Event tree analysis of the Åknes rock slope

Analyse par arbre à événement de la pente rocheuse à Åknes

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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, offensive monitoring and a warning system for the potentially unstable rock slopes were implemented to reduce hazard and consequences. As part of hazard and risk assessment, event trees were constructed by pooling the opinion of engineers, scientists and stakeholders. The objective 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 trees. The event tree analysis results in a map of the risk for the residents for the municipalities close to Åknes. The paper presents the event tree analysis process and some of the preliminary results achieved on the hazard associated with the failure of the Åknes rock slope.

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 entre des représentants de tous les partis intéressés à la stabilité du massif rocheux, tant scientifiques que sociaux, a été établi.

Keywords : rockslide, tsunami, event tree analysis.

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. 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 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 and the event tree approach, and presents examples of the preliminary results.

2 THE ÅKNES ROCK SLOPE

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

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.

Slope movements have been detected at Åknes down to 60 m depth. 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. Figure 1 presents the Åknes slope and two slide scenarios. Figure 2 shows some of the displacements observed at the upper crack. The total annual displacements vary from less than 2 cm up to about 10 cm, with the largest displacements at the south-western part of the slide. The displacements appear to increase linearly with time, i.e. the displacement rate is constant.

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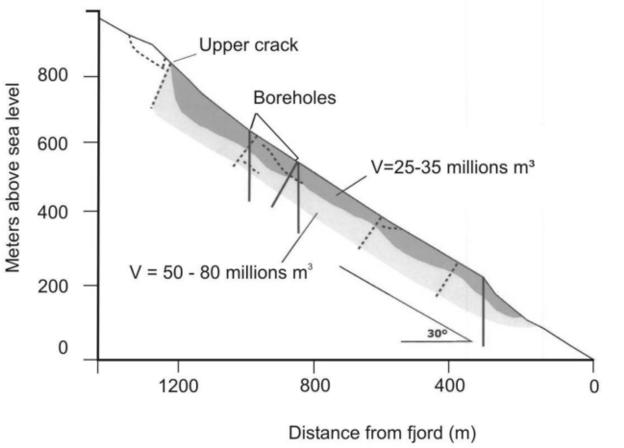

Area I: Slide volume 10-15 millions m^3, displacement=6-10 cm/yr

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

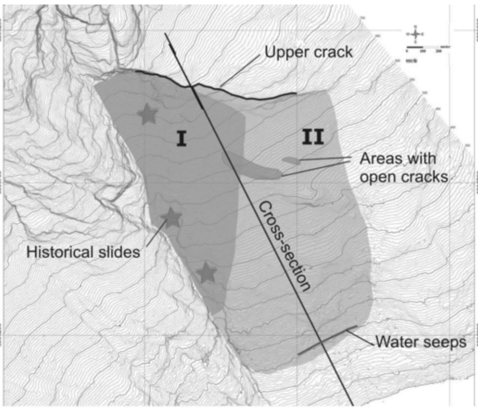

Figure 1 Sliding volume scenarios: surficial area (top) and cross-section (bottom) (modified from Blikra et al. 2007)

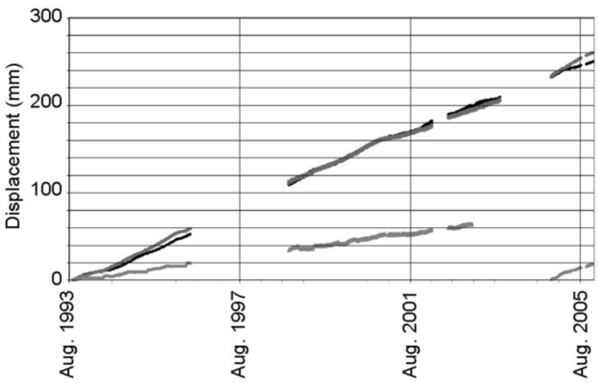

Figure 2 Displacements at slope top from 5 extensometers (Kveldsvik et al. 2006)

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 has been made to deploy robust instruments and improve data communication during periods of adverse weather. An Emergency Preparedness Centre is located in Stranda. The monitoring data are integrated into a database.

3 ROCKSLIDE AND TSUNAMI HAZARD

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

- unusual wet spring (intense rainfall and snowmelting)
- 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.

3.1 *Modeling of Rockslide-Triggered Tsunami*

The tsunami wave propagation due to a rockslide at the Åknes slope was modeled numerically for two rockslide scenarios: slide volumes of 8 mill. m^3 and 35 mill. m^3. Run-up values were estimated for 15 locations in the Storfjord (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.

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
Tafjord	3-5 m	12-18 m

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

4 EVENT TREE ANALYSIS (ETA)

An event tree is a graphical construction that describes the sequence of events in a logical system leading to different outcomes. It could be qualitative or quantitative. 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).

The qualitative event tree identifies the sequence of events resulting in a particular consequence. The events are defined such that they are mutually exclusive.

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 probability for one outcome is found by multiplying the probabilities along the corresponding 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.

5 EXAMPLES OF ETA RESULTS FOR ÅKNES

The event trees were constructed by pooling the opinion of engineers, scientists and stakeholders with relevant competence to grasp the situation as a whole. The objective was to reach consensus on the hazard (probability of a rockslide and tsunami occurring), vulnerability and risk associated with a rockslide at Åknes, to examine the required parameters for an effective early warning system and suggest possible mitigation measures.

This paper describes the event trees used for estimating hazard. Different triggers for the rockslide were analysed. The analysis is still in progress and the results are only preliminary. The other topics will be the subject of future papers.

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

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

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. The numbers are given to illustrate the process, and are not to be used as estimates for the rock slope at Åknes. Eidsvig et al. 2008 present the reasons behind the choices in the ETA and for the probabilities assigned all along the event tree.

Two examples are presented:

- Event tree for rockslide due to seismic trigger (Fig. 4)
- Event tree for tsunami propagation, given that the rockslide has occurred (Fig. 3)

5.1 *Rockslide Triggered by Earthquake*

The steps for the event tree in Figure 4 include: (i) earthquake occurs; (ii) magnitude of earthquake ($M \leq 4$ to $M \geq 6$); (iii) distance from earthquake epicenter to rockslide scarp (D=less or greater than 50 km); (iv) earthquake acceleration ($A_{max} \leq 0.1g$ to $A_{max} > 0.25g$); (v) pore pressure (PP less or greater than normal); (vi) rockslide occurrence (failure or no failure?); (vii) 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 probability values in Step i)–v) are found from statistical data on seismic activity and meteorological conditions in the area. Probability values for step vi)-vii) are estimates based on expert judgment. Comparison between step vi) for branch M≥6 and for branch 4<M<6, shows that the same peak acceleration could lead to different failure probabilities. This is due to the longer duration of a magnitude 6 earthquake compared to e.g. a magnitude 4 or magnitude 5 earthquake.

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 4 is $P_{f,\, M \geq 6} = 4 \times 10^{-5}$/yr for M≥6 and $P_{f,\, 4<M<6} = 7 \times 10^{-5}$/yr for 4<M< 6. The total probability of failure is the sum of the aggregated P_f for M≥6 and 4<M<6, i.e. $P_f = 1.1 \times 10^{-4}$/yr The values in Figure 4 are for the sake of this paper, and are not the estimated values for the Åknes site.

5.2 *Tsunami against Hellesylt*

The steps in the tsunami assessment (Figure 3) include: (i) rockslide is triggered; (ii) slide is in one massive volume or in pieces; (iii) volume of rockslide ($V \leq 0.5$ millions m^3 to $V > 35$ millions m^3); (iv) resulting run-up height on land ($R \leq 5$ m to R >20 m). Rockslide volumes are based on ongoing measurements of displacements, including measurements in boreholes, and an existing block model derived from surface measurements, Kveldsvik et al. 2008.

The probability of having the rockslide triggered needs to be entered in the calculation of the total probability. For the sake of the example, 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 was estimated, these 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 3 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.

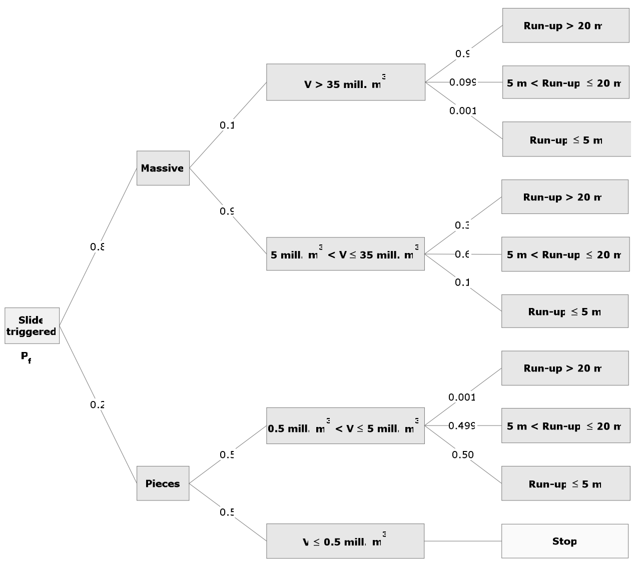

Figure 3 Event tree for tsunami propagation, given that rock slide has occured (V = rockslide volume, R = run-up height)

Table 2. Estimated probability of run-up heights (H) at Hellesylt for a tsunami triggered by a rockslide of larger volume ($P_f = 10^{-3}$/yr)

$H \leq 5$m	5 m < $H \leq$ 20 m	H > 20 m
P = 1 x 10 $^{-4}$/yr	P = 5 x 10 $^{-4}$/yr	P = 3 x 10 $^{-4}$/yr

6 SUMMARY AND CONCLUSIONS

The paper presented the application 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 effective early warning and discuss possible mitigation measures. Progress is still underway on these aspects of the analysis.

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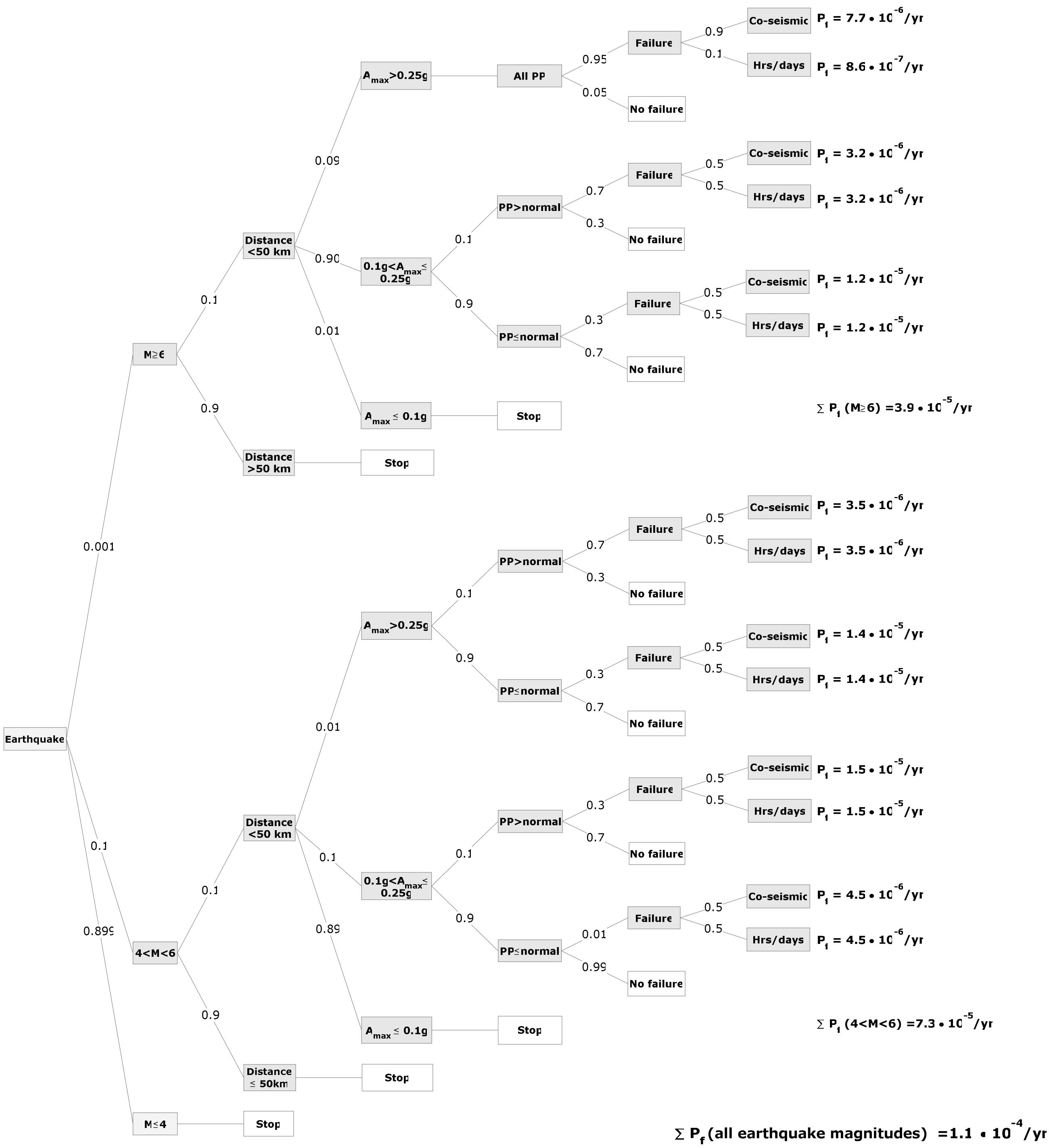

Figure 4 Event tree for earthquake-triggered rockslide (M, A_{max} = earthquake magnitude and maximum horizontal ground acceleration, PP = pore pressure)