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Reproducing the supershear portion of the 2002 Denali earthquake rupture in laboratory

M. Mello [a], H.S. Bhat [b,*], A.J. Rosakis [c], H. Kanamori [d]

[a] School of Aerospace Engineering, Georgia Institute of Technology, USA
[b] Institut de Physique du Globe de Paris, UMR 7154 CNRS, 1 rue Jussieu, Paris 75005, France
[c] Graduate Aerospace Laboratories, California Institute of Technology, USA
[d] Geological and Planetary Sciences, California Institute of Technology, USA

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ABSTRACT

A notable feature of the 2002 M_w 7.9 Denali, Alaska, earthquake was that a unique set of near-field seismic ground motion records, at Pump Station 10 (PS10), captured the passage of a supershear rupture followed by what was surmised to be a secondary slip pulse, 'Trailing Rayleigh Pulse' (Dunham and Archuleta, 2004; Mello et al., 2010). Motivated by the unique features contained in these near-field ground motion records, which were obtained only 3 km away from the fault, a series of scaled laboratory earthquake experiments was conducted in an attempt to replicate the dominant features of the PS10 ground motion signatures. Particle velocity records bearing a striking similarity to the Denali ground motion records are presented and discussed. The success of the comparison opens up the possibility of routinely generating near source ground motion records in a scaled and controlled laboratory setting that could be of great societal interest towards assessing seismic hazard from large and potentially devastating earthquakes.

1. Introduction

The nature of near fault ground motion associated with a large strike-slip earthquake is of great interest to earthquake engineers and to earth scientists alike because there are few observations with which to constrain either empirical or theoretical models (Ellsworth et al., 2004a). The 2002 (M_w 7.9) Denali fault earthquake provided a unique ground motion record close to the source, at Pump Station 10 about 3 km away from the fault. Another unique feature was that this station recorded the passage of a supershear earthquake rupture (earthquake whose rupture speed exceeds the shear wave speed of the surrounding solid; Rosakis, 2002; Rosakis et al., 2007) providing the only reliable near-source record of such an event. Supershear ruptures are expected to be more destructive since they manifest shear shock wave fronts (Rosakis, 2002; Mello et al., 2010). As a consequence the ground motion associated with supershear ruptures does not attenuate, with distance, as fast as that associated with sub-shear ruptures, sub-Rayleigh in 2D, (Rosakis, 2002; Dunham and Archuleta, 2005; Das, 2007; Rosakis et al., 2007; Dunham and Bhat, 2008; Mello et al., 2010). This doubly important nature of the 2002 Denali event recorded at Pump Station 10 has motivated the present study whose purpose was to recreate such a record in the laboratory earthquake setup (Xia et al., 2004; Rosakis et al., 2007; Mello et al., 2010), using carefully constructed scaling arguments. This opens up the potential to routinely generate near-source strong ground motion records in a controlled laboratory earthquake setting. In addition to its scientific value, this study has an important implication for the response and integrity of buildings near a major fault. For example, the probability of a major earthquake occurring on the southern San Andreas fault in the next 30 years is considered high, and its effect will be felt by large population centers in southern California (Field et al., 2009). This study provides a solid physical framework for generating realistic near-field ground motions.

2. Background

The 2002 (M_w 7.9) Denali fault earthquake was the largest strike-slip rupture to take place on the North American continent in over 150 years and was comparable in magnitude, if not rupture length, only to the 1906 (M_w 7.8) San Francisco earthquake and the 1857 (M_w 7.9) Fort Tejon earthquake. Its total rupture length of 334 km, average slip of 4.9 m, and maximum slip of 8.8 m, ranks it amongst the largest shallow-crust earthquakes recorded anywhere in the world throughout the past two centuries (Haeussler et al., 2004; Bouchon et al., 2010). Due to its remote location within south-central Alaska, there was very little damage to modern infrastructure and fortunately no loss of human life. Field evidence and ground motion data from this event have, however, provided

* Corresponding author.
E-mail address: bhat@ipgp.fr (H.S. Bhat).

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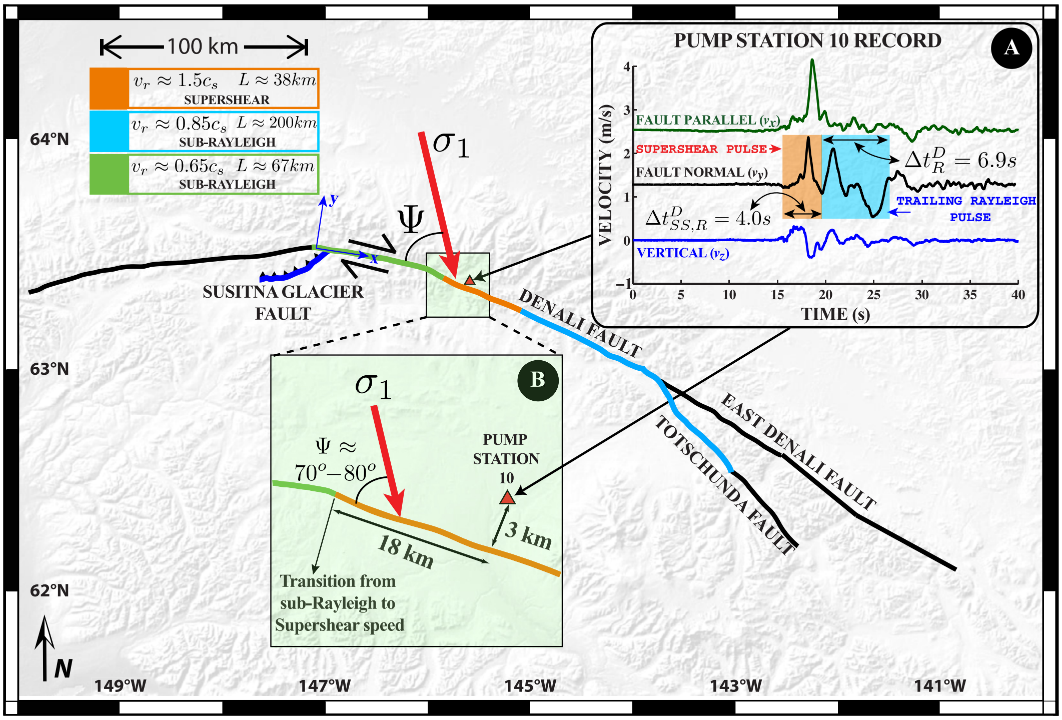

Fig. 1. 2002 M_w 7.9 Denali fault earthquake surface rupture trace annotated with the kinematic inversion results from Ellsworth et al. (2004b). Inset A shows the Pump Station 10 particle velocity records from Ellsworth et al. (2004a) and Inset B shows the region of interest for this work. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

seismologists with a rare and extraordinary opportunity to study a large, shallow crust, strike-slip earthquake, which is in many ways analogous to the major earthquakes which are known to occur along the San Andreas fault (Haeussler et al., 2004).

The Denali earthquake rupture initiated along a 40 km-long segment of the previously unknown Susitna Glacier thrust fault (Fig. 1). The rupture then transferred to the Denali strike-slip fault system and propagated 218 km from west to east along the central Denali fault. The rupture eventually branched off the Denali fault and stepped over onto the Totschunda fault where it propagated for an additional 76 km before finally arresting (Haeussler et al., 2004).

The central Denali fault ruptured beneath the trans-Alaska pipeline (TAP), which crosses the fault, and is located approximately 85 km east of the earthquake epicenter. Close to the TAP–Denali fault crossing a set of "celebrated" near-source ground motion records were obtained at Pump Station 10 (PS10) which is positioned at 63.424 N, 145.763 W along the TAP and is located just 3 km north of the fault. The accelerometer recording station at PS10 is part of the accelerograph network operated by the Alaska Pipeline Service Company. Ellsworth and colleagues (Ellsworth et al., 2004a, 2004b) conducted a thorough analysis and calibration of the PS10 instrumentation and re-processed the signals in order to recover the long-period (>10 s) ground motions. A set of instrument-corrected acceleration, velocity, and displacement time records were obtained and properly rotated into the fault normal (v_y) and parallel (v_x) directions. The fault parallel, fault normal, and vertical (v_z) velocity records are depicted in Fig. 1A.

Forward modeling of the instrument-corrected ground motion records led (Ellsworth et al., 2004a, 2004b) to conclude that a supershear burst occurred along a 38 km segment of the fault, which was nearly centered about PS10. The ground motion records were best matched by their kinematic model if a normalized sub-Rayleigh rupture speed of $V_r/C_s = 0.65$ was assumed over a 67 km stretch between the epicenter and the point of supershear transition. It also predicted that the normalized rupture speed jumped to $V_r/C_s = 1.5$ beyond supershear transition and propagated for a distance of 38 km. This was followed by a decrease to a normalized sub-Rayleigh rupture speed of $V_r/C_s = 0.85$ for points beyond the terminus of the supershear interval (i.e., distances >20 km east of PS10; see Fig. 1). The synthetic records do a reasonable job in capturing the general profile of the leading portions of the FP, FN, and vertical (UP) records although the synthetic vertical curves tend to over-predict the peak vertical ground velocity. The biggest shortcoming of the kinematic model was its inability to capture the prominent secondary pulse in the FN ground motion record which is shaded in blue in Fig. 1. Nevertheless, the careful processing of the instrument-corrected PS10 data and the interpretation of these remarkable ground motion records represent a major seismological finding and the most direct field evidence ever gathered for the existence of a supershear earthquake rupture. The existence of supershear ruptures was conclusively demonstrated in a physical setting in the laboratory earthquake experiments of Rosakis and his co-workers (Rosakis, 2002; Xia et al., 2004; Rosakis et al., 2007) but the Pump Station 10 observations provide one of the most reliable field evidence to their occurrence in the earth's crust.

The numerical investigations of Dunham and Archuleta (2004) noted specific features in the PS10 ground motion records, which they identified as characteristic ground motion signatures of a supershear earthquake rupture. The first unique feature of note involves the existence of a fault parallel (FP) velocity pulse which is approximately 1.5× greater in magnitude than the corresponding fault normal (FN) velocity pulse. The second unique feature is the existence of pronounced velocity swings following the main rupture pulse in the FN record, which (Ellsworth et al., 2004b) was unable to replicate using a simple kinematic model. Dunham and Archuleta (2004) reasoned that the secondary pulses in the FN record resulted from rupture acceleration during the supershear transition and the release of Rayleigh waves during this phase which combine to produce a secondary slip-pulse. This pulse