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THERMALLY VS. SEISMICALLY INDUCED BLOCK DISPLACEMENTS IN JOINTED ROCK SLOPES

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ABSTRACT

We explore two landslide triggering mechanisms that are associated with time-dependent, cyclic loading of the sliding interface. The first is shear strength degradation due to seismic shaking leading to velocity weakening of the sliding interface. We show how a block that is initially at a state of static limit equilibrium under constant gravitational load may undergo sliding at increasing velocities when subjected to cyclic vibrations and demonstrate, using shaking table experiments, how the observed shear strength degradation may lead to block run out. The second is sliding initiation due to cycles of seasonal heating and cooling of the jointed rock mass. We demonstrate, using field measurements, analytical and numerical approaches, how repeated cycles of heating and cooling may trigger block sliding along an inclined sliding plane via a thermally induced ratcheting mechanics in the sub vertical tension crack. We show that for Masada rock mass the thermal mechanism may lead to a faster sliding rate than the seismic mechanism for a given regional seismicity and climatic conditions for a time window of 5000 years when the shear strength of the sliding plane is considered constant over time. We therefore conclude that thermally induced sliding must be considered when studying the stability of rock slopes that are exposed to strong temperature changes between the seasons.

Key words: *landslides, seismic response, climatic response, rock slopes, DDA, shaking table*

INTRODUCTION

It is commonly assumed that large landslides in rock masses are triggered by a strength failure mechanism either within the body of the rock material in the case of weak rocks, or along a pre-existing sliding interfaces in the case of strong rocks. Therefore, typically a static limit equilibrium analysis is employed to study the stability of rock slopes and the shear strength parameters are assumed constant over time. In this paper we explore the long term stability of a potentially unstable rock slope by considering two, time dependent, weakening mechanisms. The first is velocity weakening of the shear strength of the sliding interface induced by repeated cycles of shaking which could be triggered by strong earthquakes. The second is accumulated displacements along a gently dipping sliding plane due to irreversible opening of a steeply dipping tension crack at the back of the sliding mass. We present a model for thermally induced ratcheting of the tension crack which leads to progressive displacement of the sliding block over time due to repeated seasonal temperature fluctuations. We show that for a seismically active region with high temperature gradients as the Dead Sea rift valley, the thermal mechanism may be more dominant than the seismic mechanism, provided that the friction angle along the sliding plane remains constant between earthquake episodes. We therefore conclude that the thermally induced ratcheting mechanism is a viable failure mechanism in rock slopes and it must be considered when assessing the overall stability of jointed rock slopes.

DYNAMIC BLOCK DISPLACEMENT

The dynamic displacement of a block on an inclined plane has been studied by Newmark (NEWMARK, 1965) and Goodman and Seed (GOODMAN & SEED, 1966) who showed that once the acceleration of the block exceeds the yield acceleration dynamic block displacement commences in a step wise fashion. In Figure 1 the dynamic displacement of a block resting on an inclined plane with a dip of 20 degrees and a friction angle of 30 degrees is plotted for three different methods of analysis, namely the classical Newmark's and Goodman and Seed solutions (referred to here as Newmark solution for brevity), a three dimensional analytical vector solution developed by Bakun-Mazor et al. (BAKUN-MAZOR *et alii*, 2012), and results obtained with the numerical 3D-DDA (SHI, 2001). The input motion is sinusoidal in direction parallel to the dip of the sliding plane and is shown as well.

Using the three dimensional generalization of the Newmark's approach the dynamic displacement of a wedge which rests on two inclined planes can be studied as well. In Fig. 2 the dynamic displacement of a wedge resting on two planes dipping to 52/063 and 53/296 and subjected to a sinusoidal input motion vector given by:

$$\bar{r} = [r_x \; r_y \; r_z] = [0 \quad 0.5g\sin(10t) \quad -g] \tag{1}$$

is plotted. The line of intersection of the two planes dips 30 degrees and the friction angle on both planes is 20 degrees.

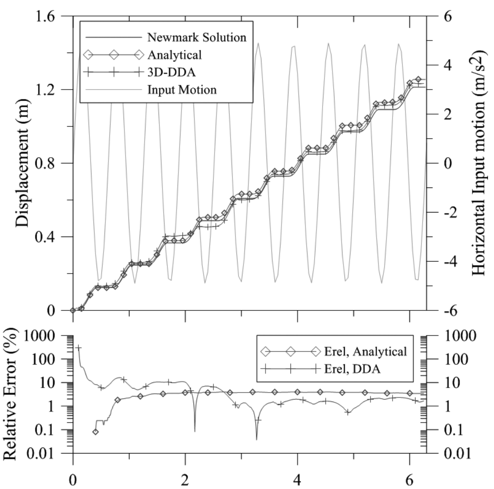

Fig. 1 - The typical step-wise dynamic displacement of a block subjected to sinusoidal input motion

To demonstrate the response of a wedge to a real earthquake the input motion is replaced with the Imperial Valley earthquake record as recorded at El Centro, California, and the resulting dynamic displacement of the wedge is shown in Fig. 3. The step wise block response to the dynamic excitation is clearly shown in Fig. 3 as well.

FRICTION ANGLE DEGRADATION INDUCED BY SHAKING

To further study the dynamic sliding of a wedge a physical model as shown in Fig. 4 was mounted on a

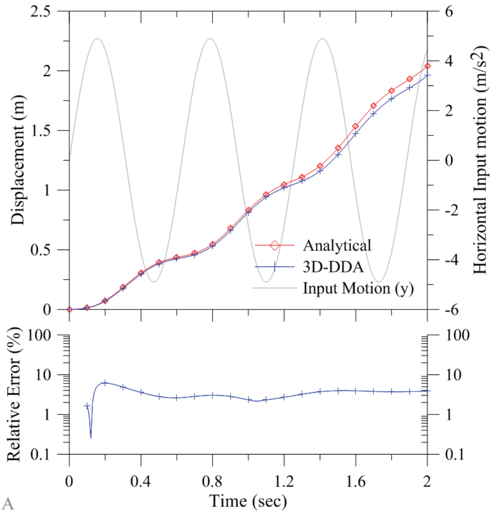

Fig. 2 - Dynamic displacement of a wedgesubjected to sinusoidal input motion

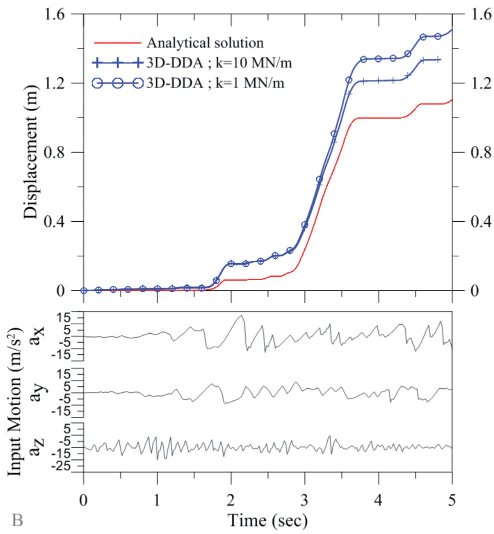

Fig. 3 - Dynamic displacement of a wedge subjected to the Imperial Valley earthquake (Lower panel) upscaled by a factor of 5

shaking table with a single degree of freedom aligned with the direction of the line of intersection of the two inclined planes. The shaking table assembly is shown in Fig. 5 and Fig. 6.

The concrete interface material was tested in a servo-controlled direct shear system where both normal and shear pistons were servo-controlled under either load or displacement control. Several velocity stepping tests were performed and it was established that the interface material clearly exhibits velocity weakening characteristics. An example of four velocity stepping segments obtained with the servo-controlled direct shear assembly is shown in Fig. 7.

Moreover, the tested concrete interface material clearly obeys the Coulomb-Mohr shear strength criterion when tested under a constant sliding velocity, but with increasing testing velocity the coefficient of friction clearly decreases (see Fig. 8).

When the interface was tested at much higher sliding velocities in the shaking table experiments the same velocity weakening behavior was observed, up to six orders of magnitude of velocity (see Fig. 9).

A very interesting phenomenon was observed however during many shaking table experiments. Once dynamic sliding was initiated, the classical step wise

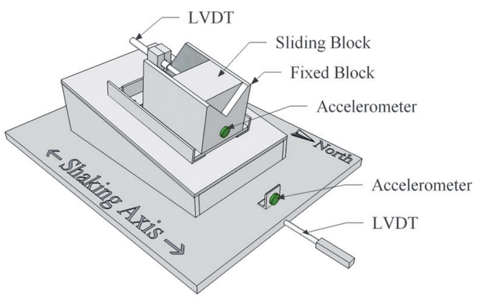

Fig. 4 - Physical model of a wedge which was mounted on a shaking table

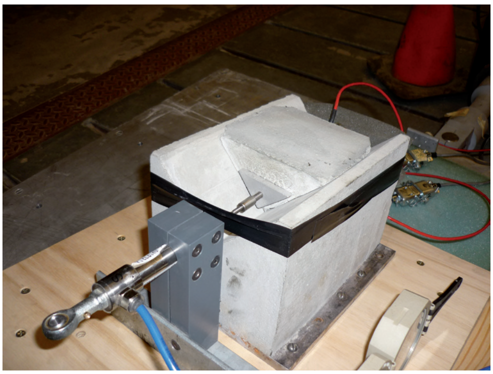

Fig. 5 - Shaking table assembly used in this research

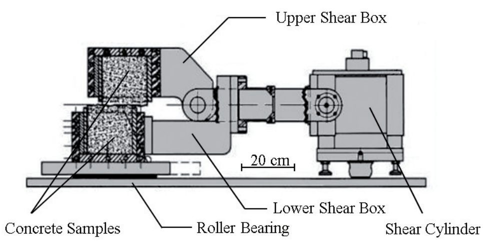

Fig. 6 - Direct shear assembly used in this research

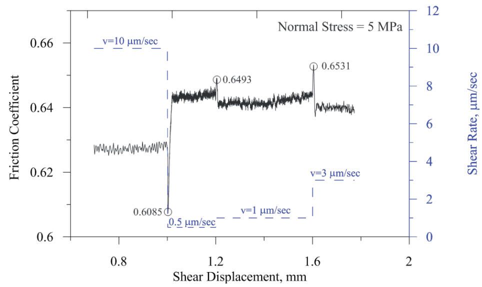

Fig. 7 - Results of velocity stepping tests obtained with the direct shear assembly

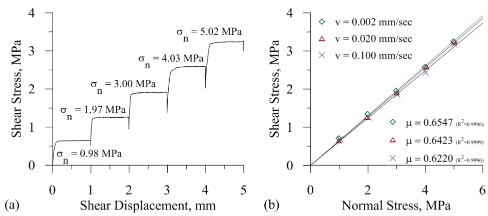

Fig. 8 - A) Example of a segment direct shear test with a constant imposed sliding velocity, B) Coulomb-Mohr failure envelopes for increasing levels of imposed sliding velocities

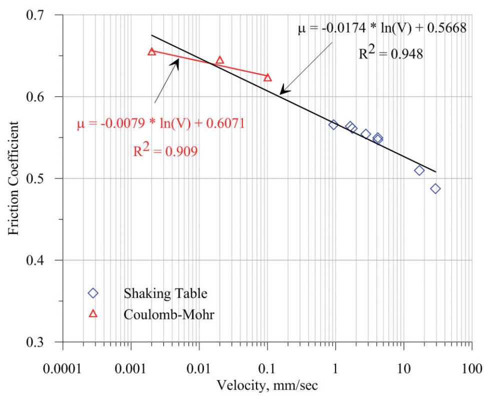

Fig. 9 - Velocity weakening of the tested interface from slow (direct shear) to high (shaking table) imposed sliding velocities

displacement was only observed up to a certain point, beyond which block run out was detected. An example of such an experimental output is shown in Fig. 10.

Inspection of Fig. 10 reveals that a friction angle degradation amounting to only 2.5 degrees was sufficient to prompt block run out. There are two possible sources for the observed friction degradation: either due to accumulated displacement, as originally proposed by Goodman and Seed (Goodman & Seed, 1966), or due to sliding velocity, as originally proposed by Dieterich (Dieterich, 1972). Either way, our experimental results clearly suggest that frictional degradation does take place as a consequence of dynamic shaking of discrete blocks resting either on a single infinite plane or on two planes in the form of a wedge. When the discrete blocks are close to a state of limiting equilibrium under static conditions, strong ground motions induced by earthquake could rapidly reduce the available shear strength below the value required for static stability and consequently sliding will commence. When the sliding interface exhibits velocity weakening characteristics, once sliding is initiated the sliding velocity could increase progressively, culminating in a catastrophic landslide.

THERMAL TRIGGERING OF BLOCK DISPLACEMENT

We have seen in the previous section the typical downslope stepwise block displacement triggered by dynamic shaking whenever the input acceleration exceeds the yield acceleration required for sliding, a value which is determined by the available friction angle of the sliding interface. We have also seen that the nominal value of the friction angle degrades as a response to shaking, and that when the sliding mass is at a state which is close to limiting equilibrium shaking induced friction angle degradation may lead to block run out.

In this section we present another source of block instability that is derived from temperature fluctuations. Consider the model of a block shown in Fig. 11 where the tension crack is filled some detrital material from the surrounding rock mass.

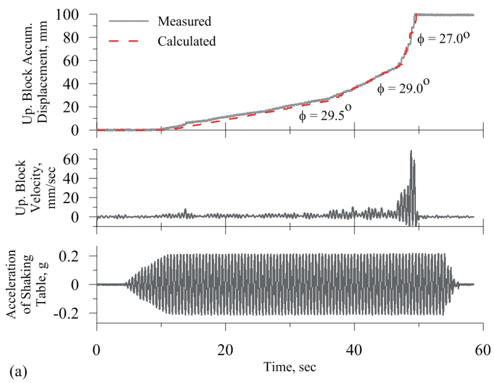

Fig. 10 - Example of an experimental output from the shaking table experiments of the concrete wedge block. Sinusoidal input motion at 2 Hz frequency and 0.21 g amplitude. The back calculated friction angles for the run-out segments are also shown

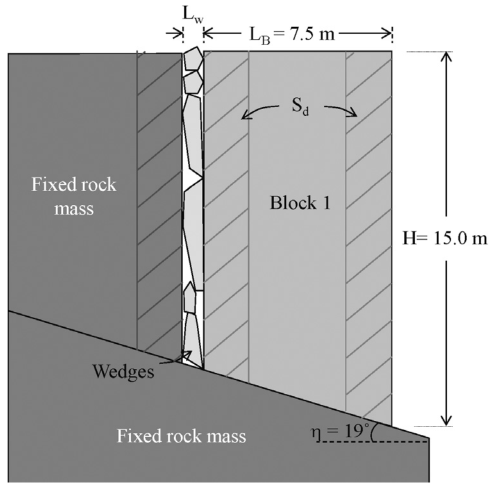

Fig. 11 - Model of a block resting on a shallowly dipping sliding plane with a tension crack at the back that is filled with some debris. Sd is the "thermal skin" depth

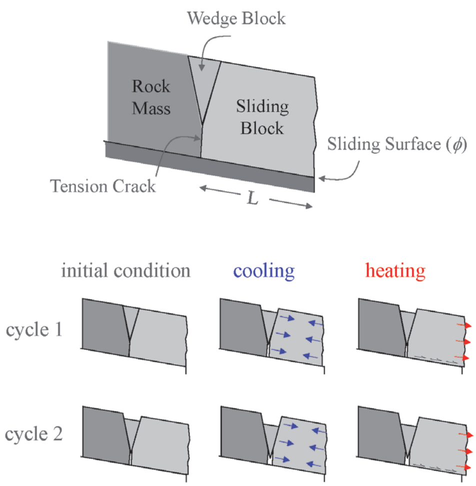

Fig. 12 Proposed thermally-induced ratcheting mechanism

For a given annual temperature cycle from the warm to the cold period the sliding block is expected to undergo much more thermal strain in comparison to the rock mass material because of its much smaller size. Consequently, during the cold season the sliding block is expected to experience shortening and as a result the tension crack is expected to open slightly. The climatically controlled opening of the tension crack will allow penetration of the fragments dipper into the tension crack as schematically illustrated in Fig. 12 with a wedge block that represents the detritus. When the season changes to the warm season, the sliding block will experience elongation prompting closure of the tension crack. But since the wedge block has already penetrated into the tension crack, the sliding block will be forced to move downslope incrementally (see Fig. 12). This process will be repeated from one season to the next, leading to cumulative downslope block displacement, the magnitude of which depends on the amplitude of the thermal fluctuation between the seasons in the respective region, the thermal conductivity, and thermal expansion coefficient of the rock.

Pasten (Pasten, 2012) developed an analytical solution for the expected "plastic" downslope displacement of a block subjected to the thermally induced ratcheting mechanism over one annual cycle, once the elastic displacement due to asperity shortening (scaled by the shear stiffness of the sliding plane), has been overcome. In addition to the geometrical variables shown in Figure 11, Pasten's solution depends on the Young's modulus of the rock material, the shear stiffness of the sliding interface, the thermal conductivity and thermal expansion coefficient of the rock, and the maximum temperature difference between the seasons (ΔT). The predicted seasonal plastic displacement that would be obtained by Pasten's model for a dolomitic rock mass for three different sliding plane inclinations under maximum temperature difference of 20° is shown in Fig. 13. It is worthwhile to point out here that dolomite has a relatively high thermal expansion coefficient in comparison to other rock types and therefore it is more susceptible to the thermally induced ratcheting mechanism.

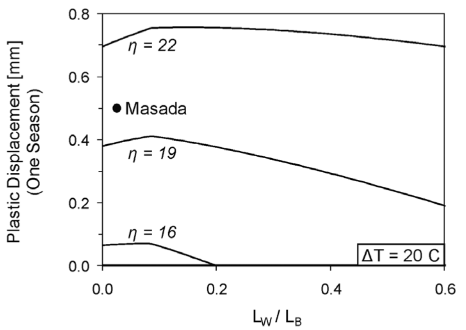

Fig. 13 - One cycle plastic displacement for three plane inclination angles η for a dolomitic limestone with maximum temperature difference between seasons of 20° (Pasten, 2012). For definition of LW and LB see Fig. 11

To test the viability of the analytical model predictions let us examine the temperature fluctuations and the resulting tension crack response in the dolomitic rock mass of Masada world heritage site which is used here as a case study. The opening and closure of several clean and tight joints at the western slope of Masada mountain were monitored over a period of several years as a function of temperature (Bakun-Mazor *et alii*, 2013). The layout of the monitoring system is shown in Fig. 14. The joint meter and temperature outputs for one annual cycle, from May 2010 to May 2011, are shown in Fig. 15. The left panel of Figure 15 shows the raw data whereas the right panel shows the same data after correction for electrical drift that was detected by comparison to the output of the neutral transducer that was mounted on an intact rock surface (WJM4). Inspection of the data presented in Fig. 15 reveals that the maximum temperature difference over an annual cycle at Masada is indeed in

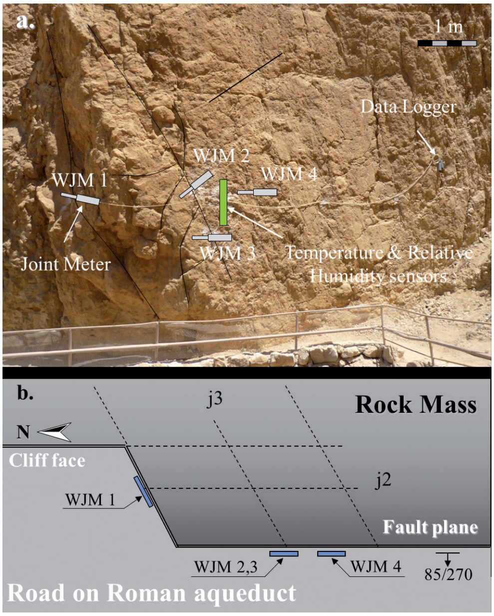

Fig. 14 - Joint displacement and temperature monitoring campaign at the west slope of Masada mountain

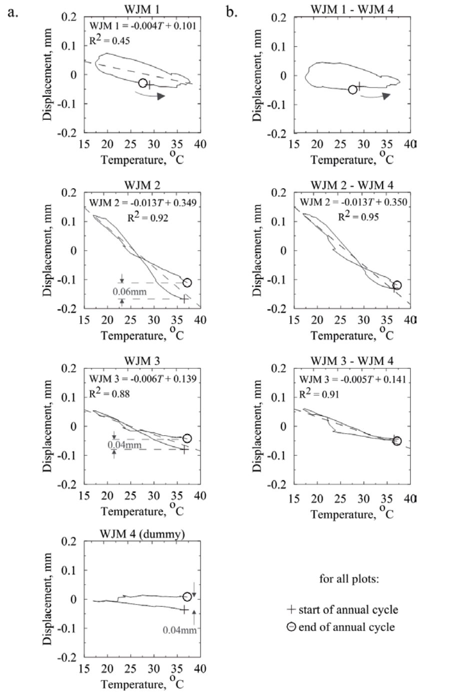

Fig. 15 - Joint meter and temperature transducer output from Masada rock slope over one annual cycle

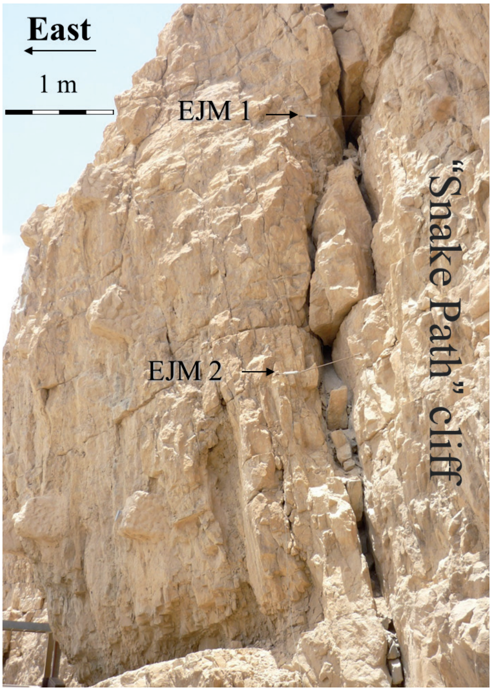

Fig. 16 - A displaced block that was mapped in the East slope of Masada mountain that could have been subjected to both seismically as well as thermally induced displacements

the vicinity of 20°. Moreover, the relationship between temperature increase and joint closure (negative joint meter output) and between temperature decrease and joint opening (positive joint meter output) is clearly portrayed in Fig. 15.

COMPARISON BETWEEN THE SEISMICALLY AND THERMALLY INDUCED DISPLACEMENTS

It is interesting to compare between the sources of instability discussed above and ask: in a given region where everything else is kept equal, which mechanism would amount to a greater block displacement over time? To try and address this question we use a single discrete block in the East slope of Masada that is shown in Figure 16 with geometrical dimensions similar to those shown in Fig. 11.

Let us consider a time window of 5000 years during which the east slope of Masada can be safely assumed to have been exposed in its current topographical and geomorphological configuration. Since its exposure the block has undergone an accumulated displacement of 200 mm, the amount of opening of the tension crack that can be readily measured in the field (see Fig. 16). This cumulative joint opening distance provides a physical constraint on the total amount of displacement that could have taken place in the past in either one of the two triggering mechanisms discussed

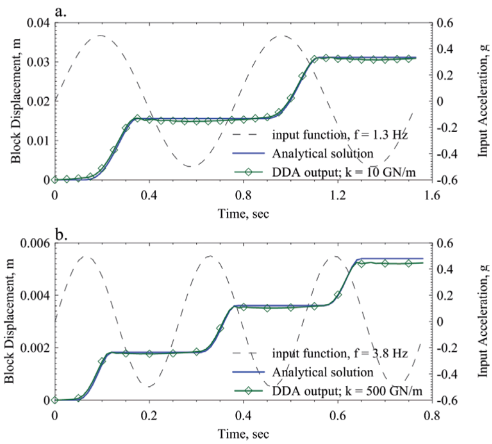

Fig. 17 - DDA results vs. analytical (Newmark's) solution for the dynamic displacement of the analyzed Block (Figs 11, 16) when subjected to asinusoidal input function with 0.5g amplitude and the two dominant frequencies for Masada (HATZOR et alii, 2004): 1.3 Hz (a) and 3.8 Hz (b). (k is the numerical contact spring stiffness used in DDA)

here. We can safely assume that no block run-out due to frictional degradation has taken place because the block exhibits a finite amount of displacement, and therefore it would be permissible to use a constant friction angle in the dynamic analysis.

We shall use the analytical solution derived by Pasten (PASTEN, 2012) to compute the accumulated displacement over time due to the proposed thermally induced ratcheting mechanism, and the numerical discrete element DDA method (SHI, 1993) to compute the dynamic displacement of the block due to shaking that is expected to have struck the mountain during the past 5000 years.

The DDA solution is quite sensitive to the user's choice of the penalty value, or the so called "contact spring stiffness" (k). Indeed, our research indicates that the optimal k value also depends on the motion frequency. A topographic site response study performed at Masada (HATZOR *et alii*, 2004) indicates that the two dominant frequency modes of the mountain are 1.3 Hz and 3.8 Hz. An optimization of the best value of k for these two frequencies for the geometry of the modeled block is shown in Fig. 17.

In order to assess the expected seismically induced displacement of the studied block we need to consider: 1) a characteristic earthquake input motion, 2) the attenuation law for the region, and 3) the recurrence times of earthquakes of different magnitudes in the studied region. For the input motion we use the 1995 Nuweiba record corrected for rock response and amplified to the topographic site effect measured at Masada as explained elsewhere (HATZOR *et alii*, 2004, BAKUN-MAZOR *et alii*, 2013). The assumed attenuation law for the region in terms of magnitude, distance from source, and expected ground acceleration is adopted from (SHAPIRA *et alii*, 2007) and is plotted in Fig. 18. Also shown in Fig. 18 are the "stable" and "sliding" modes of the analyzed block with respect to regional earthquake magnitude and distance based on pseudo-static analysis.

Inspection of Fig. 18 reveals that the relevant earthquakes to cause seismically induced displacements of the studied block are between magnitudes 6.0 and 7.5 and a distance from Masada of up to 20 km. Using the attenuation relationship the Nuweiba earthquake was up-scaled so as to represent each relevant earthquake magnitude with the corresponding accelerogram for input directly into the centroid of the analyzed block at top of Masada (BAKUN-MAZOR *et alii*, 2013). The scaled records were applied to the analyzed block using DDA after the contact spring stiffness value has been properly optimized, and the resulting dynamic block displacements for single earthquake episodes of different magnitudes at a distance of 1km from Masada are shown in Fig. 19. Using the mapped joint opening as a physical constraint on the numerical results shown in Figure 19 we may conclude that the analyzed block at the top of the east Masada cliff has

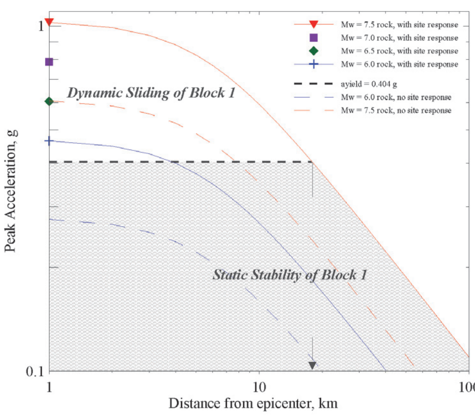

Fig. 18 - Assumed attenuation curves for Dead Sea Rift earthquakes (SHAPIRA et alii, *2007) (dashed lines) with amplification due to topographic site effect at Masada (HATZOR* et alii, *2004) (solid lines and symbols). Shaded region delineates conditions at which seismically-induced sliding of the analyzed block 1 at Masada (Block 1) is not possible*

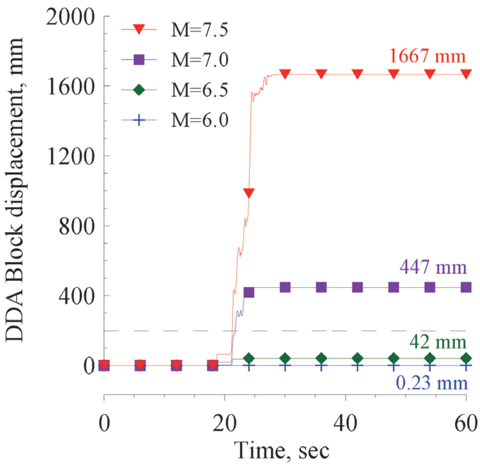

Fig. 19 - DDA results for dynamic displacement of the analyzed block when subjected to amplified Nuweiba records corresponding to earthquakes with moment magnitude between 6.0 to 7.5 and epicenter distance of 1 km from Masada. Mapped joint opening in the field is plotted (dashed) for reference

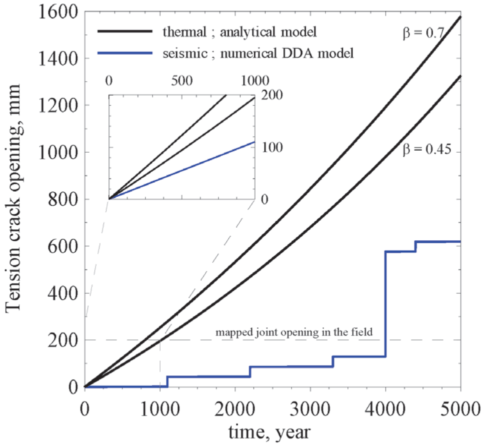

Fig. 20 - Comparison between thermally and seismically induced displacement rates for the analyzed block. Thermal displacement rate is calculated assuming b= 0.45 and 0.7 (Bakun-Mazor et alii, 2013). Seismic displacement rate is obtained by summation of earthquake magnitudes 6.0 to 7.0 with epicenter located 1 km from Masada based on the seismicity of the region. The seismic rates in the zoom-in box are for the long term seismicity (5000 years)

never been subjected to Dead Sea rift type earthquakes with magnitudes greater than 6.5 with epicenter at a distance from Masada greater than 1 km.

Using published forecasts for recurrence times of earthquakes of different magnitudes in the Dead Sea region (Begin, 2005) we can now compare between the seismic and thermal loading mechanisms for a time window of 5000 years, keeping in mind that since the studied block has not run out we use the constant friction angle value in our analyses. The results of such a comparison are shown in Fig. 20. Inspection of Fig. 20 reveals that the seismic loading mechanism, given the seismicity of the region, would amount to a total of 600 mm overt a period of 5000 years, taking into consideration all the earthquakes and their respective magnitudes that could have hit the region during that period. The thermal mechanism, however, if allowed to continue for 5000 years, would lead to greater block displacements, and at a greater displacement rate.

SUMMARY AND CONCLUSIONS

We present in this paper the possibility for a thermally induced wedging mechanism for rock slopes using the monitored rock blocks at Masada Mountain, Israel, as a case study. The thermal mechanism involves the rock mass, a wedge filled tension crack, a sliding block, and a sliding interface with the rock mass. We show that for the dolomites of Masada the seasonal temperature amplitude is sufficient to induce permanent plastic displacement of rock blocks via a wedging - ratcheting mechanism, although the blocks are situated on relatively shallow dipping planes.

Since Masada is situated on the margins of a seismically active rift, we use numerical discrete element analysis to compute the seismically induced displacement of the same block we use to demonstrate the thermal loading mechanism and find that for the assumed seismicity of the region, the 200 mm displacement of the studied block is more likely to have been thermally, rather than seismically, induced.

We conclude that the thermally induced sliding mechanism should be considered when quantitatively assessing surface erosion or rock slopes with thermal and mechanical properties that permit this failure mechanism to take place. This mechanism may explain rock failure episodes occurring more frequently than is generally assumed or explained.

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