

The Slapdown Phase in High-acceleration Records of Large Earthquakes

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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 to buildings and extensive landslides. The shallow event occurred in southwestern Iwate Prefecture (39.03°N, 140.88°E, depth 8 km) on 13 June 2008 at 23:43:45 GMT (Japan Meteorological Agency 2008). This earthquake produced relatively high-frequency ground motions, which resulted in large values of peak ground acceleration (PGA). 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 (4,278 cm/s² for the vector sum of the three components) ever recorded (http://www.kik.bosai.go.jp/kik/index_en.shtml).

The new accelerometers installed in KiK-net last year have a recording range up to 4,000 cm/s², which made it possible to record such large ground motions near the source (http://www.kik.bosai.go.jp/kik/index_en.shtml). The sampling rate of the record of IWTH25 is 100 Hz (http://www.kik.bosai.go.jp/kik/index_en.shtml).

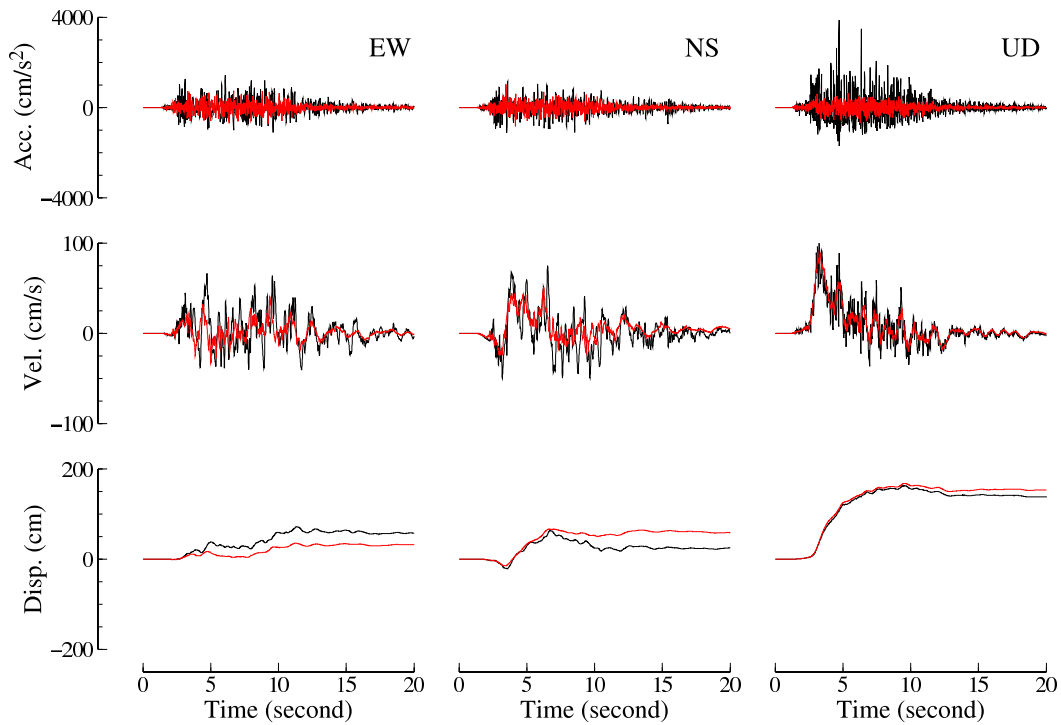
The surface acceleration record at station IWTH25 shows an asymmetric amplification in the vertical components (Aoi *et al.* 2008). The upward vertical acceleration is much larger than the downward direction, although in the borehole record at a depth of 260 m at the same site, the upward and downward 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 nonlinear 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.

THE 2008 IWATE-MIYAGI NAIRIKU EARTHQUAKE

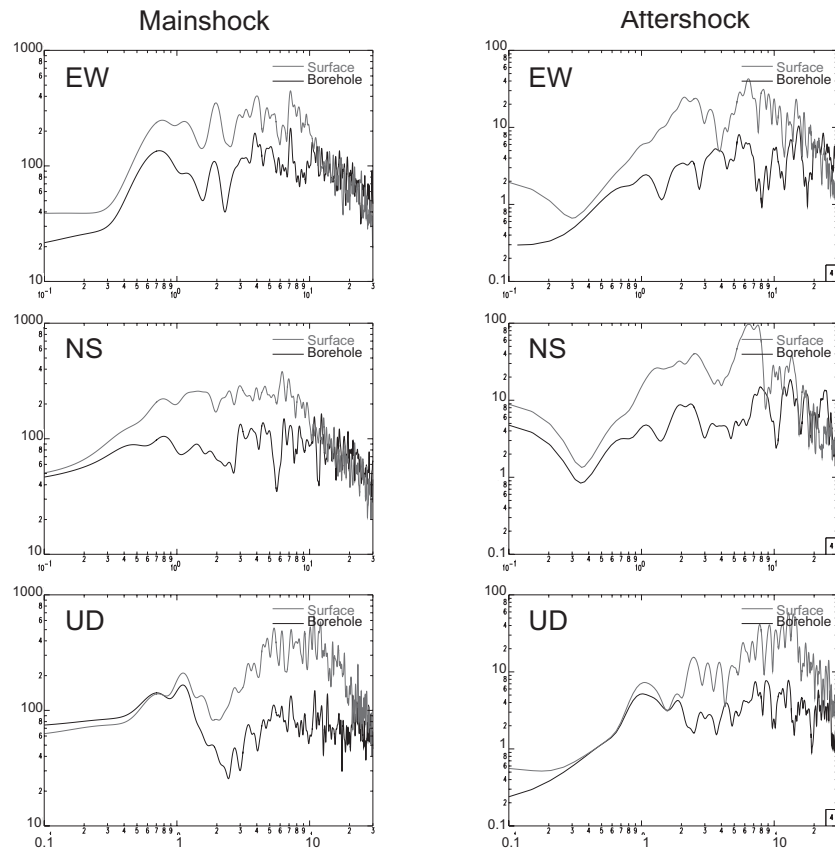
The KiK-net station IWTH25 (operated by the National Research Institute for Earth Science and Disaster Prevention) has accelerometers on the surface and in a borehole at a depth of 260 m. In Figure 1, the red and black lines show the borehole and ground surface records, respectively. The amplification 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 for the mainshock and a large aftershock (M_j 5.6). On the horizontal component 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.

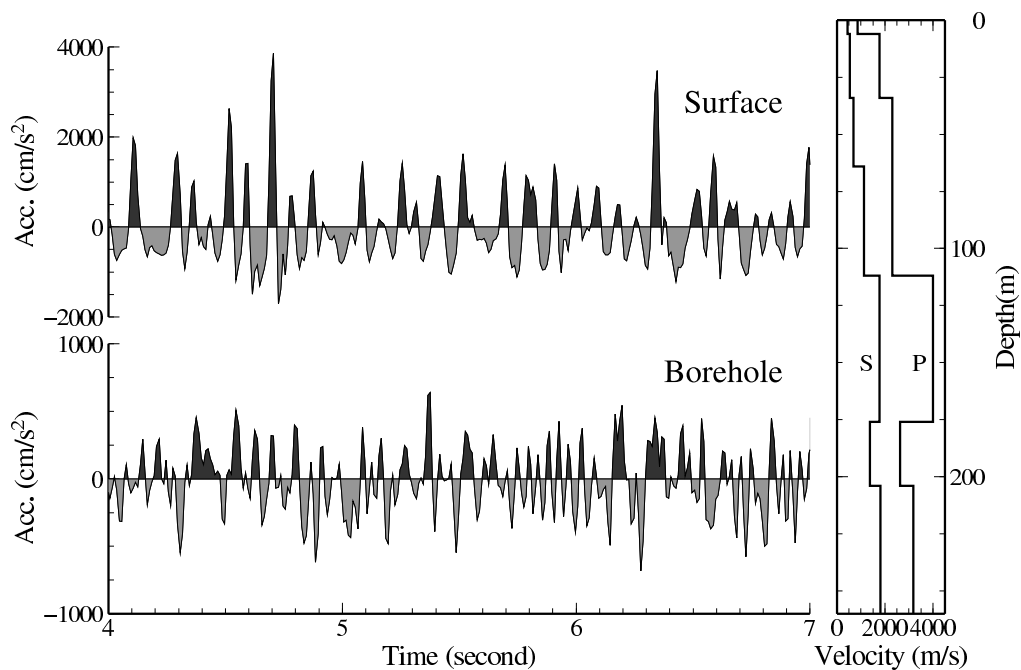
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▲ **Figure 1.** Three-component acceleration, velocity, and displacement records at station IWTH25 for the 2008 Iwate-Miyagi Nairiku earthquake. The red and black lines are records for the borehole and surface, respectively.



▲ **Figure 2.** Acceleration amplitude spectra at 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.

LARGE VERTICAL ACCELERATIONS FOR OTHER EARTHQUAKES

Figure 4 shows the available strong-motion records that have vertical accelerations over 1 g. 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 ($1,310 \text{ cm/s}^2$) that is about twice as large as the horizontal PGA (729 cm/s^2). The vertical PGA ($2,321 \text{ cm/s}^2$) of site1 for the 1985 Nahanni earthquake (M_w 6.4) is also twice as large as the horizontal PGA ($1,338 \text{ cm/s}^2$).

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 1 g (980 cm/s^2), and the U/D ratio is significantly larger if the vertical PGA is greater than 1 g. For records that have accelerations greater than 1 g, 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 1 g (Figure 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 explosion seismology beginning in the 1960s (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 1 g 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 characteristics similar to records for large earthquakes, as the positive amplitudes are larger than the negative amplitudes and the downward accelerations have a lower bound of about 1 g.

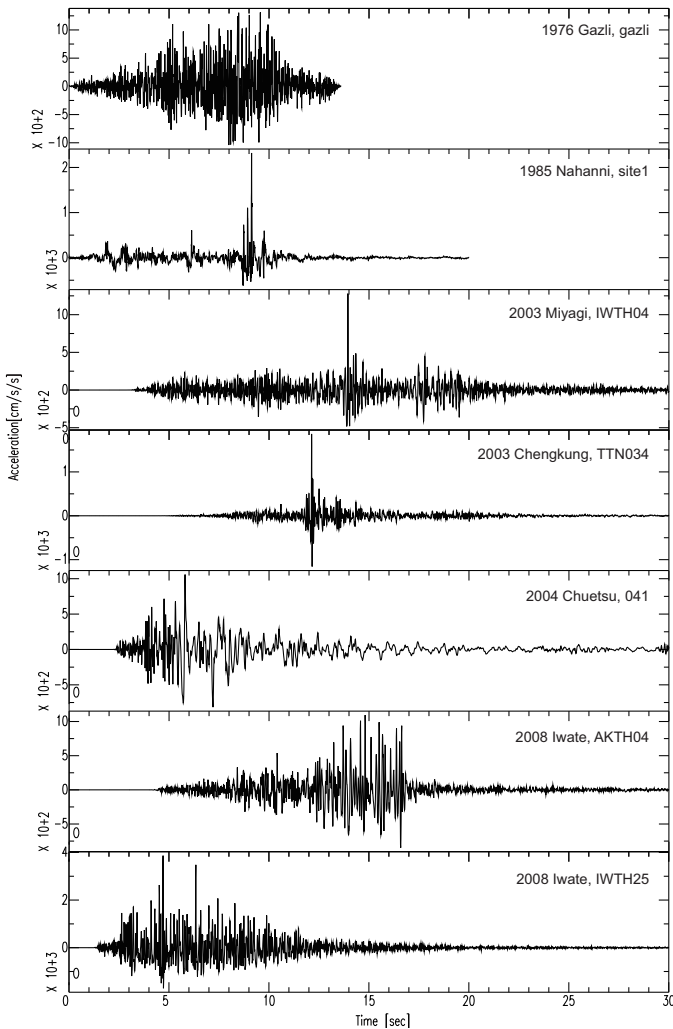
Figure 6 (middle) and Figure 6 (right) are earthquake strong-motion records which we interpret in the same way, assuming that there is a near-surface soil layer separated from a sublayer. The relatively long-period negative acceleration is associated with the free flight of the near-surface layer that 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 1-g accelerations.

In Figure 4, the large upward spikes in the records at site1 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 considered to be on relatively stiff sites, so the slapdown phase is likely to be generated by a brittle fracture in the sub-surface.

There are several reasons why the slapdown phases are not seen in the borehole record of the 2008 Iwate-Miyagi Nairiku earthquake. Note that similar to acceleration waveforms from nuclear explosions, the slapdown phase was not clearly seen on a borehole accelerometer (Eisler *et al.* 1966). The downhole accelerometer is four to eight 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 important, although the stress at the separated boundary is the same in the upward and downward directions, is that the acceleration of the upper separated layer will be larger than that of 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.



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

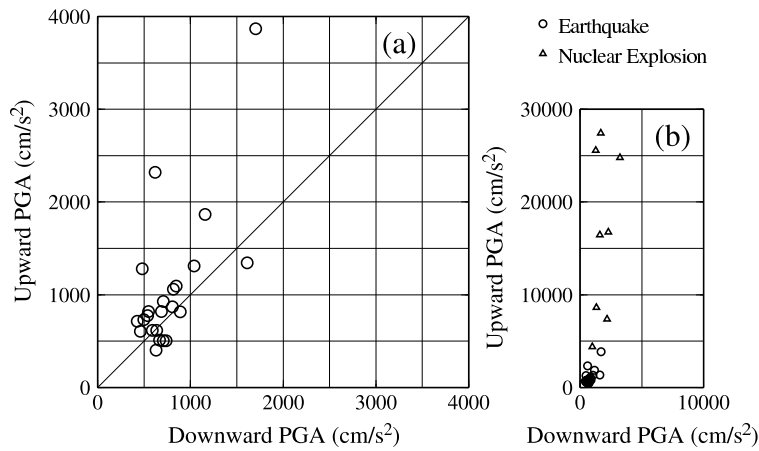
SEPARATION OF THE NEAR-SURFACE LAYER

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 sepa-

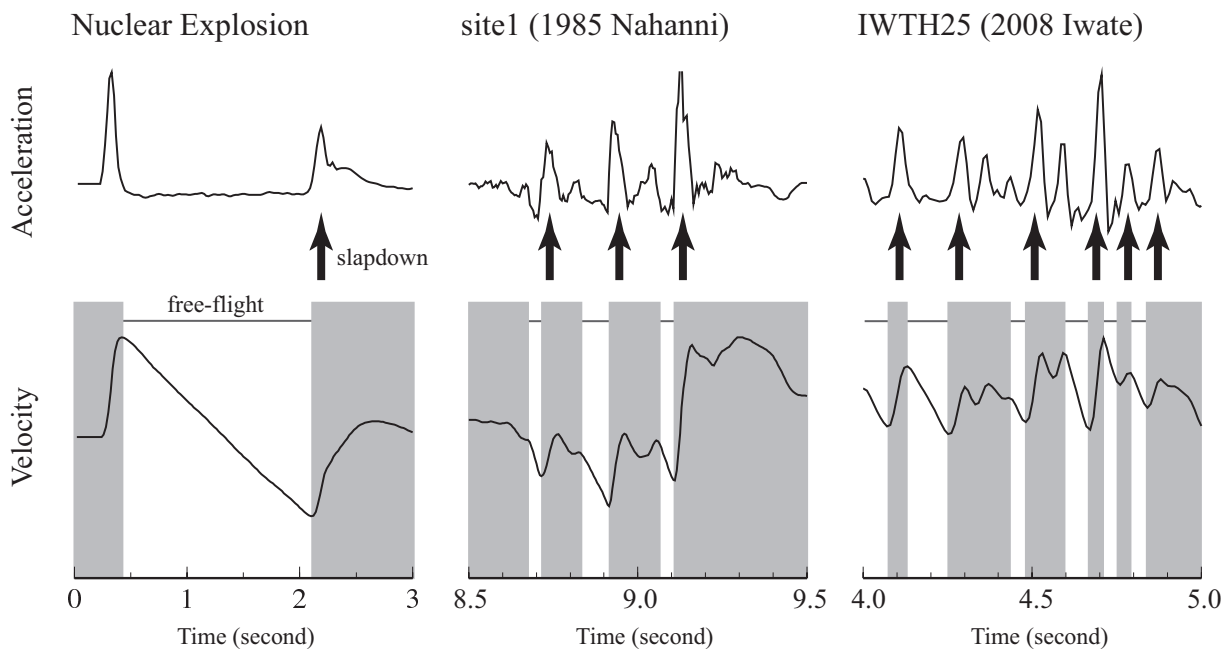
TABLE 1

List of the records in which the vertical acceleration exceeds 1,000 cm/s². The columns show the station ID, earthquake, date of the earthquake, upward PGA (cm/s²), downward PGA (cm/s²), and soil condition. The soil condition is cited from the COSMOS Virtual Data Center Web site, <http://db.cosmos-eq.org/scripts/default.plx>; KiK-net website, http://www.kik.bosai.go.jp/kik/index_en.shtml; personal communication with Central Weather Bureau in Taiwan; and Kubo *et al.* 2003. The VS30 is the average shear wave velocity for the surface 30 m. Class D corresponds to the Vs30 = 180–360 m/s.

Station	Earthquake	Date	Acc+	Acc–	Soil Condition	Reference
gazli	Gazli	1976/5/17	1310	1040	3.5cm 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 <i>et al.</i> 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



▲ **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 from Perret (1972), at site 1 during the 1985 Nahanni earthquake, and at IWTH25 during the 2008 Iwate-Miyagi Nairiku earthquake.

ration 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,

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

where S_{\max} is the maximum spall gap, g is a gravity acceleration, and Δt_g is the total free-flight time. The slapdown 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 slapdown phase, the thickness

of the spalled layer (d) is computed from the duration of the slapdown phase (Δt_s) and the P -wave velocity (v_p):

$$d = \frac{t_s}{2} v_p. \quad (2)$$

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 IWITH25 in Figure 4. The layer thickness is consistent with the velocity profile for this station, which shows sand and sandy clay layers (http://www.kik.bosai.go.jp/kik/index_en.shtml). In the record at site1 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 $v_p = 1$ km/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.

CONCLUSIONS

We analyzed the 4-g 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 and 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 60 m. ☒

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REFERENCES

Aoi, S., T. Kunugi, and H. Fujiwara (2008). Trampoline effect in extreme ground motion. *Science* **322**, 727–729.

- Chilton, F., J. Eisler, and H. Heuback (1966). Dynamics of spalling of the Earth's surface caused by underground explosions. *Journal of Geophysical Research* **71**, 5,911–5,919.
- Day, S., and K. McLaughlin (1991). Seismic source representations for spall. *Bulletin of the Seismological Society of America* **81** (1), 191–201.
- Day, S., N. Rimer, and J. Cherry (1983). Surface waves from underground explosions with spall: Analysis of elastic and nonlinear source models. *Bulletin of the Seismological Society of America* **73** (1), 247–264.
- Eisler, J. (1967). Near-surface spalling from a nuclear explosion in a salt dome. *Journal of Geophysical Research* **72**, 1,751–1,760.
- Eisler, J., and F. Chilton (1964). Spalling of the Earth's surface by underground nuclear explosions. *Journal of Geophysical Research* **69**, 5,285–5,293.
- Eisler, J., F. Chilton, and F. Sauer (1966). Multiple subsurface spalling by underground nuclear explosions. *Journal of Geophysical Research* **71**, 3,923–3,927.
- Japan Meteorological Agency (2008). Iwate-Miyagi Nairiku earthquake in 2008. http://www.seisvol.kishou.go.jp/eq/2008_06_14_iwate-miyagi/index.html.
- Kubo, T., Y. Hisada, A. Shibayama, M. Ooi, M. Ishida, H. Fujiwara, and K. Nakayama (2003). Development of digital maps of site amplification factors in Japan, and their applications to early strong motion estimations. *Journal of the Seismological Society of Japan* **56** (1), 21–37.
- Perret, W. (1972). Close-in ground motion from the MILROW and CANNIKIN events. *Bulletin of the Seismological Society of America* **62** (6), 1,489–1,504.
- Perret, W. (1973). *Ground Motion in the Vicinity of the CANNIKIN Nuclear Explosion*. Report SLA-73, 0043, Sandia Laboratories, Albuquerque, NM.
- Springer, D. (1974). Secondary sources of seismic waves from underground nuclear explosions. *Bulletin of the Seismological Society of America* **64** (3–1), 581–594.
- Viecelli, J. (1973). Spallation and the generation of surface waves by an underground explosion. *Journal of Geophysical Research* **78** (14), 2,475–2,487.

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