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Dynamic distinct-element analysis of the 800 m high Åknes rock slope

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ABSTRACT

The seismic stability of the Åknes rock slope, western Norway, was analysed by using the distinct element code UDEC (Universal Distinct Element Code). The slope poses a threat to the region as a sudden failure may cause a destructive tsunami in the fjord. The dynamic input was based on earthquakes with return periods of 100 and 1000 years, and in most models the input shear wave was a harmonic function (sine wave). Models with depths of the sliding surface up to 200 m and with ground water conditions derived from site investigations were analysed, as well as models with ground water conditions assumed from possible future draining of the slope. The analyses indicate that an earthquake with a return period of 1000 years is likely to trigger sliding to great depth in the slope at the present ground water conditions and that the slope will be stable if it is drained. The analyses also indicate that sliding is not likely to be triggered by an earthquake with a return period of 100 years at the present ground water conditions.

1. Introduction

Earthquakes are one of the main triggering factors for landslides. Investigations have been conducted on the types of ground failures induced by earthquakes, statistical distribution of landslides, the relations between the magnitude of earthquakes and epicentral distance to the fall or slide, areas affected by earthquakes of different magnitudes, the relation between earthquake magnitudes and volumes of landslides and the significance of slope angles [1–11]. The relations derived in the work mentioned above are useful for estimating landslide hazard on a regional scale. For seismic stability of specific slopes, the Newmark sliding block analysis [12,13] is widely used. This method also represents a useful and practical tool for evaluation of earthquake-induced landslide hazard [11,14].

The stability of rock slopes subjected to seismic effects can be analysed using appropriate numerical techniques. Several researchers have attempted using continuum (finite element) and discontinuum (distinct-element) techniques to study the behaviour of rock slopes subjected to dynamic loading. Some continuum codes can consider the effect of pseudo-static earthquake loading by applying a seismic body to each finite element in the model. Such approaches are useful for analysis of underground structures but are considered inadequate for dynamic analysis of rock slopes. In the pseudo-static analysis approach, the ground deformations and/or inertial forces are imposed as static loads and the rock-structure interaction does not include dynamic or wave propagation effects.

When the stability of the rock slope is controlled by movement of joint-bounded blocks, the use of discontinuum discrete-element codes, which allow one to conduct fully dynamic analyses under plane-strain conditions, are more appropriate than the continuum codes. Eberhardt and Stead [15] and Stead et al. [16] provide an example of dynamic distinct-element analysis of a natural rock slope in western Canada. In that case, the dynamic input was introduced along the bottom boundary of the model as a harmonic stress function (sine wave) of a specified amplitude, frequency and duration. The model considered an initially stable slope subjected to an earthquake, resulting in yielding and tensile failure of intact rock at the slope's toe. Bhasin and Kaynia [17] illustrated the application of dynamic distinct-element analysis to a 700 m high Norwegian rock slope to estimate the potential rock volumes associated with a potential catastrophic rock failure. Liu et al. [18] simulated the dynamic response of a jointed rock slope subject to effects of an explosion using the distinct element code UDEC (Universal Distinct Element Code) [19]. Their results showed that the computed velocity history of the toe of the slope agrees well with that of observations. They concluded that UDEC can be used effectively to simulate the dynamic response of jointed rock slopes.

In this study the stability of the Åknes rock slope, western Norway (Fig. 1), when subjected to earthquakes with return periods of 100 and 1000 years, was investigated using UDEC. None

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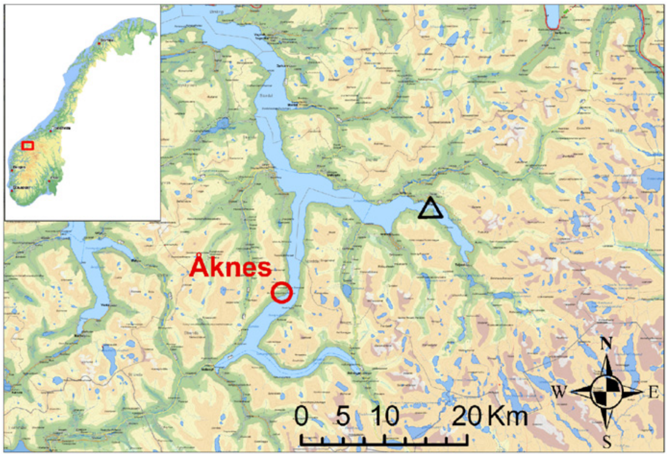

Fig. 1. Map of Storfjorden showing the location of the Åknes rock slope and the site for earthquake hazard analysis.

of the documented historical (about year 1700 to present) large rock slides/rock avalanches in Norway have been triggered by earthquakes; with the possible exception of the Tjelle rock slide of $15 \times 10^6\,m^3$ which occurred in 1756. Rock falls were reported for the M5.8 Mo i Rana earthquake in 1819. For older events Blikra et al. [20] include the possibility that one or more large earthquake(s) may have caused some of the observed clusters of rock avalanches.

2. Description of the Åknes rock slope

Åknes is a rock slope on the Storfjord in Norway (Fig. 1). Massive slides have occurred in the region in historical times, e.g., the Loen and Tafjord disasters [21]. Bathymetric surveys of the fjord bottom deposits show that numerous and gigantic rockslides have occurred in the past [20]. About 650,000 m^2 of the Åknes rock slope is unstable (Fig. 2) and a sudden failure may trigger a destructive tsunami in the fjord [22]. The dip of the slope is about 35° between the top scarp/upper tension crack and the fjord. The rock mass consists of biotitic, granitic and dioritic gneisses. Three distinct fracture sets have been identified: fractures parallel to the foliation and sub-parallel to the slope surface (strike about E–W and dip to the south) and sub-vertical fractures with strike directions approximately N–S and E–W, respectively [23]. The fractures with strike directions approximately N–S are orientated sub-parallel to the dip direction of the slope and act as lateral releases. The E–W fractures are orientated about perpendicular to the dip direction of the slope. Ganerød et al. [23] proposed a geological model for the rock slope, and details about the geology of the site are given in their article. Widening of the upper tension crack has been recognised since the late 1950s/early 1960s. Monitoring of the upper tension crack started in 1986 [24,25]. Today, movements at the slope surface and movements in the sub-surface are monitored by various techniques as an early warning system has been implemented [26]. The instability is caused mainly by the orientation of the foliation of the gneisses, which is sub-parallel to the slope surface [27,28].

3. Model description

Kveldsvik et al. [22] performed static stability analyses on a number of models of the Åknes rock slope. They used the UDEC, and varied the fracture geometry, fracture friction and ground water conditions based on site specific data. One of the

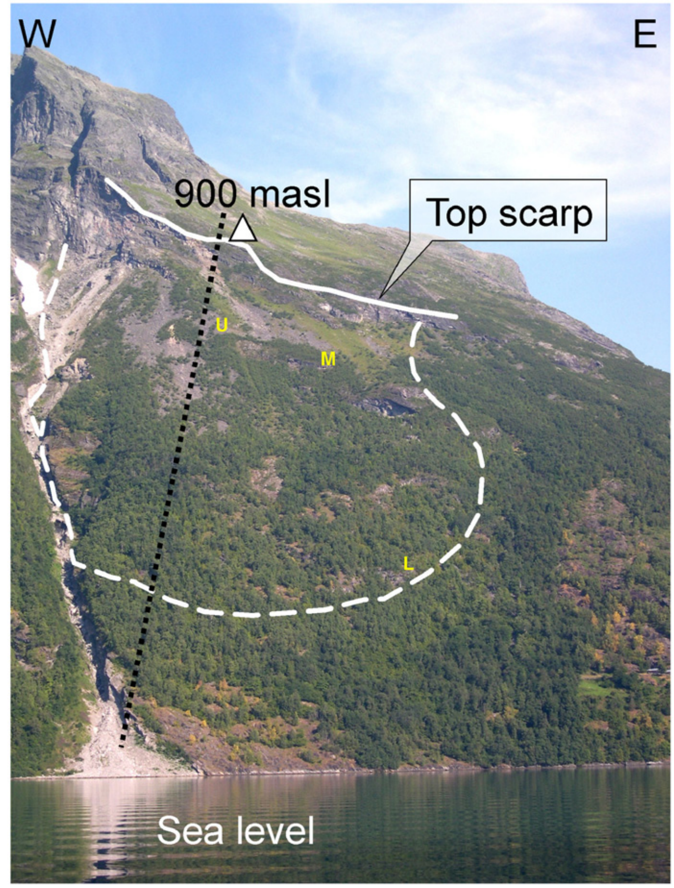

Fig. 2. Overview of the Åknes rock slope. The white lines indicate the contour of the unstable area (slightly modified after [38]). The length of the "top scarp"/upper crack is about 800 m. U, M, L: upper, middle and lower borehole sites. Black dotted line: profile used in the numerical modelling.

conclusions was that the static models that were unstable to great depths agreed better with shear strength parameters derived from an earlier study [28] than the models that were unstable to smaller depths. Later, after moving the installations for measuring displacements in the upper borehole to a greater depth interval (83–133 m), displacements have been measured at depths 87, 97, 107 and 120 m. This study considers two models in which the maximum depths of instability are, respectively, 110 and 200 m.

Kveldsvik et al. [22] defined "limiting" friction angles for the various numerical models, i.e., the friction angles that were just large enough to result in equilibrium in the numerical model. In most models the friction angles were made dependent on the estimated effective normal stresses based on the Barton–Bandis shear strength criterion [29,30]. Stress-dependent friction angles were used in all models in this study (Fig. 3). Details of the numerical models and the geotechnical data are given in [22,28].

The "limiting" friction angles defined above imply that the available friction is fully mobilised in the most critical part of the numerical models. Exposing the numerical models with "limiting" friction angles derived in Kveldsvik et al. [22] would result in sliding, even for very small earthquakes. The numerical models used in this study represent a rock slope where available friction is not fully mobilised and the static factor of safety is somewhat higher than 1. This was achieved by using higher frictions angles than the limiting values derived in [22]. The higher friction angles correspond to a higher joint roughness coefficient (JRC). Fig. 3