1 INTRODUCTION

Large rock-slope failures are common events in the inner fjord areas of western Norway, and represent one of the most serious natural hazards in Norway. Rock avalanches and related tsunamis have caused serious disasters, and during the last 100 years more than 170 people have lost their lives in western Norway. The first stage in the hazard evaluation has been the registration of historical events and mapping of rock-avalanche deposits in selected regions. The spatial pattern has been revealed in order to set priority areas for identification of future unstable rock slopes.

Evaluation of rockslide hazard has been performed at different levels or scales. First, a regional hazard zonation has been performed based on the spatial distribution and temporal pattern of events. Secondly, a more detailed and quantitative zonation has been performed in some selected fjord areas. This is mainly based on the frequency, age and size of events in selected areas in Storfjorden, focused on seismic stratigraphy and swath bathymetry in the fjords to determine the size / frequency distribution of events. These data are then combined with the morphology of the fjords and tsunami-modeling results in order to distinguish different fjord sectors.

There is a large need in the society for quantification of hazard, especially when the individual municipality is going to make priorities between a series of important tasks. The present paper focuses on
some of the new data from western Norway and how this can be used to evaluate and quantify hazard related to large rock avalanches and tsunamis.

A series of fjords have been mapped by swath bathymetry, and the sea-floor images show excellent examples of rock-avalanche deposits (Figure 2). These data together with seismic reflection data is the basis for the mapping of distribution of events (Figure 3). They also give a clue to the magnitude of events (run-out, extent and volume) and also the chronology. In addition to seismic stratigraphy, also radiocarbon dating, exposure dating and relative sea-level correlations have been used to investigate the temporal pattern (Blikra et al., 2005).

2 MAPPING AND DATING ROCK-AVALANCHE EVENTS

The first phase of the hazard evaluation has been the registration of historical rock-avalanche and tsunami events and mapping of rock-avalanche deposits in selected regions. The spatial pattern has been revealed also in order to set priority areas for identification of potential large unstable rock slopes.

Geological mapping on land and in fjords has identified a high frequency of rock-slope failures throughout the last 10,000 years. In the Møre & Romsdal County in northern West Norway, almost 200 individual events have been mapped, with distinct concentrations in the inner fjord areas (Figure 1). Furthermore, some minor clusters also occur in the outer coastal parts. The largest concentration on land is found in Romsdalen, were more than 15 large rock avalanches cover almost the entire valley floor over a distance of 25 km. In Tafjorden, more than 10 rock-avalanche deposits have been mapped in the fjord covering a distance of less than 7 km.

3 TSUNAMI MODELLING

Wave formation and propagation due to rock-avalanches are a complex phenomenon that may be divided into four parts: rock-avalanche dynamics, energy transfer from rock-avalanche motion to water motion, wave propagation in open water, and wave run-up along the shores.

Waves generated by rock-avalanches depend upon the volume, the shape (frontal area), the permeability, and the dynamics of the sliding masses, as well as the water depth of the reservoir.

The waves can be classified as long waves if most of the energy transferred from the rock-avalanche to water motion is distributed on waves...
with typical wavelength several times larger than the characteristic water depth. From this assumption it follows that the particle motion is approximately uniform over the entire water column.

Figure 4. Calculated tsunami 50 s (A) and 290 s (B) after a possible 6 million m$^3$ rockslide has reached the fjord below Åkneset (NGI, 1996).

Outside the wave generation area, the characteristic maximum surface elevation of the waves is normally much less than the characteristic water depth. Hence, the waves can most often be considered linear except during the run-up part.

Although non-linear effects in most cases will be pronounced for a rock-avalanche generated tsunami, simulations of tsunamis generated by rock-avalanches in fjords have found to give reasonable results.

Harbitz et al. (1993) simulated the 1934 Tafjord tsunami using a linear long-wave model for tsunami generation and propagation. The model results revealed wave energy trapping due to the fjord geometry. This causes standing wave oscillations in accordance with the observations.

The same model has also been used to predict waves generated by potential rock-avalanches from Åkneset into Sunnylvsfjorden (NGI, 1992; 1996), Figure 4, and from Hegguraksla into Tafjorden (NGI, 2003), and by mapped events from Langflåa/Grautnibba into Geirangerfjorden (NGI, 2003), figure 5.

4 QUANTIFICATION OF HAZARD

Evaluation of rock-avalanche hazard has been performed at different levels or scales. First, a regional map is produced based on the spatial distribution and temporal pattern of events (Figure 1). Secondly, a more detailed and quantitative zonation has been performed in a selected fjord area. This is mainly based on the frequency, age and size of events in defined areas. In Storfjorden this has been focused on seismic stratigraphy in the fjords to determine the size/frequency distribution of events (see figure 2 and 3). The Storfjorden area in Møre & Romsdal is one of the high-risk areas related to such disasters, including villages as Stranda, Hellesylt, Geiranger, Norddal and Tafjord (Figure 1).
Figure 5: Perspective view of simulated wave structure 20 s after slide impact of the Grautnibba/Langflåa slide in Geirangerfjorden (NGI, 2003). See location of the area in figure 6.

Figure 6. The distribution and volume estimates of rock avalanches in the Storfjorden area, see localization in figure 1. The numbers refer to the defined fjord sectors used in the hazard evaluation. Inner frames show location of areas in figure 4 and 5.

Figure 7. The diagrams show the number of rock-avalanche events and the volume distribution in the entire Storfjorden (upper) and in Tafjorden (lower). The Tafjorden area is fjord sector 1 shown in figure 6.
The mapping of rock-avalanche events in the Storfjorden area (Figure 6 and 7) shows a total number of 59 individual events larger than 0.5 million m$^3$. This is a minimum amount, as some of the larger deposits may constitute several individual events (e.g. the largest event in figure 2). Half of these events are larger than 1 million m$^3$ (Figure 7). In the Tafjord basin (right-hand side in figure 6), 13 individual events have been found (Figure 6 and 7).

Based on the fjord morphology, the distribution of rock-avalanche events and the tsunami modeling results, the Storfjorden area have been divided into 6 separated fjord sectors (Figure 6). Based on the minimum frequency of mapped events in these sectors and the time since the deglaciation (10-12 000 years), an annual probability has been estimated (Figure 8). Large parts of the fjord area have an annual probability, which is larger than 1 event each 1000 years. This annual probability is the safety demand for living houses in Norwegian regulations. For other buildings like industry, schools and hotels, there are even stronger regulations. These regulations are meant for "normal" mass movements like snow avalanches, debris flows and rockfalls, and the hazard related to large rock avalanches and tsunamis has not been taken into account when these regulations were established. The obvious problems with large rock avalanches and related tsunamis are their enormous consequences. This means also that the risk is very high although the hazard may be relatively low. The weakness with the Norwegian regulations is thus related to the fact that they are mainly based on probability and not on risk.

It has to be emphasized that the quantitative hazard map proposed here is only a first approximation, but will already now be important for the municipalities along the fjords in connection with aerial planning and specifically how they want to develop the villages and the infrastructure along the fjords. This first quantitative assumption is also highly valuable in order to evaluate the probability of failures related to specific unstable rock-slope failures. For example, this hazard information has been an important argument for the priority of detailed investigations and plans for continuous monitoring at the Åknes slide in Sunnøyfjorden (Figure 9, see locality in figure 1 and 8). The preliminary results show that the potential unstable slide area covers about 600 x 1300 m ($780,000 \text{ m}^2$). The geometry and structure of the failure is complex, and the instable area seems to be composed of several individual blocks. Based on the relatively frequent slide events documented in the fjord areas, it has been estimated that a flank collapse of the Åknes failure in the order of 1-8 million m$^3$ may have an annual probability of less than 1 event/1000 years.

Figure 8. Hazard zones for tsunamis generated by rock-avalanche events larger than 1 million Storfjorden area in Møre & Romsdal county (annual probability). See location of area in figure 1.

Figure 9. The upper part of the rock-slope failure at Åknes in Sunnøyfjorden showing the open clefts in the southwestern part were the fracture is widest (NGU, 2004). The view covers a length of about 250 meters of the 600 m long upper zone of fractures. A graben structure is located in the upper left side. Continuous monitoring by use of extensometers in the area to the right demonstrates movements of 3-4 cm/year. See locality in Figure 1 and 8.
5 CONCLUSIONS

A first approximation to a quantification of hazard level for large rock avalanches and related tsunamis has been performed in Storfjorden in Møre and Romsdal County. This has been based on historical data and geological mapping including spatial distribution of individual events, some temporal data (ages) and estimates of rock-avalanche volumes. The specific hazard zonation has been done taking the fjord morphology and tsunami-modeling results into account. The results demonstrate that the annual probability exceeds 1-event/1000 years in large portions of the fjord system. These data is important for the municipalities along the fjords for how they want to develop the villages and the infrastructure along the fjords. It is also highly valuable for the priority of detailed investigations and continuous monitoring of specific instable rock-slope failures.

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7 REFERENCES


