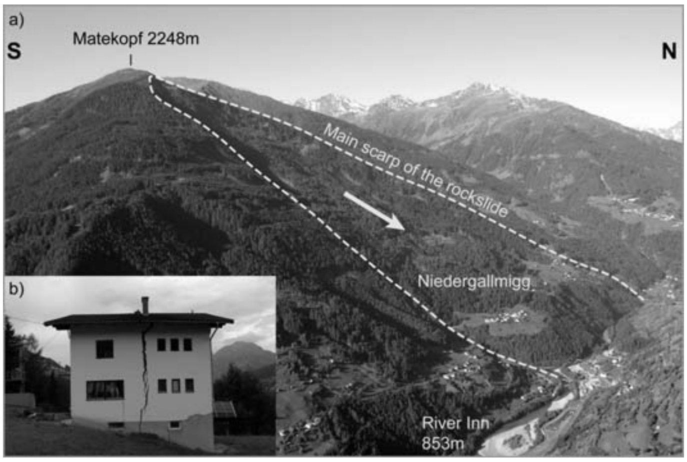


Figure 2. a) Rock slide system Niedergallmigg with the main head scarp, the river Inn and the location of the village Niedergallmigg, b) damaged house located close to the western boundary of the slide.

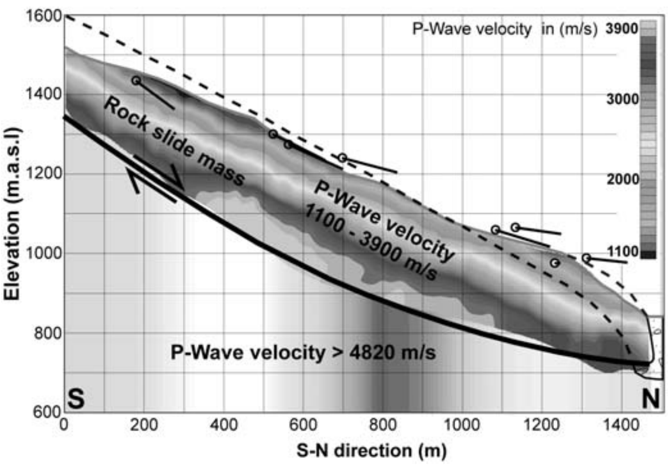


Figure 3. Seismic cross section (N-S direction), close to A-A'.

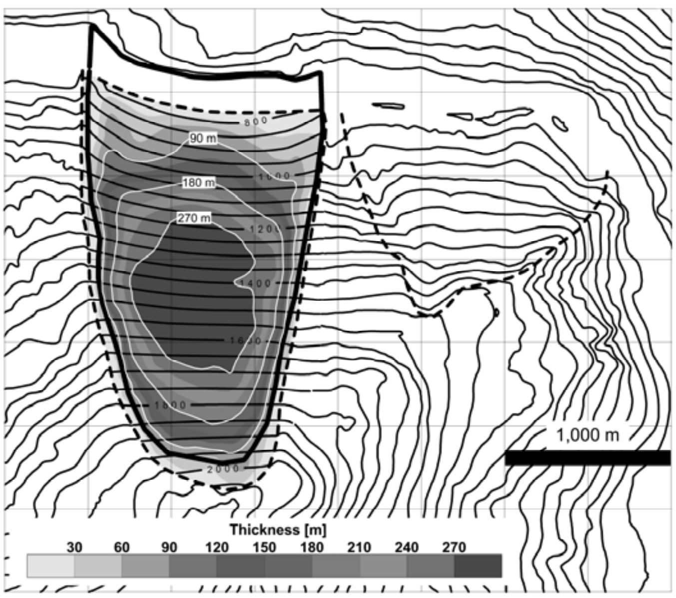
Therefore, a combination of seismic refraction tomography for the landslide mass and standard seismic refraction method for the compact rock were applied. In order to analyse the measured data, 3-D processing techniques (Brückl et al. 2003) and tomographic inversion algorithm (Hole 1992) were applied. As a result, the 3-D seismic velocity distribution of the landslide system and its stable surrounding is gained.

P-wave velocities of the sliding mass are near the surface 1000-2000 m/s, at depths of 25-150 m 2000-3000 m/s and below 150 m 3000-4000 m/s. Further below, velocities of 4800-5200 m/s were measured, which can be interpreted as the basis of the landslide (Figs. 3,4).

Plotting the P-wave velocities of the sliding mass versus depth an average velocity-depth function that is based on the assumption of dry or drained rock mass conditions can be fitted. The porosity of the fractured rock mass is based on P-wave velocities and is estimated from a relationship according to Gassmann (1951) and Watkins et al. (1972) and. For the Niedergallmigg rock slide an average rock mass porosity of 0.21 was estimated.

4 DEFORMATION MONITORING

In the Niedergallmigg rockslide area deformation measurements were performed since 1975 (Fig. 1). The Federal Office of Metrology and Surveying (BEV) instrumented about 11 targets at the foot of the north-dipping slope whereby five targets were installed inside the rockslide area (no. 131, 133, 138, 139, 140). The four targets no. 132, 134, 135 and 136 were placed at a currently dormant deep-seated rockslide which is located east from the Niedergallmigg rock slide. The two targets 130 and 137, respectively, were installed outside of the rock slide. The initial measurement was performed by means of triangulations methods whereby for several points no height determination was performed.



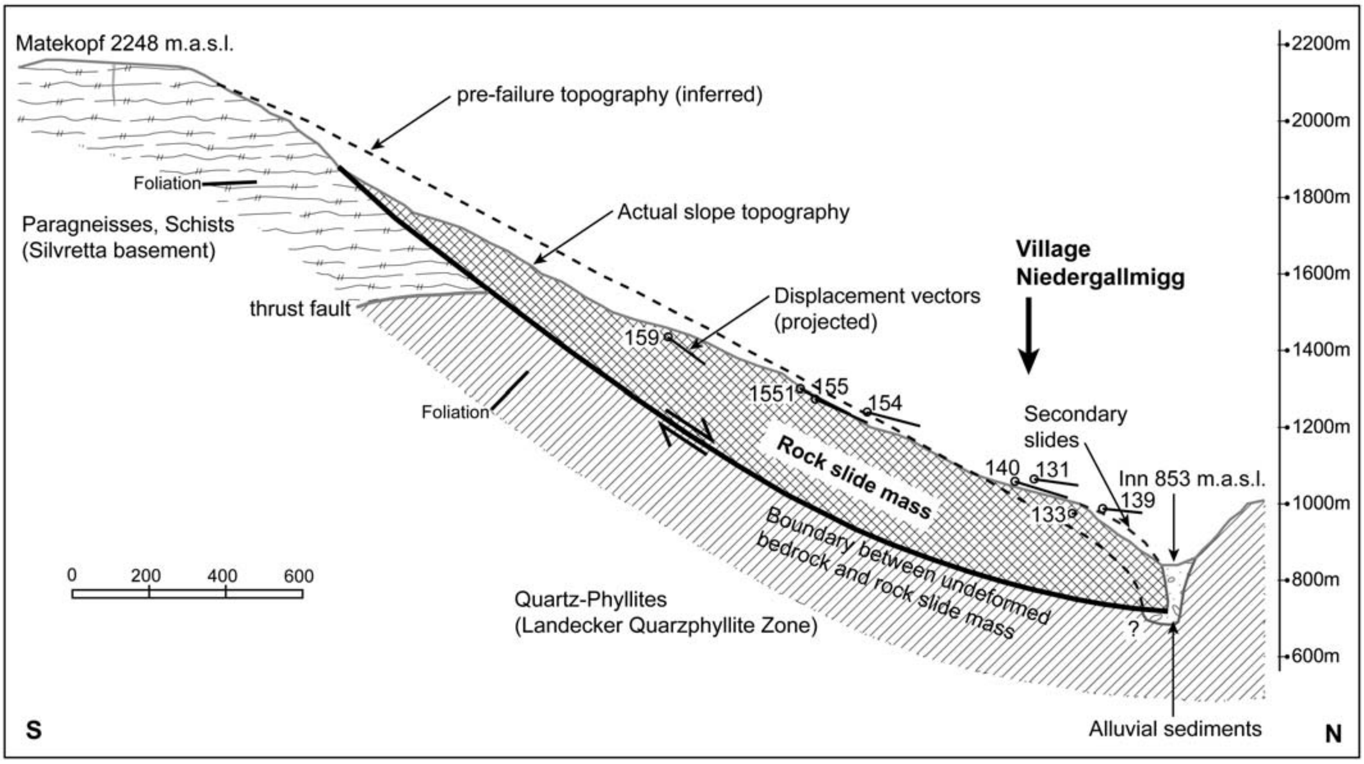


Figure 4. Thickness map of the Niedergallmigg rock slide system (modified after Zangerl et al. 2009).

Figure 5. N-S cross section along A-A' (for location see Fig. 1) showing the rock slide geometry, the actual and pre-failure topography, displacement vectors of geodetic targets and geological setting.

In the framework of a diploma thesis, i.e. in 1996 the targets were remeasured by means of GPS methods (Rittinger 1997). According to this campaign mean annual velocities of more than 10 cm/year were obtained. Furthermore it was found that the mean slope velocity continuously decreases for targets located close to the primary scarp (i.e. 6.2 cm/year for target no. 138 to 10.6 cm/year for target no. 140). Target no. 133, which is installed at the toe of the rock slide near the eastern boundary shows very low displacement rates of 3 mm/year. Given that no surveying precision values are available it is questionable whether the slope is creeping at extremely slow rates or whether it is actually inactive (dormant).

In the framework of a new and more detailed investigation program the Niedergallmigg rockslide was re-surveyed by means of tachymetric methods. In Oct/Nov. 2003 (i.e. 22.10.2003, 12.11.2003, 17.11.2003) the pre-existing targets and 20 additionally installed ones were measured in order to determine their 3-D coordinates. In order to minimize refraction influences on accuracies two-way measurements by using total stations were performed. Follow-up measurements were performed on 18.05.2004, 14.04.2005 and 04.11.2005. Results show that for the targets no. 131, 138, 139 and 140 within the time interval 2003 to 2005 the mean annual velocity varied between 3.5 to 7.1 cm/year. The previous obtained observation of a velocity increase towards the centre of the slide was confirmed by these campaigns. New targets installed higher up on the rock slide (i.e. 154, 155, 1551 and 159) show velocities between 7.1 and 7.8 cm/year. Given that these surveys obtained the horizontal position and the height of the targets, mean dip angles of total displacement vectors can be determined (regression analyses). It was found that the dip angle of displacement vectors increase from 6° at the toe to 36° in the upper part of the slope (Fig. 5). Again, for target no. 133 only minor slope activity in the range of mm per year was observed which is within the accuracy of ±2 cm for a survey. Based on this it is assumed that target no. 133 is not affected by considerable slope deformations. Hence between targets no. 133 and 140 a discrete strike-slip shear zone may exit which is morphologically traceable (SSF3 in Fig. 1).

5 GEOMETRY, KINEMATICS AND INTERNAL DEFORMATION CHARACTERISTICS

Geological mapping, seismic investigations (Fig. 4) and deformation monitoring show that the Niedergallmigg rock slide system features a maximum thickness of more than 300 m and a volume of 0.43 km^3. Surface deformation measurements indicate that the dip angle of total displacement vectors increase from 6° at the lower part to 36° in the upper part of the slope. This and the results from the 3-D refraction seismic survey suggest that the slope kinematics is characterized by a rotational sliding behavior along one or several shear zones (Fig. 5). The dip angle of the inferred basal sliding zone varies between 5° and 45°. The occurrence of a fully persistent basal sliding zone is not proven so far by inclinometer instrumented boreholes. Nevertheless the appearance of a primary scarp across the entire slope, the large shear offset along scarp faces (i.e. more than 200 m at Matekopf area) and the seismic velocity contrast between the rock slide mass and the undeformed rock suggest that a coherent basal sliding zone was already developed. Furthermore it was observed that a simple back-rotation of the slide mass along the inferred basal sliding zone does not successfully fit into the pre-failure topography.

The ongoing slope movement towards north cause the compression of and/or thrusting on the valley infill sediments (Figs. 1,5). The course of the river Inn was deflected and pushed towards north. At the western boundary i.e. along the strike-slip fault SSF1 the rock slide offset exceeds more than 120 m. Similar observations were found at the eastern boundary of the rock slide mass (i.e. strike-slip fault SSF2), where the river Inn was considerable deflected from his original river course. The dextral strike-slip fault SSF3 split the rock slide body into two slabs: a western active one and an eastern most likely dormant one. In the valley floor a dextral slip offset of about 30 m was measured for the fault SSF3. This led to further compression of the valley infill deposits in front of the western slide mass. The eastern part of the rock slide system i.e. the slab between the strike slip faults SSF2 and SSF3 is either inactive/dormant or only very little active (a few mm/year). This is opposed to the western sliding slab i.e. between SSF1 and SSF2 where increasing velocities towards the center of the slide were measured (i.e. 3.5 to 7.1 cm/year).

As mentioned above the extent of the primary head scarp indicates total displacements of more the 200 m. A main geomorphological feature of the Niedergallmigg rock slide but also of numerous other case studies in mica-rich crystalline rock masses is related to the enormous failure-induced change of the pre-failure slope topography. On the one hand, the middle to upper area of the rock slide mass is characterized by considerable surface subsidence and mass losses. And on the other hand, the foot of the slope features bulge-like slope geometries and rock mass accumulation. Furthermore the advancing slope deformation process causes an oversteepening of the foot slope. In Niedergallmigg the turnabout between mass loss (settlement) and mass accumulation areas was found at an elevation between 1000 to 1100 m.a.s.l.. Thus the newly formed slope geometry is the product of failure and sliding-induced internal strains, fracturing and fragmentation of the rock mass. The reduced strength of the rock mass and slope toe oversteepening entail to first-time, small-scale secondary rock slides (Fig. 1).

Given that the north facing Niedergallmigg rock slide system is characterized by an excellent defined primary scarp boundary, a pre-failure topography reconstruction can be performed reliably. Based on this volume balance analyses between the pre- and post-failure slope were done. Herein rock mass volume loss in the middle to upper height is compared with volume increase in lower height areas of the slide. The first method focuses on an area balance i.e. area loss and area increase along the cross section A-A' (Figs. 1,5). The second method is based on GIS (Geographical Information System) analyses where the pre-failure topography i.e. elevation lines were reshaped and volume balances performed (difference models). According to the first method, results show that along profile A-A' the cross section area was reduced by 92,000 m^2 for upper and middle height areas. In contrast an area increase of only 36,000 m^2 was obtained in lower height areas. Thus a ratio of 2.6 is obtained.

The GIS based volume analyses between the upper and middle part, respectively and the lower part shows similar trends. The volume loss (i.e. surface subsidence) area gains more than 85 million m^3. In the lower part a rock mass volume increase of 30 million m^3 was obtained. This yields into a ratio of 2.8 which coincides with estimations from the area-based method. If deformation-induced dilatation effects (i.e. mean porosity increase to 0.21) of the rock mass are additionally considered, then the volume unbalance is even larger. These mass balance analyses suggest that the rock slide system experience considerable rock mass volume loss in the past of more than 55 million m^3.

Failure volume estimations focusing on the present-day secondary scarps at the toe result in secondary slide volumes of a few million m^3. The magnitude lower volume suggests that rock mass degradation is driven by several secondary rock slide events and/or continuous erosion processes.

6 DISCUSSION AND CONCLUSION

Large displacements of the Niedergallmigg rock slide changed the pre-failure slope topography and rock slide geometry considerably and induced internal rock mass strains. This affected the mechanical and hydrogeological rock mass properties as well as the in-situ stress conditions especially at the toe due to slope oversteepening. As a consequence of the reduced rock mass strength and the newly formed slope geometry secondary rock slides developed. Furthermore it is assumed that slope erosion at the toe by the river Inn and heavy rainfall as well as snowmelt additionally forced the formation of these secondary slides.

Volume balance analyses showed that at the slope toe a rock slide volume of more than 55 million m^3

is missing. The appearance of secondary slides, the deflection of the river Inn course suggest that fluviatile erosion processes led to such mass losses. The complex interaction between geometrical changes and strength reduction of rock slides, the formation of secondary failure events at the toe and river erosion may play an important role in keeping deep-seated rock slides active. A comparison with measured annual erosion/transport capacities of rivers in alpine catchment areas (Tschada & Hofer 1990) suggest that the volume loss of the Niedergallmigg rock slide can be easily obtained during a time span of several hundred years. Furthermore abnormally flood events may even increase the erosion capacity of the river Inn.

The case study Niedergallmigg further shows that mechanical interaction with the valley infill cause self-stabilization of a rock slide slab.

The discrepancy between the pre-failure topography and the rock slide geometry indicate that considerable internal strains of the rock slide must have occurred in the past. Geodetic measurements show increasing velocities and hence evidence for differential lateral movements. Whether vertical internal strains are actually occurring remains so far unclear due to the lack of borehole measurements. A comparison with borehole instrumented case studies in similar rock masses show that often internal strains are actually small or even unverifiable (Bonzanigo et al. 2007, Noverraz 1996, Watson et al. 2007, Zangerl et al. 2010). Given that those observations are transferable to the case study Niedergallmigg internal slide mass deformation was a primary process during the initial formation of the slide. However subsequently and actually, slope deformation is characterized by strain localization along a basal or several shear zone(s) and en bloc movement.

REFERENCES

Bonzanigo, L., Eberhardt, E. & Loew, S. 2007. Long-term investigation of a deep-seated creeping landslide in crystalline rock - geological and hydromechanical factors controlling the Campo Vallemaggia landslide. Canadian Geotechnical Journal 44 (10): 1157-1180.

Brandner, R. 1980. Geologische und Tektonische Übersichtskarte von Tirol, Tirol-Atlas, C1, C3. - Univ.-Verlag Wagner, Innsbruck.

Brückl, E., Behm, M., Chwatal, W. 2003. The application of signal detection and stacking techniques to refraction seismic data. Oral Presentation at AGU, San Francisco, 08-12 December 2003.

Chwatal, W., Kirschner, H., Brückl, E. & Zangerl, C. 2006: Kinematics and Hazard of the Niedergallmigg-Matekopf mass movement. EGU 2006, Wien, Geophys. Res. Abstract 8, 05998.

Gassmann, F. 1951. Über die Elastizität poröser Medien. Vierteljahrsschrift der Naturforschenden Gesellschaft in Zürich 96(1): 1-23.

Hole, J.A. 1992. Nonlinear high-resolution three-dimensional seismic travel time tomography. Journal of Geophysical Research 97: 6553-6562.

Noverraz, F. 1996. Sagging or deep-seated creep: fiction or reality? In: Senneset (Ed.), 7th International Symposium on Landslides. 821–828. Rotterdam: Balkema.

Rittinger, P. 1997. Ermittlung der Verschiebungen eines Festpunktfeldes im Oberinntal GPS. University Innsbruck, Austria, unpublished diploma thesis, p. 106.

Tschada, H. & Hofer, B. 1990. Total solids load from catchment area of the Kaunertal hydroelectric power station: the results of 25 years of operation. In: Hydrology in Mountainous Regions II – Artificial Reservoirs, Water and Slopes, IAHS Publ. no. 194: 121-128.

Watkins, J.S., Walters, L.A., Godso, L.A. 1972. Dependence of in-situ compressional wave velocity on porosity in unsaturated rocks, Geophysics 37(1): 29-35.

Watson, A.D., Moore, D.P., Stewart, T.W. & Psutka, J.F. 2007. Investigations and monitoring of rock slopes at Checkerboard Creek and Little Chief Slide. In: Eberhardt, E., Stead, D. & Morrision, T. (eds), Proceeding of the 1st Canada - U.S. Rock Mechanics Symposium, Vancouver, Canada, (2): 901-908. London: Taylor & Francis Group.

Zangerl, C., Prager, C., Engl, D.A., 2010. Self-stabilisation mechanisms of slow rock slides in crystalline bedrock (Tyrol, Austria). In: A.L. Williams, G.M. Pinches, C.Y. Chin, T.J. McMorran & C.I. Massey (eds), Geologically Active, 11th Congress of the International Association for Engineering Geology and the Environment (IAEG), Auckland, New Zealand, 903-910. London: Taylor & Francis Group.

Zangerl, C., Eberhardt, E., Perzlmaier, S. 2010. Kinematic behaviour and velocity characteristics of a complex deep-seated crystalline rockslide system in relation to its interaction with a dam reservoir. Engineering Geology 112: 53–67.

Zangerl, C., Prager, C., Chwatal, W., Mertl, S., Renk, D., Schneider-Muntau, B., Eberhardt, E., Kirschner, H., Brandner, R., Brückl, E., Fellin, W., Tentschert, E, Eder, S., Poscher, G. & Schönlaub, H. 2009. Landslide failure and deformation mechanisms, investigation and monitoring methods. In.: Veulliet E, Stötter J., & Weck-Hannemann H. (eds), Sustainable Natural Hazard Management in Alpine Environments, 135-173, Springer.

7 ACKNOWLEDGMENTS

The authors wish to acknowledge and thank the Tiroler Wasserkraft AG (TIWAG), A-6020 Innsbruck, ILF Consulting Engineers Ltd., A-6063 Rum, GEO-ZT GmbH, A-6060 Hall, Kplus-FFG and Tiroler Zukunftsstiftung for supporting this ongoing research project.