EVENT TREE ANALYSIS OF ÅKNES ROCK SLIDE HAZARD

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RÉSUMÉ
Un glissement massif sur les pentes rocheuses d'Åknes dans la municipalité de Stranda en Norvège pourrait avoir des conséquences désastreuses, puisque le glissement pourrait générer un tsunami qui engloutirait plusieurs villages le long du fjord Storfjord. Reconnaissances de site, instrumentation et un système d'alerte ont été établis afin de protéger la population de la région. Une analyse par arbre à événements a été menée pour quantifier le hazard et le risque associés avec une rupture de pente suivie par un tsunami. L'analyse avait aussi pour but d'examiner les paramètres requis pour un système d'alerte préventif fiable, et établir une liste de mesures pour réduire le risque. L'article décrit les problèmes géotechniques et les résultats d'une analyse de génération d'un tsunami. Il décrit la méthode d'analyse ETA (arbre à événements) et présente les premiers résultats de l'analyse. Un consensus d'opinions parmi des représentants de toutes les parties intéressées à la stabilité du massif rocheux et tsunami à Åknes, tant scientifiques que sociétales, a été établi.

ABSTRACT
A massive rockslide at Åknes in the Stranda municipality in western Norway would have dramatic consequences, as the tsunami triggered by the slide would endanger several communities around Storfjorden. Site investigations, monitoring and warning system for the potentially unstable rock slopes were implemented to reduce the hazard and risk. As part of hazard and risk assessment, event trees were constructed by pooling the opinion of engineers, scientists and stakeholders. The objecttive was to reach consensus on the hazard, vulnerability and elements at risk (consequences) associated with a rockslide and tsunami, quantify the hazard (probability of a rockslide and tsunami occurring) and the potential losses (human life and material and environmental damage). The probability of occurrence and the risk were obtained through a consolidation of all the branches of the event tree. The event tree analysis results in a map of the risk for the residents for the municipalities close to Åknes. The paper presents the evaluation process followed and some of the preliminary results achieved.

1. INTRODUCTION

Rock falls and rockslides are among the most dangerous natural hazards in Norway, mainly because of their tsunamigenic potential. The three most dramatic natural disasters in Norway in the 20th century were tsunamis triggered by massive rockslides into fjords or lakes (Loen in 1905 and 1936 and Tafjord in 1934), causing more than 170 fatalities. As public attention on natural hazards increases, the potential rockslides in the Storfjord region in western Norway have earned renewed focus. A massive rockslide at Åknes could be catastrophic as the tsunami triggered by the rockslide represents a threat to the communities around the fjord. The Åknes/Tafjord project was initiated in 2005 by the municipalities, with funding from the Norwegian government, to investigate rockslides, establish monitoring systems and implement a warning and evacuation system to prevent fatalities, should a massive rockslide take place.

The potential disaster associated with a rockslide and tsunami involves many parties, with differing opinions and perceptions. As part of the on-going hazard and risk assessment and validation of the early warning system, event trees were prepared by pooling the opinion of engineers, scientists and stakeholders. The objective was to reach consensus on the hazard and risk associated with a massive rockslide at Åknes. The paper describes the potential hazards, the event tree approach and preliminary examples of the results.

2. THE ÅKNES ROCK SLOPE

Åknes is a rock slope over a fjord arm on the west coast of Norway (Figure 1). The area is characterised by frequent rockslides, usually with volumes between 0.5 and 5 millions m^3. Massive slides have occurred in the region, e.g. the Loen and Tafjord disasters (Figure 2). Bathymetric surveys of the fjord bottom deposits show that numerous and gigantic rockslides have occurred many thousands of years ago. The Åknes/Tafjord project (www.aknes-tafjord.no) includes site investigations, monitoring, and an early warning system for the potentially unstable rock slopes at Åknes in Stranda County and at Hegguraksla in Norddal County. The project also includes a regional susceptibility and hazard analysis for the inner Storfjord region, which includes Tafjord, Norddalsfjord, Sunnylvsfjord and Geirangerfjord (Figure 1).

2.1 Observed displacements

Experience from Norway and abroad shows that rockslide events are often preceded by warning signs such as increased displacement rate, micro-tremors and local sliding. Accelerating rate of displacement several weeks and even months before a major rockslide event is typical.

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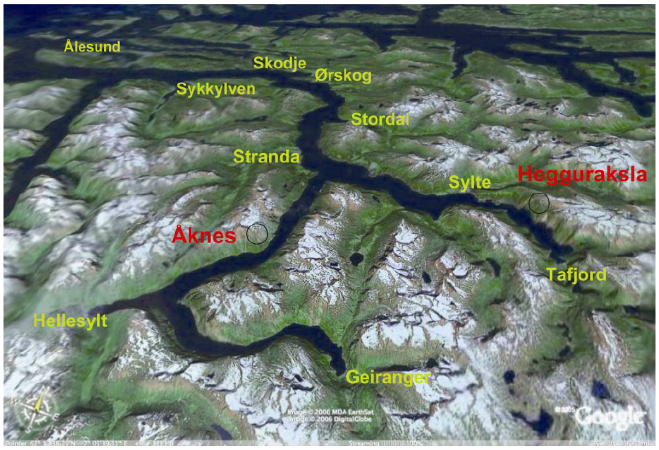


Figure 1. Location map for Åknes, Tafjord and Geiranger

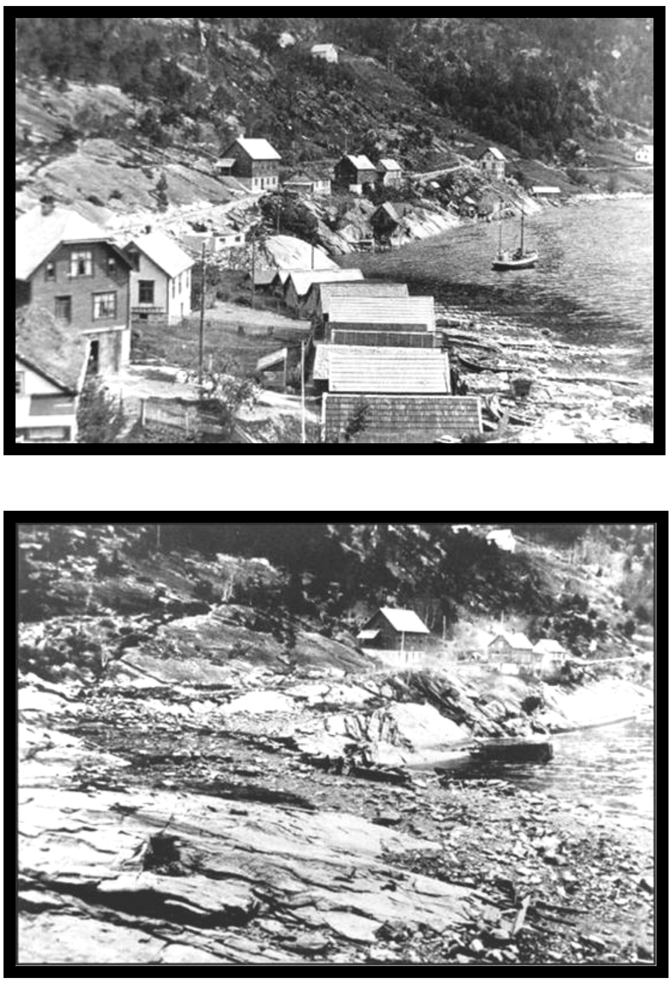
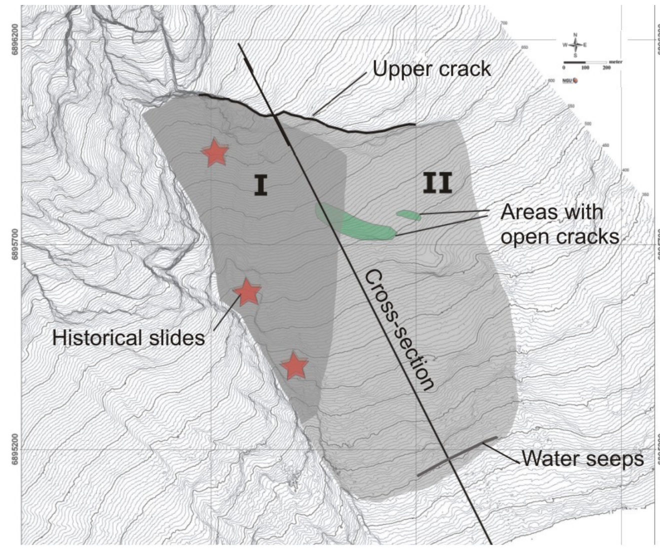


Figure 2. Fjøra in Tafjord before and after rockslide-triggered tsunami in 1934

Slope movements have been detected at Åknes down to 60 m depth (Figure 3). New borehole data suggest movements down to 100 m. Important uncertainties lie in the most likely failure depth and location, and whether the slide will occur as one large 30-60 millions m^3 sliding event or a succession of several 'small' slide events. Figures 3 presents the Åknes slope and two slide scenarios. Figure 4 shows some of the displacements observed at the upper crack. Water seeps ("springs") are seen emerging on the downstream slope. The displacements in Figure 4 appear to move linearly with time. The total annual displacements vary from less than 2 cm up to about 10 cm.



Area I: Slide volume 10-15 millions m^3, displacement=6-10 cm/yr
Area II: Slide volume 25-80 millions m^3, displacement=2-4 cm/yr

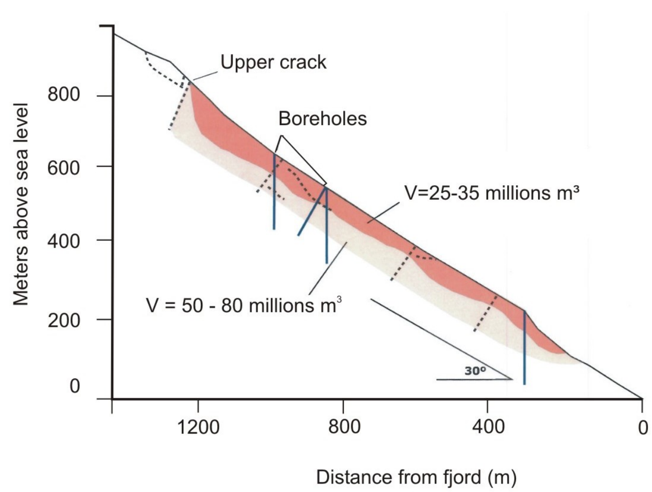


Figure 3. Sliding volume scenarios: surficial area (top) and cross-section (bottom) (modified from Blikra *et al.* 2007)

The large variations in weather and atmospheric conditions in the fjord and mountain areas pose unusual challenges to the instrumentation. For example, the hazard due to snow avalanche and rock bursts is high in most of the area to be monitored. Solar panels do not provide sufficient electricity, and energy has to be obtained from several sources to ensure a stable and reliable supply.

Significant effort is underway to deploy robust instruments and improve data communication during periods of adverse weather. An Emergency Preparedness Centre is located in Stranda. The monitoring data will be integrated into a database that will form the basis for future analyses.

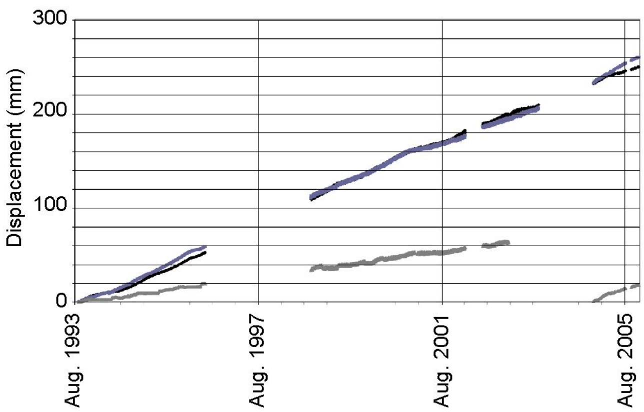


Figure 4. Displacements at slope top from 5 extensometers (Kveldsvik *et al.* 2006)

3. HAZARD AND RISK

Figure 5 illustrates in a “bow-tie” diagram the components of hazard and risk mitigation. Risk is the measure of the probability and severity of an adverse event to life, health, property or the environment. Quantitatively, risk is the probability of an adverse event times the consequences if the event occurs, where consequences are obtained from the elements at risk and their vulnerability. Mitigation of risk can be done by reducing the frequency (probability) of the adverse event or by reducing the vulnerability and/or exposure of the elements at risk.

The Åknes slope is exposed to several potential natural hazards: extreme rainfall, earthquake, slope instability and tsunami generated by a massive rock failure.

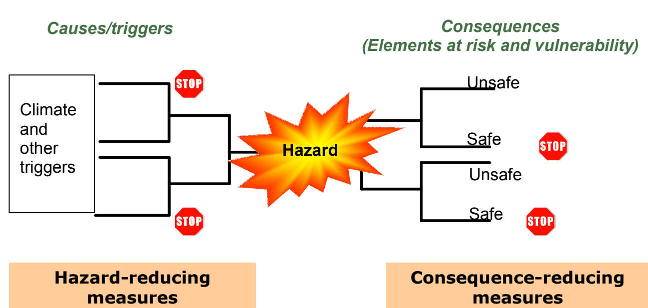


Figure 5. Illustration of hazard and risk

3.1 Triggers of rock instability

The statistics of triggers observed or inferred for rockslides in the European Alps are illustrated in the chart in Figure 6. The reference database is somewhat limited, as only 16 slides underlie the distribution shown. Rainfall and earthquakes tend to dominate the statistics, although melting of snow and mining or tunneling in the vicinity also play a role.

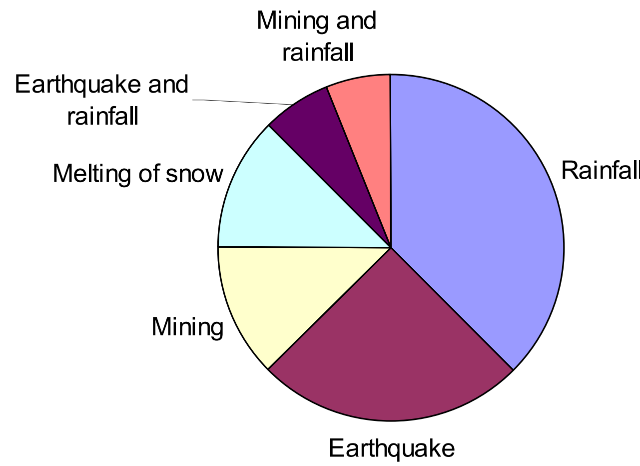


Figure 6. Rockslide triggers, European Alps (Irasmos 2007)

As part of the construction of the event tree, a brainstorming was done among the participants on the possible triggers for a rockslope failure at Åknes. The triggers considered were:

– unusual wet spring (intense rainfall and melting of snow)

– large earthquake

– "aging" of slope, weakening of sliding plane, weathering and creep, with change in properties (gouge characteristics, roughness, breakdown of ridges in intact rock)

– combination of the above processes

– shallow partial failure triggering a large failure volume.

Originally, the participants brought forward the first three triggers. During the discussions, two event trees were added: (1) an event tree covering the combination of unusual rapid snow melting with intense rainfall at the same time as the sliding planes had been weakened, and (2) an event tree covering a shallow slide triggering a large rockslide.

3.2 Modeling of rockslide-triggered tsunami

The tsunami wave propagation due to a rockslide at the Åknes slope was modelled numerically for two rockslide scenarios: slide volume of 8 mill. m^3 and 35 mill. m^3. Run-up values were estimated for 15 locations in the Storfjord region (Eidsvig & Harbitz, 2005; Glimsdal & Harbitz 2006). The results are shown in Table 1 for selected locations. The results suggest an inundation height of up to 35 m at Hellesylt for a rockslide volume of 35 millions m^3.

The time estimated for the wave to reach the communities around the fjord was between 5 and 15 minutes. The modelling of the tsunami caused by the rockslide involves several uncertainties. To reduce the uncertainties, physical modelling is underway to improve the understanding of the initial wave pattern generated by the sliding rock masses.

Table 1. Estimated run-up heights in the Storfjord region

Location	Run-up heights 8 millions m^3	Run-up heights 35 millions m^3
Hellesylt	8-10 m	25-35 m
Geiranger	8-15 m	20-40 m
Stranda	1-3 m	3-6 m
Fjøra	1-2 m	5-7 m
Tafjord	3-5 m	12-18 m

4. EVENT TREE ANALYSIS (ETA)

4.1 Approach

An event tree is a graphical construction that describes the sequence of the occurrence of events in a logical system. The tree identifies the possible outcomes and contains estimates of their probability of occurrence. As the number of events increases, the construction fans out like the branches of a tree. Each path in the event tree represents a specific sequence of events, resulting in a particular consequence. The events are defined such that they are mutually exclusive. ETA is a valuable analysis tool because it is simple and graphic, it provides qualitative insight into a system, and it can be used to assess a system's reliability in a quantitative manner (Hartford and Baecher 2004).

4.1.1 Qualitative assessment

Figure 2 gives an example of a qualitative event tree to analyse the possible outcomes of a fire. The system has 2 components to contain the fire event: a sprinkler system and an automated call to the fire department. If the sprinkler system works, but the fire department is not notified, the fire will be only partly contained. Partial damage is also the outcome if the fire department is notified, but the sprinklers fail. If the sprinkler system fails and the call to the fire department is unsuccessful, the fire will finally cause complete failure. The only desirable outcome is if both the sprinkler system and the call to the fire department are effective.

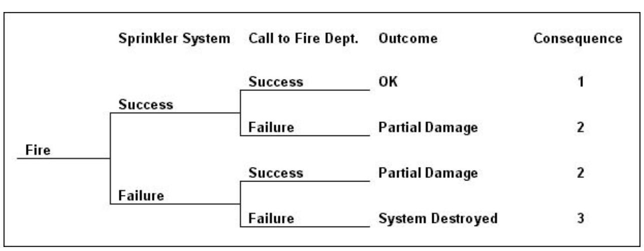


Figure 5. Qualitative event tree on the outcomes of a fire

4.1.2 Quantitative assessment

The step from qualitative to quantitative assessment is straightforward in situations where the event tree is well defined and the statistical bases for deriving the probabilities of occurrence are available. When each event in the tree is associated with a probability of occurrence, the process of quantifying the hazard or risk is simply a matter of multiplying the probabilities along each branch of the event tree. The result is a set of frequency-consequence pairs that are fundamental components of a quantitative analysis. ETA presumes that engineering judgement is necessary at several levels (e.g. models, parameters and assumptions). To achieve consistency in the evaluation of the probabilities (from one expert to the other and from one structure to another), conventions have been suggested to anchor the probabilities (Vick 2002; Høeg 1996; Lacasse *et al.* 2003).

Verbal description of uncertainty	Event probability
Virtually impossible	0.001
Very unlikely	0.01
Unlikely	0.10
Completely uncertain	0.50
Likely	0.90
Very likely	0.99
Virtually certain	0.999

where

Virtually impossible: event due to known physical conditions or processes that can be described and specified with almost complete confidence

Very unlikely: the possibility cannot be ruled out on the basis of physical or other reasons

Unlikely: event is unlikely, but it could happen

Completely uncertain: there is no reason to believe that one outcome is more or less likely than the other to occur

Likely: event is likely, but it may not happen

Very likely: event is highly likely, but may not happen, although one would be surprised if it did not happen.

Virtually certain: event due to known physical conditions or processes that can be described and specified with almost complete confidence.

4.2 Achieving consensus

In a multi-disciplinary process such as the analysis of hazard and risk associated with natural hazards, a number of "experts", specialists and stakeholders are assembled and need to agree on the numbers set on the branches of the event tree. One needs then to achieve 'consensus'. Consensus derives from Latin, 'cum' meaning 'together with' and 'sentire' meaning to 'think' or 'feel'. Etymologically, 'consensus' therefore means to think or feel together'. In a decision-making process, consensus aims to be:

- inclusive: as many stakeholders as possible should be involved in the consensus decision-making process.
- participatory: the process should actively solicit the input and participation of all decision-makers
- cooperative: participants should strive to reach the best possible decision for the group and all of its members, rather than opt to pursue a majority opinion, potentially to the detriment of a minority.

- egalitarian: all members of a consensus decision-making body should be allowed, as much as possible, equal input into the process; all members have the opportunity to table, amend, veto or "block" proposals.
- solution-oriented: the decision-making body strives to emphasise common agreement rather than differences and use compromise and other techniques to reach decisions and resolve mutually-exclusive positions.

4.3 Examples of ETA results for Åknes

The event trees were constructed by pooling the opinion of engineers, scientists and stakeholders. The objective was to reach consensus on the hazard, vulnerability and risk associated with a rockslide at Åknes and quantify the hazard (probability of a rockslide and tsunami occurring) and the potential losses (human life and material and environmental damage). Different triggers for the rockslide were analysed.

The ETA was carried out over three days, where scientists and stakeholders with relevant competence to grasp the situation as a whole were assembled. The objectives of the analysis were also to examine the required parameters for an effective early warning system and suggest possible mitigation measures, e.g. drainage wells and drainage galleries. The paper describes the event trees used for estimating risk. Progress is underway on the analysis and the results are only preliminary. The other topics will be the object of future papers.

The participant list for the results shown below included the following representatives:

- manager for Åknes/Tafjord project
- mayor of community
- social scientist from community
- city planner from community
- policeman working on emergency plans and evacuation
- local politician
- representative from community office
- directorate for safety and emergency preparedness
- journalist/media
- officer from ministry of highways
- meteorologist
- physical geographer
- social geographer
- geologist
- engineering geologist
- rock mechanics specialist
- geotechnical engineer
- tsunami specialist
- instrumentation specialist
- earthquake engineer
- seismologist
- mathematician
- statistician
- risk analysis specialist

The following event trees were constructed during the three-day meeting:

- event tree, rockslide due to seismic trigger
- event tree, rockslide due to high pore pressure trigger
- event tree, rockslide due to weathering and creep trigger
- event tree, tsunami wave against Hellesylt
- event tree, consequences of tsunami
- event tree, optimum observations for early warning

Event trees were constructed for three triggers of rock slope instability: earthquake, high pore pressure and weathering , creep and weakening of sliding plane. The event trees represent the judgment for the "today" (October 2007) situation. The trees set numbers for the probability of a slide within the next year, but the probability changes with time. The event trees should therefore be updated as new information becomes available.

Figures 7 and 8 present two examples: (1) event tree for a seismic trigger and (2) event tree for tsunami propagation, given that the rockslide has occurred. The numbers are given to illustrate the process, and are not to be used as estimates fro the rockslope at Åknes.

For simplicity, the steps for the event tree in Figure 7 (seismic trigger) are shown for earthquake magnitude of 6 only. Earthquake magnitude (M) of 4 and M between 4 and 6 are treated in the same fashion as magnitude 6, but the probability estimates are different from those in Figure 7. Eidsvik *et al.* 2008 present the reasons behind the choices n the ETA and for the probabilities assigned all along the event tree.

The steps for the event tree in Figure 7 include: 1) earthquake occurs; 2) magnitude of earthquake (M = 4 to 6); 3) distance from earthquake epicentre to rockslide scarp (D=less or greater than 50 km); 4) earthquake acceleration (A_{max} < 0.1g to A_{max} > 0.25g); pore pressure (PP less or greater than normal); rockslide occurs co-seismically, i.e. at the same time or within 10 minutes of earthquake, or earthquake may lead to a degradation process leading to slope failure at a later stage (co-seismic , yes or no).

The failure probability is the summation of the failure probabilities, P_f, in all the branches of the tree. The aggregated annual failure probability in Figure 7 is $P_f = 4 \times 10^{-5}$/yr. The values in example in Figure 7 are for the sake of this paper, and are not the estimated values for the Åknes site.

In a similar way, Figure 8 presents the steps for the tsunami event tree. The steps include: 1) rockslide is triggered; 2) slide is in one massive volume or in pieces; 3) volume of rockslide (V < 5 millions m^3 to V > 35 millions m^3); 4) resulting run-up height on land (R ≤ 5 m to R > 20 m).

The probability of having the rockslide triggered needs to be entered in the calculation of the total probability. For the sake of the example, if the initial probability of the rockslide due to all plausible triggers is taken as $P_f = 10^{-3}$/yr, the probability of three different run-up heights are given in Table 2. The sum of the probabilities is $P_f = 9 \times 10^{-4}$/yr for all run-up heights. As mentioned earlier, the values in Figure 8 and Table 2 are given for the sake of this paper, and not for extrapolation to the the Åknes site. The problem is in reality more complex than shown in the examples. One needs, for example, to account for the relationship between the failure probability from the seismic trigger with the depth of the failure surface and possible volume of sliding rock.

Table 1. Estimated probability of run-up heights at Hellesylt, given that a rock slide of larger volume has occurred

Run-up height ≤ 5 m	Run-up height > 5m; ≤ 20 m	Run-up height > 20 m
$P = 3 \times 10^{-4}$/yr	$P = 5 \times 10^{-4}$/yr	$P = 1 \times 10^{-4}$/yr

As part of the evaluation of the consequences of a rockslide and tsunami, the magnitude of the consequences (loss of life and material property and environmental damage) depends on: warning time before the rockslide or tsunami hazard occurs, reliability of emergency preparedness plan, run-up height, local water level, local water flow velocity, availability of escape routes and distance to safe havens, time of the day, time of the year, training of professionals and public, unforeseen concurrent event etc. These factors will form the steps of the event tree on consequences.

5. EARLY WARNING, EMERGENCY PREPAREDNESS

5.1 Instrumentation and monitoring

Based on the experience with similar projects and the specific needs in Storfjord, the overall monitoring system was equipped as follows:

Surface monitoring
- GPS-network with 8 antennas
- total station with 30 prisms
- ground-based radar with 10 reflectors
- 5 extensometers measuring crack opening
- 2 simple lasers measuring opening of the 2 largest cracks
- geophones that measure vibrations

Monitoring in borehole
- Inclinometers measuring displacements
- piezometers measuring pore pressure
- temperature
- electrical resistivity of water

Meteorological station
- temperature
- precipitation and snow depth
- wind speed
- ground temperature
- radiation

Several independent systems were installed to ensure continuous operation at all times, and different communication systems were implemented to ensure continuous contact with the Emergency Preparedness Centre in Stranda.

5.2 Early warning and emergency preparedness

The Åknes/Tafjord early warning and emergency preparedness system was implemented early 2008. As part of this system, the Emergency Preparedness Centre Stranda is in operation continuously (24 hours, 7 days). Alarm levels and responses are under development. The aim is to establish guidelines for monitoring and alert levels in the case of impending failure. Figure 9 and Table 3 present an example of the alarm and response system.

Table 3. Sketch of possible alarm and response levels

Level	Observations and alarm level	Response
Level 1 Normal situation	Minor seasonal variations No alarm	EPC staff only Technical maintenance
Level 2 Awareness	Important seasonal fluctuations for individual and multiple sensors Values < excess thresholds for Level 2	Increase frequency of data review, compare different sensors Call in geotechnical/geological/monitoring expert
Level 3 Increase awareness	Increased displacement velocity, agreement from several individual sensors Values < excess thresholds for Level 3	Do continuous review, do field survey, geo-expert team at EPC full time Inform police and emergency/preparedness teams in municipalities
Level 4 High hazard	Accelerating displacement velocity observed on multiple sensors Values < excess thresholds for Level 4	Increase preparedness, continuous data analysis Alert municipalities to stand prepared for evacuation
Level 5 Critical situation	Continuous displacement acceleration Values > excess thresholds for Level 4	Evacuation

EPC = Emergency Preparedness Centre in Stranda

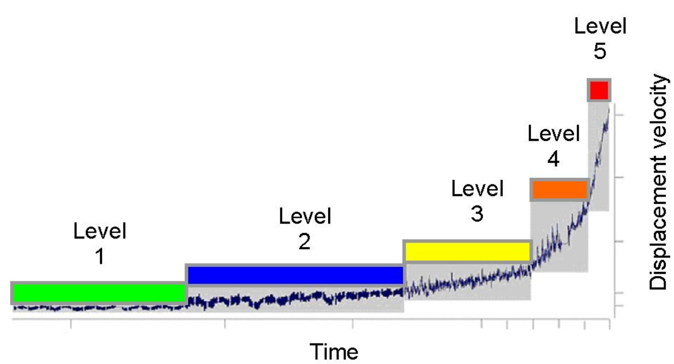


Figure 9. Alarm levels as a function of displacement velocity (Level 1, low velocity; Level 2, increasing fluctuation; Level 3, increasing velocity; Level 4, accelerating displacement; Level 5, continuous displacement acceleration) – Modified from Blikra 2008

The event tree for the Åknes early warning system involved, among others, the following steps: 1) time needed for warning (t in weeks, days or hours, some triggers give more time than other); 2) technology (working, yes or no); 3) are signals picked up? (yes or no); 4) are signals correctly interpreted? (human element, time available, delegation of authority, etc); 5) warning parameter(s) to follow up before and during warning; 6) choice of threshold values. A number of factors were seen as important to consider:

- 4-5 wks/yr are the most critical because of climatic factors; at that time, one should define an increased alarm level
- life and range of operation of sensors (e.g. extensometers) should be checked continuously
- any presence of large amount of water should be monitored
- careful thought should be given to what is/are the most representative measurements for early warning
- monitoring should be spread out, as failure may occur in other locations than crack; consider additional boreholes and other measurements
- when making decision, look at snow avalanche warning
- statistical evaluation of measured data should be built in system; consider Bayesian updating
- adapt warning curve (Figure 9) as more knowledge is acquired
- consider whether police and other authorities should be on standby earlier than suggested in Table 3 (police needs 72 hours to evacuate entire Storfjord area)
- establish threshold values to decide on when to move back after false alarm, but bake in the possibility of slide developing with time
- be prepared with a new monitoring system to be set in operation quickly after a first slide that has probably destroyed the instrumentation in place

6. SUMMARY AND CONCLUSIONS

The paper presented the versatility of the event tree analysis to help make decisions. The approach can quantify hazard and risk, and indicate the most critical situations. The ETA approach is especially useful for geotechnical problems that involve large uncertainties. The examples given for the Åknes/Tafjord project illustrated the method. One should refer to the Åknes/Tafjord project (www.aknes-tafjord.no) for site-specific quantitative estimates.

The consensus process with a group of scientists from several fields of expertise, including the geoscientific, political, social and public arenas, enabled the participants to quantify the probability of occurrence of a catastrophic rockslide and tsunami, examine the required parameters for effecttive early warning and discuss possible mitigation measures. Progress is still underway on these aspects of the analysis.

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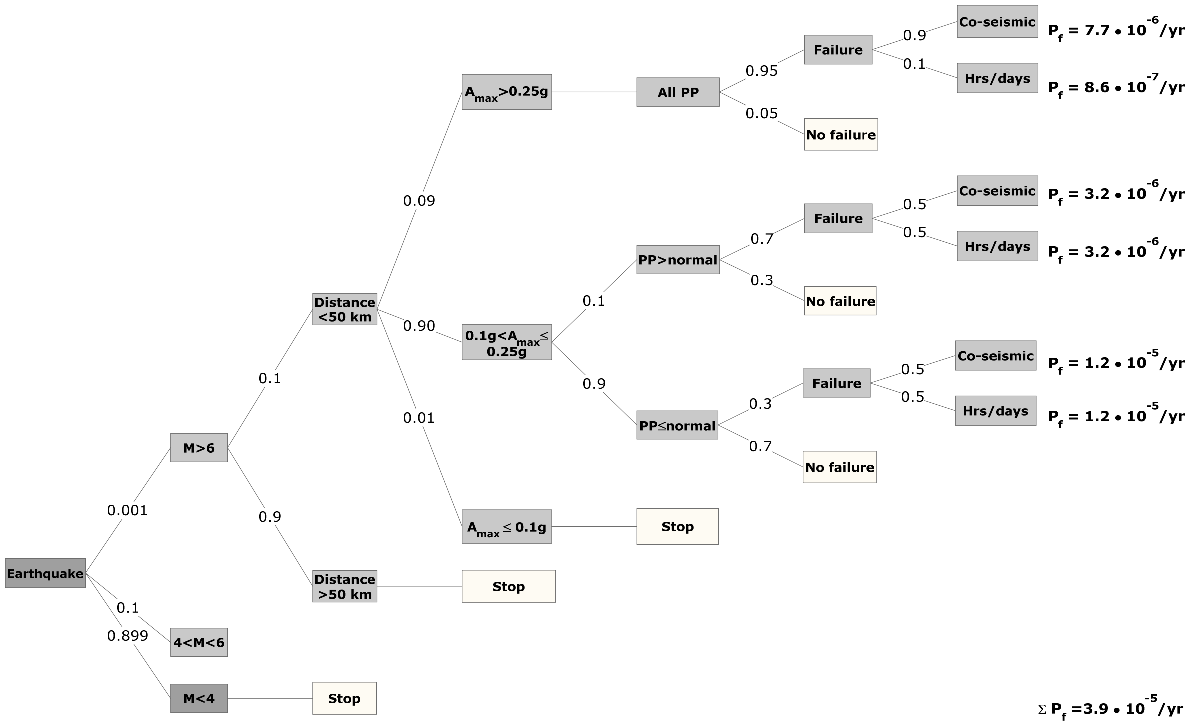

Figure 7. Event tree for earthquake-triggered rockslide (M, A_{max}= earthquake magnitude and acceleration, PP=pore pressure)

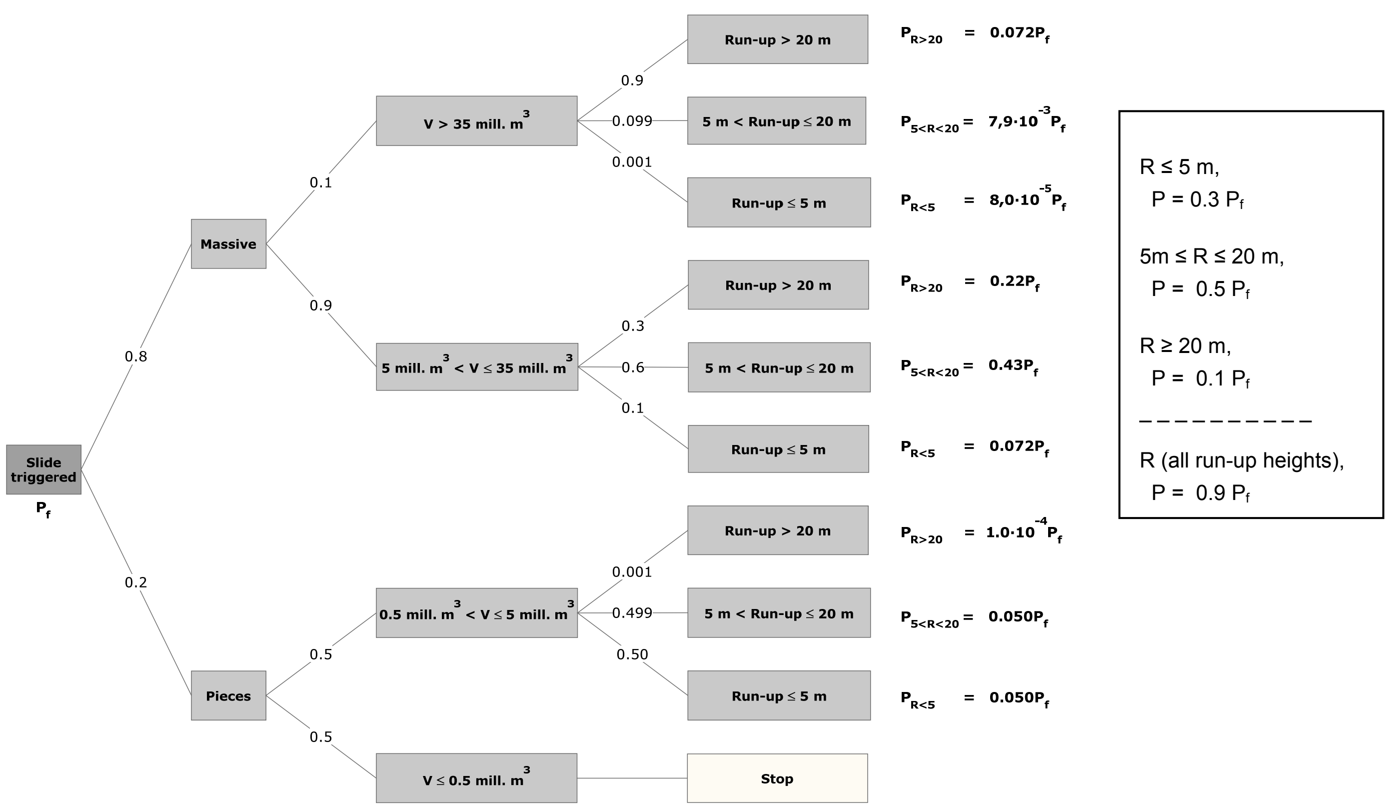

Figure 8. Event tree for tsunami propagation, given that rock slide has occurred (V= rockslide volume, R=run-up height)