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Formation processes, geomechanical characterisation and buttressing effects at the toe of deep-seated rock slides in foliated metamorphic rock

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ABSTRACT

In order to increase the understanding of deep-seated rock slides in terms of formation processes, kinematics, and the impact of geometrical factors on slope stability and deformation behaviour, a 300 m thick active rock slide located in Austria was investigated. Results of geological and geodetic field surveys, geophysical in-situ investigations and numerical modelling are presented and analysed. Particular focus is given on the geomechanical characterisation of the rock slide mass, progressive topographical slope changes due to initial rock slide formation processes, internal rock mass deformation processes and back-calculated strength properties of the basal shear zone. Back calculations considering the actual rock slide geometry yields a friction angle of the basal shear zone of about 24°. Rock slide volume balance analyses are performed in order to determine mass loss due to secondary slides and river erosion. In relation to the pre-failure topography, the middle to upper part of the rock slide has lost (zone of depletion) and the foot of the slope has accumulated rock mass material (zone of accumulation). GIS-based estimations show an enormous volume imbalance between the depletion and accumulation zones. Given that the volume accumulation at the foot of the slope is nearly three times smaller than the volume depletion at higher elevations, considerable erosion of the toe by the river has occurred. The complex geological interaction of the rock slide with the alluvium at the toe of the slope was a key question of this study, and thus the geomechanical impact of the alluvium on slope deformation and stability behaviour was studied by applying 2D discrete element modelling methods. Results show that the alluvium at the foot of the slope has a positive effect on the slope stability and the sensitivity of the stability behaviour.

1. Introduction

The mechanisms and processes that cause fracturing, fragmentation, and internal deformation of rock masses and the initial formation of failure and shear zones of very slow deep-seated rock slides in foliated metamorphic rock are still not fully understood (Cruden and Varnes, 1996). New models focusing on these geomechanical processes need to be established. Analyses of post-failure rock slide geometries in relation to pre-failure slope topographies and surface deformation monitoring as well as subsurface investigation data (e.g. boreholes, seismic surveys, inclinometers) help to obtain new fundamental information about these complex slope processes.

It is frequently observed that deep-seated rock slides experience considerable changes in their geometry in the course of their development and deformation history. Numerous field observations of rock slides which developed in metamorphic rock (e.g. schists, paragneisses, and phyllites) show considerable changes between the pre-failure slope topography and the post-failure one (Bonzanigo et al., 2007). The characteristics of post-failure slope geometries is usually 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. Field surveys show that the newly formed slope geometries result from gravitational slope processes where overall internal rock mass deformation has occurred within the slide. Cataclasis, fracturing, shearing and dilatation are the key deformation processes. Analyses of cored drillings from deep-seated slides in similar metamorphic rock masses (i.e. mica schist and paragneiss) show relative to the stable bedrock underneath an increased density of brittle shear zones (i.e. fault gouges and breccias) and meso-scale fractures (Bonzanigo et al., 2007; Watson et al., 2007; Agliardi et al., 2009, 2012; Barla, 2010; Zangerl et al., 2010a,b). The increased fragmentation and loosening of the rock mass predominately results from internal rock mass strains, most likely initiated during the first-time rock slide formation process.

A slope deformation mechanism which is often observed during the initial formation process of rock slides is toppling which can penetrate

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deeply into the rock mass. It is also observed that this type of failure mechanism is linked to geological structures (i.e. foliation, joints and fault planes) which are dipping steeply into the slope and thus are prone to toppling. Whereas in some cases the toppling activity is advancing at slow rates or comes to a halt, others are characterised by a transition from toppling to sliding kinematics (Zischinsky, 1969; Guglielmia et al., 2000; Amann, 2006). In this situation a basal shear zone is newly formed along the inflexion points of the rock strata at great depths. A case study exemplarily for such slope behaviour is the well known La Clapiere rock slide in France (Guglielmia et al., 2000; Helmstetter et al., 2004).

However, rock mass fracturing and deformation processes which cause internal rock mass fragmentation, strain localisation and finally the formation of basal shear zones are still poorly understood. As a hypothesis, internal rock mass deformation may result from advanced toppling processes (Sjörberg, 2000) or from increased internal rock mass straining. Later on, ongoing slope deformations lead to strain localization and subsequently to the formation of discrete shear zones at the base of the slide and inside of the rock mass. Along these shear zones most of the actually measured slope displacement takes place (Noverraz, 1996) and sliding becomes the final slope deformation process. This has been proven by numerous inclinometer measurements in active rock slides (Noverraz, 1996; Watson et al., 2007; Zangerl et al., 2010a). Often the measurements show that separate blocks or rafts of blocks in between the active shear zones experience either no or only minor strain and thus are dominated by en bloc movement.

The consequences of internal rock mass deformation processes on slope behaviour are manifold. Firstly, strain localization leads to the formation of one or several discrete shear zones composed of fault breccias and gouges (similar to tectonically formed fault zones) which control the deformation and strength behaviour (Zangerl et al., 2009). Secondly, internal rock mass strains can change the sliding mass geometry considerably and thus affect the in-situ stress condition along the active sliding zone(s). Thirdly, the internal deformation process causes rock cataclasis, fracturing and fragmentation which reduces the strength of the rock mass and alters its hydrogeological properties (i.e. increasing porosity, permeability and storativity). This can favour the formation of secondary rock slides at the toe of large rock slide systems.

In order to increase the fundamental understanding of formation processes, the impact of geometrical factors on slope stability and deformation behaviour, and the kinematics of deep-seated rock slides in general, the 300 m thick Niedergallmigg rock slide in Austria was investigated in great detail. Particular focus is given on the geomechanical characterisation of the rock slide mass, progressive topographical slope changes due to initial rock slide formation processes, internal rock mass deformation processes and back-calculated strength properties of the basal shear zone. The complex geological interaction of the rock slide with the alluvium at the toe of the slope was investigated and the mechanical impact of the alluvium on slope deformation and stability behaviour was studied by using 2D numerical modelling methods. Furthermore, rock slide volume balance analyses are performed in order to determine mass loss due to secondary slides and river erosion.

2. Geological and hydrogeological setting

The Niedergallmigg rock slide is located in Northern Tyrol, Austria (ETRS89 10°37′29″ / 47°06′38″, Zangerl et al., 2012). It has a difference in elevation between the toe where the River Inn is located and the main scarp of about 1400 m and a maximum E–W extension of almost 1500 m (Figs. 1 and 2). Morphological features, in particular the location of the main scarp just under the summit of the Matekopf (2248 ma.s.l) indicate a total displacement of the rock slide mass of at least 200 m (Fig. 1). The large slope displacements caused the formation of a remarkably well-shaped main scarp as well as left and right flanks which are traceable across the entire slope. The pre-failure mean slope inclination was around 30°.

Tectonostratigraphically, the rock slide is situated within the Silvretta Crystalline Complex which comprises the upper part of it (Fig. 3; Brandner, 1980). The middle to lower part of the slide consists of strata belonging to the Landecker Quartzphyllite Zone. The main thrust fault between these two main tectonostratigraphic units is flatly dipping and outcrops at an elevation between 1500 and 1600 ma.s.l. (Fig. 3). Hence the paragneisses and schists of the Silvretta Crystalline were thrust over the phyllitic gneisses and 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 the main structural lineaments in a strike-slip mode. Within the units, polyphase deformation processes formed ductile and brittle structures that influence the rock mass strength and anisotropy. Based on aerial views, digital terrain models from airborne laser scanning and field surveys E–W striking steeply dipping fault zones were found to be the dominant structures in the area mapped (Fig. 1). These structures dissect the rock mass into E–W striking platy-shaped blocks which are prone to toppling towards the north under stress release conditions.

The meso-scale fracture network in the scarp area (Fig. 4) is dominated by two steeply inclined joint sets, one striking NE–SW with a mean dip direction/dip angle of 136°/84° (Joint set JS1) and another one striking NW–SE showing a mean dip direction and dip angle of 209°/81° (Joint set JS2). In addition, two intermediately inclined joint sets dipping NE (Joint set JS3; dip direction and dip angle of 42°/54°) and W (Joint set JS4; dip direction and dip angle of 264°/45°), respectively, were observed. In the scarp area a dominantly and favourably oriented joint set sub-parallel to the basal shear zone of the rock slide was not observed. However, at local scale a few joints can be aligned sub-parallel to the basal shear zone of the rockslide.

In the upper part of the slope i.e. within the Silvretta Crystalline Complex, foliation planes are nearly flat i.e. at a mean dip direction/dip angle of 126°/04° (Fig. 4). Within the Landecker Quartzphyllite Zone, in the lower part of the slope, the foliation dips moderately to the south and therefore into the slope (Fig. 4). Based on statistical analyses a mean dip direction and dip angle of 172°/60° was determined. Similar to other geological structures the foliation was oriented unfavourably to favour slope failure in a simple dip-slope sliding mode. As opposed to other case studies in similar rock types, the structural inventory does not indicate the presence of fracture sets which are aligned sub-parallel to the slope and would therefore favour the formation of a coherent basal shear zone (Zangerl and Prager, 2008). In contrast, some of these structures, especially the steeply inclined brittle fault zones, joints and foliation planes favour toppling processes.

Glacial and fluvial processes have caused deep erosion of the valley which was subsequently filled with alluvium i.e. fluvial soils (silt, sand and gravel, Fig. 3). A detailed depiction of the geomorphological situation at the toe of the slide is given in Fig. 5. The formation and ongoing movement of the Niedergallmigg rock slide have compressed these sediments and formed a gorge-like relief in the bedrock. Based on unpublished seismic investigations and borehole data obtained for an investigation of a power supply weir located further east, an alluvium thickness of at least 100 m is assumed in the rock slide area. The lack of borehole data directly at the foot of the Niedergallmigg rock slide does not enable a detail study about the complex interplay between alluvial sedimentation processes and ongoing rock slide deformation.

Generally, due to deficiency of subsurface investigations e.g. the installation of piezometers, the groundwater system of the Niedergallmigg rock slide is poorly understood. So far only spring and stream mapping data are available, which roughly show a major spring line between 1000 and 1300 ma.s.l. (Fig. 3). Surrounding the rock slide mass, springs are also located at higher elevation levels. Rock mass porosity estimations (11 to 33%, see below) based on seismic investigations suggest the presence of a highly permeable rock slide body with intercalations of less permeable gouge-rich shear zones.