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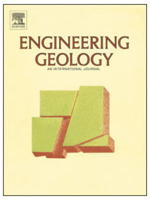

Detection and location of rock falls using seismic and infrasound sensors

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ABSTRACT

We deployed seismic and infrasound sensors at a historically active cliff in Yosemite Valley for the purpose of detecting and locating rock falls at local (<1 km) distances and demonstrate the potential for using these techniques for real-time rock fall monitoring. The project ran for two winters: the first deployment was a system feasibility study consisting of a single station with a geophone and an accelerometer; the second deployment was a network of seven stations at four different locations with the addition of infrasound sensors. We demonstrated that small (<20 m^3) rock falls are detectable at distances of several hundred meters, individual impacts can be identified, and seismic waves are generated prior to the first main impact for some rock falls. We also found that infrasound is viable and compliments seismic, especially for locating events. We correlated the data with environmental conditions and extracted information about the initiation, triggering, and dynamics of rock falls. A major part of the research effort was the development of a triggering algorithm and criteria for distinguishing rock falls from thousands of seismic triggers. Twelve rock falls were identified in the continuous seismic recording by searching for triggers and comparing them with known rock falls and other forms of seismic activity. Physical evidence or reports of rock falls exist for only eight of the twelve rock falls that we identified; thus, we have demonstrated that instrumented monitoring can significantly augment the detection of rock falls even in heavily-trafficked areas such as Yosemite Valley. Six of the rock falls appear to be related to each other as an ongoing instability, while the rest appear to be independently occurring events. After we identified the individual rock fall events, we focused on characterizing the seismic data in terms of timing, frequency, and P/S/Rayleigh wave phases in order to develop a set of characteristic parameters indicative of rock fall signals.

1. Introduction

Rock falls are the most common type of slope instability in Yosemite Valley, with 40–70 rock falls reported per year (Stock et al., 2013) in an area measuring only 15 km^2 and bounded by nearly vertical walls rising 1000 m above the valley floor. Current rock fall documentation in Yosemite relies solely on people who report observations of rock falls in-progress or the presence of fresh rock fall debris. The reliance on witnesses results in underreporting of observable rock falls and biasing of the data to popular locations. Thus, having a tool capable of passive monitoring of rock falls, such as seismic and acoustic, would significantly augment the existing rock fall documentation and help in identifying patterns of increased (or decreased) rock fall activity. Rock fall patterns are significant because smaller rock falls or loud popping noises occasionally precede larger rock falls in Yosemite Valley for hours or days. Two notable examples of rock falls with precursory activity were the largest historic rock falls at Middle Brother in 1987 (600,000 m^3) and the deadliest rock fall at Yosemite Falls in 1980, killing 3 people and leaving 19 injured (Wieczorek et al., 1995; Stock et al., 2013). Seismic monitoring may also help to assess rock fall dynamics, identify triggering activity, or even rock fall initiation in the case of fracture propagation that causes audible cracking and popping noises (Stock et al., 2012). In order to assess the potential of seismic and acoustic to aid in rock fall monitoring, we installed instrumentation at a historically active cliff in Yosemite Valley over two winter seasons and collected data that helps in assessing the potential for rock fall detection, location, data quality, and interpretation of data in a topographically challenging environment.

This experiment was not the first attempt to seismically monitor for rock falls in Yosemite Valley. Instruments were installed following the 1996 Happy Isles and the 1999 Glacier Point rock falls, but the results were inconclusive as no notable rock falls occurred during the experiment (Myers et al., 2000). Rock fall events are occasionally large and energetic enough to be detected by nearby strong motion seismic networks. Two notable examples are the two 1996 Happy Isles rock falls (Wieczorek et al., 2000; Uhrhammer, 1996; Morrissey et al., 1999) and the 2009 Ahwiyah Point rock fall (Zimmer et al., 2012), registering as earthquake magnitude-equivalent (Mw) 1.5, 2.1, and 2.4, respectively. However, these three events were all unusually large (6650 m^3, 31,350 m^3, and, 46,700 m^3 respectively). Most damaging rock falls in

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Yosemite are 2–2000 m^3 in volume, too small to be detected by existing strong motion seismic networks.

There are numerous scientific studies of Yosemite Valley rock falls aimed at documenting the mechanisms of failure when possible and at identification of rock fall hazard and risk (Guzzetti et al., 2003; Stock and Uhrhammer, 2010; Stock et al., 2011, 2012, 2013, 2014; Wieczorek and Jäger, 1996; Wieczorek and Snyder, 1999; Wieczorek et al., 1995, 1998, 1999, 2000, 2008; Zimmer et al., 2012). The reported number of rock falls has increased from an average rate of 5 per year from 1950 to 2000 to 41 per year from 2000 to 2011, as a result of better reporting and documentation (Stock et al., 2013). Thus, understanding the true rate and nature of rock falls in Yosemite is still a subject of research; for many rock falls, there is no known associated trigger, and the mechanics by which the rock fall was initiated is unknown.

The seismic signature of a rock fall is related to the initial mechanics, dynamics, and physical parameters of a rock fall. The initiation of a rock fall can occur in several ways: the rock can fail in a stress-induced burst, it can slide off a ledge where it has been meta-stable for years, and it can topple over. Often, a rock fall is not one instantaneous event, but rather a series of events that comprise the initial failure of the cliff, the breakup of the falling rock as it strikes and bounces down the cliff face, multiple large impacts on the ground surface, and the deceleration of rocks as they roll and slide to a stop at the bottom of the talus slope. All of these events are recorded as parts of a single rock fall signal, and individual impacts may or may not be distinguishable.

Most previous studies of the seismic signatures of rock falls and associated physical parameters fall into two broad groups: those detecting large events, often rockslides, at distances >5 km and those studying microseismic phenomena associated with cracking at a very close range (<50 m). In the French Alps, studies have linked the seismic characteristics with the physical parameters of rockslides using existing strong motion seismic networks (Dammeier et al., 2011; Deparis et al., 2008). Special monitoring networks have been installed at sites in order to monitor the slide behavior and to attempt the prediction of a potentially catastrophic failure at the Åknes rockslide in Norway (Roth and Blikra, 2004), the Randa rockslide in Switzerland (Burjánek et al., 2010, 2012; Moore et al., 2011; Spillmann et al., 2007), the Séchilienne rockslide in the French Alps (Helmstetter and Garambois, 2010; Lacroix and Helmstetter, 2011), and the La Clapière rockslide in the French Alps (Gaffet et al., 2010)

Microseismic monitoring of rock slopes (mined and natural) is a technique that has existed since the early 1990s (Hardy and Kimble, 1991) and shows potential to detect precursory activity, such as cracking or small rock falls. Rock slope microseismic monitoring is an extension of the techniques developed for underground mining: in one study, shallow underground roof failures were predicted ~75% of the time (Iannacchione et al., 2005). Microseismic sensors installed in a chalk cliff in France detected cracking two hours before the cliff failed a few meters away (Amitrano et al., 2005). Analysis of microseismic events has provided insight into rock bridge failures leading to rock falls on the Vercors Massif in France (Lévy et al., 2010, 2011). Monitoring of a limestone cliff in southeast France has detected increases in high frequency seismic noise and changes in spectral modes associated with fracture growth and increasing instability prior to failure (Got et al., 2010). A microseismic monitoring system has been installed at the Matterhorn to investigate the link between thermal changes associated with permafrost degradation and rock mass response (Amitrano et al., 2010; Occhiena et al., 2012).

While these previous studies contain important lessons for interpreting seismic data and phenomena associated with rock failures, the steep cliffs and narrow valley dictate that the most common type of hazard are rock falls (not rockslides) of a relatively small volume (<2000 m^3) and high free-fall distance (>100 m) and that instrumentation must be located close enough to detect events (<1000 m), but cannot be located too closely due to the difficulty of access and the unpredictability of release zone locations (>100 m). In terms of these criteria, volcano-monitoring studies are some of the most similar in terms of event volumes and distance between seismic stations and rock fall impacts. Seismic signatures associated with rock falls at volcanoes have been noted since, at least, the early 1970s (Tilling et al., 1975; Norris, 1994). Hibert et al. (2011) were able to record >1700 individual rock falls at Dolomieu crater on Réunion Island at distances ranging from 50 m to 2 km to the crater rim. Rock falls were distinguished by their impulsive onset and short duration, but the frequency content was heavily dependent on distance to the event with an average of 7 Hz but impulses up to 40 Hz at the closest stations. Vilajosana et al. (2008) demonstrated that individual rock fall impacts at recording distances under 200 m can be distinguished and located with polarization analysis of seismic data. At the “Rappenlochschucht” in the Vorarlberg Alps, Austria, Walter et al. (2012) recorded a large (15,000 m^3) rock fall at a distance of 5 km, consisting of several individual impacts and rock fall runout over 20 s and preceded by two smaller events described as being similar to avalanche signals lasting 5–7 min. Most of the seismic energy was in frequencies less than 20 Hz, and no seismic phases were identifiable from the rock fall or precursory avalanches.

2. Field data collection

The initial objective of this experiment was to test the feasibility and limitations of a passive seismic monitoring system installed within 1 km of a potentially active rock fall zone in Yosemite Valley. We initially were permitted to install instruments at one location at one cliff, and the following year permitted to install instruments at 3 locations at one cliff and one location in Yosemite Village. Due to regulations on infrastructure in wilderness areas and a requirement to keep installations small and invisible to visitors, we were not permitted to instrument the entire valley, locate instruments on the rim, or have visible large solar panels or antenna. Thus, part of the experiment design was to select an appropriate site for monitoring using a minimum amount of equipment in an inconspicuous location. We targeted the Middle Brother cliff formation due to its history of winter rock falls, access to the cliff face via a ledge system called “Michael's Ledge”, relatively inconspicuous (away from hiking trails) location where hikers would be unlikely to see instrumentation, and southeast-facing aspect. Middle Brother is an 800 m tall rock formation that juts out on the north side of Yosemite Valley (Fig. 1). The rock formation has three major rock fall source areas, identified by prominent talus piles below light-colored, highly fractured fresh rock surfaces that contrast with the darker gray, weathered surrounding cliffs (Fig. 2). The largest source area, identified as “MB-A” in Fig. 2, is more than 300 m wide and 300 m tall, and sits perched above a section of Michael's Ledge that is notorious for rock falls among rock climbers, who use the ledge to access climbs. Two additional major source areas, MB-B and MB-C, sit to the east of MB-A. Cliff profiles of the three source areas are shown in Fig. 3.

Large rock falls have been reported from Middle Brother dating back to before 1851, including at least one rock fall-induced airblast in January of 1923 (Wieczorek et al., 1992). The largest rock fall in the historical record of Yosemite, on 10 March 1987, occurred at Middle Brother after two days of small rock falls and popping noises. This precursor activity led to the closure of a major road underneath the cliff, only two hours before the rock fall buried it in 4 m of rock debris totaling 600,000 m^3 (Wieczorek and Snyder, 2004; Wieczorek et al., 1992, 1995; Yosemite Association, 1987). Rock falls at the Three Brothers, of which Middle Brother is the predominantly active cliff, have been reported, on average, every ten years between 1873 and 1999 and twice a year from 2000 to 2011, due to increased diligence of rock fall reporting (Stock et al., 2013). More than half of the rock falls in this area have occurred during the four winter months of December through March, including five that are classified as very large (≥5000 m^3). Winter storms bring freezing temperatures and high amounts of precipitation followed by sunny days and melting of snow and ice; this freeze–thaw cycle may explain the propensity of this cliff to experience winter rock