Nanoseismic monitoring of slope dynamics caused by softrock landslides in the Vorarlberg and the French Alps

Marco Walter & Manfred Joswig

Seminar at the University of Strasbourg

December 9th, 2008
Overview

• Seismic Monitoring of mass movements
• Heumoes slope in the Vorarlberg Alps
  • General setting
  • Introduction to the Research Unit
  • Seismic Monitoring of fracture processes
• Mudslide at Super-Sauze in the French Alps
  • General setting
  • Seismic Monitoring of slope dynamics
• Possible source mechanisms
• Outlook
Seismic Monitoring of mass movements

Most of the mass movements are mainly observed by geological, geotechnical, hydrological, hydraulic and mechanical investigations and models.

Geophysical methods are mostly applied to determine internal structures and material parameters, e.g. geoelectrical measurements, active seismic.

Passive seismic applications are used to determine internal structures (H/V-method) or to monitor slope dynamics caused by brittle failures in hard rock mass.

BUT: Compared to that, the Heumoes slope and the mudslide at Super-Sauze consist of weak sediments → detectable fracture processes?
Seismic Monitoring of mass movements

Observation of single fractures as a result of brittle failure in hard rock mass:

Brückl et al. (University of Vienna), unstable slope in the Austrian Alps
Seismic Monitoring of mass movements

Observation of single fractures as a result of brittle failure in hard rock mass:

Roth et al. (NORSAR) at Aknes Fjord, Norway

Roth et al., 2005
Seismic Monitoring of mass movements

Seismic monitoring of signals generated by avalanches or rockfalls:
(Weichert et al., 1994; Surinach et al., 2005)
Seismic Monitoring at the Heumoes slope

• Located in the Vorarlberg Alps (Austria), ~25 km south of Lake Constanze
Seismic Monitoring at the Heumoes slope

- Slope length ~1800 m, width ~500 m, altitude ranges from 960 m to 1360 m
- Slope consists of very heterogeneous loamy scree and glacial till
- Natural spring at the interface between the basement and the sliding body
Seismic Monitoring at the Heumoes slope

- Borehole with piezometric devices and inclinometer
  - fast water infiltration
- Weather station
- GPS measurements
Seismic Monitoring at the Heumoes slope

Coupling of Flow and Deformation Processes for Modeling the Movement of Natural Slopes

Sub-Project 1: 'Hydrology'
Field Data Measurement and Analysis, Hydrological Modeling, General Process Analysis for Movements of Large Hill Slopes, Universities of Munich, Stuttgart, Karlsruhe

Sub-Project 2: 'Subsurface Hydraulics'
Numerical Simulation of Two-Phase Flow and Mass-Transfer Processes in the Subsurface, Universities of Berlin, Stuttgart

Sub-Project 3: 'Continuum Mechanics'
Continuum Mechanics for Movement of Large Hill Slopes, University of Stuttgart

Sub-Project 4: 'Technical Scale Experiments'
Laboratory-Based Experiments on Different Technical Scales for Process Exploration, Parameter Identification and Model Verification, University of Stuttgart

Sub-Project 5: 'Geophysics'
Geophysical Investigations of the Movement at Heumoes Slope, Vorarlberg, University of Stuttgart
Seismic Monitoring at the Heumoes slope

Nanoseismic monitoring

➢ Detecting and locating of single fracture processes

➢ Temporal occurrence of fractures should indicate influencing parameters to the slope stability

➢ Spatial distribution of fractures should correlate to parts of the slope showing higher movement rates on the surface

➢ Determination of slope dynamics and influencing parameters
Seismic Monitoring at the Heumoes slope

Questions:

• Which processes can lead to spontaneous stress relief in weak sediments?

• Are possible events strong enough to be detected by nanoseismic monitoring?

• What are possible source mechanisms in a generally cohesive material?
Data aquisition:

- Several field campaigns
- 2-3 seismic mini-arrays (SNS)
- Aperture of 25-30 m
- Continuous recording
- 400 Hz sampling rate
Seismic Monitoring at the Heumoes slope

Experimental criteria / signal analysis:

• valid signals had to be detected on all stations
• minimal signal duration 0.5 sec
• maximal signal duration 5.0 sec
• SNR >2.0
• signal frequency characterization by sonograms
• waveforms analysis
Seismic Monitoring at the Heumoes slope

Field campaign in September 2005:

- Two monitoring periods (September 8th – 14th and September 23rd – 29th)
- Two SNS

- 28 events were recorded during the first monitoring period
- None within the second monitoring period
- $-0.7 > M_L > -2.2$
Seismic Monitoring at the Heumoes slope

- Seven events located outside of the slope represent a separated slip
- 21 events, mainly located in the mid-part of the slope
  - correlates to the part of the slope showing higher movement rates
Seismic Monitoring at the Heumoes slope

- Similar waveforms of fractures
- Sonogram pattern similar to those of local earthquakes
- Emergent phase-onsets caused by scattering of energy
- Detection threshold of $M_L = -1.4$ for a slant distance of 350 m
Seismic Monitoring at the Heumoes slope

- events recorded between 5 to 26 hours after rainfall
- events occurred in the time gap between response time of the spring (few minutes) and response time of piezometers (5-26 hours after intense rainfall)

No events during rainfall in 2nd period:
- lower precipitation
- higher background noise during rainfall
Seismic Monitoring at the Heumoes slope

- 2 local earthquakes in June 2007:
  - 19.06.2007: $M_L=2.0$
  - 21.06.2007: $M_L=1.9$
Institute for Geophysics, Universität Stuttgart, Germany

Seismic Monitoring at the Heumoes slope

Five fractures \((-1.2 > M_L > -1.4)\) within the slope occurred between 5 minutes and 1 hour after these local earthquakes.

Can such weak local earthquakes induce material failure within the slope?
Fractures in the western part of the slope correlate with movement velocities.

No fractures in the eastern part of the slope?
• triggered in the 1960's
• altitude ranges between 2105m and 1740m
• length of 825m, average width of 135m
• estimated volume of 750,000 m³
• movement velocities between 0.01 and 0.40 m per day
• mudslide consists of jurassic marls with moraine components
10 days field campaign from 14th – 24th of July 2008:

• Installation of 4 seismic small arrays (SNS)

• Sampling rate of 400 (500) Hz

• Continuous recording

• 8 calibration shots
Seismic Monitoring at Super-Sauze

- 8 calibration shots
- determination of phase velocities within the unstable slope and the bedrock below

→ underground model for passive seismic monitoring

shoot point at S3N
Seismic Monitoring at Super-Sauze
Seismic Monitoring at Super-Sauze

1. Phase determination

2. Phase picking / Determination of $v_P$

Slope:

- $v_P \sim 600 \text{ m/s}$
- $v_S \sim 310 \text{ m/s}$

\[ \frac{v_P}{v_S} \sim 1.95 \]

Bedrock below:

- $v_P \sim 2000 \text{ m/s}$

Layer above homogeneous halfspace as underground model

3. Adaption of s-p circles to calibration shot location / Determination of $v_S$
During the fieldcampaign in July 2008, we recorded, processed and located different types of signals caused by varying slope dynamics:

**Mass accumulation:** caused by rockfalls

**Fracture processes:** caused by material failure

**Local earthquakes**
Seismic Monitoring at Super-Sauze

- High frequent „noise“ comparable to avalanches
- spikes caused by falling blocks
- duration of a few seconds up to 20 minutes

~80 % with backazimuth of ~ 160° to S1C
~20 % with backazimuth of ~ 220° to S1C
Seismic Monitoring at Super-Sauze

- 34 fracture processes generated by material failure
- signals recorded and located with at least 3 SNS
- magnitude: $-3.1 < M_L < -1.4$
- events located in the upper and the mid-part of the mudslide
- the three events „outside“ probably generated by cracking hardrock
Seismic Monitoring at Super-Sauze

- sonogram patterns of fractures are similar to them at the Heumoes slope
- average signal-duration: 2 to 4 seconds

event $M_L$ -1.4 at Heumoes slope

event $M_L$ -2.2 at Super-Sauze
Seismic Monitoring at Super-Sauze

- spatial distribution of events correlates with higher movement velocities of the slope

Amitrano et al., 2007
Seismic Monitoring at Super-Sauze

- 90% of the fractures have been recorded at the night-time.
- During day-time, the detection threshold is ~ one magnitude order lower than at night.

Spectrogram of 24 hours
Seismic Monitoring at Super-Sauze

- 90% of the fractures have been recorded at the night-time.
- During day-time, the detection threshold is ~ one magnitude order lower than at night.

Median-spectra at night (red) and during daytime (blue).
Institute for Geophysics, Universität Stuttgart, Germany

Seismic Monitoring at Super-Sauze

- 44 fractures „Type B“ generated by material failure
- detected with one single SNS
- signal duration between 5-8 seconds
- not located, but source area estimated
- ~64% of these events detected in the mid-part of the slope
Seismic Monitoring at Super-Sauze

- amplitude decreases ~ 30 times within 1 SNS (~50m)
Seismic Monitoring at Super-Sauze

• amplitude decreases ~ 30 times within 1 SNS (~50m)
• enormous absorption of higher frequencies within 1 SNS

→ very weak signals, only detectable within a few meters
• ~64% of these events generated at the boundary between the mudslide material and emerging in situ crests
Institute for Geophysics, Universität Stuttgart, Germany

Seismic Monitoring at Super-Sauze

Typ A  15%
Typ B  4,5%

Typ A  25%
Typ B  68%

Typ A  18%
Typ B  22%

spatial distribution of fractures „Type B“ correlates with spational distribution of fractures „Type A“
Seismic Monitoring at Super-Sauze

normalized amplitude-spectra:

- scattered spectra of fracture type B due to ~50 times weaker amplitude compared to type A and longer signal duration
- similar spectra indicate comparable source mechanisms!
Seismic Monitoring at Super-Sauze

- hundreds (!) of fractures type C
- signals which lie barely above the natural noise-level
- only recordable within a few meters
Seismic Monitoring at Super-Sauze

In-situ experiments in dried sediments (Israel), single event

fractures type C at Super-Sauze, multiple event

Similar sonogram patterns indicate similar source mechanisms
Possible source mechanisms

partly water saturated area

water saturated area

Spatial distribution of fractures located at the Heumoes slope

Correlation of spatial distribution of located fractures with parts of the slopes showing the highest velocities
Possible source mechanisms

fracture type A  fracture type B  fracture type C

Similar spectra of different „types of fractures“ at Super-Sauze indicate comparable source mechanisms

→ Generation of fractures in dependence of the water saturation close to the surface
Summary

• Single fracture processes caused by softrock landslides have been monitored and detected by applying Nanoseismic Monitoring

• ~5 times more events at Super-Sauze compared to Heumoes slope caused by stronger dynamics and better noise-conditions

• different types of events resolvable at Super-Sauze

• distribution of events correlates with movement velocities

• generation of fractures in dependence of water saturation
Heumoes slope:

• Installation of a permanent network in spring 2009 consisting of 3 SNS
• longtime observation under varying climate and conditions
• determination of influencing parameters (e.g. snow coverage, intense rain events,…)
• determination of the influence of local earthquakes to the slope stability
• determination of source mechanisms
Outlook

Mudslide at Super-Sauze:

- data processing of 10 days field-campaign in october 2008
- fractures vs. Piezometers/Inclinometers
- shear strength analysis
- determination of source mechanisms
Thank you for your attention!