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Constraining regional paleo peak ground acceleration from back analysis of prehistoric landslides: Example from Sea of Galilee, Dead Sea transform

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A R T I C L E I N F O

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A B S T R A C T

Accurate estimation of expected peak ground acceleration (PGA) in seismically active regions is a challenging task. The best way to estimate, quantitatively, expected PGA is by investigating instrumental data of past strong earthquakes in a given area. In some regions of the world however recorded data are scarce, and if they exist, they are typically available only since the late 19th century. As such they are hardly representative of the true seismicity in the studied region. We propose here an analytical approach to constrain the lower threshold of paleoseismic PGA on the basis of back analysis of old landslides. To perform the analysis we need a mapped landslide with geomorphic features that have been preserved in the field, the slip surface, a good reconstruction of the slope geometry and ground water level prior to failure, and the mechanical properties of the sheared material. We perform static and pseudo-static limit equilibrium analyses using standard solution procedures to obtain lower bounds of paleoseismic PGA. Back analyses of three different landslides around the Sea of Galilee (SOG) return similar results that range between 0.15 and 0.5 g, thus constraining the threshold paleoseismic PGA range for this region. The analytically inferred regional PGA is supported by results of an independent numerical analysis of toppled columns in a nearby Byzantine church. Using results from a recent paleoseismic trenching study performed on one of the studied landslides and a modified attenuation relationship for the study area we localize the loci of moment magnitude $M_w = 7.0$ earthquakes that can explain the studied failures along the boundaries of the SOG, and find that they coincide with traces of the Eastern and Western Margin faults of the Dead Sea transform. The temporal relationships between the observed failures are discussed on the basis of dated colluvial sediments, geomorphologic constraints, and archeological evidence.

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1. Introduction

Accurate estimation of expected peak ground acceleration (PGA) in seismically active regions is crucial for risk preparedness and sound engineering design. The best way to estimate quantitatively expected PGA would be to investigate long term recorded data of past strong earthquakes in the studied region. In some regions of the world however recorded data are scarce due to lack of seismic network infrastructure, and in all regions the availability of recorded data is restricted to the late 19th century. Therefore, existing instrumental data are hardly representative of the true seismicity of a region. When recorded data are scarce or not available, alternative methods may be applied, for example adopting a quantitative paleoseismic approach.

In this paper we suggest a new and relatively simple paleoseismic approach for estimating a characteristic paleo PGA for a specific region, through back analysis of seismically triggered landslides. By back analysis, in the context of this paper, we mean that we seek a PGA value that will be sufficient to bring the modeled slope to a state of limiting equilibrium. The obtained results, coupled with qualitative intensity scale classification for the region, for example using the ESI 2007 scale (Guerrieri and Vittori, 2007), provide a useful seismic hazard assessment for a given region. Using intensity levels alone does not provide the valuable information regarding expected ground motions, as scaled by the expected PGA, necessary for seismic engineering design.

The approach is demonstrated through the study of three landslides triggered around the circumference of the Sea of Galilee (SOG) during the Pleistocene.

The SOG is a rhomb-shaped graben formed due to left segmentation of the sinister Dead Sea transform (DST) fault (Garfunkel, 1981; Hurwitz et al., 2002). The eastern and south-western margins of the SOG are normal faults associated with the DST system, whereas the northern and north-western margins exhibit a more complicated structure (Ben-Avraham et al., 1996). The stratigraphy of the SOG region largely consists of Miocene to Pleistocene lacustrine and fluvial

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sediments with episodic events of lava flows, the entire sequence of which rests on an Eocene basement. The lithology consists of clay, marl, chalk, limestone, sandstones and conglomerates, capped by the Plio-Pleistocene Cover Basalt formation (Mor and Sneh, 1996).

Seismicity in the SOG region is moderate (Arieh and Rabinowitz, 1989; Shapira, 1983), with an estimated $M_w = 6$ earthquake reoccurrence time interval in the order of 10^2 years increasing to 10^3 years for $M_w = 7$ earthquakes (Begin, 2005). The last strong event ($M_s = 6.2$) was recorded at the northern Dead Sea area in 1927 (Enzel et al., 1997; Niemi and Ben-Avraham, 1997; Shapira et al., 1993), about 100 km south of SOG. In 1973 a $M_L = 4.5$ earthquake occurred a few kilometers south of the SOG (Arieh et al., 1977). According to the national seismic building code (S.I.I., 2004) a horizontal PGA of 0.3 g is estimated for this region with 10% probability of exceedence for every 50 years. The seismicity of this region and the population density around the SOG warrant such an attempt. The three analyzed landslides presented in this paper are Ein-Gev, Berniki Beach, and the Fishing Dock (Fig. 1). All three landslides are analyzed here using the same approach, but with different qualities of input data, depending upon their availability and accessibility in each case. We argue that the fact that not all data are available in each case is not necessarily a weakness of our approach. It proves, rather, that a regional PGA may be reasonably estimated from back analysis of several landslides even when the required data set is incomplete. The PGA for the SOG region thus estimated can be used to improve the existing building code and consequently reduce the seismic hazard in the next large earthquake expected in this region.

Finally, landslides near major faults like the ones existing in the study area are often induced by coseismic fracturing, and fractures that are kept open by surface faulting; the influence of late Pleistocene tectonic deformation and fault displacement on the slope stability near the Sea of Galilee is discussed by (Katz et al., in press).

2. Qualitative and quantitative paleoseismic approaches

Various geological features have been used recently to deduce paleoseismic information for the DST. Seismites, defined as disturbed sedimentary structures, have been used to estimate earthquake recurrence intervals in the DST (Ken-Tor et al., 2001; Marco and Agnon, 1995, 2005; Migowski et al., 2004). Such methods provide reasonably accurate chronology of seismic events but no quantitative measure of the ground motion at the site that must have caused the mapped damage in the field.

Trenching faults that are displacing the ground surface has been used as a methodology to obtain both earthquake chronology as well as quantitative measures of fault displacement during strong earthquakes (Amit et al., 2002; Marco et al., 2005).

Stalactites and stalagmites can also be used as paleoseismic indicators (Kagan et al., 2005). Using this approach regional earthquake chronology may be obtained as well as recurrence interval, and in some cases upper constrains on paleo PGA can be evaluated (Szeidovitz et al., 2008).

Another paleoseismic approach suggested by Matmon et al. (2005), utilizes soil dating below toppled rock blocks with cosmogenic isotopes and optically stimulated luminescence (OSL) to deduce recurrence intervals of earthquakes in the Timna valley, southern DST.

The paleoseismic methods discussed thus far enable direct determination of earthquake chronology and indirect estimate of earthquake intensity, yet a quantitative assessment of paleo PGA is difficult

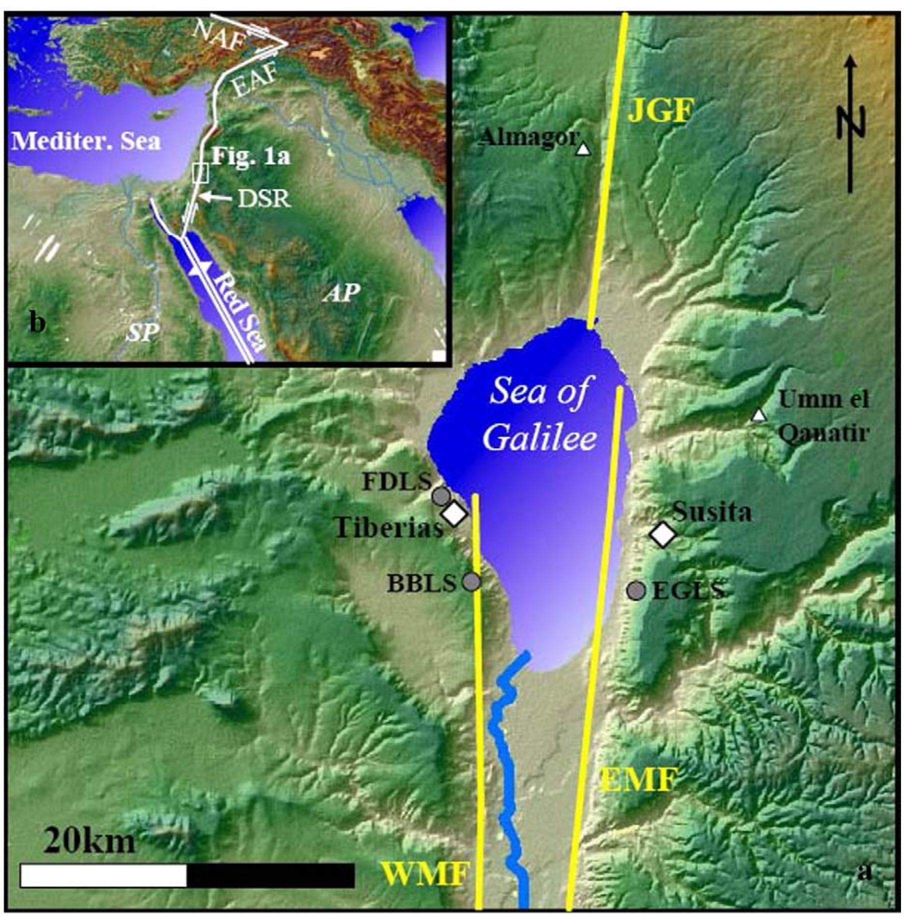

Fig. 1. (a) Location map of the study area based on a DEM of the Sea of Galilee region (shaded relief from Hall (1994)). Active faults are yellow (EMF = Eastern Margin Fault, WMF = Western Margin Fault, JGF = Jordan Gorge Fault). Studied landslides marked by grey circles (EGLS = Ein-Gev landslide; BBLS = Berniki Beach landslide; FDLS = Fishing Dock landslide). Also shown in grey triangles are the landslides of Umm El Qanatir and Almagor. Inset (b) shows the plate tectonic setting of the Dead Sea Transform (DST).

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