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Some insight on why Bam (Iran) was destroyed by an earthquake of relatively moderate size

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[1] The Bam (Iran) earthquake of 2003 resulted in one of the worst human disaster in recent years. Yet the magnitude of the event - M_w = 6.6 - was relatively moderate. We show that the remarkable recording of the ground motion produced in the city itself contains some clues which help explain this disaster. We identify three factors whose unfortunate combination led to the strong ground shaking which destroyed the city: 1) The Rayleigh-like speed of the rupture, 2) The high slip velocity, which exceeded 2m/s over a large part of the fault, 3) The strong directivity, which focused the elastic energy released directly toward the city. **Citation:** Bouchon, M., D. Hatzfeld, J. A. Jackson, and E. Haghshenas (2006), Some insight on why Bam (Iran) was destroyed by an earthquake of relatively moderate size, *Geophys. Res. Lett.*, *33*, L09309, doi:10.1029/2006GL025906.

1. Introduction

[2] On December 26 2003, an earthquake of relatively moderate size - M_w = 6.6 - occurred in southern Iran. The earthquake destroyed the ancient city of Bam, killing about 26,000 people in this city and suburbs of about 140,000 inhabitants. 70% of the houses and buildings in the city collapsed, resulting in a casualty rate extraordinarily high [*Zaré*, 2004]. About one earthquake of magnitude similar or higher occurs every week worldwide. Why then was this particular event so destructive, resulting in one of the highest death toll in recent years? Part of the answer has to do with the location of the city near the fault itself and the structural weakness of many houses made of masonry and adobe. Nevertheless damage seems disproportionate for this magnitude earthquake. Rupture directivity has been suggested as an aggravating factor [*Nakamura et al.*, 2005] but has not been quantified due to the poorly-known hypocentral location. We will show that the recording of the ground motion produced by the earthquake in the city itself contains some clues which help explain this disaster.

2. The Earthquake

[3] The earthquake involved rupture of a nearly vertical north-south trending right-lateral strike-slip fault [*Talebian et al.*, 2004]. Exceptionally good images of the ground deformation were obtained by satellite Interferometric Synthetic Aperture Radar (InSAR) [*Talebian et al.*, 2004; *Wang et al.*, 2004]. They show the precise location of the rupture which extends directly southward from Bam for about 15km, resulting in the configuration depicted in Figure 1. The inversion of the InSAR data gives the spatial distribution of slip on the fault [*Funning et al.*, 2005] (Figure 1). The ground motion produced by the earthquake was recorded in the destroyed city itself. This is a unique case where a direct recording of the ground motion was made in a place so massively destroyed. The station was installed and maintained by the Iranian Building and Housing Research Center. The instrument is a Kinemetrics SSA2 accelerograph and has a flat response in frequency so that the integration of the records yields the ground velocity (Figure 2) while a second integration yields the ground displacement. The dominant feature of the ground motion is the high-amplitude EW pulse, transverse to the fault. During the 2 to 3s duration of this pulse, the NS and vertical motions are small as theoretically expected because the station sits nearly on the fault strike where motion is mostly transverse to the fault [*Aki*, 1968]. The origin of the predominantly NS disturbance which arrives 2s after the EW pulse is unknown.

3. Rupture Directivity

[4] The records allow a precise measurement of the distance between the station and the hypocenter. The characteristic of the transverse motion is the one theoretically expected for a NS trending right-lateral strike-slip fault where rupture propagates northward toward the station. The arrival of the hypocentral S-wave corresponds to a polarity reversal from the eastward motion of the near-field P-wave to the westward motion of the S-wave. The records thus yield a S-P time of 1.9s (Figure 2), which, for the upper-crustal velocities inferred in the region [*Tatar et al.*, 2005], places the zone of rupture initiation at about 13.7km from the station. The spatial distribution of slip on the fault obtained from InSAR shows that the earthquake was a shallow event with most of the slip occurring between 2 and 8km depth [*Funning et al.*, 2005] (Figure 1). The hypocentral distance inferred places the point of initiation near the southern edge of the ruptured area. In such a configuration, the strain elastic energy released is strongly focused in the direction of the propagating rupture [e.g., *Favreau and Archuleta*, 2003], that is northward. It is precisely there, near the northern edge of the slip patch that Bam was located.

4. Rupture and Slip Velocities

[5] To understand how other factors played a role in the destruction of the city, we calculate the ground motion

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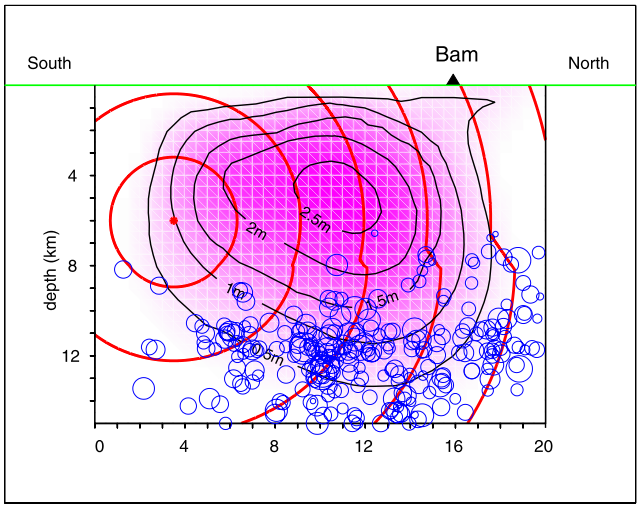


Figure 1. Configuration of the Bam earthquake: The fault geometry and slip distribution are the ones inferred by InSAR [*Funning et al.*, 2005]. The position of the rupture front (red curves) is shown at 1s intervals for the favored hypocenter (red dot). The triangle shows the location of the city (the precise location of the accelerograph station relative to the fault can be seen in the work by *Fielding et al.* [2005]). The blue circles are the aftershocks [*Tatar et al.*, 2005] and their size scales with magnitude.

produced in Bam using the InSAR-inferred slip model and the hypocentral distance just determined and compare it to the recorded one. As the hypocentral depth is not directly known, we shall first consider two possibilities: 5km, which is the depth at which the largest slip occurred, or 10km, which places the initiation of rupture near the bottom of the slip patch. The upper-crustal velocity model is known from the recordings of aftershocks at stations deployed in the field after the earthquake [*Tatar et al.*, 2005] and was obtained by inverting the arrival times of over 300 events recorded at 23 stations. It consists of an 8km-thick upper layer with P-wave velocity of 5.3km/s overlaying a medium with P-wave velocity of 6.17km/s. The *Vp*/*Vs* ratio of P to S-wave velocities inferred from a total of 9300 arrivals is 1.731 ± 0.002. Subsoil in Bam is hard and bedrock lies only about 25m below the surface [*Towhata et al.*, 2004], so the upper few meters of soil should have had little effect on the ground velocity. Locally on the fault, slipping begins at the arrival of the rupture front and lasts for a certain duration, called the rise time. After this time, slip has reached its final value which is the one inferred from InSAR. How slip evolves with time over the rise time interval depends on the friction law parameters [e.g., *Das and Kostrov*, 1988; *Cochard and Madariaga*, 1994; *Guatteri and Spudich*, 2000], which are largely unknown. As we shall show later however, this is not critical to the present analysis and we will first simply assume that slip increases smoothly with time over this interval. We choose to represent this evolution by the smooth ramp function:

$$s(t) = \frac{s_o}{2}\left[1 + \tanh\left(\frac{t - t_{rise}/2}{t_{rise}/8}\right)\right]$$

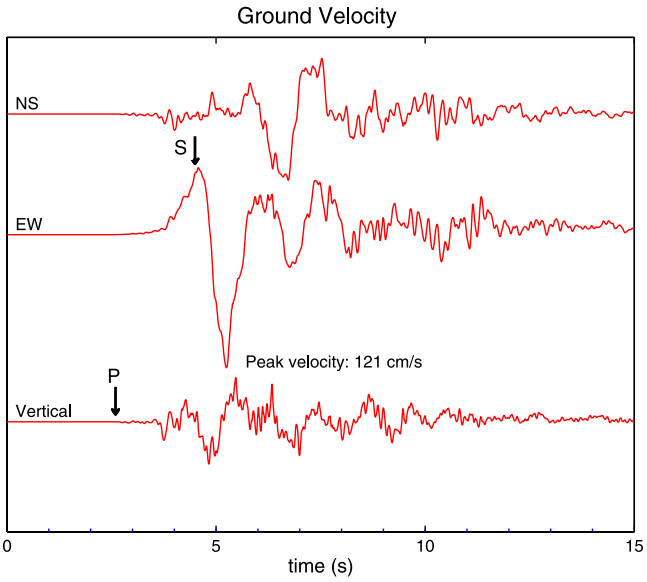


Figure 2. Ground velocity recorded in Bam. P indicates the timing of the first seismic arrival. S shows the onset of polarity reversal associated with the S arrival.

where s_o is the final slip and t_{rise} the rise time. The corresponding peak slip velocity is $2s_o/t_{rise}$.

[6] The only unknown parameters of the problem are thus the rupture velocity that we choose to be a fraction of the local shear wave velocity and the rise time. We first set rupture velocity at 75% of the local shear wave velocity, which may be considered an "average" value representative of the range of rupture velocities inferred in earthquakes [e.g., *Madariaga*, 1976], and assume a uniform value of t_{rise}

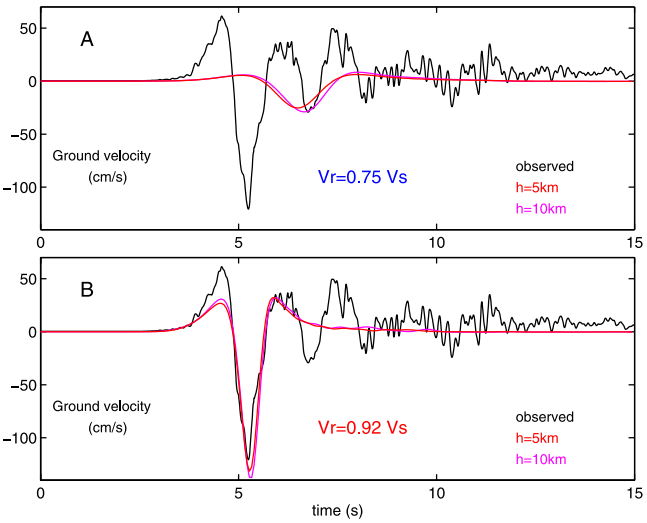


Figure 3. Comparison of the observed EW ground velocity with the one calculated using (a) a rupture speed equal to 75% of the local shear wave velocity and a peak slip velocity averaging 1m/s over the slip patch and (b) a rupture speed equal to the Rayleigh velocity and a peak slip velocity averaging more than 2m/s over the slip patch. h denotes the hypocentral depth. Traces begin at the inferred origin time of the earthquake.

of 3s, chosen so that peak slip velocity over the slip patch is, on average, of the order of 1m/s, typical of values determined for well-resolved earthquakes [e.g., *Heaton*, 1990]. The calculation is done by the discrete wavenumber method [*Bouchon*, 2003]. The comparison with the recorded ground velocity (Figure 3a) shows that the calculated amplitude is much smaller than the observed one. The late timing of the peak velocity, known theoretically to be associated with the passage of the rupture front, indicates that rupture velocity is too low, while the too broad pulse suggests that the rise time is too long. The best fit of timing and width of the pulse is obtained for a rupture velocity equal to 92% of the local shear wave velocity and a value of t_{rise} of 1.4s (Figure 3b). This rupture velocity is, surprisingly, the Rayleigh wave velocity of the medium. The value inferred for t_{rise} implies that slip velocity exceeded 2m/s over most of the slip patch. These values explain remarkably well, not only the timing and shape, but also the amplitude of the ground velocity recorded in Bam.

[7] To test the robustness of the results, we consider alternative slip-time evolutions. Dynamic rupture simulations [e.g., *Madariaga*, 1976; *Das and Aki*, 1977] show that slip duration varies over the fault and is strongly correlated to the final slip. Using a local rise time proportional to final slip, $t_{rise} = 0.8 s_o$ (Figure 4a), still requires a Rayleigh rupture velocity. The whole fault now slips with a uniform peak velocity of 2.5m/s.

[8] The slip-time evolution that we have considered so far is characterized by a smooth onset and healing of the rupture. Theoretical work in fracture dynamics [e.g., *Madariaga*, 1976; *Das and Aki*, 1977] predicts a more abrupt onset of rupture that we simulate by the functional representation, derived from crack solutions:

$$s(t) = H(t)H(t_{rise} - t)s_o\sqrt{1 - \left(\frac{t - t_{rise}}{t_{rise}}\right)^2}$$

where $H(t)$ is the Heaviside function. Comparable expressions compatible with dynamic solutions have been derived by *Nielsen and Madariaga* [2003] and *Piatanesi et al.* [2004]. Following these authors, we avoid the unphysical slip velocity singularity of this function at time 0, by smoothing it in time with a triangular window and assume again a rise time proportional to final slip. The best fit (Figure 4b) is obtained for a rupture velocity equal to 91% of the local shear wave velocity - 1% below the Rayleigh velocity - and a slip velocity on the high-slip patch exceeding 2m/s. These values reproduce remarkably well not only the timing and width of the recorded ground velocity pulse, but also its amplitude.

5. Discussion

[9] The simulation of the recorded ground motion yields the following results: 1) Rupture propagated over the fault at Rayleigh or very near Rayleigh speed; 2) Slipping occurred at high slip velocity exceeding 2m/s over a large part of the fault; 3) Strong directivity, resulting from the location of the hypocenter opposite the city relatively to the ruptured area, focused the elastic energy released directly toward Bam. The unfortunate combination of these three factors resulted in the strong ground shaking which destroyed the city.

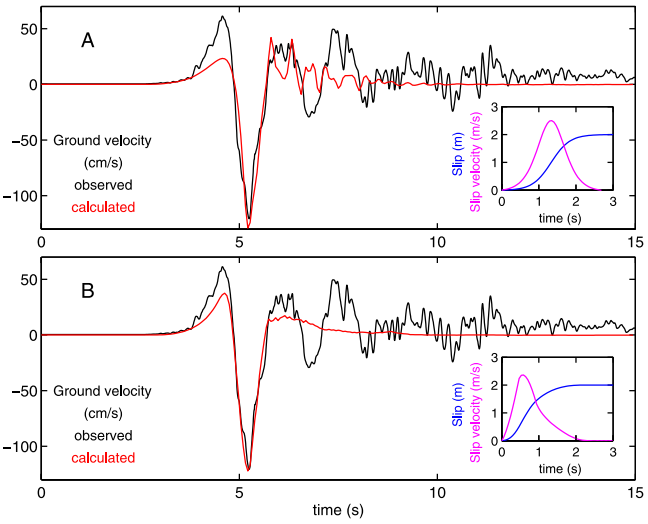


Figure 4. Comparison of the observed ground velocity with the ones calculated for two different assumptions of the slip-time evolution. Corresponding slip and slip velocity at fault locations where final slip is 2m are displayed in each figure inset. The rupture velocity is (a) the Rayleigh velocity and (b) 1% below the Rayleigh velocity. The hypocentral depth (6km) is the one which best fits the data.

[10] Rupture velocities inferred in earthquakes are commonly in the range 0.65 to 0.85 *Vs* [e.g., *Madariaga*, 1976; *Heaton*, 1990]. As rupture velocity increases in this range, larger ground motions are produced near the fault. For a rupture propagating at Rayleigh-like speed, this amplification is maximum, as the Rayleigh velocity is the classical upper limit for mode II ruptures like the Bam earthquake. Theoretical work in fracture dynamics [*Richards*, 1973] predicts that a rupture propagating at near Rayleigh velocity is associated with high slip velocity, thus further increasing near-fault motion as observed in the Bam earthquake.

[11] Although the rupture velocity inferred - about 2.8km/s - is not unusually high for earthquakes, because most observations of rupture velocity come from deeper events for which the medium shear velocity is higher than in the present case, its Rayleigh-like value holds special significance and may help explain some of the other unusual characteristics of this event. During an earthquake, part of the strain energy released by the rocks is supplied to the crack tip where it provides the energy necessary for fracturation. Theory [*Freund*, 1990; *Broberg*, 1999; *Rosakis*, 2002] shows that this energy supply decreases to zero as rupture speed increases to the Rayleigh velocity limit. For a crack propagating at near Rayleigh speed little energy is available for fracturation which implies that the bond between the crack faces must be very weak. A mode II rupture cannot propagate at speeds between Rayleigh and shear velocity because in this range the energy supplied to the crack tip would be negative. Beyond the shear wave speed, energy can be supplied again and a few observations of supershear ruptures have been made. Thus, the Rayleigh-like speed of the Bam rupture implies that the fault was weak and broke easily. This could explain the unusual

pattern of aftershocks which are conspicuously absent from the slip patch but concentrate below it [*Tatar et al.*, 2005] (Figure 1). The two slip time functions used may be interpreted in terms of friction law parameters. The last one considered (Figure 4b) resembles the slip evolution obtained for small values of D_c, the slip-weakening distance, while the first one (Figure 4a) is more representative of a large D_c [*Guatteri and Spudich*, 2000; *Piatanesi et al.*, 2004; *Tinti et al.*, 2005]. The better fit of the early part of the record achieved with the short D_c time function is consistent with a fast rupture requiring little energy to advance, because fracturation energy is proportional to D_c [e.g., *Favreau and Archuleta*, 2003; *Tinti et al.*, 2005].

[12] Another peculiarity of the earthquake is that, although fault slipped at shallow depth, little of this slip reached the surface. Even more surprisingly, the fault was unknown before the earthquake, as no land feature indicates its presence. The ease with which it broke, however, shows that it is a mature seismogenic fault. The fact that the shearing of the rocks took place at high velocity, exceeding 2m/s, might have helped decouple the upper few hundred meters from the rocks below and might have contributed to the lack of surface rupture.

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