Systematic mapping and hazard and risk classification of unstable rock slopes with a potential of forming displacement waves in Norway

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Martina Böhme
Gro Sandøy

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Content

• Historic rock slope failures in Norway triggering displacement waves
• Hazard and risk classification
• Mapping methodology for unstable rock slopes
The challenge:
Norway

- 68. largest country on earth
- 7. longest coast line
- coast line > 100,000 km long + lakes
Historic rockslide disasters in Norway

Tafjord 1934
### Certain fjellskred events

<table>
<thead>
<tr>
<th>Name</th>
<th>County</th>
<th>Municipality</th>
<th>Year</th>
<th>Volume [Mm³]</th>
<th>Lives</th>
<th>Displacement wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tjelle</td>
<td>More og Romsdal</td>
<td>Nesset</td>
<td>1756</td>
<td>15.0</td>
<td>32</td>
<td>Yes</td>
</tr>
<tr>
<td>Tafjordulykka</td>
<td>More og Romsdal</td>
<td>Norddal</td>
<td>1934</td>
<td>3.0</td>
<td>40</td>
<td>Yes</td>
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<tr>
<td>Skafjellet</td>
<td>More og Romsdal</td>
<td>Stranda</td>
<td>1731</td>
<td>6.0</td>
<td>17</td>
<td>Yes</td>
</tr>
<tr>
<td>Lausneset</td>
<td>More og Romsdal</td>
<td>Stranda</td>
<td>1300</td>
<td>-</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>Løenulykke 1</td>
<td>Sogn og Fjordane</td>
<td>Stryn</td>
<td>1905</td>
<td>0.4</td>
<td>61</td>
<td>Yes</td>
</tr>
<tr>
<td>Løenulykke 3</td>
<td>Sogn og Fjordane</td>
<td>Stryn</td>
<td>1936</td>
<td>1.0</td>
<td>74</td>
<td>Yes</td>
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<tr>
<td>Pollfjellet</td>
<td>Troms</td>
<td>Lyngen</td>
<td>1810</td>
<td>-</td>
<td>14</td>
<td>Yes</td>
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</table>

### Uncertain fjellskred events

<table>
<thead>
<tr>
<th>Name</th>
<th>County</th>
<th>Municipality</th>
<th>Year</th>
<th>Volume [Mm³]</th>
<th>Lives</th>
<th>Displacement wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storefonna</td>
<td>More og Romsdal</td>
<td>Sande</td>
<td>1700</td>
<td>-</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>Geirangerfjorden</td>
<td>More og Romsdal</td>
<td>Stranda</td>
<td>1749</td>
<td>0.1</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>Skafjellet</td>
<td>More og Romsdal</td>
<td>Stranda</td>
<td>1938</td>
<td>0.4</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>Arnafjord</td>
<td>Sogn og Fjordane</td>
<td>Norddal</td>
<td>1811</td>
<td>-</td>
<td>45</td>
<td>Yes</td>
</tr>
<tr>
<td>Hestadfjorden</td>
<td>Sogn og Fjordane</td>
<td>Gaular</td>
<td>1786</td>
<td>-</td>
<td>0</td>
<td>Yes</td>
</tr>
<tr>
<td>Årdalsfjorden</td>
<td>Sogn og Fjordane</td>
<td>Årdal</td>
<td>1983</td>
<td>0.2</td>
<td>0</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Mapping of unstable rock slopes in Norway

The vision:

• to characterize all unstable rock slopes which can course effects in a distance larger than the shadow angle of rock falls

• 0 loss of life due to large rock slope failures in the next centuries

http://www.skrednett.no/
Assumption:

• Slow deformation indicating slope instability
• Acceleration phase prior to collapse
Hazard and risk classification of unstable rock slopes

"As the likelihood of failure cannot be given quantitatively in hundreds or thousands of years with today's scientific knowledge, the risk analysis is built on a qualitative hazard analysis and a quantitative consequence analysis."

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(***) University of Milano-Bicocca, Italy
(****) Norwegian Road Authorities, Norway
(******) Norwegian Water and Energy Directorate, Norway
(*******) University of Lausanne, Switzerland
(********) ETH Zurich, Switzerland
(*********) The county of Møre og Romsdal, Norway

http://www.ngu.no/upload/Publikasjoner/Rapporter/2012/2012_029.pdf
## Hazard and risk classification of unstable rock slopes

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Not developed</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Partly open over length of slide body (few cm to m)</td>
<td>0.5</td>
<td>20</td>
<td>20.0%</td>
</tr>
<tr>
<td>Fully open over length of slide body (few cm to m)</td>
<td>1</td>
<td>80</td>
<td>80.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No penetrative structures dip out of the slope</td>
<td>0</td>
<td>10</td>
<td>10.0%</td>
</tr>
<tr>
<td>Penetrative structures dip on average &lt; 20 degree or steeper than the slope</td>
<td>0.5</td>
<td>80</td>
<td>80.0%</td>
</tr>
<tr>
<td>Penetrative structures dip on average &gt; 20 degree and daylight with the slope</td>
<td>1</td>
<td>10</td>
<td>10.0%</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Not developed</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Partly developed on 1 side</td>
<td>0.25</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fully developed or free slope on 1 side or partly developed on 2 sides</td>
<td>0.5</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Fully developed or free slope on 1 side and partly developed on 1 side</td>
<td>0.75</td>
<td>100</td>
<td>100.0%</td>
</tr>
<tr>
<td>Fully developed or free slope on 2 sides</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic feasibility test does not allow for planar, wedge sliding or toppling</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Failure is partly kinematically possible (movement direction is more than ± 30° to slope orientation)</td>
<td>0.5</td>
<td>100</td>
<td>100.0%</td>
</tr>
<tr>
<td>Failure is partly kinematically possible (movement direction is more than ± 30° to slope orientation)</td>
<td>0.75</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Failure is partly kinematically possible on persistent discontinuities (movement direction is more than ± 30° to slope orientation)</td>
<td>0.75</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Failure is kinematically possible on persistent discontinuities (movement direction is less than ± 30° to slope orientation)</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No indication on slope morphology</td>
<td>0</td>
<td>75</td>
<td>75.0%</td>
</tr>
<tr>
<td>Slope morphology suggests formation of a rupture surface (bulging, concavity-convexity, springs)</td>
<td>0.5</td>
<td>25</td>
<td>25.0%</td>
</tr>
<tr>
<td>Continuous rupture surface is suggested by slope morphology and can be mapped out</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No significant movement</td>
<td>0</td>
<td>50</td>
<td>50.0%</td>
</tr>
<tr>
<td>0.2 - 0.5 cm/yr</td>
<td>1</td>
<td>50</td>
<td>50.0%</td>
</tr>
<tr>
<td>0.5 - 1 cm/yr</td>
<td>2</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>1 - 4 cm/yr</td>
<td>3</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>4 - 10 cm/yr</td>
<td>4</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>&gt; 10 cm/yr</td>
<td>5</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. Acceleration (if velocity is &gt;0.5 cm/yr and &lt; 10 cm/yr)</th>
<th>Score</th>
<th>Rel. prob.</th>
<th>Norm. prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No acceleration or change in slope deformation</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Increase in slope deformation</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>8. Increase of rock fall activity</th>
<th>Score</th>
<th>Rel. prob.</th>
<th>Norm. prob.</th>
</tr>
</thead>
<tbody>
<tr>
<td>No increase of rock fall activity</td>
<td>0</td>
<td>75</td>
<td>75.0%</td>
</tr>
<tr>
<td>Increase of rock fall activity</td>
<td>1</td>
<td>25</td>
<td>25.0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No post-glacial events of similar size</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>One or several events older than 5000 years of similar size</td>
<td>0.5</td>
<td>100</td>
<td>100.0%</td>
</tr>
<tr>
<td>One or several events younger than 5000 years of similar size</td>
<td>1</td>
<td>0</td>
<td>0.0%</td>
</tr>
</tbody>
</table>

Hermanns et al. 2012, 2013
Gamanjunni 3
Hazard and risk classification of unstable rock slopes
Hazard and risk classification of unstable rock slopes

1) Back scarp
Hazard and risk classification of unstable rock slopes

2) Potential sliding structures
Hazard and risk classification of unstable rock slopes

3) Development of lateral release surfaces
Hazard and risk classification of unstable rock slopes

4) Kinematic feasibility
Hazard and risk classification of unstable rock slopes

5) Basal rupture surface
Hazard and risk classification of unstable rock slopes

6) Displacement velocity
7) Acceleration of displacement velocity
Hazard and risk classification of unstable rock slopes

7) Acceleration of displacement velocity
7) Acceleration of displacement velocity

Hazard and risk classification of unstable rock slopes
8) Enhanced rock fall activity
9) Past events along slope

Two postglacial events along same slope
Hazard and risk classification of unstable rock slopes

Risk matrix Gamanjunni 3
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope

Sign of instability?

YES

Entry into database

No entry into database

Reconnaissance

Real rock slope instability?

NO

No unstable rock slope

TOO small, rock fall problematic

YES

Preliminary consequence analysis

Are there consequences?

NO

Volume assessment

Automated run-out assessment

YES

Simple geological mapping

Hazard analysis

Consequence analysis including automated run-out assessment

Are there consequences?

NO

YES

Preliminary risk analysis

Geology with high uncertainty and medium or high risk object

Geology with low uncertainties and medium or high risk object

Detailed mapping + Periodic displacement measurements (until determined with low uncertainty)

Periodic displacement measurements (until determined with low uncertainty)

More than one scenario possible?

NO

Establish scenarios

Hazard and risk classification

High uncertainty on consequences (crossing limits of risk classes)?

YES

Detailed run-out analysis

Detailed consequence analysis

NO

Medium risk object

High risk object

Entry in database as not relevant

Entry in database as not yet relevant, but has to be checked in future

InSAR data Troms (NGU, NORUT, ICG, Norsk Romsenter)
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope

- Sign of instability? NO
  - No entry into database

  YES
  - Entry into database

  YES
  - Reconnaissance
  - Real rock slope instability? NO
    - No unstable rock slope
    - Potential unstable rock slope but no sign of past or present activity
  
  YES
  - Preliminary consequence analysis
  - Are there consequences?
    - NO
      - Simple geological mapping
        - Hazard analysis
        - Consequence analysis including automated run-out assessment
          - Are there consequences?
            - NO
              - No entry into database
            - YES
              - Preliminary risk analysis
            
    - YES
      - Preliminary risk analysis
      - Geology with high uncertainty and medium or high risk object
      - Geology with low uncertainties and medium or high risk object
      - Detailed mapping + Periodic displacement measurements (until determined with low uncertainty)
      - Periodic displacement measurements (until determined with low uncertainty)

      YES
      - More than one scenario possible?
        - NO
          - Establish scenarios
            - Hazard and risk classification
              - High uncertainty on consequences (crossing limits of risk classes)?
                - YES
                  - Detailed run-out analysis
                  - Detailed consequence analysis
                  - Medium risk object
                - NO
                  - High risk object

              - Low risk object

Potential unstable slope

Old eroded fault as back-crack and river drainage

Unstable slope
Mapping methodology for unstable rock slopes

1. **Air photo / InSAR analyses of rock slope**
   - Sign of instability?
     - Yes: Entry into database
     - No: No entry into database

2. **Reconnaissance**
   - Real rock slope instability?
     - No: No unstable rock slope
     - Yes: Potential unstable rock slope but no sign of past or present activity

3. **Preliminary consequence analysis**
   - Are there consequences?
     - No: Entry in database as not relevant
     - Yes: Volume assessment, Automated run-out assessment

4. **Simple geological mapping**
   - Hazard analysis
   - Consequence analysis including automated run-out assessment
   - Are there consequences?
     - No: Entry in database as not yet relevant, but has to be checked in future
     - Yes: Preliminary risk analysis

5. **Preliminary risk analysis**
   - Geology with high uncertainty
     - and medium or high risk object
   - Geology with low uncertainties
     - and medium or high risk object

6. **Detailed mapping**
   - Periodic displacement measurements
     - Until determined with low uncertainty

7. **Periodic displacement measurements**
   - Until determined with low uncertainty

8. **Establish scenarios**
   - More than one scenario possible?
     - No: Medium risk object
     - Yes: Hazard and risk classification

9. **Hazard and risk classification**
   - High uncertainty on consequences (crossing limits of risk classes)?
     - Yes: Detailed run-out analysis, Detailed consequence analysis
     - No: Medium risk object
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope
- Sign of instability?
  - No
    - No entry into database
  - Yes
    - Entry into database

Reconnaissance
- Real rock slope instability?
  - No
    - No unstable rock slope
  - Yes
    - Potential unstable rock slope but no sign of past or present activity

Preliminary consequence analysis
- Are there consequences?
  - No
    - Entry in database as not relevant
  - Yes
    - Volume assessment
    - Automated run-out assessment

Simple geological mapping
- Hazard analysis
- Consequence analysis including automated run-out assessment
  - Are there consequences?
    - No
    - Low risk object
    - Yes
    - Geology with high uncertainty and medium or high risk object

Detailed mapping + Periodic displacement measurements (until determined with low uncertainty)
- More than one scenario possible?
  - No
    - Medium risk object
  - Yes
    - Hazard and risk classification
      - High uncertainty on consequences (crossing limits of risk classes)?
        - Yes
          - Detailed run-out analysis
          - Detailed consequence analysis
        - No
          - Low risk object
      - No
        - Medium risk object
# Mapping methodology for unstable rock slopes

<table>
<thead>
<tr>
<th>Air photo / InSAR analyses of rock slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sign of instability? NO</td>
</tr>
<tr>
<td>YES Entry into database</td>
</tr>
<tr>
<td>Reconnaissance</td>
</tr>
<tr>
<td>Real rock slope instability? NO</td>
</tr>
<tr>
<td>YES Entry in database as not relevant</td>
</tr>
<tr>
<td>Too small, rock fall problematic</td>
</tr>
<tr>
<td>No unstable rock slope</td>
</tr>
<tr>
<td>Potential unstable rock slope but no sign of past or present activity</td>
</tr>
<tr>
<td>Preliminary consequence analysis</td>
</tr>
<tr>
<td>Are there consequences? NO</td>
</tr>
<tr>
<td>Simple geological mapping</td>
</tr>
<tr>
<td>* Hazard analysis</td>
</tr>
<tr>
<td>* Consequence analysis including automated run-out assessment</td>
</tr>
<tr>
<td>* Volume assessment</td>
</tr>
<tr>
<td>* Automated run-out assessment</td>
</tr>
<tr>
<td>YES Entry in database as not yet relevant, but has to be checked in future</td>
</tr>
</tbody>
</table>

**Low risk object**

<table>
<thead>
<tr>
<th>Preliminary risk analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology with high uncertainty and medium or high risk object</td>
</tr>
<tr>
<td>Geology with low uncertainties and medium or high risk object</td>
</tr>
<tr>
<td>Detailed mapping + Periodic displacement measurements (until determined with low uncertainty)</td>
</tr>
<tr>
<td>Periodic displacement measurements (until determined with low uncertainty)</td>
</tr>
<tr>
<td>More than one scenario possible? NO</td>
</tr>
<tr>
<td>Establish scenarios</td>
</tr>
<tr>
<td>* Hazard analyses</td>
</tr>
<tr>
<td>* Consequence analyses including automated run-out assessment</td>
</tr>
<tr>
<td>Hazard and risk classification</td>
</tr>
<tr>
<td>High uncertainty on consequences (crossing limits of risk classes)? YES</td>
</tr>
<tr>
<td>* Detailed run-out analysis</td>
</tr>
<tr>
<td>* Detailed consequence analysis</td>
</tr>
<tr>
<td>NO Medium risk object</td>
</tr>
</tbody>
</table>

**High risk object**
# Mapping methodology for unstable rock slopes

**Air photo / InSAR analyses of rock slope**

- **Sign of instability?**
  - **NO**
  - **YES** → Entry into database

**Reconnaissance**

- **Real rock slope instability?**
  - **NO**
  - **YES** → Preliminary consequence analysis

**Preliminary consequence analysis**

- **Are there consequences?**
  - **NO**
  - **YES** → Simple geological mapping

**Simple geological mapping**

- **Volume assessment**
- **Automated run-out assessment**

**Preliminary risk analysis**

- **Geology with high uncertainty and medium or high risk object**
- **Geology with low uncertainties and medium or high risk object**

**Detailed mapping + Periodic displacement measurements**

- **(until determined with low uncertainty)**

**Establish scenarios**

- **More than one scenario possible?**
  - **NO**
  - **YES** → Hazard and risk classification

**Hazard and risk classification**

- **High uncertainty on consequences (crossing limits of risk classes)?**
  - **YES** → Detailed run-out analysis
  - **NO** → Detailed consequence analysis

---

**Entry into database as not relevant**

**Entry in database as not yet relevant, but has to be checked in future**

**Low risk object**

**Medium risk object**

**High risk object**
Mapping methodology for unstable rock slopes

<table>
<thead>
<tr>
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<td>Reconnaissance</td>
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<tr>
<td>Real rock slope instability? NO</td>
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<tr>
<td>YES</td>
</tr>
<tr>
<td>Preliminary consequence analysis</td>
</tr>
<tr>
<td>Are there consequences? NO</td>
</tr>
<tr>
<td>YES</td>
</tr>
<tr>
<td>Simple geological mapping</td>
</tr>
<tr>
<td>• Hazard analysis</td>
</tr>
<tr>
<td>• Consequence analysis including</td>
</tr>
<tr>
<td>automated run-out assessment</td>
</tr>
<tr>
<td>⇒ Are there consequences? NO</td>
</tr>
<tr>
<td>YES</td>
</tr>
<tr>
<td>Preliminary risk analysis</td>
</tr>
<tr>
<td>Geology with high uncertainty and</td>
</tr>
<tr>
<td>medium or high risk object</td>
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<tr>
<td>High uncertainty on consequences</td>
</tr>
<tr>
<td>(crossing limits of risk classes)?</td>
</tr>
<tr>
<td>YES</td>
</tr>
<tr>
<td>Detailed run-out analysis</td>
</tr>
<tr>
<td>• Detailed run-out analysis</td>
</tr>
<tr>
<td>• Detailed consequence analysis</td>
</tr>
<tr>
<td>High risk object</td>
</tr>
</tbody>
</table>

Entry in database as not relevant

Entry in database as not yet relevant, but has to be checked in future

Low risk object

Medium risk object

High risk object

Flow-R, University of Lausanne
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope

- Sign of instability? NO
  - No entry into database
- Yes
  - Entry into database

Reconnaissance

- Real rock slope instability? NO
  - Too small, rock fall problematic
  - No unstable rock slope
- Yes
  - Potential unstable rock slope but no sign of past or present activity

Preliminary consequence analysis

- Are there consequences? NO
  - Simple geological mapping
    - Hazard analysis
    - Consequence analysis including automated run-out assessment
    - Are there consequences? NO
    - Preliminary risk analysis
      - Geology with high uncertainty and medium or high risk object
      - Detailed mapping + Periodic displacement measurements (until determined with low uncertainty)
        - More than one scenario possible? NO
        - Establish scenarios
          - Hazard and risk classification
            - High uncertainty on consequences (crossing limits of risk classes)? YES
            - Detailed run-out analysis
            - Detailed consequence analysis
    - Low risk object
      - Medium risk object
      - High risk object
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope

- **Sign of instability?**
  - **YES** → Entry into database
  - **NO** → No entry into database

**Reconnaissance**

- **Real rock slope instability?**
  - **NO** → No unstable rock slope
  - **YES** → Potential unstable rock slope but no sign of past or present activity

**Preliminary consequence analysis**

- **Are there consequences?**
  - **YES** →
    - Volume assessment
    - Automated run-out assessment
  - **NO** → Entry in database as not relevant, but has to be checked in future

**Simple geological mapping**

**Extensiometers**

**dGNSS**

**LIDAR**

**Gb InSAR**

**InSAR**
Mapping methodology for unstable rock slopes

**Air photo / InSAR analyses of rock slope**

- **Sign of instability?**
  - NO
  - Entry into database
- **Reconnaissance**
  - Real rock slope instability?
    - NO → No unstable rock slope
    - YES → Potential unstable rock slope but no sign of past or present activity
- **Preliminary consequence analysis**
  - Are there consequences?
    - NO → Simple geological mapping
      - Hazard analysis
      - Consequence analysis including automated run-out assessment
      - Are there consequences?
    - YES → Low risk object
- **Preliminary risk analysis**
  - Geology with high uncertainty and medium or high risk object
  - Periodic displacement measurements (until determined with low uncertainty)
- **Detailed mapping**
  - More than one scenario possible?
    - NO → Detailed run-out analysis
    - YES → Hazard and risk classification
      - High uncertainty on consequences (crossing limits of risk classes)?
        - NO → Detailed consequence analysis
        - YES → Establish scenarios
          - Hazard analyses
          - Consequence analyses including automated run-out assessment

---

**Landslide generated impulse waves in reservoirs - Basics and computations**

<table>
<thead>
<tr>
<th>Control buttons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input control</td>
</tr>
<tr>
<td>Prepare to print</td>
</tr>
</tbody>
</table>

**Governing parameters**

<table>
<thead>
<tr>
<th>Wave generation (Subsection 3.2.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slide impact velocity ( V_f ) [m/s]</td>
</tr>
<tr>
<td>Bulk slide density ( \rho_s ) [kg/m³]</td>
</tr>
<tr>
<td>Bulk slide volume ( V_s ) [m³]</td>
</tr>
<tr>
<td>Idle thickness ( x ) [m]</td>
</tr>
<tr>
<td>Slide impact angle ( \alpha ) [°]</td>
</tr>
<tr>
<td>Wave propagation angle ( \beta ) [°]</td>
</tr>
<tr>
<td>Wave propagation angle ( \gamma ) [°]</td>
</tr>
<tr>
<td>Wave propagation angle ( \delta ) [°]</td>
</tr>
<tr>
<td>Wave run-up and overtopping (Subsection 3.3.2)</td>
</tr>
<tr>
<td>Still water depth ( h ) [m]</td>
</tr>
<tr>
<td>Freeboard ( f ) [m]</td>
</tr>
<tr>
<td>Run-up angle ( \beta ) [°]</td>
</tr>
<tr>
<td>Crest width ( b_d ) [m]</td>
</tr>
</tbody>
</table>

**Main results**

**Figure 3.3** Sketches defining the given parameters on impulse wave generation and the most important wave parameters in (a) 2D and (b) 3D.
Mapping methodology for unstable rock slopes

Air photo / InSAR analyses of rock slope

- **Sign of instability?**
  - **YES** → Entry into database
  - **NO** → No entry into database

Reconnaissance

- **Real rock slope instability?**
  - **NO** → No unstable rock slope
  - **YES** → Potential unstable rock slope but no sign of past or present activity

Preliminary consequence analysis

- **Are there consequences?**
  - **YES** → Entry in database as not relevant
  - **NO**
    - **Volume assessment**
    - **Automated run-out assessment**

Simple geological mapping

- **Hazard analysis**
- **Consequence analysis including automated run-out assessment**
  ⇒ **Are there consequences?**
  - **YES** → Preliminary risk analysis
  - **NO**

Preliminary risk analysis

- Geology with high uncertainty and medium or high risk object
  + Detailed mapping
  + Periodic displacement measurements (until determined with low uncertainty)

Geology with low uncertainties and medium or high risk object

Periodic displacement measurements (until determined with low uncertainty)

More than one scenario possible?

- **YES** → Establish scenarios
- **NO** → Hazard and risk classification

Establish scenarios

- **Hazard analyses**
  - **YES** → High uncertainty on consequences (crossing limits of risk classes)?
  - **NO** → Detailed run-out analysis
  - **Detailed consequence analysis**

Hazard and risk classification

- **YES** → Medium risk object
- **NO** → High risk object

Figure 11: Modelled maximum surface elevation and comparison to measured run-up values.
Mapping methodology for unstable rock slopes

Table 11: Number of inhabitants and tourists exposed to displacement waves created by rockslides from Stampa with different volumes.

<table>
<thead>
<tr>
<th>Volume [Mm$^3$]</th>
<th>Inhabitants $W_I$ Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Tourists $W_T$ Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Total exposed persons, $W_{TOT}$ Min.</th>
<th>Max.</th>
<th>Mean</th>
<th>Potential life loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>5</td>
<td>0</td>
<td>3600</td>
<td>500</td>
<td></td>
<td></td>
<td>5</td>
<td>1805</td>
<td>130</td>
<td>91</td>
</tr>
<tr>
<td>5</td>
<td>106</td>
<td>0</td>
<td>9000</td>
<td>1250</td>
<td></td>
<td></td>
<td>106</td>
<td>4606</td>
<td>419</td>
<td>74</td>
</tr>
<tr>
<td>40</td>
<td>325</td>
<td>0</td>
<td>9000</td>
<td>1250</td>
<td></td>
<td></td>
<td>325</td>
<td>4825</td>
<td>638</td>
<td>228</td>
</tr>
</tbody>
</table>

For volumes greater than 40 Mm$^3$, more than one scenario might be presented.
Mapping methodology for unstable rock slopes
Mapping methodology for unstable rock slopes

http://www.skrednett.no/
Thank you for your attention

Reginald.Hermanns@NGU.NO