Slope instability mechanisms in dipping interbedded conglomerates and weathered marls—the 1999 Rufi landslide, Switzerland

E. Eberhardt*, K. Thuro1, M. Luginbuehl

Abstract

In May of 1999, melting snow cover combined with heavy rainfalls in the northeastern part of Switzerland resulted in the occurrence of numerous shallow landslides. Many of these slides were located in the subalpine Molasse, a series of interbedded marls, conglomerates and sandstones. The subalpine Molasse is highly prone to such sliding activity given the dip of bedding, the surface topography and the weak nature of the marls that rapidly degrade when exposed to weathering. Historically, the subalpine Molasse has been the source of numerous slides of varying orders of magnitude and the surficial morphology is primarily dictated by previous rockslides, which periodically reactivate as secondary soil slips. Given the conditions contributing to the slope failure and the history of previous sliding, similar slides within the region are highly probable. This paper presents the findings from a detailed investigation of one such slide, the 1999 Rufi slide. Results from a detailed engineering geological investigation show that the initial rockslide failure plane predominantly developed and passed through the marl beds, as dictated by the penetration of the weathering front into the marls, and not along reactivated shears or the bedding plane contact between the marls and overlying conglomerates. Numerical modelling results based on a coupled hydromechanical distinct-element analysis were able to reproduce this mechanism by incorporating a progressive strength degradation procedure correlated to mapped weathering grades.

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Keywords: Rockslide mechanisms; Molasse; Weathering; Strength degradation; Marls; Distinct-element analysis

1. Introduction

Melting snow cover combined with heavy rainfalls in the year 1999 resulted in over 350 recorded landslides and debris flows in Switzerland (Lateltin et al., 2001). These slides resulted in 2 deaths and over 100 million SFr in direct losses. In the prealpine belt of northern Switzerland, numerous shallow landslides
occurred in the subalpine Molasse, a series of interbedded marls, conglomerates and sandstones. The subalpine Molasse is highly prone to such sliding activity given the dip of bedding subparallel to the surface topography.

Historically, the subalpine Molasse has hosted numerous slides of varying sizes. Heim (1932) describes numerous slides involving the conglomerates of the subalpine Molasse (“Nagelfluh”). Most of these instabilities involve the breaking off, toppling and/or sliding of conglomerate blocks, which collect over time as debris at the foot of the slope. If adverse groundwater conditions were present and the slope of piled-up debris was steep enough, these “debris streams”, as they were termed by Heim (1932), would reactivate to form a debris slide/debris flow.

Probably the best-known failure in the subalpine Molasse was the Goldau rockslide (also referred to as the Rossberg slide or Goldauer Bergsturz; Figs. 1 and 2). The 1806 failure claimed 457 lives when a slide involving 20 million m$^3$ of rock was triggered by a rapid snowmelt coinciding with heavy rainfall (Eisbacher and Clague, 1984). The slide mass primarily consisted of conglomerate beds dipping between 15° and 30°, purportedly failing along bedding plane contacts with the underlying marls (Fig. 1). Given the kinematic feasibility promoted by the geological conditions, it is not surprising that earlier failures preceded the 1806 event, including one in 1354, and that remnants of prehistoric slides cover the lower Rossberg slopes (Eisbacher and Clague, 1984). Since the 1806 event, smaller slides have also occurred, notably in 1874 and 1910, the latter involving the reactivation of old slide debris (Heim, 1932).

Similar landslide problems involving weak mudstones, shales or marls have been encountered in numerous other regions as well, many of which suggest interbedding, solifluction/periglacial disturbance and/or weathering as key factors in promoting failure. For example, Yue and Lee (2002) describe an interbedded slope failure in southwestern China involving planar sliding along the bedding contact between an upper weathered mudstone and a lower more competent sandstone. Deere and Patton (1971) point to interbedded shales and sandstones as being one of the most slide-prone geologic settings throughout the world. In some cases, the weak nature of these rocks may be such that with heavy precipitation, the material liquefies above the more competent underlying sandstones or limestones producing mudslides/mudflows; e.g. landslides in the shales of the Ionian flysch in northwestern Greece (Christaras, 1997) and the Boule Mondorës landslide within the marls of the southeastern French Alps (Bogaard et al., 2000).
However, these slope hazards do not always involve failure of weaker material overlying stronger materials. Citing experiences from the Big Horn Mountains (Wyoming, USA), Deere and Patton (1971) observed modes of failure similar to those experienced in the subalpine Molasse arising from contrasts in strength where the maximum resistance of the weaker underlying shales is exceeded leading to sliding of overlying large blocks of stronger rock (e.g. dolomite, sandstone, etc.). Xu et al. (1998) describe creep deformations in mudstones along the Jialin Jiang River in China where the overlying sandstones crack in tension leading to slope failure. Similar time-dependent downslope movements in the form of solifluction have been described by Hutchinson et al. (1973) as preceding a landslide in Etruria Marls (Staffordshire, UK), where periglacial disturbance and pore pressures along pre-existing slip surfaces were key factors in reactivating and promoting instability. Periglacial disturbance and other forms of weathering in the context of promoting slope failures in mudrocks have been reviewed by Taylor and Cripps (1987), where in addition to describing the various processes under which these rocks may disintegrate, show that in natural slope investigations, the mudrocks may undergo significant losses in cohesion with smaller decreases in the effective friction angle.

Many of these features and processes can be observed in landslide prone areas within the subalpine Molasse of Switzerland. Given the propensity for failures in the interbedded marls and clastic rocks of the subalpine Molasse, a detailed investigation of one such slide, the 1999 Rufi slide, was conducted immediately following its occurrence. This paper presents the results from this study, which includes the detailed mapping and analysis of the underlying processes and mechanisms contributing towards shallow planar sliding in interbedded conglomerates and marls. The paper primarily focuses on the geological and geomechanical factors contributing to the initial rockslide event. Results are presented with respect to a series of coupled hydromechanical distinct-element models, constrained by field observations and data, which focus on comparing alternative failure mechanisms: (1) failure being solely controlled by slip along bedding planes and (2) failure incorporating both slip along bedding planes and weathering-induced strength degradation of the marls.

2. The 1999 Rufi slide

The Rufi slide is located near the town of Rufi in the Canton St. Gallen in northeastern Switzerland (Fig. 2). As previously noted, the year 1999 in Switzerland was marked by extraordinary precipitation events. Most notable were heavy snowfalls that fell in the Alps over a 4-week period towards the end
of January and into February, and strong rainfalls that occurred in May. The latter produced considerable flooding and landsliding. The primary events of the Rufi slide occurred during this period on the night of May 13th.

The slide events involved the initial failure of conglomerate and marl bedrock that in turn loaded and caused the failure of weathered slide debris (colluvium) below it (Figs. 3 and 4). The total distance from the head scarp of the rockslide to the toe of the debris slide deposit was approximately 800 m. According to local reports, the rockslide occurred suddenly overnight carrying with it a 30-m stretch of road. Asphalt from the road was found 150 m downslope (Fig. 5). Damage resulting from the reactivation of the lower colluvium was mostly in the form of destroyed or disturbed forest and pastureland (approximately 1 km²). Several days after the main event, and over the course of several weeks (each time coinciding with heavy precipitation events), a series of smaller secondary slide events occurred involving heavily saturated fine-grained materials located in the toe of the debris slide deposit (Fig. 6).

3. Geological overview

The Molasse basin of northeastern Switzerland consists of thick beds of detrital sediments deposited
Fig. 5. Detailed geological map of the Rufi slide area (after Lugnibuehl, 2001).

Fig. 6. Geological section of the 1999 Rufi slide showing the primary upper rockslide, subsequent debris slide and later soil slips.
during the alpine emergence in the Alpine foreland trough. Its greatest thickness reaches 5000–6000 m along its southern margin below the front of the Alpine nappes (Trümpy, 1980). The subalpine Molasse forms the transition between the thrusting alpine nappes of the Helvetic belt and the flat-lying Molasse. The subalpine Molasse units are strongly overthrust and generally consist of thick slabs of conglomerates (“Nagelfluh”), dipping SE between 20° and 80°, which act to build-up entire mountains. These conglomerate beds are generally several meters thick and alternate between sequences of thin sandstone and marl beds.

3.1. Site geology

A detailed geological, geomorphological and geotechnical mapping investigation was carried out for the site immediately following the slide events (Luginbuehl, 2001). The rock units found in the Rufi slide area consist primarily of Tertiary sediments from the deposits of the lower Freshwater Molasse (Upper Oligocene and early Lower Miocene). These sediments were deposited within a continental alluvial fan environment and consist of a series of interbedded conglomerates, sandstones and marls (Fig. 7). The conglomerates make up approximately 50% of the conglomerate–sandstone–marl sequence thickness. Most of the clasts in the conglomerate are derived from dolomites and limestones from the prealpine nappes, and show fining upwards. The relative strength of the conglomerates makes them more resistant to weathering resulting in the formation of cliffs with heights of 2–20 m (Figs. 7 and 8). The sandstone consists of coarse-grained, cross-bedded calcarenite. It appears grey in colour when weathered and brown when fresh. The marls are grey to bluish grey in colour and are highly susceptible to weathering. Laboratory testing shows that the carbonate content of the marls belonging to the Rufi slide is in the range of 40–50% (Luginbuehl, 2001).

The tectonics of the investigation area are representative of the subalpine Molasse, consisting of thick over-thrust layers which were pushed over by the folded Helvetic nappes. For this reason, the different tectonic units are easily differentiated. In the slide area the bedding layers dip to the southwest and are cross-cut by near-orthogonal joint sets (Fig. 8). These joints, found primarily in the conglomerate and sandstone units, play a major role in promoting instability.

![Bedding sequence of the interbedded conglomerates and marls along the margin of the Rufi slide.](image-url)
Fig. 8. Cliff-forming conglomerates showing subvertical joints.

Fig. 9. Upper Rufi slide surface showing the stepped nature of slide surface down through marl layers (note camera lens cap in centre of photo for scale).
3.2. Site geomorphology

During the last glaciation event (Würm), the area was covered by ice reaching the top of the existing mountains (meaning a minimum height of about 1100 m). Moraine deposits reach the higher elevations and are often overtopped by colluvium. The surface morphology is one that has been carved and shaped by glaciation taking the form of a series of gentle slopes following the dipping of the conglomerates. Permafrost action at the end of the last ice age appears to have had an influence on

Fig. 10. Daily precipitation records for the Ruci region during the first half of 1999. Note that the slide occurred May 13th following a large precipitation event the day before (May 12th).

Fig. 11. Model geometry and modelled material zones used for distinct-element modelling of the Ruci slide with cut-away showing finite-difference mesh.
the disintegration of the different materials during weathering.

Following deglaciation, numerous debris fans evolved covering the slopes (Fig. 5). The debris consists of weathered material and deposits from smaller block falls. These deposits are mostly found at the foot of conglomerate cliffs. The conglomerate cliffs outline the scarps of previous shallow rockslides that have been retrogressively working their way up slope. Above these scarps, the conglomerate bedrock is largely undisturbed. Below, the lower slopes are covered by weathered/ancient slide debris. Numerous signs of subsurface creep are observable in these areas, as are colluvial material incorporating large blocks that appear to reactivate during heavy precipitation events. Typically, the areas with coarse blocks (lower slopes) and the undisturbed conglomerate bedrock (upper slopes) are covered with forest. Areas with finer debris have been converted into pastureland.

3.3. Site hydrogeology

Surface drainage in the area runs north-east to south-east eventually draining into the Linthebene River and afterwards into Lake Zurich (Fig. 2). The substratum typically consists of jointed rock cover and weathered debris. Infiltration occurs in the upper slopes where the permeability in the underlying bedrock is largely joint-controlled. Vertical joint systems in the thick conglomerate sequences (Fig. 8) allow for easy infiltration and circulation of groundwater. Underlying marl layers act as aquitards. Fracture systems in the conglomerate layers together with the interbedded sandstones also help to store large volumes of frozen water during the winter months. Upon thawing, the water is released to drain along the orthogonal fracture systems and their contact with the impermeable marls. Flow anisotropy in the subsurface due to lithology changes, structure or weathering results in the formation of numerous springs. Weathered debris material in the lower sections of the slope is found to be largely impermeable owing to the large proportion of silts and clays that the rocks break down into.

3.4. History of earlier slide events

Prior to the 1999 event, a history of previous instabilities had determined the composition of the reactivated slide material covering the lower slopes. Numerous indications of post-glacial slide events can be found in lower sections of the slope, one dating back 800 years (as determined through tree dating by Bollinger et al., 2000; the black solid circle in Fig. 3 marks the location where the date was derived). The first recorded slide at the Rufi site, as noted by local residents, occurred around 1900. To stabilize lower sections of the slope, a surface drainage system was constructed.

Given this history of previous sliding, activities along the slope can be described as a series of retrogressive, multiple translational slides. The material found along the profile of the slope thus involves undisturbed, in-place rock in the upper sections (interbedded conglomerates and marls) and weathered, disturbed debris along the lower sections. The 1999 slide reflects this complexity and can be viewed as a composite slide for which two events involving different materials can be discerned. The first event was the planar failure of conglomerate and marl bedrock from the upper sections of the slope. The second was the reactivation and failure of weathered colluvium that the initial failed rock mass slid onto.

4. Instability mechanisms in interbedded marls and conglomerates

Examination of the pre-failure slope conditions suggests that the uppermost sections of the slide mass involved a thin interval of interbedded conglomerate
and marls. Contrary to reports involving other slides in the subalpine Molasse, where the contact between the conglomerate and the underlying marls was assumed to form the failure surface (e.g. the 1806 Goldau slide), observations at the Rufi site indicate that the slide surface passed primarily through the marls (Luginbuehl, 2001). Furthermore, these observations suggest that the slide surface occurred along a weathering boundary within the marls, separating the upper highly weathered layers from the underlying moderately weathered layers.

Examination of the slide scarp and lateral boundaries indicates that the thickness of the conglomerates was approximately 2 m at the head of the slide. Within these scarps, the stratigraphy is preserved and undisturbed (Fig. 7). At the back scarp, the slide surface most closely coincides with the contact between the conglomerate and marl. The sliding surface in this upper section is planar and dipping at approximately 22°. Moving down slope, the slide surface progressively cuts down into the marls in a step-like fashion (Fig. 9) over a slope length of 100–200 m.

4.1. Geological controls and triggering event contributing to the Rufi slide

The 1999 Rufi slide can be viewed as a cause–effect scenario in which the “cause” is attributed to
several geological controls and processes relating to 
structure, bedding, weathering and strength degrada-
tion within the slope mass. The trigger that initiated 
the slide was an intense precipitation event, one of 
several that fell throughout Switzerland that spring. 
Precipitation records for the Rufi area show that two 
intensive precipitation events occurred on May 12th 
and 21st, involving rainfalls of almost 100 mm in a 
24-h period (Fig. 10). The primary Rufi slide 
occurred following the first of these two events on 
the evening of May 13. In terms of relative 
magnitude, it can be noted that monthly precipitation 
totals for February and May 1999, exceed their 
yearly averages. In the 1-week precipitation period 
preceding failure, approximately 200 mm fell. These 
intense precipitation events likely also led to the 
release of large stored water volumes through 
accelerated snow melt and ground ice thaw, thereby 
both saturating the marls and increasing groundwater 
pressures along open fractures.

4.2. Back-analysis of coupled hydromechanical pro-
cesses assuming slip along bedding planes

Given the role of the conglomerate/marl bedding 
plane contact reported in earlier slides located within

Fig. 13. Schematic diagram of the weathering profile mapped in the Rufi slide area. Descriptions for the different weathering classes are given in 
Table 2.
the subalpine Molasse (e.g. Goldau), a back analysis
was performed for the 1999 Rufi slide using the
commercial two-dimensional distinct-element code
UDEC (Itasca, 2000). UDEC treats the problem
domain as an assemblage of deformable blocks for
which the dynamic equation of equilibrium for each
block in the system is formulated and repeatedly
solved until the boundary conditions and laws of
contact and motion are satisfied. The method thus
accounts for complex non-linear interaction between
blocks (i.e. slip and/or opening/closing along dis-
continuities). The method is also capable of model-
ing the deformation and material yielding of the
joint-bounded intact rock blocks. UDEC is partic-
ularly well suited to problems involving jointed
media and has been used extensively in the inves-
tigation of rockslide failure mechanisms (Eberhardt,
in press).

The objective of this first-step modelling exercise
was to back-calculate a range of bedding-plane
contact strengths. Given the uncertainty of the
groundwater conditions prior to failure, several
different groundwater/coupled-hydromechanical sce-
arios were tested, including: (i) a dry slope, (ii) a
water table located 1.25 m below surface, (iii) a water
table at surface and (iv) artesian conditions. Within
the model, as in the actual slope, structure provided
both discrete surfaces along which failure could be
accommodated and pathways for fluid flow within
the slope mass (i.e. fracture permeability and
connectivity in the form of cross-cutting joints).
Fig. 11 shows the geometry used, which incorporates
an upper conglomerate bed underlain by two marl
layers resting on a base of conglomerate and sand-
stone. The bedding plane contacts were assumed to
be cohesionless.

Permeability and fluid flow in the UDEC formul-
ation is controlled by the input for the fracture
aperture as dictated through the cubic law:

\[
q = \frac{a^3}{12\mu} \frac{dp}{dl}
\]  

(1)

where \( q \) = unit flow rate, \( a \) = contact hydraulic aper-
ture, \( \mu \) = the dynamic viscosity of the fluid and \( \frac{dp}{dl} \) =
hydraulic gradient for a fracture of unit width. The
problem may be analysed such that the fracture
apertures are stress dependent (i.e. fully coupled) or
constant (partially coupled). In this study, the hydro-
mechanical coupling was assumed to be partial to
reduce solution run times and constant fracture
apertures were adopted approximated from outcrop

![Fig. 14. Schematic cross-section of the Rufi landslide prior to failure showing location of the slide plane through the weathered marls (after
Luginbuehl, 2001).](image-url)
observations. This assumption was held to be valid
given the relatively shallow depth of failure and
therefore the diminished influence that stress would
have on fracture aperture (as opposed to greater
depths where apertures may be significantly reduced
under higher overburden loads). Input values for the
fracture apertures were varied between the conglom-
erates and the marls. Values for the conglomerate-
hosted cross-joints were based on observations of
open fractures at surface, whereas those for the marls
at depth were assumed to be tighter. Material prop-
erties used in these model runs are given in Table 1, and
were based on field observations and representative
values found in the literature.

Modelling results assuming dry slope conditions,
produced a back-calculated limit equilibrium friction
angle along the conglomerate/marl contact of 21°.
This value is in agreement with the overall average
bedding dip angle of 21° (20.5° in the upper slope
steepening to 22° over the lower slope). Failure
occurs in a planar fashion. Similar limiting-equili-
brium frictional strength values were determined for
the second case where the water table was located
1.25 m below surface (i.e. 1.25 m above the
conglomerate marl bedding contact). When the water
table is assumed to be located at surface (i.e. pore
pressures along marl/conglomerate contact corre-
sponding to 2.5 m head) or artesian (5 m head), the
back calculated friction angle for which failure occurs
is approximately 23°.

To put these back calculated values into perspec-
tive, comparisons can be made to those obtained
through laboratory testing of marls reported in the
literature. Of course, these may not be indicative of
those in place for the marl-conglomerate contact.
Depending on the degree of weathering, Chandler
(1969) reported laboratory-based peak friction
angles, $\phi$, for Keuper Marls between 25° and 42°.
Similar results were obtained by Reißmüller (1997)
for direct shear tests performed on weathered
Kössener marls (Fig. 12; the corresponding weath-
ering grades are depicted in Fig. 13 as compiled for
the Rufi marls). Close inspection of these test values
indicate that with the exception of one test value,
where $\phi = 17°$, a range of effective friction angles
between 23° and 29° can be resolved (Reißmüller,
1997), and values less than 25° require very high
degrees of weathering. Thus, the hydromechanically
coupled back calculated friction values for failure
along the conglomerate/marl bedding contact are
relatively low (i.e. 21–23°).

This agrees with field evidence that showed that
the extent of the failed slope mass encompassed more
than the conglomerate blocks, and that a large
percentage of marl material was also involved owing
to the down stepping of the failure surface through the
intact marls (Fig. 14). Thus, to properly model the
Rufi sliding/failure mechanism, consideration should
also be given to the effects of weathering on the intact
marl materials.

4.3. Strength degradation of marls due to weathering

4.3.1. Weathering of Rufi marls

Detailed mapping and some laboratory analysis
was performed on the weathering characteristics of the
Rufi marl. As noted above, the weathering profile and

<table>
<thead>
<tr>
<th>Weathering grade</th>
<th>Description</th>
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<tbody>
<tr>
<td>W0 fresh</td>
<td>fresh and intact rock</td>
</tr>
<tr>
<td>W1 slightly weathered</td>
<td>bright-grey marl with slightly weathered joint surfaces, blocks are well formed up to 20 cm and water permeable</td>
</tr>
<tr>
<td>W2 moderately weathered</td>
<td>bright-grey marl with higher water permeability; can be divided in 3–8 cm large blocks with a hammer, block size increases with depth, red-brown joint surfaces with slightly plastified surfaces</td>
</tr>
<tr>
<td>W3 highly weathered</td>
<td>dark-grey to black marl with frequent microcracks, red-brown weathered surfaces, slightly plastified, can easily be broken in small pieces by hands</td>
</tr>
<tr>
<td>W4a completely weathered</td>
<td>dark-grey to black marl mixed with completely decomposed light brown silty-clayey soil, very inhomogeneous material</td>
</tr>
<tr>
<td>W4b completely weathered</td>
<td>light brown silty-clayey soil mixed with remnants of marls in sizes of 1–5 cm, red-brown colours dominate</td>
</tr>
<tr>
<td>W5 residual soil</td>
<td>brown debris with coarse material mixed with a clayey, sandy silt</td>
</tr>
</tbody>
</table>
degree of weathering in the marl beds appeared to control the development of the failure surface along sections of the Rufi slide profile. Fig. 13 shows the weathering profile derived for the marls in the slide area based on methods by Einsele et al. (1985). These weathering grades are described in Table 2. The degree of weathering of the marl below the slide surface was characterized as W1 (slightly weathered). The upper marl layers constituting the slide body range in their weathering state from W2 to W5 (moderately weathered to residual soil). Field observations suggest that the more defined the weathering contrast between the marl layers, the greater the tendency for overlying conglomerate blocks to creep along the weak interfaces or incompetent layers formed in the marls (Fig. 15).

Weathering of the marls involves both physical and chemical processes. Physical weathering appears to involve material strength degradation through wet–dry cycling, freeze–thaw cycling and swelling pressures created by the clay fraction in the marls. In general, wet–dry cycling may be considered limited in depth of penetration to areas immediately neighbouring fractures in the otherwise low permeable marl. However, fracture permeability and connectivity are not deemed entirely necessary as wet–dry cycling can still be promoted through water content fluctuations over large periods of time. The penetration depth of frost action may also be limited, but in the pre-alps can reach depths of 120 cm (Prinz, 1997). Physical weathering through swelling pressures generated by clay minerals is attributed to the Montmorillonite found in the marls. Chemical weathering was also believed to be significant in the Rufi case due to reactions of the marls with slightly acidic rainwater. Such reactions in which the calcite would be progressively dissolved would lead to increased pore volumes, thereby allowing more water to seep into the marls. This would significantly aid the physical weathering process and, as a consequence, cause the intact strength properties of the marls to degrade (Fig. 12).

With increased weathering comes further strength degradation of the over-consolidated marls in the form of fractures opening along bedding planes and other tectonic structures in the marls. These features then help to promote further weathering at a much quicker rate, increasing the degree of segmentation between layers within the marls. Field observations suggest that these processes were the controlling factor with respect to how deeply the slide surface cut down into the marls.

Fig. 15. Conglomerate block overlying weakened weathered marl.
4.3.2. Numerical analysis of strength degradation of marls promoting planar slope failure

Stead and Eberhardt (1997) and Eberhardt and Stead (1998) demonstrated that when analysing slope failures in weak bedded rock, the continuum behaviour of the intact rock is of comparable importance to that of the discontinuum behaviour of discontinuities. In other words, the continuum behaviour of the intact rock also contributes to the development of the instability in the discontinuous rock mass and must therefore be incorporated in the analysis to properly model and predict the correct failure mechanism. As presented earlier, a failure mechanism for the Rüfi slide based solely on shear slip along bedding planes

![Model geometry and simulated weathering progression used for distinct-element analysis examining strength degradation effects in the Rüfi marls. The progressive weathering sequence adopted in this first model series assumes a 'continuous' weathering penetration rate with depth. The weathering grades correspond to those given in Fig. 13 and described in Table 2. Results are presented in Fig. 17.](image-url)
(i.e. planar failure of the conglomerates sliding over the marls) could not be supported by field observations. Such observations instead indicate that the failure surface extended down through the marls and that the slide debris contained a large percentage of marl material in addition to the conglomerate.

Numerical modelling was therefore extended to incorporate the other key factor deduced from field mapping, namely the effects of strength degradation in the intact marl due to weathering. To do so, an elastoplastic Mohr-Coulomb constitutive yield criterion was used to model intact block deformation of the marls. These effects were applied to the same set of distinct-element models presented in the previous section, with the exception that the bedding plane spacing within the marl interval was refined to accommodate an upper, middle and lower weathering levels (Fig. 16). Models, as before, were run adopting a partial hydromechanical-coupled solution (i.e. constant joint hydraulic aperture). Modelled groundwater conditions were assumed to reflect the heavy and prolonged precipitation preceding the Rufi slide event, i.e. a fully saturated slope.

As depicted in Fig. 16, the modelling procedure involved the simulation of the progressive weathering of the marl and penetration of the weathering front down through the upper, middle and lower marl beds in accordance with the weathering classes previously described (i.e. W0 to W5). The question as to whether the weathering front could penetrate several metres down through the overlying conglomerates and into the upper and lower marls, could be confirmed by field observations, which showed that weathering of the marls at depth is accommodated by means of subvertical fractures that extend from surface down through the marls (e.g. Fig. 8). Strength degradation was then modelled with respect to the established weathering classes using the laboratory shear strength values determined by Reißmüller (1997). The input material values used are given in Table 3. Thus, progressive strength degradation due to weathering in the marls was modelled through staged reductions in the cohesive and frictional strength components as a function of depth, both for the intact marl material and the intra-marl bedding contacts. The procedure used to do this involved: (i) stepping the model to an initial equilibrium state, (ii) reducing the cohesion and frictional strength in accordance with one weathering increment (as shown in Fig. 16), and stepping to an approximate equilibrium, and (iii) repeating until failure occurs. Defining failure in such models may be subjective; in this case, catastrophic failure was associated with large displacements (>2 m) and the continued acceleration of block movements.

Fig. 17 provides the results from these models, which show the progressive development of the failure surface leading to catastrophic slope failure due to yielding of the weathered marls. As the upper layers of the weathered marl yield and deform, tensile failure of the overlying conglomerate blocks occurs as well. Of key interest in terms of better understanding the primary slope failure mechanism at Rufi is that the models do not predict a slip surface confined to the conglomerate/marl contact, but instead one that also passes through the weathered marls. This would be in agreement with field observations, reinforcing the hypothesis that strength degradation and yielding of the marls were instrumental in the failure process.

Further inspection of Fig. 17, however, suggests that although the outline of the modelled failure surface closely coincides with the mapped extent of the 1999 Rufi slide surface, it does in places over-predict the depth of failure (by 2.5 m). Similarly, the upslope limit of the modelled failure also extends beyond the mapped location of the head scarp (the

<table>
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<th>Parameter</th>
<th>Conglomerate</th>
<th>Rufi marl</th>
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<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>2600</td>
<td>2400</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>25.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.20</td>
<td>0.30</td>
</tr>
</tbody>
</table>

W0 to W5 refer to mapped weathering grades (see Figs. 12 and 13). Shear strength properties are taken from laboratory based direct shear box tests by Reißmüller (1997).
Further model simulations showed that these shortcomings were due to the adoption of a continuous weathering penetration rate in which each modelled weathering stage represented a uniform one-step increase in weathering class (e.g. W1 to W2, W2 to W3, etc.) down through each marl bed (Fig. 16). In other words, the weathering rate was assumed to be the same at surface as at depth. As a result, the penetration of the W5 weathering grade at the point of modelled failure reaches a depth extending 66% of the way through the marl bed (i.e. W5 in the upper two-thirds of the marl and W4 in the lower-third; Fig. 16). The modelled failure therefore leads to an over-prediction of the depth of failure, specifically in the upper sections of the slope.

A second series of models was therefore developed for which the weathering penetration rate was assumed to decrease with depth (i.e. discontinuous). The basis for this assumption was that weathering near the surface would occur much more quickly than at depth. As such, the modelling sequence for the location of which is marked by arrows in Fig. 17).
advancement of the weathering front incorporated a three-stage delay for the middle and lower marl layers with respect to the initial penetration of the weathering front. Once the weathering front completely penetrated the layer, it was assumed that the layer would weather at the same rate as the layer above it (Fig. 18). Results from these models show a similar mode of failure as those in which the progressive weathering sequence was modelled as being continuous, only a much better fit was obtained between the modelled failure and the mapped slide surface. Fig. 19 shows the evolution of tensile failure and yield (i.e. intact shear) in the conglomerate and marl blocks as a function of progressive strength degradation of the marls. As the degree of weathering increases, failure develops through intact shearing of the marls. The resulting increased deformation subsequently causes tensile damage to develop in the overlying, stronger, more brittle conglomerate blocks. This failure mechanism can be compared to spreading type failures and/or soil creep processes evident in the slopes neighbouring the Rufi slide where large blocks of the conglomerate slowly sink into the softer underlying marls and creep down the slope.

Another key insight into the failure mechanism as disclosed by these models, is the yielding of the marls in the region where the slide’s toe develops (magnified in the inset diagram of block deformation in the lower corner of Fig. 19). Whereas in the upper slope, where the driving forces are lower, the modelled failure surface is controlled by the W5 weathering grade, in the lower slope, where the driving forces are greater, failure occurs in the marl beds where strengths correspond to the W4 weathering grade. As such, the accumulation of yield and damage in the less weathered marls can be seen to play a significant role in the overall failure mechanism, especially with respect to the evolution of shear stresses and strains in the lower sections of the slope. The models show a failure mechanism where failure initiates through yielding of the intact marls at the toe of the slope, allowing for the kinematic release and failure of the upper slope.

Inspection of Fig. 19 confirms that damage in the marls and conglomerates initiates and begins to accumulate in the early stages, i.e. for weathering grades as low as W1. The accumulative nature of the damage results in the gradual deformation of the

![Fig. 18. Simulated weathering progression used in second series of distinct-element models examining strength degradation effects in the Rufi marls. The progressive weathering sequence adopted in this second model series assumes a ‘discontinuous’ weathering penetration rate with depth. The weathering grades correspond to those given in Fig. 13 and described in Table 2. Results are presented in Figs. 19–21.]
slope eventually leading to catastrophic failure. This is illustrated in the history plot of horizontal slope displacements provided in Fig. 20. These history plots show that displacements in the slope are gradual and that for the first several weathering stages, the model solution converges to an approximate equilibrium. However, when the weathering grade in the middle marl bed reaches W4 (bounded by W5 in the upper marl and W1 in the lower marl), a chain reaction begins where catastrophic failure is slowly realised as elements begin to yield. As elements yield, excessive loads are shed/transferred to neighbouring elements, which in turn may yield leading again to the transfer of loads to neighbouring elements. This chain reaction slowly manifests itself in the form of small slope displacements (between 0.05 and 0.25 m over 100,000 time steps; left-hand plot in Fig. 20), which gradually
increase until they begin to occur on the scale of metres (e.g. after an additional 1 million time steps; right-hand plot in Fig. 20). Eventually, damage and failure in the marls evolve and reach a point where catastrophic failure occurs (Fig. 21).

5. Discussion and conclusion

Results from a detailed mapping investigation of the 1999 Rufi slide show that problematic rock slope instabilities in the subalpine Molasse of northern Switzerland are largely due to adverse dipping of interbedded conglomerates and marls. Primary sliding can be attributed to strength degradation in the marls due to weathering processes and saturation during periods of heavy precipitation. Field observations reveal that these processes control how deeply into the rock mass the slide surface cuts. Thus, understanding these weathering processes and their temporal and spatial evolution is necessary for hazard assessment and mitigation of those slopes neighbouring the failed Rufi slope mass. As was seen in the 1999 slide, these rockslide events can lead to larger, more destructive slides by running onto and loading unstable, saturated colluvial debris covering lower sections of the slope, triggering their failure.

Numerical models were used to better understand processes relating to the initial bedrock failure by means of discontinuum techniques (i.e. distinct-element method). Initial models focussing on a failure mechanism restricted to planar failure along bedding plane contacts due to increased pore pressures, failed to reproduce the mapped 1999 Rufi slide surface outline. These models suggest that the resulting slide debris would mostly encompass conglomerate material (given that the models predict planar sliding of the conglomerates over the underlying marls); field observations immediately after failure indicated otherwise, showing that a significant volume of marl was mixed with the conglomerate in the slide debris.

Models were then further extended to allow for the consideration of strength degradation of the marls through weathering processes coupled together with increasing pore pressures between weak layers in the marls. Mohr-Coulomb strength parameters for the progressively weakening marls were based on laboratory derived shear strength values for six different weathering grades (W0 to W5). Results based on this analysis showed a much better fit to field observations.

Fig. 20. History plot of slope displacement as a function of distinct-element time step, showing horizontal displacements at the head and toe of the slope for the initial stages of strength degradation (left) and the progressive development of catastrophic slope failure once weathering in the middle marl layer reaches W4 (right).
and mapped extents of the slide surface, predicting a failure surface that initiated, developed and propagated in the weaker intact marls. These findings provided key insights into the failure mechanisms responsible for the slide, especially with respect to the geological factors controlling the location and development of the shear surface. Numerical models showed that through the accumulation of damage and yielding in the weathered marls, the evolution of shear stresses in the lower sections of the slope led to the initiation and propagation of failure through the intact material. Failure was then accommodated along weak bedding planes within the marls leading to catastrophic failure.

Overall, these models demonstrated their usefulness in helping to understand complex slope instability mechanisms related to coupled geological, geomechanical, hydromechanical and environmental processes (i.e. weathering). Input and constraints provided by detailed mapping and field-based investigations were essential in developing and constraining both hypotheses of likely causes and their numerical simulation. Ultimately, such information, analyses and understanding are essential to properly investigate and mitigate other problematic slopes in the region involving interbedded conglomerates and marls.

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