Geophysical Research Abstracts
Vol. 16, EGU2014-11286, 2014
EGU General Assembly 2014

Consequence assessment of large rock slope failures in Norway

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Steep glacially carved valleys and fjords in Norway are prone to many landslide types, including large rockslides, rockfalls, and debris flows. Large rockslides and their secondary effects (rockslide-triggered displacement waves, inundation behind landslide dams and outburst floods from failure of landslide dams) pose a significant hazard to the population living in the valleys and along the fjords shoreline. The Geological Survey of Norway performs systematic mapping of unstable rock slopes in Norway and has detected more than 230 unstable slopes with significant postglacial deformation.

This large number necessitates prioritisation of follow-up activities, such as more detailed investigations, periodic displacement measurements, continuous monitoring and early-warning systems. Prioritisation is achieved through a hazard and risk classification system, which has been developed by a panel of international and Norwegian experts (www.ngu.no/en-gb/hm/Publications/Reports/2012/2012-029). The risk classification system combines a qualitative hazard assessment with a consequences assessment focusing on potential life losses. The hazard assessment is based on a series of nine geomorphological, engineering geological and structural criteria, as well as displacement rates, past events and other signs of activity.

We present a method for consequence assessment comprising four main steps: 1. computation of the volume of the unstable rock slope; 2. run-out assessment based on the volume-dependent angle of reach (Fahrböschung) or detailed numerical run-out modelling; 3. assessment of possible displacement wave propagation and run-up based on empirical relations or modelling in 2D or 3D; and 4. estimation of the number of persons exposed to rock avalanches or displacement waves.

Volume computation of an unstable rock slope is based on the sloping local base level technique, which uses a digital elevation model to create a second-order curved surface between the mapped extent of the unstable rock slope. This surface represents the possible basal sliding surface of an unstable rock slope. The elevation difference between this surface and the topographic surface estimates the volume of the unstable rock slope. A tool has been developed for the present study to adapt the curvature parameters of the computed surface to local geological and structural conditions.

The obtained volume is then used to define the angle of reach of a possible rock avalanche from the unstable rock slope by using empirical derived values of angle of reach vs. volume relations. Run-out area is calculated using FlowR; the software is widely used for run-out assessment of debris flows and is adapted here for assessment of rock avalanches, including their potential to ascend opposing slopes. Under certain conditions, more sophisticated and complex numerical run-out models are also used.

For rock avalanches with potential to reach a fjord or a lake the propagation and run-up area of triggered displacement waves is assessed. Empirical relations of wave run-up height as a function of rock avalanche volume and distance from impact location are derived from a national and international inventory of landslide-triggered displacement waves. These empirical relations are used in first-level hazard assessment and where necessary, followed by 2D or 3D displacement wave modelling.

Finally, the population exposed in the rock avalanche run-out area and in the run-up area of a possible displacement wave is assessed taking into account different population groups: inhabitants, persons in critical infrastructure (hospitals and other emergency services), persons in schools and kindergartens, persons at work or in shops, tourists, persons on ferries and so on. Exposure levels are defined for each population group and vulnerability values are set for the rock avalanche run-out area (100%) and the run-up area of a possible displacement wave (70%). Finally, the total number of persons within the hazard area is calculated taking into account exposure and vulnerability.

The method for consequence assessment is currently tested through several case studies in Norway and, thereafter, applied to all unstable rock slopes in the country to assess their risk level. Follow-up activities (detailed investigations, periodic displacement measurements or continuous monitoring and early-warning systems) can then be prioritized based on the risk level and with a standard approach for whole Norway.