The Slapdown Phase in High Acceleration Records of Large Earthquakes

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Abstract:

This paper focuses on the acceleration records of the station IWTH25, one of which recorded 4g during the 2008 Iwate-Miyagi Nairiku earthquake and high vertical acceleration records from other earthquakes. The vertical acceleration record has asymmetric amplification between the upward and downward directions. We explain this asymmetric amplification for this and other earthquakes with large vertical accelerations, in terms of a slapdown phase, which is typically seen in near-field recordings of nuclear explosions. We assume that there is a near-surface soil layer that separats from a sublayer and is flung upwards by large vertical accelerations. When this layer returns striking the separation surface, the high acceleration slapdown phase is produced. We estimate that the separation distance of the layer is 1 to 12 mm.

1 Introduction

The 2008 Iwate-Miyagi Nairiku earthquake (M_w 6.9, M_{jma} 7.2) produced strong shaking throughout northern Honshu, Japan with severe damage of buildings and extensive landslides. The shallow event occurred in southwestern Iwate prefecture (39.03°N, 140.88°E, depth 8 km) on June 13, 2008 at 23:43:45 GMT (Japan Meteorological Agency, 2008). This earthquake produced relatively high-frequency ground motions, which resulted in large values of PGA (peak ground acceleration). The surface accelerometer of the station IWTH25 of KiK-net, located 3 km southwest of the epicenter, produced one of the largest strong-motion values of PGA (4278 cm/s^2 for the vector sum of the three components) ever recorded (KiK-net, 2000).

The new accelerometers installed in KiK-net last year have a recording range up to 4000 cm/s^2, which made it possible to record such large ground motions near the source (KiK-net, 2000). The

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sampling rate of the record of IWTH25 is 100 Hz (KiK-net, 2000).

The surface acceleration record at the station IWTH25 shows an asymmetric amplification in the vertical components (Aoi et al., 2008). The upward vertical acceleration is much larger than the downward direction, although in the borehole record at a depth of 260 m at the same site, the upward and downward accelerations have symmetric amplitudes (Figure 1). On the other hand, the horizontal components do not show this asymmetric effect. This difference between the surface and borehole recordings for the vertical component implies a strong non-linear amplification. In this paper, we will analyze these records and propose a mechanism to produce the large vertical accelerations. The predominance of large upward acceleration spikes is not unique to the Iwate-Miyagi Nairiku earthquake, so our proposed mechanism may be applicable to a number of large vertical acceleration records.

2 Observation for the 2008 Iwate-Miyagi Nairiku earthquake

The KiK-net station IWTH25 (operated by the National Institute for Earth Science and Disaster Prevention) has accelerometers on the surface and in a borehole at a depth of 260 m. In Figure 1, the red and black lines show the borehole and ground surface records, respectively. The amplification of the vertical acceleration is much larger than that of the horizontal acceleration, and many of the upward peaks of the vertical acceleration are much larger than the downward peaks. However, the velocity and displacement waveforms (time-domain integration of acceleration) are quite similar for the borehole and ground surface data. These data indicate that the large amplitude high-frequency accelerations are due to near-surface effects and are not coming from the earthquake source. The frequency-dependent amplifications in the near-surface are somewhat different between the mainshock and a large aftershock (M_j 5.6). On the horizontal components there appears to be larger amplification for the aftershock in the 10 to 20 Hz range, while for the vertical component there is a larger amplification for the mainshock in the 10 to 20 Hz range (Figure 2).

Taking a closer look at the acceleration record, Figure 3 shows the borehole and surface accelerations focused on the time of the large amplitudes. The borehole acceleration is symmetric, but the surface acceleration is asymmetric in both amplitude and frequency. The positive pulses (dark-gray-colored sections) are narrow with large amplitude, while the negative pulses (light-gray-colored sections) are broader with smaller amplitude. The areas of the upward and downward pulses are the same, which explains why integrating the acceleration records gives similar velocity records for the borehole and surface records. Therefore, the borehole record is regarded as the input ground motion, and the surface record is a combination of this input motion and the high-frequency near-surface response. Note that the 100 Hz sampling might not be high enough to record the actual high frequency accelerations associated with the impact of a separated layer at depth, although the near-surface attenuation will also damp the motions.

3 Large Vertical Accelerations for Other Earthquakes

Figure 4 shows the available strong motion records that have vertical accelerations over 1g. Table 1 shows the PGA values and soil conditions at the stations. Most of the records are on stiff soil. One can see that all the records tend to have larger upward accelerations than downward. Also, the vertical component tends to be larger than the horizontal component. For example, the record of the 1976 Gazli earthquake (M_w 6.3) shows a vertical PGA (1310 cm/s^2) that is about twice as large as the horizontal PGA (729 cm/s^2). The vertical PGA (2321 cm/s^2) of site 1 for the 1985 Nahanni earthquake (M_w 6.4) is also twice as large as of the horizontal PGA (1338 cm/s^2).

The asymmetric amplification of the vertical acceleration is also very obvious for a number of the vertical acceleration records from around the world (see Figure 4). Figure 5 (a) shows the relationship between the upward and downward PGA of the vertical records that have amplitudes greater than 500 cm/s^2. The U/D ratio (upward-to-downward peak acceleration ratio) is close to 1 if the vertical PGA is less than 1g (980 cm/s^2), and the U/D ratio is significantly larger if the vertical PGA is greater than 1g. For records that have accelerations greater than 1g, the positive amplitudes of the vertical acceleration are larger than the negative amplitudes and the downward accelerations seem to have a lower bound of about 1g (Figure 4).

4 Slapdown Phase

Large upward spikes in acceleration are observed in near-field observations of nuclear explosions (Eisler and Chilton, 1964; Chilton et al., 1966), which may be analogous to these strong motion records. There is a substantial body of work on spall that comes from the explosion seismology during 1960 to 1970 (Eisler et al., 1966; Day et al., 1983; Viecelli, 1973; Springer, 1974; Day and McLaughlin, 1991). In the process of nuclear explosions, an upper soil layer separates (spalls) and is flung upward due to large tensile stress from extremely large accelerations caused by the explosion (on the order of several tens of g). Then, the layer free flies to the ground with a downward acceleration controlled by gravity. When the returning layer hits the original separated surface, a large upward spike in acceleration is produced (slapdown phase) . Figure 6 (left) shows the particle acceleration and velocity from a surface instrument during a nuclear explosion (Perret, 1972). The velocity was digitized from the original figure in the paper and differentiated to acceleration. In the acceleration record, the first upward spike is the direct shock from the nuclear explosion, then the extended acceleration at negative 1g is due to free flight, and the second upward spike is the slapdown phase. Figure 5 (b) shows the comparison of the U/D ratio of vertical accelerations for large earthquakes and nuclear explosions (Perret, 1973). The records for the nuclear explosions also have similar characteristics with records for large earthquakes, as the positive amplitudes are larger than the negative amplitudes and the downward accelerations have a lower bound of about 1g.

Figure 6 (middle) and Figure 6 (right) are earthquake strong-motion records which we interpret in the same way, assuming that there is a near-surface soil layer separated from a sublayer. The relatively long period negative acceleration is associated with the free flight of the near surface layer that has been flung upward by large vertical accelerations. When the surface layer returns and hits the sublayer, the positive sharp spike in acceleration is produced. One difference from the explosion record is that the input ground motions from the earthquake are not a single pulse, as in the explosion. This interpretation is somewhat similar to the explanation of Aoi et al. (2008), which uses a model of a mass bouncing on a trampoline. Both of these interpretations invoke a free flight of the near-surface layer to explain the negative 1g accelerations.

In Figure 4, the large upward spikes in the records at site 1 for 1985 Nahanni earthquake, station IWTH04 for the 2003 Miyagi-ken Hokubu-oki earthquake, and station TTN034 for the 2003 Chengkung earthquake appear to show clear individual slapdown phases. The records at stations IWTH25 and AKTH04 for the 2008 Iwate-Miyagi Nairiku earthquake and station Gazli for the 1976 Gazli earthquake show more complicated waveforms that may include multiple slapdown phases along with the input ground motion. All stations in Figure 4 are on considered to be on relatively stiff sites, so the slap-down phase is likely to be generated by a brittle fracture in the subsurface.

There are several reasons why the slapdown phases are not seen in the borehole record. Note that similarly for acceleration waveforms from nuclear explosions, the slapdown phase was not clearly seen on a borehole accelerometer (e.g. Eisler et al., 1966). The downhole accelerometer is 4 to 8 times as far as the surface accelerometer, assuming the separation of the surface layer is 30 to 60 m (this assumption is explained in the next section), so that the high frequency waves may largely be attenuated. Also, the shallow lower velocity material tends to amplify the waves more than the harder layers at depth. Probably most importantly, although the stress at the separated boundary is the same in the upward and downward directions, the acceleration of the upper separated layer will be larger than the basement rock which is fixed to the rest of the Earth. This is somewhat analogous to the larger ground motions seen for the hanging wall of thrust faults, compared to the foot wall.

5 Separation of the Near-Surface Layer

Using this model of a spalling near-surface layer, we can estimate the dimensions of the thickness of the layer and the amount it separates from the sublayer. Eisler and Chilton (1964) show that the thickness of the spalled layer and the spall gap (vertical displacement of the surface layer from the separation surface) can be computed from the acceleration data. When spalling occurs, surface acceleration records consist of a direct pulse and slapdown phase separated by a period of constant negative gravity acceleration (Eisler and Chilton, 1964; Eisler, 1967). Assuming the separation surface does not move and the spalled layer returns to the original level,

$$S_{max} = \frac{g}{8}(\Delta t_g)^2, \tag{1}$$

where S_{max} is the maximum spall gap, g is a gravity acceleration, and Δt_g is the total free-flight time. The slap-down phase is generated while the compressional wave travels from the surface, and reflects back from the now-closed spall gap. Again, assuming no seismic wave follows the slap-down phase, the thickness of the spalled layer (d) is computed from the duration of the slap-down phase (Δt_s) and the P-wave velocity (v_p);

$$d = \frac{\Delta t_s}{2} v_p. \tag{2}$$

If we assume the seismic ground motion can be treated as a sequence of multiple slapdown phases, the thickness of the layer and the separation gap can be computed from the records. In Figure 3, the duration of Δt_g varies for the pulses, and the duration of Δt_s is almost constant. This observation implies that the spall gap changes depending on the pulse, but the thickness of the spalled layer is constant. By equations 1 and 2, the amount of separation of the layer (S_{max}) is about 1 to 12 mm, and the thickness of the layer (d) is about 46 to 58 m for the acceleration record at station IWTH25 in Figure 4. The layer thickness is consistent with the velocity profile for this station which shows sand and sandy clay layers (KiK-net, 2000). In the record at site 1 for the Nahanni earthquake in Figure 6, the separation distance is about 2 to 8 mm, and the layer thickness is about 30 m, assuming v_p=1km/s. For these examples, the range of the separation gap is roughly less than 1 cm, and the range of the thickness of the near-surface layers is 30 to 60 m. These numbers seem to be reasonable values for the mechanism to produce the asymmetric acceleration records.

6 Conclusions

We analyzed the 4g record of the 2008 Iwate-Miyagi Nairiku earthquake and provide an explanation for the asymmetric amplification in the vertical acceleration. We interpret the large upward spikes in acceleration as slapdown phases, which are also typically observed in near-field recordings of nuclear explosion tests. The large upward acceleration is produced when a near-surface layer separates from the sublayer then returns, striking the separation surface. This effect is seen in a number of strong-motion records that have larger upward than downward accelerations. If we assume the near-surface layer returns to the original level, the separation gap is roughly 1 to 12 mm, and the thickness of the layer that is flung upward is 30 to 60m.

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Acknowledgments

The authors acknowledge the National Research Institute for Earth Science and Disaster Prevention (NIED) and JMA for the use of strong motion data. We thank Dr. Yih-Min Wu in National Taiwan University to offer the record of Chengkung Earthquake, and Dr. Luis Rivera in Louis Pasteur University and Dr. Hiroyuki Goto in Kyoto University for the meaningful discussion. Reviewers provided detailed comments that greatly improved this manuscript. This research was funded by the Program for Improvement of Research Environment for Young Researchers from Special Coordination Funds for Promoting Science and Technology (SCF) commissioned by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

Figures and Tables

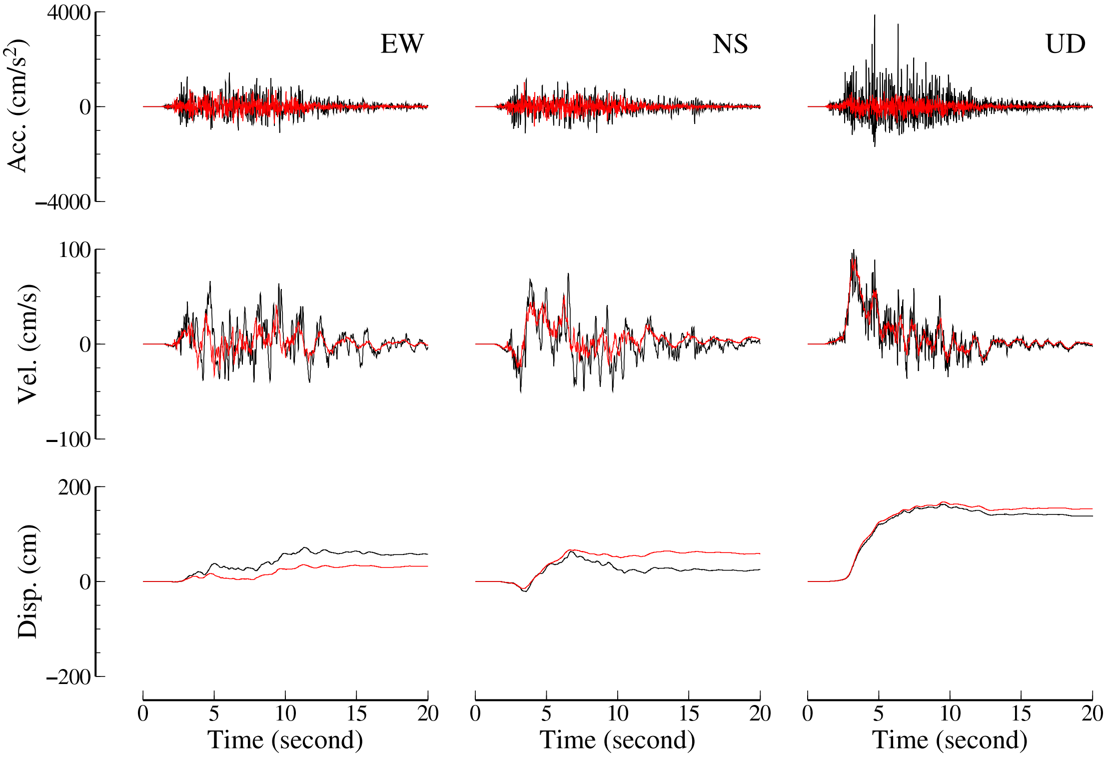

Figure 1: Three-component acceleration, velocity, and displacement records at station IWTH25 for the 2008 Iwate-Miyagi Nairiku earthquake. The red and black lines are records for the borehole and surface, respectively.

Station	Earthquake	Date	Acc+	Acc-	Soil condition	Reference
gazli	Gazli	1976/5/17	1310	1040	tertiary sedimentary rock	COSMOS VDC
site1	Nahanni	1985/12/23	2309	631	bedrock	COSMOS VDC
IWTH04	Miyagi	2003/5/26	1280	480	Vs30: 456m/s	KiK-net
TTN034	Chengkung	2003/12/10	1866	1157	Class D	CWB
041	Chuetsu	2004/10/23	1059	815	Vs30: 641m/s	Kubo et al. (2003)
AKTH04	Iwate-Miyagi	2008/6/14	1094	847	Vs30: 459m/s	KiK-net
IWTH25	Iwate-Miyagi	2008/6/14	3866	1703	Vs30: 526m/s	KiK-net

Table 1: List of the records of which the vertical acceleration exceeds 1000 cm/s^2. The columns show the station ID, earthquake, date of the earthquake, upward PGA (cm/s^2), downward PGA (cm/s^2), and soil condition. The soil condition is cited from the COSMOS Virtual Data Center website, KiK-net website, personal communication with CWB, and Kubo et al. (2003). The VS30 is the average shear wave velocity for the surface 30m. Class D corresponds to the Vs30 is equal to 180-360 m/s.

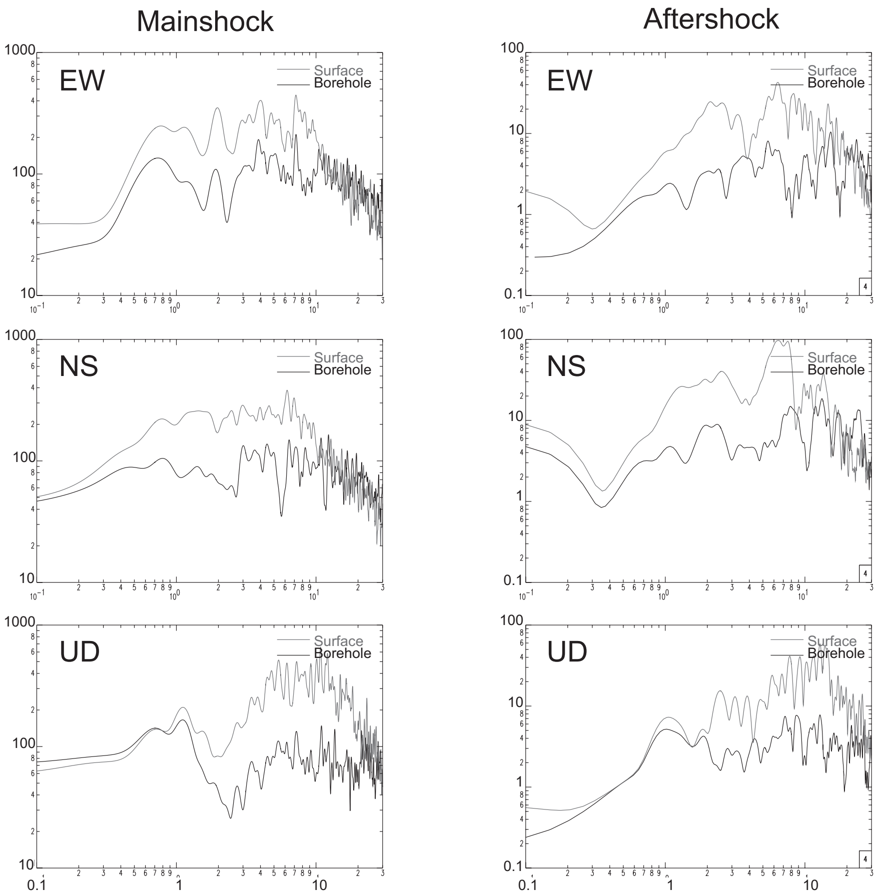

Figure 2: Acceleration amplitude spectra at the station IWTH25 in the EW, NS, and UD components from the top. The black and gray lines show the borehole and ground surface records, respectively. The left column is for the mainshock, and the right column is for the largest aftershock (M_j 5.6).

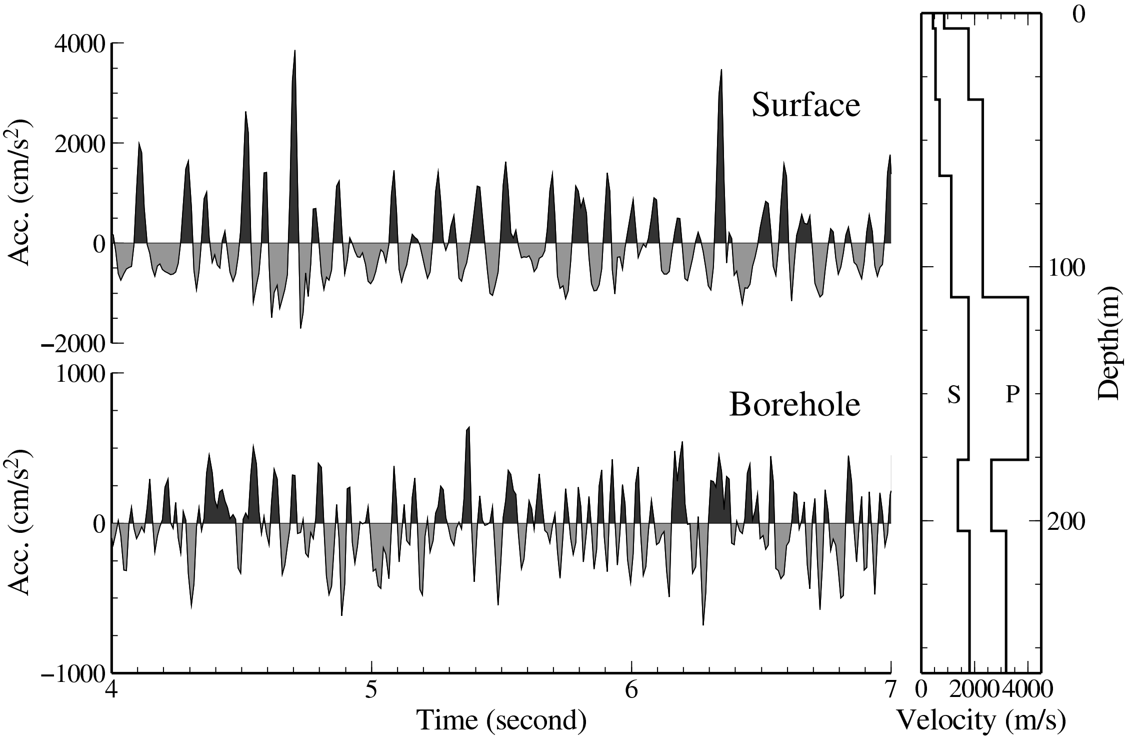

Figure 3: Expanded view of acceleration waveforms of station IWTH25. Top is the surface record and bottom is the borehole record. The right figure shows P- and S-wave velocity structures at the station.

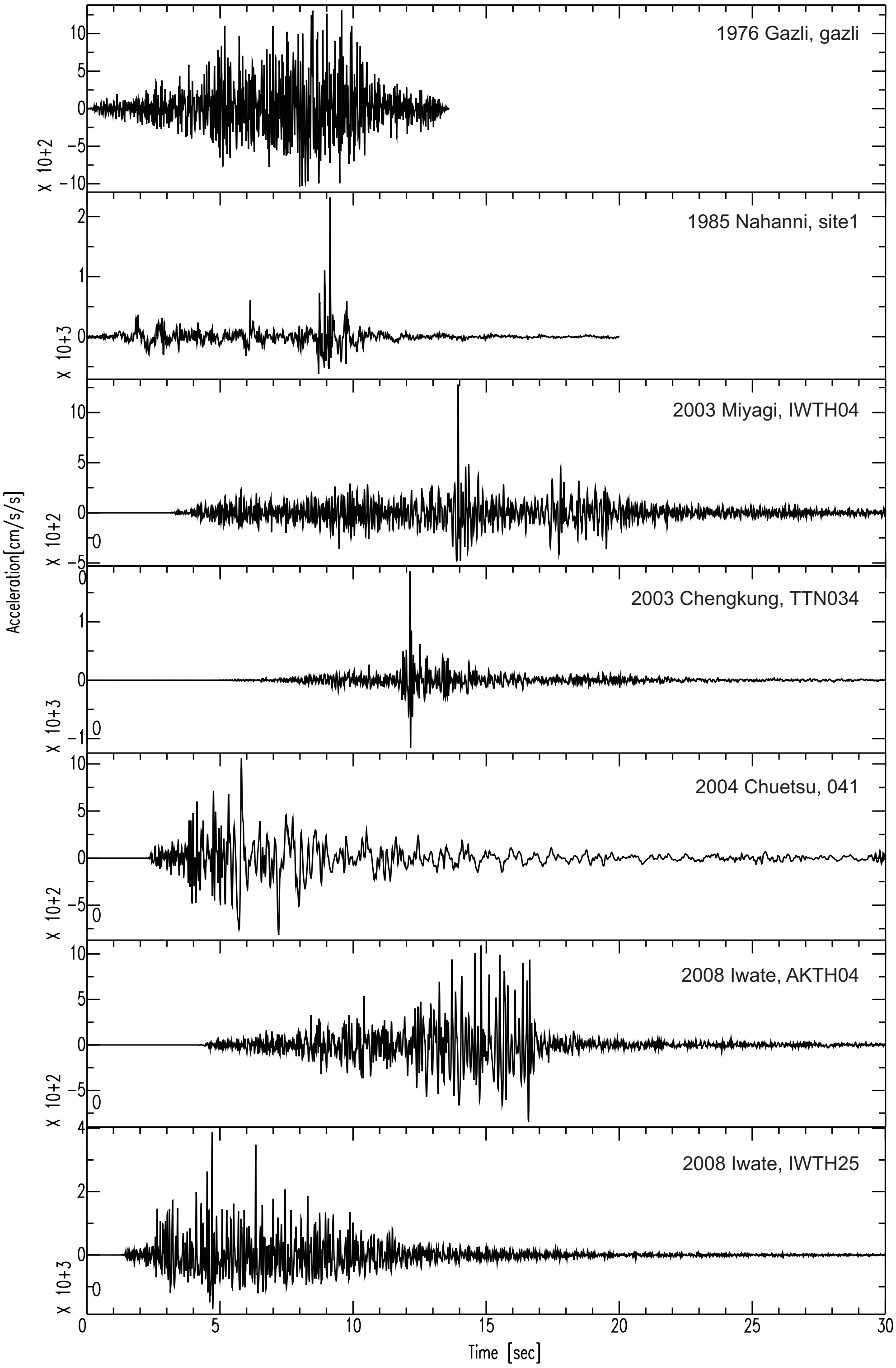

Figure 4: Acceleration records on stiff sites that have vertical accelerations over 1g.

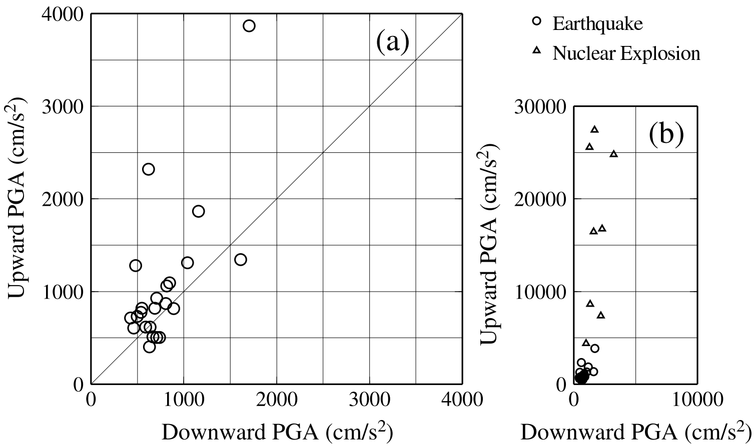

Figure 5: Relationship between the upward and downward PGA for large acceleration records.

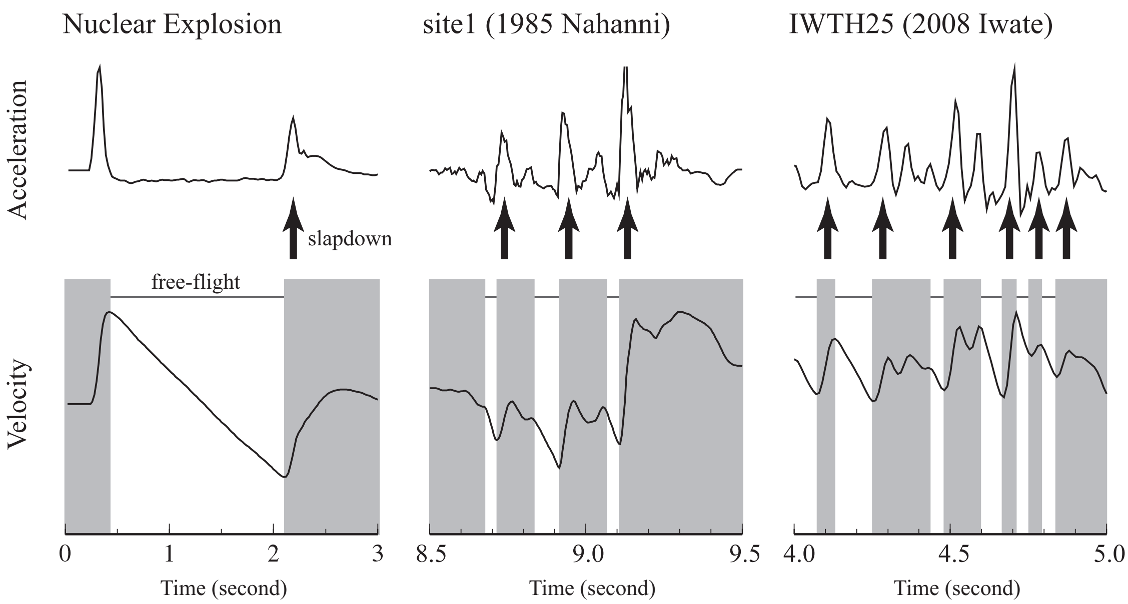

Figure 6: Slapdown phase observed in the record of the nuclear explosion on Perret (1972), site1 during the 1985 Nahanni earthquake, and IWTH25 during the 2008 Iwate-Miyagi Nairiku earthquake.