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Thermally vs. seismically induced block displacements in Masada rock slopes

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ABSTRACT

We compare thermally and seismically induced sliding mechanisms of blocks that are separated from the rock mass by a tension crack and slide along a frictional interface. The rock slopes of Masada Mountain, Israel, are used to demonstrate our approach. Crack displacement coupled with thermal fluctuations is measured in the West slope of the mountain during two years (2009–11). Physical and mechanical lab tests provide the assumed depth of penetration of the heating front during seasonal cycles of exposure as well as the thermal expansion coefficient of the rock mass. These, along with the shear stiffness of the sliding interface, allow us to quantify the expected thermally induced displacement rate of blocks in Masada, through a proposed wedging–ratcheting failure mechanism. A distinct block in the East slope of the mountain exhibiting a tension crack opening of 200 mm was monitored for displacement and temperature during a single seasonal cycle in 1998. Based on the assumed seismicity of the region and the known topographic site effect, along with the laboratory measured frictional resistance and shear stiffness of the sliding interface, we subject the mapped geometry of the block in the East face to simulated cycles of earthquake vibrations utilizing the numerical, discrete element, discontinuous deformation analysis (DDA) method. We find that for a time window of 5000 years, the observed 200 mm displacement of the East slope block is more likely to have been thermally, rather than seismically, controlled. This result implies that in climatic regions where the temperature amplitude over a seasonal cycle is sufficiently high, thermally induced displacements play an important role in rock slope erosion.

1. Introduction

Various environmentally induced mechanisms have been considered in an attempt to explain slope failures in rock masses along pre-existing discontinuities. High-magnitude earthquakes e.g. [1,2], pore pressure buildup in rock joints e.g. [3,4], and freezing and thawing of water in joints e.g. [5–7] have been suggested as trigger factors for landslides and rock avalanches. These suggested mechanisms fail to describe time-dependent, thermally controlled, sliding along discontinuities or opening of tensile fractures which may ultimately culminate in slope failure.

1.1. Thermal considerations in rock slope stability

Considering daily and seasonal temperature influences, many researchers have detected extremely slow, creep-like, slope displacements due to cyclic temperature changes in long-term monitoring surveys [8–13]. The motivation for some of these monitoring surveys was the preservation of cultural heritage sites around the world, for example in Slovakia [14], Japan [15], and Israel [16].

Gunzburger et al. [10], in their investigation of the Rochers de Valabres slope in the Southern Alps of France, found that daily surface temperature oscillations played an important preparatory role in rock fall events using a high-precision geodetic monitoring system and numerical modeling. They showed that daily temperature fluctuations may be responsible for generating irreversible displacements on some fractures. Nevertheless, they concluded that the monitoring of preparatory factors was not sufficient to predict eminent slope collapse. Mufundirwa et al. [12] monitored natural rock slope deformation due to thermal stresses across fractures in a chert rock mass. By a new method to minimize displacement proportional to temperature, they recovered the recognized displacement that has been related to reversible thermo-elastic response of the rock mass and the sensor and concluded that thermal fatigue predominantly caused permanent fracture deformations. Gischig et al. [8,9] demonstrated how thermo-mechanical effects can drive rock slope deformation at greater depths below the annual thermally active layer. They found that deformation and progressive rock slope failure can be driven solely by thermo-mechanical forcing.

Various researchers have suggested that daily and seasonal temperature fluctuations may generate thermally induced stresses sufficiently high to propagate pre-existing cracks in the rock mass [17]. Although the seasonal temperature front penetrates only

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a few meters into the rock mass, it may still have significant mechanical consequences in terms of displacements or stress changes far from the rock surface, especially for rock slopes with critically stressed discontinuities e.g. [8–10].

Watson et al. [13] utilized data obtained from an extensive instrumentation monitoring program at the Checkerboard Creek in British Columbia, Canada. Their monitoring record indicates a persistent annual displacement cycle that matches the thermal cycle, as recorded near the bedrock surface. Their numerical analysis indicates that the permanent displacement occurs along steeply dipping discontinuities which often intersect in the rock mass to form wedges. They showed that the thermal displacement occurs in response to reduction in effective stress during the cooling season.

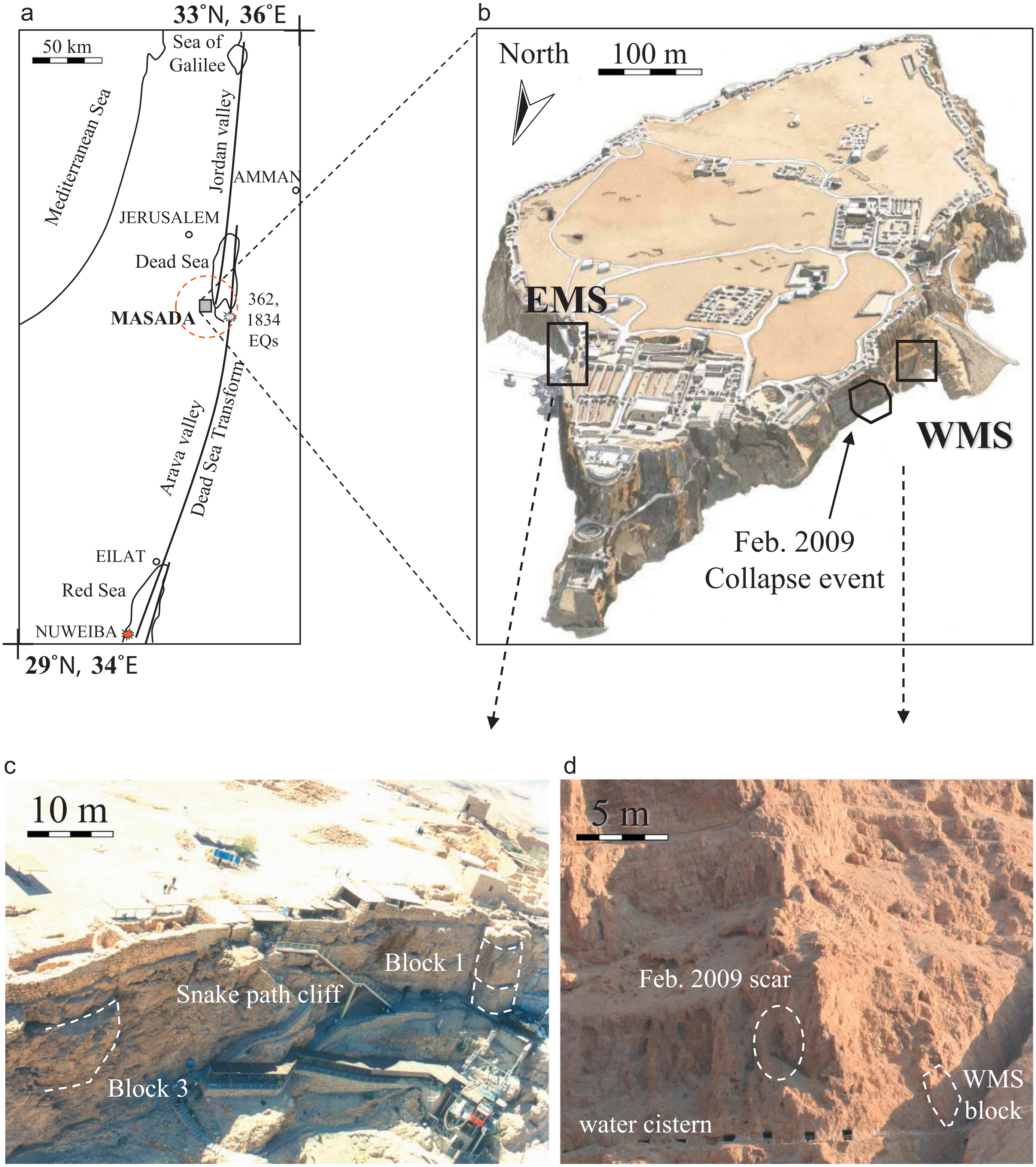

Fig. 1. Location maps: (a) Masada Mountain in the Western margins of the Dead Sea rift valley, (b) location of the monitoring stations (EMS=East Masada Station; WMS=West Masada Station), (c) monitored blocks in the "Snake Path" cliff (EMS), (d) collapsed block at WMS.