Lakes at risk: A bottom-up approach to rock slide hazard assessment

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Abstract. In this study we describe a methodology that was developed for an initial evaluation of topographic rock slide threat to a set of lakes. Analysing the potential intersection between rock slides and water bodies is important for the assessment of tsunami hazard. The method relies on two input datasets only: a digital elevation model (DEM) and a map of target features (lakes). An intermediate result of the analysis is a surface where the value at each point is the mobility required for a slide released at that point to reach its candidate lake. This mobility surface can be used to generate indices for topographic rock slide potential for each lake. The mobility surface may also serve as a useful tool for further analysis of rock slide hazard to lakes in a given area. For example it can be used for definition of additional data needs and as a guide during planning and carrying out field campaigns.

Introduction

Historical records indicate that we should expect 2-3 large rock slides in Norway over the next century. Such events pose a large threat to human life and the built environment. Rock slides may be especially devastating when plunging into a lake or fjord. During the 20th century we experienced three such events in Norway (Loen in 1905 and 1936, Tafjord in 1934) where the consequent tsunamis caused a total loss of 175 lives. Clearly a detailed study of rock slide threat to all lakes and fjords in Norway is desirable, but such a study will require a huge amount of resources and in a country with more than 200.000 lakes and 25.000 km of coastline it may be difficult to decide where to begin.

In this paper we suggest a method for calculation of topographic rock slide potential to a set of lakes. An index is calculated for each lake that indicates the rock slide threat based on its topographical setting alone. The index should not be interpreted as a measure of rock slide susceptibility, but is merely meant as an indication of which lakes that have a topographical setting that favours tsunami generating rock slides. This can then be used together with ancillary information to focus further research. The method also defines which areas around a given lake that may serve as potential release areas due to their topographic setting, and the mobility required for a slide to reach the lake if released there. This "mobility surface" effectively illustrates the maximum spatial extent of the problem in an area and can e.g. be used to focus the collection of additional data.

Both the method and the results from applying it to all Norwegian lakes larger than 0.1 km^2 are described in more detail below.

Background

From a process point of view, regional modelling of slide related hazards can be divided into two main parts. First, potential release areas and their properties (potential slide volume) must be defined. The results of this analysis is then used as input when modelling run out zones for each individual slide, preferably with some measure of probability attached to it. The data requirements for defining potential release areas can be quite exhaustive, especially when the model is supposed to cover a large geographical area. Rock slide release is dependant on conditions such as geology, hydrology along with triggering factors such as extreme climatic events or earthquakes. The significance of each of the factors may vary considerably between different locations and most often the required data are not available on a suitable format if they are available at all.

The problem can also be approached statistically by establishing a statistical relationship between known rock slides and a set of relevant factors. But as in the above case, the problem of acquiring relevant data over the whole study area may be too exhausting. In addition land slide inventories are often sparse and incomplete and do not cover the whole area of interest. Therefore, even if the model proves to be valid within the area where it was calibrated, it may perform poorly when transferred to a new area.

Considering the above it may currently seem unfeasible to build a regional model of rock-slide hazard that is generally applicable for all of Norway. In many cases, however, we are concerned about the rock-slide risk to a given set of geographical features. If we can define the features of concern beforehand we may limit the problem of defining release areas dramatically using a bottom-up approach. In our case we are concerned about rock slides that may generate a destructive tsunami in a lake. It may therefore be sensible to use the lakes themselves as a starting point and evaluate the conditions around each lake. The only relevant dataset available on a national scale is a raster based digital elevation model (DEM). The model must therefore be dependant solely on that dataset as input.

The first question we may ask is whether or not a rock slide may hit the lake at all. Basic physical laws will prohibit a slide from being released at slopes below a certain angle so the potential release cells around a lake can be defined by thresholding the slope. If we find that no such steep slopes exist in the lake's surroundings we can exclude the lake from further analysis. Otherwise we will have to evaluate the lake surroundings further.

For any point around the lake, the horizontal distance (L) and the vertical distance (H) to the lake can be calculated. The ratio between H and L is often used as a measure of a slide's mobility. Thus the calculation of H/L for each cell yields a "mobility surface" where the value at each cell is the mobility required for a slide to reach the lake if released there. Even though the dynamics of rock slides are extremely complex it has been shown that there is a fairly robust statistical relationship between rock slide volume (V) and mobility (e.g. Scheidegger, 1973). This relationship is shown in equation 1.

$$10\log(h/l) = -0.15666*10\log(V)+0.62419 \qquad \mathbf{(1)}$$

Figure 1 illustrates that there is a fairly good agreement between this modelled relationship and a number of known Norwegian rock slides. Thus we can use this relationship along with the mobility surface to approximate a minimum volume required for a slide to reach the lake if released at any cell (see figure 2). In areas that have a high H/L ratio even a small rock slide may generate a destructive tsunami if released, while in areas with a low H/L ratio only a very large slide will have mobility high enough to reach the lake.

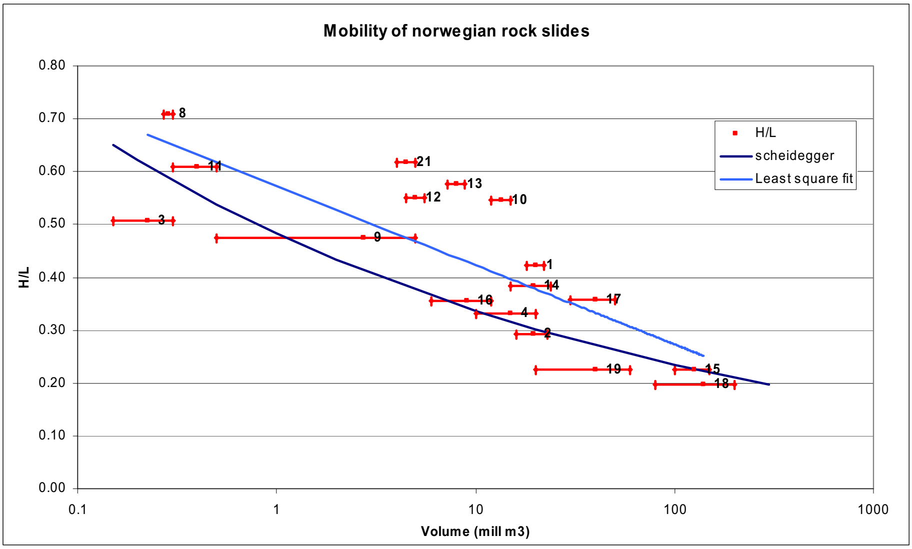

Fig. 1. Slide mobility as a function of volume for 17 known Norwegian rock slides

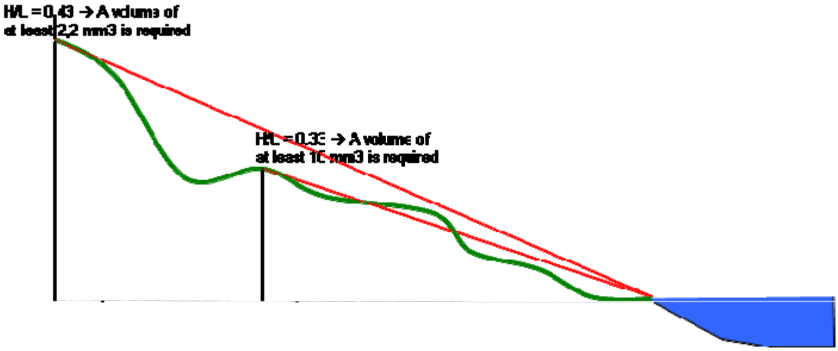

Fig. 2. Example of required volumes for two H/L values

The a priori probability of a small rock slide event to occur is much higher than the probability of a large event. Several studies have shown that the magnitude frequency distribution of events such as rock slides follow a power law distribution (Guzzetti et al, 2002; Malamud et al 2004). Such a distribution can be written as

$$N(V) \sim V^{-b} \tag{2}$$

where N(V) is the number of slides per time interval with a volume larger than V. By compiling information from a number of landslide inventories Hergarten (2003) found that the exponent b for landslides typically ranges between 1.5 and 2.4.

Since we are able to calculate the minimum volume required for a rock slide to reach the lake from any point we can use equation 2 to convert this to a probability of a tsunami generating event to occur in one point, relative to another point. The higher the exponent, b, the larger will the difference in probability be for small versus large slides.

Converting the volume surface to a probability surface allows us to summarize the probabilities within the lake's surroundings and use that value as a measure of topographic rock slide potential for the candidate lake. This value is now comparable between lakes and is dependent on the area with a slope above a given value and each point's position relative to its candidate lake.

Method

The method relies only on a DEM and a digital map of the lakes under investigation. First a relationship between each cell in the DEM and its candidate lake is established. Then the potential slide height (H) and slide length (L) can be calculated for each cell. The ratio between the two yields a surface of required mobility which again can be transformed to a surface of required volume using the mobility-volume relationship described in Scheidegger (1973). We can then use power-law relationship between volume and frequency to estimate a relative probability for a tsunami generating rock slide to be initiated from each cell. The sum of probabilities in all the cells around a given lake can be then used as a measure of topographic rock slide potential for that lake.

The method is based on a set of simple assumptions:

1. Potential release areas must be located within the target feature's watershed
2. Rock slides will follow local drainage, or flow direction
3. Rock slides will only be released in areas with slope above certain angle (30°)
4. There is a quantifiable relationship between rock slide volume and mobility
5. The frequency-magnitude distribution of rock slides follows a power law relation

With only a cell based DEM and a map of the lake polygons we can use GIS methods to quantify the topographical potential for rock slide risk around each lake using the four simple criteria above. First each lake's potential release area is narrowed down to its local watershed, thus creating a one-to-one relationship between each cell and its candidate feature/target. Then the elevation difference between each cell and its lake can be saved to a new layer (H), as well as the distance between the cell and the lake along the path of steepest descent (L). The mobility (height over length ratio) required for a slide released at any cell in order to reach the target can now be expressed as H/L. This yields a mobility surface where the value at each point is the mobility required for a slide released at that point to reach its candidate lake (see figure 4). According to assumption 3 all cells with slope below 30° can be discarded. This slope threshold is supported by empirical studies of known rock slides in Norway (Romstad et al, 2006). It can also be argued that this value is conservative as it is smaller than the angle of internal friction for most rock types.

The mobility surface can then be converted to a surface of required volumes using the volume-mobility relation from equation 1. A conservative estimate of the minimum slide volume required to generate a destructive tsunami is about 5000m^3. Therefore cells values lower than 5000 were adjusted up to this minimum volume. Now the relative probability of the release of a tsunami generating slide from each cell could be calculated using equation 2. We used an exponent (b) of 1.5 which is in the lower range of common values. Thus it is a conservative value in the sense that it is least likely to overestimate the probabilities of areas that only require small volumes compared to those which require high volumes. All the probabilities within each watershed were then summed together and saved in a database together with their candidate lake-id, thus making further analysis of the results possible.

All processing was done in ArcGIS 9.2, the model was run for one municipality at the time and each run took from 1-5 minutes on a 4 year old PC. This means that the model is by no means fast, but it was still feasible to run it over a large area such as Norway within a reasonable time.

Results and discussion

The results of the analysis showed that out of the about 19.000 lakes investigated 11.600 had a potential slide threat. The topographic rock slide potential score for these lakes ranged between ~0 and 0.025. For simplicity the scores were scaled to a fraction of the highest value yielding an index between ~0 and 1.

The distribution of index values among the 11.600 lakes were heavily skewed with 55% of the lakes having a value less than 0.001, 90% a value less than 0.01 and less than 1% having a value above 0.1.

Table 1. Distribution of index values among the lakes with rock slide potential

Percent of lakes	Scaled index value
55%	<0.001
90%	<0.01
99.3	<0.1

The frequency distribution of index values indicates that the topographic rock slide potential is negligible for a large share of the lakes, but still one must remember that the index is based on the topographic potential alone so categorically disregarding the potential for any of the lakes, however small the index value, is problematic. For this reason a sorted list of the lakes with the highest score is not presented in this paper, but the location of the top most 100 lakes are shown in figure 2. It is also interesting to note that the lake Lovatnet, where the two catastrophic events occurred in 1905 and 1936, are among the top 10 lakes on the list.

Figure 3 shows the location of the 100 lakes with the highest topographic rock slide potential. Not surprisingly most lakes are situated in the western parts of the country together with some areas in the north where the relief is high. The topographic rock slide potential could also be aggregated over municipalities. This is also shown in figure 2. This spatial pattern here is in agreement with the top 100 lake distribution.

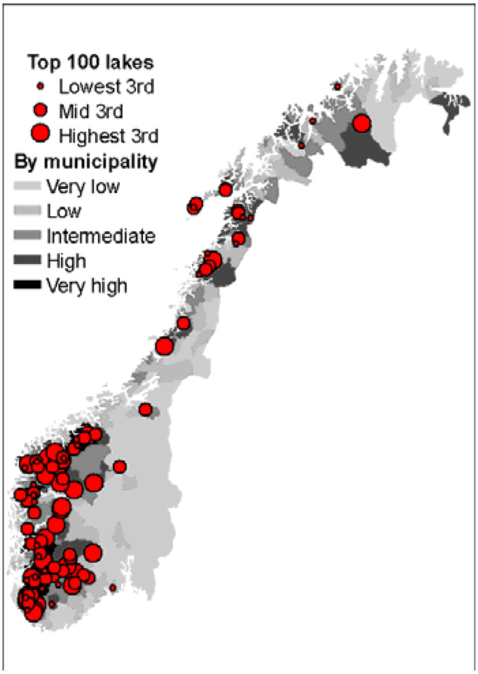

Fig. 3. Location of the 100 lakes with the highest topographic rock slide potential and the topographic rock slide potential by municipality.

The index values for individual lakes may be useful when carrying out further studies of tsunami risk in Norwegian lakes. It can be used as tool to point out lakes in an area that topographically are particularly exposed to rock slides and thus should be investigated further. The intermediate results of the analysis can also provide useful qualitative information about the topographic conditions in a specific area with regards to rock slide threat. The mobility surface shown in figure 4 may e.g. be used to pinpoint where field studies should be carried out, and during a field campaign it may be used to eliminate areas that are susceptible to failure, but where the potential slide volume would be too small to reach the lake if a failure took place. It can also be used to indicate where the most probable points of impacts would be along the shoreline of a lake. This information can again be used for more detailed modelling of the tsunami itself.

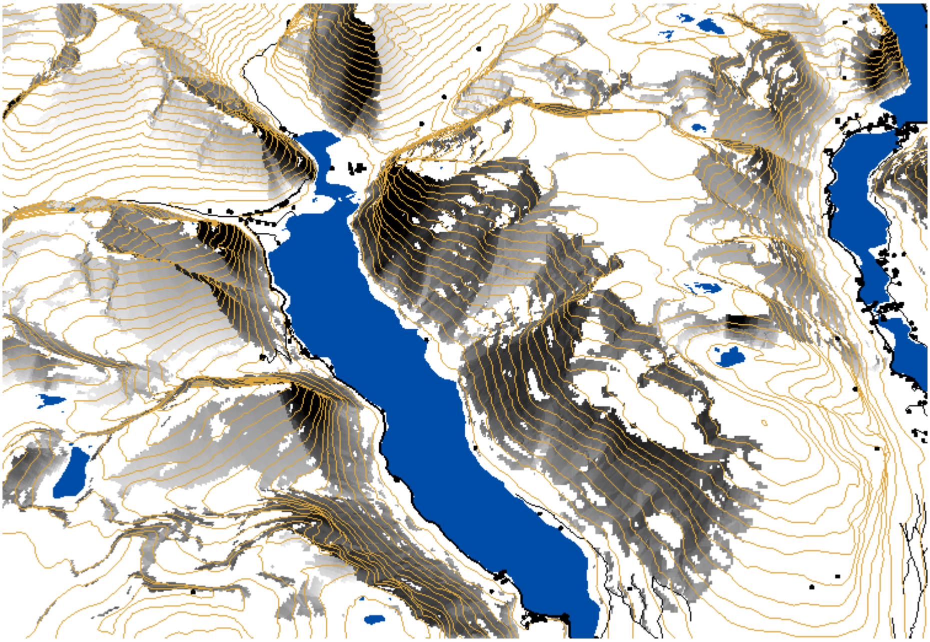

Fig. 4. 3D view of the surface of required mobility for the area around Lovatnet, Stryn, Norway. Dark values means that even slides with low mobility may reach the lake. Roads and buildings are also shown in the map.

Even though a detailed evaluation of the results of the model has not been carried out yet, the prospects for this type of analysis look promising. The next step should be to validate the intermediate modelling steps against areas that have been investigated thoroughly in the field.

The assumption that slides follow the steepest downslope path is clearly a simplification of the slide process. Especially after the slides have gained momentum their path may deviate significantly from the direction of steepest descent. But for the case of lakes it will generally lead to a worst case scenario result since lakes are located in local depressions and the slide paths thus rarely passes by without intersecting them.

The method was specifically designed to analyse the rock slide threat to lakes, but it could also be used to investigate the threat to other features. Especially it could be applied to linear features such as segments of roads or rivers with only minor modifications. If this is done, however, care must be taken when defining the relationship between the feature of interest and its potential release cells. For lakes this could be simplified by calculating the watershed, but this approach may not be valid for other types of features.

Conclusion

In this paper we described a bottom-up approach to rock slide hazard assessment to all Norwegian lakes. The analysis resulted in a topographic rock slide potential score for each lake in the area of analysis. Even though the accurate score each lake received should be interpreted with caution, the distribution of score values showed that we are able to make a clear distinction between lakes with a high vs. lakes with a low score. The results also showed a clustering of threatened lakes in parts of western Norway as well as some locations in northern Norway. This makes the results useful as a tool for focusing further studies to regions or specific lakes that received high scores. In addition the intermediate results of the model can be helpful when carrying out more detailed studies in a specific area. For example can the surface of mobility be used to guide field campaigns, and further processing of the potential release areas can serve as input to modelling of tsunami movement in the lake.

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