The 1806 Goldau landslide event – analysis of a large rock slide

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Anschrift:

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Abstract:

September 2006 marked the 200th anniversary of one of the best-known landslides in the subalpine Molasse of the Swiss Alps, the Goldau rockslide (also referred to as the Rossberg slide or Goldauer Bergsturz). The 1806 failure claimed 457 lives when a slide involving about 36 million m³ of rock was triggered by heavy precipitation. The slide mass mostly consisted of conglomerates dipping between 17° and 27° and was reported as having failed along bedding plane contacts between the conglomerates and underlying marlstones. Today, numerous signs of activity can be observed along the upper scarp of the slide, and the potential for failure along the neighbouring slopes is high given the history of previous slide events. The last recent event occurred August 2005 and involved a rock slide-debris flow of some 200,000 m³ from the slope’s eastern scarp.

Given the potential for future landslide events, a detailed field investigation was conducted, the first objective of which involved the field reconnaissance and mapping of past phenomena to develop a hazard map for the immediate vicinity. Since the propensity for failures in the bedded rocks of the Molasse is high, the study next focussed on rock slope failure mechanisms in bedded marlstones and conglomerates. One of the key objectives was to understand failure evolution processes leading to unstable slope conditions due to weathering of the marlstones. Weathering leads to decalcification, increases in porosity and strength degradation. Since the sliding plane not only intersects marlstones but also conglomerates, the progressive development of a brittle rupture surface parallel to bedding as a function of time was addressed as well.

Subsequently the mechanisms and kinematics was analyzed with the help of the 2D distinct element code (UDEC©Itasca), simulating the progressively developing damage of the rock mass by reducing the shear parameters of the marlstones due to weathering using an elasto-plastic Mohr-Coulomb constitutive yield criterion.

1 Introduction

About 200 years ago, in the late afternoon of September, 2nd, 1806, some 36 million m³ of rock were detached from the Rossberg ridge and buried the village of Goldau claiming 457 lives. 111 houses, 2 churches and 220 farm buildings were lost in this disaster and 6.5 km² of pasture land were covered by the rock slide debris. As trigger, heavy precipitation has been reported, connected with a long, snowy previous winter (Meyer 1806, Zay 1807). Eyewitnesses reported a 20 m high tsunami wave on the lake of Lauerz, demolishing the buildings and a chapel on the island of Schwanau. Throughout the debris avalanche, the area of the lake Lauerz was downsized by 1/7. The disaster hit the valley incredibly hard, already afflicted by chaos of war, releasing an international wave of solidarity and help (Zehnder 1988). The Goldau rock slide was the first gravitational mass movement that, in the beginning of the Age of Enlightenment, has been studied intensively by scientists rather than to be accepted as a punishment of God. In consequence, during the next centuries scientists (Meyer 1806, Zay 1807, Blatzer 1875, Riedl 1877, Ott 1905, 1920, Heim 1932, Kopp 1936, Lehmann 1942) as well as artists like W. Turner, H. Keller or D.A. Schmid concentrated on the natural disaster and it's appearance (Bollinger 2006).
2 Characterization of the Rossberg slide

Since Heim 1932, Kopp 1936 and Lehmann 1942, no modern analysis has been undertaken. In 2003, the whole landslide area has been mapped in detail (Berner 2004) and the event and its causes and processes have been refurbished since then (Thuro et al. 2006a, b, c, Bollinger 2006). Besides hazard mapping, the intention was to establish a constitutional model of the failure mechanism and to set up a numerical model of the failure process. Albert Heim (1932) presented the most accepted scientific approach in his monograph “Bergsturz und Menschenleben” (landslides and human life). But further research once more uncovers some discrepancies to the view given by him. In this paper, some results will be highlighted in this respect.

2.1 Geological setting

The landslide area is situated about 50 km south of Zurich in the Canton of Schwyz, at the tectonic border between the Molasse basin and the Helvetic napes of the Alps (Figure 1).

Figure 1. Geological overview of Switzerland with study area (red frame). Molasse basin in yellow, Helvetic napes in green colors.

The village of Goldau is situated between the lake of Zug and the lake of Lauerz (Figure 2), the Goldau rock slide is indicated with blue dots below the Rossberg. The bedding planes are generally dipping south. The Rossberg massive as well as the Rigi on the other side of the valley is composed of abundant conglomerates interbedded with clayey marlstones and sandstones of the Lower Freshwater Molasse (age about 24 my, upper Oligocene/lower Miocene; Heim 1932, Vogel & Handtke 1988, Handtke 2006).
The sedimentological environment of these deposits is an alluvial fan with coarse channel fills and debris flows as well as fine slack water and flood plain deposits. This explains the interstratifications of the various grain sizes from fines over sand to gravel deposits at a small scale. The marlstones turn out to be clay-siltstones with considerably high calcite content of up to 40% when fresh. The thickness of the conglomerate layers varies from several meters up to 20 m typically (Figure 3 left) but may exceed up to 80 m without interception of any marlstone layer. These extremely thick and coarse conglomerate beds originate from large debris flows on the alluvial fan. The marlstone layers increase in thickness to the north and to the ridge respectively. They often are interbedded with thin to intermediate sandstone layers (Figure 3 right).
In the zone of the subalpine Molasse, the strata is generally dipping 20°-30° to the south, in the region of the valley the dipping decreases to 17°. In the upper detachment zone the gradient is steeper with about 27° whereas the bedding plane is more or less parallel to the slope surface (Figure 4). Compared to Heim's section (Heim 1932), the eastern scarp of the landslide is much more complex caused by the depositional environment (Figure 5). The inclined marlstone layers seem to act like a shoot for the conglomerate beds, which may slide down on their slippery basis of weathered marlstones.

![Figure 4](image1.png)
Figure 4: Longitudinal section through the sliding plane of the Goldau rockslide (Berner 2004, modified).

![Figure 5](image2.png)
Figure 5: Detailed longitudinal section along the eastern scarp of the rock slide (from Figure 4; Berner 2004, modified) with rupture surface. There is a discrete transition between marl and conglomerate.

### 2.2 Type of movement and geological controls

After own recalculation based on the digital elevation model and a presumed topography the rock slide volume is about 36 million m³ (Berner 2004). Through the high volume, the debris acted as a rock avalanche (Eisbacher & Clague 1984) or *sturzstrom* (Heim 1932) surging on the opposite hill about 120 m high. After Varnes
(Cruden & Varnes 1996) the landslide can be named as a complex, extremely rapid, dry rock slide – debris flow.

The bedding planes of the conglomerates and marlstones control the rupture surfaces of the main slide. Near the main scarp, the sliding planes run through the marl layers following the dipping of the strata (Figure 5 left side; Figure 6 left picture). In the middle part, there is a transition between the marlstones and conglomerates (Figure 6 right picture), where the rupture surface still follows the bedding, but cuts through conglomerates in a staircase-shaped way using steep joints. Where joints are not available, the conglomerates fail in a brittle manner forming arch-like fractures, intersecting deeper and deeper into the thick conglomerate beds (Figure 7).

![Figure 6: Left: Conglomerate – marl contact. The failure plane develops in the upper highly weathered part of the marl. Right: View looking upwards towards the main head scarp. The upper part of the sliding surface (Plane 3 in Figure 4) is located in marlstones, the lower part intersects conglomerates.](image)

![Figure 7: Surface of rupture developing in the conglomerates along bedding planes, stepped at steep joints (left) and without joints (right), but arch-like.](image)

As a result of the detailed mapping, the rupture surface has developed in the conglomerates over a large distance in a brittle manner. If available, of course the
marlstones are the easier way to fail. Therefore one has to deal with the failure mechanism in the marlstones as well as the brittle failure in the conglomerates.

2.3 Sliding planes on the Rossberg

Besides the sliding planes of the 1806 rock slide in the upper area, numerous other planes are visible at the Rossberg slope (Figure 8). Particularly there is a large sliding plane covered with forest and pasture (Plane 1 in Figure 8) visible below the stepped and exposed rock-like surface of the 1806 plane (Plane 3). The volume of the debris of this presumably prehistoric landslide of Oberarth can be estimated with 100 million m$^3$ and is supposed to build the saddle and watershed between the lakes of Zug and Lauerz. The slide of Röthen with a presumed volume of at least 20 million m$^3$ has been dated with the year 1222 after historic sources (Plane 2), though the upper scarp is not well conserved.

![Figure 8. Stepped series of sliding planes at the Rossberg: Plane (1) prehistoric slide, (2) 1222 Röthen slide, (3) 1806 rock slide, (4) 2002 Gninen rock slide, (5) 2005 Gribsch rock slide – debris flow, (6) signs of slope movement (future event?). Debris material and present-day village of Goldau and Oberarth.]

Smaller events like the rock fall in 1970 from the eastern scarp or the rock slide on October 15th, 2002 (Plane 4) show the constant activity in this area. The youngest event at the moment is the 2005 rock slide – debris flow of Gribsch (5), occurring after heavy precipitation on August 22nd, 2005. Also, parallel to the eastern scarp numerous open joints and cracks clearly loom the next possible event (6).
2.4 Failure mechanism

Weathering in the marlstones clearly leads to decalcification to a clayey-silty soil with high porosity (Figure 9 right diagram). Applying the international standard of weathering grades, the weathering profile of the marlstone comprises the grades between fresh rock and residual soil (Figure 9 left profile). Along with increasing porosity and decreasing material strength, cohesion and friction of the friable rock were lowered (Figure 10) significantly in direct shear box tests in the laboratory.

Figure 9: Left: Weathering profile of the marlstones with classification of weathering grades and critical or possible shear horizon. Right: Decreasing calcite content with increasing weathering grade.

Figure 10: Decrease of soil properties with increasing weathering grade. Left friction angle, right cohesion. Both parameters derived from direct shear box tests in the laboratory.

Figure 9 and 10 indicate, that the calcite content drops only about 5% during weathering grades I (fresh) to IV (highly weathered). Nevertheless the friction angle
decreases from 37° to 23° and cohesion from nearly 60 kPa to 26 kPa in the same weathering range. The slope angle following the dip angle of the bedding plane is in the same range as the angle of friction. This leads to the conclusion that, simplifying, the slope is in a very instable equilibrium, if neither cohesion nor pore water is considered. Given an average dip angle of the slope of 22.5°, a shear horizon between grade IV (highly weathered) and V (extremely weathered) should be possible. On top of the ridge the dip angle increases to 27°, therefore the possible shear horizon may lower to weathering grade III. The decalcification process leads to a loosening of the marl structure when slightly weathered already. With increasing loosening and porosity throughout the following weathering stages, all material properties decrease significantly. Eberhardt et al. (2005) stated this process already when analyzing the 1999 Rufi slide in nearly the same Tertiary marlstones.

However, this only is applicable for near-surface conditions, where the weathering reaches deep into the marlstones. In greater depth of about 80 to 150 m (= maximum thickness of the slide volume), the marlstone should be only slightly weathered and behave in a more brittle way. As already described, stepped and arch-like rupture surfaces were encountered in the conglomerates indicating a brittle behavior of the failure process. The main scarp follows a steeply inclined joint set that is orthogonal to the direction of the principal stress (through Alpine thrusting). The eastern scarp (to be seen in Figure 5) is a fault and runs more or less at right angle to the main scarp, representing also the second joint set. In the conglomerates of the upper sliding plane, a diamond shaped set of shear joints can be observed acute angled to the previously mentioned joint sets. The high compressive strength (∅ 85 MPa) and tensile strength (∅ 4 MPa) of the conglomerates indicate, that without progressive failure processes the rupture in this material is difficult to achieve.

3 Modelling Approach and Outlook

The various rock slides have been modeled with UDEC 2D v. 4.0, since simple limit equilibrium techniques are not adequate. The strength degradation in the marlstones has been simulated, taking into account high ground water levels in the conglomerates and high precipitation, infiltrating at the main scarp. A critical value of the friction angle was found with 21°, where deformations develop that cause the slope to fail. The results show that tension failure starts in the toe region (Figure 11 left), while yielding takes place in the conglomerate bedding planes and steeply inclined joints. The diagram on the right in Figure 11 shows horizontal deformations in the various weathering stages. For further results and discussion see Hatem et al. (2009) and Hatem (in prep.). All in all the stated failure process could be supported by the modeling results.
Figure 11: Left: Detail of slide toe with beginning tension failure in the bedding plane of the conglomerates. Right: Horizontal deformations in correlation with weathering grades during numerical time steps.

Acknowledgments: The authors wish to thank Prof. Simon Löw, Engineering Geology, ETH Zurich, supporting the work during 2002 to 2004, Dr. Daniel Bollinger for supporting the hazard mapping and the University of Al-baath, Homs, Syria, giving the grant during 2004 to 2009 for the PhD thesis of Majd Hatem.

4 Quellennachweis


Zay, K. 1807: *Goldau und seine Gegend, wie sie war und was sie geworden*. 390 p., Zürich: Orell Füssli.