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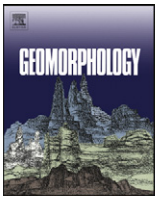

Are microseismic ground displacements a significant geomorphic agent?

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ABSTRACT

This paper considers the role that microseismic ground displacements may play in fracturing rock via cyclic loading and subcritical crack growth. Using a coastal rock cliff as a case study, we firstly undertake a literature review to define the spatial locations that may be prone to microseismic damage. It is suggested that microseismic weakening of rock can only occur in 'damage accumulation zones' of limited spatial extent. Stress concentrations resulting from cliff height, slope angle and surface morphology may nucleate and propagate a sufficiently dense population of microcracks that can then be exploited by microseismic cyclic loading. We subsequently examine a 32-day microseismic dataset obtained from a coastal cliff-top location at Staithes, UK. The dataset demonstrates that microseismic ground displacements display low peak amplitudes that are punctuated by periods of greater displacement during storm conditions. Microseismic displacements generally display limited preferential directivity, though we observe rarely occurring sustained ground motions with a cliff-normal component during storm events. High magnitude displacements and infrequently experienced ground motion directions may be more damaging than the more frequently occurring, reduced magnitude displacements characteristic of periods of relative quiescence. As high magnitude, low frequency events exceed and then increase the damage threshold, these extremes may also render intervening, reduced magnitude microseismic displacements ineffective in terms of damage accumulation as a result of crack tip blunting and the generation of residual compressive stresses that close microcracks. We contend that damage resulting from microseismic ground motion may be episodic, rather than being continuous and in (quasi-)proportional and cumulative response to environmental forcing. A conceptual model is proposed that describes when and where microseismic ground motions can operate effectively. We hypothesise that there are significant spatial and temporal limitations on effective microseismic damage accumulation, such that the net efficacy of microseismic ground motions in preparing rock for fracture, and hence in enhancing erosion, may be considerably lower than previously suggested in locations where high magnitude displacements punctuate 'standard' displacement conditions. Determining and measuring the exact effects of microseismic ground displacement on damage accumulation and as a trigger to macro-scale fracture in the field is not currently possible, though our model remains consistent with field observations and conceptual models of controls on rockfall activity.

1. Introduction and scope

Microseismic monitoring techniques have recently been used to detect and characterise a range of geomorphic processes, including ocean wave energy delivery to coastal cliffs (Adams et al., 2002; Young et al., 2011; Dickson and Pentney, 2012; Young et al., 2012), river bedload transport (Hsu et al., 2011; Tsai et al., 2012), glacier fracture and hydrology (Roux et al., 2008; West et al., 2010) and rock sliding and avalanching (Deparis et al., 2008; Dammeier et al., 2011). Whilst microseismicity has been used in these studies as a remote proxy for process, Adams et al. (2005) hypothesised that microseismic ground motions may themselves constitute a significant yet largely unrecognised geomorphic process that is worthy of further attention.

Adams et al. (2005) reported an exponential decay in the magnitude of micron-scale (0.1 to 1×10^1 μm) displacements along a transect perpendicular to the face of a coastal rock cliff at Monterey Bay, California, USA. By comparison with ocean wave data, Adams et al. (2005) demonstrated that the observed flexure results from the loading of the foreshore platform by water waves, notably longer-period incident sea swell ocean waves (10 to 20 s period). Similar observations were also made by Young et al. (2011, 2012) at infragravity frequencies (20 to 170 s period). Adams et al. (2005) suggested that the low magnitude (micron-scale) cyclic nature of cliff-top microseismic ground displacements may be sufficient to damage the rock mass via a fatigue process, such that overall rock mass strength is progressively reduced as microcracks propagate, interact and coalesce (Attewell and Farmer, 1973; Main et al., 1993). If microseismic ground motions are significant in reducing rock mass strength, macro-scale rock fracture could therefore occur at ambient deviatoric stresses that are considerably less than the peak strength values of intact (undamaged) rocks (Sunamura, 1992; Xiao et al., 2011). Under this model, by creating planes of weakness, microseismic fatigue could play a key role in governing the timing and distribution of landform and landscape susceptibility to change

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(cf. Allison, 1996; Molnar et al., 2007; Moore et al., 2009; Clarke and Burbank, 2010; Dühnforth et al., 2010; Clarke and Burbank, 2011; Koons et al., 2012). If microseismic cyclic loading is effective in weakening rocks in an incremental, preparatory manner and, hence, permitting fracture to occur more readily, this may be an important yet rarely considered process in driving slope failure.

As a preparatory geomorphic process (cf. Gunzberger et al., 2005), microseismic cyclic loading theoretically relies on an extremely high number of effective (damaging) load cycles to exert any significant geomorphic consequence, since the damage increment resulting from each loading cycle is likely to be exceedingly small, yet not cumulatively negligible (Adams et al., 2005). For this to occur to a degree sufficient to be comparable to other damage-inducing processes, the spatial and temporal opportunities for microseismic damage must be sufficiently extensive. As such, the Adams et al. (2005) microseismic damage model is based on two critical and implicit assumptions, as follows:

1. The spatial extent of the 'damage accumulation zone' is sufficiently large and continuous that the low magnitude strains have sufficient opportunity to operate for a period of time sufficient to cause significant damage to rock. The exact spatial extent of the damage accumulation zone was not physically or theoretically constrained by Adams et al. (2005), but was suggested to be of the order of tens of metres inland from the cliff face. As such, ongoing microseismic strains were implicitly assumed to be able to cause damage at any location within the damage accumulation zone, to a degree commensurate with the magnitude of strain resulting from microseismic cliff flexure.
2. All microseismic ground displacements resulting from ocean wave loading of the foreshore platform create incremental rock-damaging strains. The magnitude of damage resulting from each load cycle was deemed to be a function of the magnitude of strain and the existing damage condition of the rock mass relative to its pristine state. Damage (weakening) was assumed to be cumulative and ongoing, increasing with the number of loading cycles experienced by the rock and, hence, through time.

We address these assumptions to provide an alternative interpretation of the potential effectiveness of microseismic ground motions in accumulating damage in rock and to reconsider the microseismic damage model proposed by Adams et al. (2005). We firstly present an alternative assessment of how and where microseismic ground motions are likely to act as an effective geomorphological process in brittle materials. Secondly, a 32-day record of microseismic displacements recorded in a rocky coastal cliff environment is analysed to consider the key characteristics of the observed microseismic displacements to explore the possible temporal evolution of rock strength in response to microseismic loading. Thirdly, a conceptual model of the spatial and temporal occurrence or rock-damaging microseismic ground motions is developed. Finally, we explore the implications of the model and consider its potential validity using previously published datasets on rockfall activity in rocky coastal cliffs.

2. Defining the damage accumulation zone

2.1. Microseismic strain and stress magnitudes

Subcritical brittle microfracture and fatigue crack growth caused by cyclic loading have been shown to damage and weaken rocks in laboratory studies under compressive and tensile loading conditions (Attewell and Farmer, 1973; Lavrov et al., 2002; Erarslan and Williams, 2012a). Such laboratory studies report results from tests that employ a variety of dynamic loading frequencies, including those comparable with the longer-period ground motions observed in coastal cliffs by Adams et al. (2005) and Young et al. (2011) (cf. Attewell and Farmer, 1973; Tien et al., 1990; Li et al., 1992). Attewell and Farmer (1973) concluded that the lowest frequencies tested (0.1 Hz; 10 s period) caused failure in fewer cycles than those of the same stress amplitude but higher frequency ($\leq$20 Hz; 0.05 s period), suggesting that ground motions resulting from foreshore wave loading, comparable to those observed by Adams et al. (2005) and Young et al. (2011) are potentially, in relative terms, highly damaging and conducive to fatigue crack growth.

Adams et al. (2005) and Young et al. (2012) estimated strains (dimensionless) resulting from microseismic ground motions in the order of 0.1 to 1×10^{-6}. These estimated strain values are many orders of magnitude lower than the peak strain values of rocks under monotonic loading (Young et al., 2012). For example, for a variety of rock types tested in unconfined compression, such peak strain values are in the range of 0.5 to 2×10^{-2} (e.g. Heap et al., 2010).

Prior to failure, microseismic displacement and, hence, strain (ε, i.e. relative displacement and deformation within the cliff-forming material) result in a (quasi-)proportional application of a stress (σ) to the rock mass, following Hooke's law:

$$\sigma = E\varepsilon \tag{1}$$

where E is Young's modulus of elasticity. Applied microseismic stresses ($\sigma_{\min}$ and $\sigma_{\max}$) act relative to the mean (in situ static) stress (σ_{mean}). Calculated and reported dynamic stresses resulting from microseismic loading are in the order of 1 to 10×10^{-3} MPa (Adams et al., 2005; Young et al., 2012), assuming $E = 20$ GPa. Peak unconfined compressive strength values (UCS) can range from 40 MPa (Bentheim Sandstone; Heap et al., 2009) to 360 MPa (Icelandic basalt; Vinciguerra et al., 2005). Rocks tend to be weaker under tensile loading conditions and peak tensile strength values can range from 4 MPa (Ellington Mudstone) to 70 MPa (Cefn Coed Sandstone) (Hobbs, 1964). Stresses resulting from cliff flexure may therefore represent a greater proportion of peak (failure) stress under tensile baseline conditions.

2.2. Brittle microfracture and subcritical crack growth

Whilst stresses and strains induced by microseismic ground motions are a small fraction of peak values observed under monotonic loading, localised brittle microfracture damage can occur in rock at stresses significantly less than peak strength (Scholz, 1968; Martin and Chandler, 1994; Mitchell and Faulkner, 2008). The macro-scale mechanical behaviour of rock in the brittle domain is dependent on rock microstructure (Potyondy, 2007), notably the presence, density and interaction of microcracks (Tapponier and Brace, 1976; Eberhardt et al., 1999). The remotely applied microseismic stresses are not necessarily transmitted equally throughout the rock mass (Potyondy, 2007). Stress magnitudes can be locally modified within the rock mass at sites of stress concentration, such as pore spaces, grain or crystal boundaries, microscopic flaws and petrological structures (Cai et al., 2004), allowing microcrack nucleation as stresses exceed local strength (Kranz, 1983). The magnitude of the elastic stress field at the microcrack tip is described by K, the stress intensity factor (cf. Janssen et al., 2002, for example), defined as:

$$K = \sigma\sqrt{\pi a} \tag{2}$$

where σ is the remotely applied stress and a is the microcrack length. Eq. (2) describes a an isolated two-dimensional crack in an infinite space, which we use for simplicity but note that alternative terms are required for microcracks of differing geometry (cf. Brady and Brown, 2004). Increasing K values results in an increase in the potential for microcrack growth (Janssen et al., 2002).

When populations of microcracks are sufficiently dense to permit interaction at a critical scale, crack coalescence results, ultimately culminating in macro-scale fracture (Bieniawski, 1967; Main et al., 1993; Martin and Chandler, 1994). The process of microcrack propagation and coalescence can result in measurable and continuous pre-failure