EXTREMELY LARGE ASYMMETRIC, VERTICAL ACCELERATIONS (AsVA) DURING RECENT EARTHQUAKES

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Abstract

Large ground motion records are critical for seismic hazard assessment and seismic design for buildings and infrastructures. Extremely large, asymmetric, vertical accelerations (AsVA) have been observed at strong motion stations during recent events including the 2011 Mw6.2 Christchurch and the 2016 Mw7.8 Kaikoura earthquakes. The mechanism responsible for AsVA has previously been attributed to the decoupling of near-surface materials, namely trampoline effect or rocking effect. In this paper, we present the analysis of AsVA using the peak ground acceleration of 3.2g in the upward direction recorded at seismic station WTMC during the 2016 Mw7.8 Kaikoura earthquake in New Zealand. We find that the record of the AsVA, also observed during a Mw6.3 aftershock, can be explained by a flapping effect, that is, the local elastic bouncing of a foundation slab on which the sensor was installed. This suggests that large AsVA waveform records cannot be used as direct input motion for engineering applications. The implications of these results for AsVAs observed elsewhere. We also examine AsVAs recorded at several strong motion stations during the 2011 Mw6.2 Christchurch earthquakes.

Keywords: Ground Motion Records; Large Asymmetric, Vertical Accelerations; Soil Structure Interaction; Kaikoura Earthquake, Christchurch Earthquake

1. Introduction

Large ground motion records are critical for seismic hazard assessment and seismic design of buildings and infrastructures. Key engineering structures such as hospitals, dams and power plants are often designed based on the analysis of past records of large ground motions to prevent catastrophic damage brought about by future earthquakes. These ground motion records are also used in assessing the landslide potential and liquefaction hazard. Most applications stand on an assumption that instrumental ground motion records correctly reflect the actual ground shaking during an earthquake. If these records are contaminated with a local, system response, i.e., the response of a structure at which the sensor is installed, it should not be used as direct input for other applications.

Extremely large, asymmetric, vertical accelerations (AsVA) have been observed at strong motion stations during recent events including the 2011 Mw6.2 Christchurch earthquakes [1], and the 2016 Mw7.8 Kaikoura earthquake [2-3] in New Zealand. The mechanism responsible for the AsVA has been attributed to the decoupling of near-surface materials referred to as a ‘trampoline’ effect [4-5], or a rocking effect [6-7]. The trampoline effect occurs when a rebound force causes a large upward acceleration while a downward motion is limited to the gravitational acceleration (1g) due to the bouncing of a deformable soil. In contrast, the rocking effect is characterized by upward accelerations induced by large horizontal motion when the structural basement underneath the seismic sensor impacts on the ground surface. The important difference between the trampoline and rocking effects is that the former is caused by actual ground shaking, whereas the latter is due to the interaction between the structure and soil.

Recently, Goto et al. [8] analyzed AsVA with the peak value of 3.2g in the upward direction recorded at seismic station WTMC during the Kaikoura earthquake. They found that the record of the AsVA, also observed during a M6.3 aftershock, can be explained by a flapping effect. This is the local elastic bouncing of a foundation slab on which the sensor was installed. This suggests that large acceleration records with AsVA cannot simply be used as input motion for engineering applications.

This study aims to further understand the nature of AsVA records in terms of the flapping effect. We discuss the implications of results. We then quantify the AsVAs from waveform records during the 2011 Christchurch earthquakes.

2. Flapping effect at station WTMC

During the 13th November 2016 Mw7.8 Kaikoura earthquake, an anomalously large peak acceleration of 3.23g was recorded at seismic station WTMC. This station is located in Waiau, Northern Canterbury, approximately 8km from the epicenter and in the vicinity of faults that ruptured during this earthquake event as shown in left panel of Fig.1. This peak gound acceleration (PGA) was considered as the second highest PGA ever observed for any earthquake in the world, with the highest PGA of 4.10g recorded at seismic station IWTH25 during the 2008 Mw6.9 Iwate-Miyagi earthquake, Japan [4]. At seismic station WTMC, an accelerometer is situated on a concrete slab in a farm shed. Site investigation immediately after the Kaikoura earthquake concluded that this seismometer at seismic station WTMC functions correctly and the sensor box had been firmly attached to the concrete slab [2].

The AsVA recorded at the station WTMC is not consistent with the trampoline or rocking effect. The trampoline effect would involve a free-fall of the soil ground caused by the vertical acceleration exceeding 1g. However, interestingly, one of the major aftershocks (M6.3 event shown in Fig.1) also shows similar acceleration characteristics at seismic station WTMC despite a much smaller PGA (~0.1g), and hence the trampoline effect cannot explain relatively small AsVA. In addition, vertically eccentric structures needed to induce the rocking effect were not found at station WTMC. Therefore another mechanism must be responsible for the origin of the AsVA.

Goto et al. [8] considered a physical model of station WTMC consisting of a foundation slab and an irregular contact surface between the slab and underlying soil. Such an irregular contact surface, which would have been created by differential settlement of the soil or soil erosion over time, was confirmed in our site investigation. There are some minor gaps (< 1 cm) between the concrete slab and soil ground. The irregular surface contact allows local elastic bouncing of the concrete slab during earthquake ground shaking.

Simulations based on the model reproduce the main characteristics of the recorded accelerations at station WTMC for both the mainshock and aftershock, as depicted in Fig.1. The irregular contact surface enables the separation of the slab from the soil locally, even during weaker ground motions (~0.1g), resulting in enhanced positive accelerations at the location of the sensor. The elastic bouncing occurs in the form of the flapping of a smaller section of the slab on which the sensor is located, resulting to AsVA and high-frequency horizontal oscillations. Some contacts between the slab and soil always remain even during the large mainshock motions (>1g). During the weaker aftershock motion (<1g), the negative acceleration is controlled by the input ground motion (<1g), whereas the positive acceleration is enhanced when the slab impacts the soil ground locally, and hence the AsVA occurs.

The elastic bouncing of the slab, referred to as the flapping effect, is induced by the vertical motion of a system with variation in the horizontal direction, e.g., the foundation slab sitting on an irregular surface. The analysis suggests that the soil-slab interactions characterized by the flapping effect led to the AsVA and the extreme acceleration at station WTMC. Also, the large AsVA (the peak value of 3.23g) does not reflect the actual ground motions generated by the seismic waves during the Kaikoura earthquake. The large AsVA may have been attributed to the local, system response around the sensor.

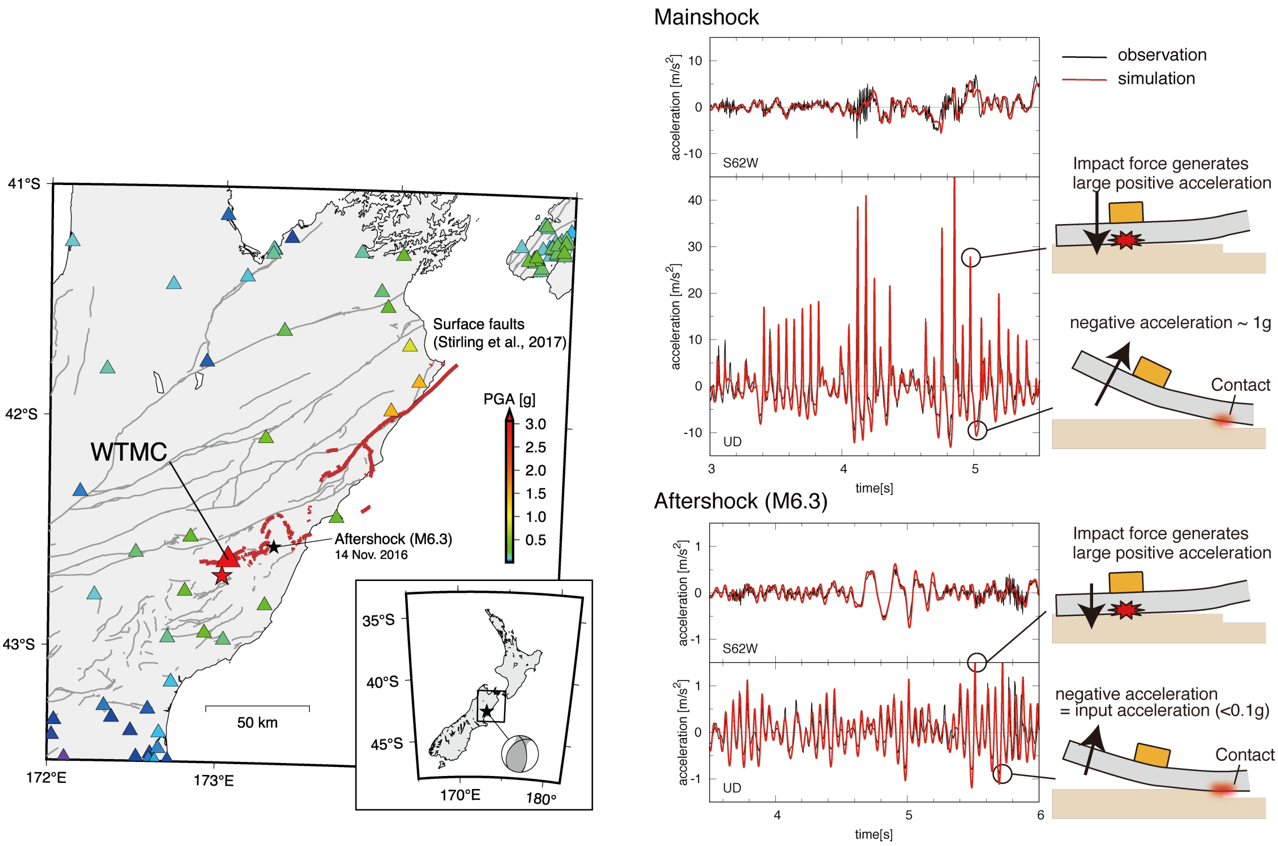

Fig. 1 – Location of seismic station WTMC (left). Simulated large, asymmetric, vertical accelerations (AsVA) for the mainshock and aftershock of the 2016 Kaikoura earthquake (right).

3. Quantification of AsVA records

While extremely large AsVAs, such as the WTMC record during the Kaikoura mainshock, is visually identifiable, evaluating AsVAs in weaker (<1g) ground-motion records has been largely subjective. In order to objectively assess the occurrence of AsVAs during weaker motions, we define several metrics to quantify the degree of waveform asymmetry and quantitatively evaluate the presence of AsVA at strong-motion seismic stations.

Our simulations shown in Section 2 suggest that the presence of AsVA depends on the set-up and installation conditions of a seismometer and that waveform asymmetry caused by the flapping effect is enhanced when the input ground motion is larger. Therefore, stations susceptible to the flapping effect would show a systematic bias in asymmetry characteristics in the waveform records.

Aside from WTMC, other acceleration records from 5 strong-motion stations in Christchurch are used in the analysis. During the 2011 Mw6.2 Christchurch earthquake, stations HVSC and PRPC recorded large AsVAs, with the vertical PGA exceeding 1g in the upward direction [1]. Station CCCC also recorded AsVA, but the asymmetry characteristics was not as clear as those at stations HVSC and PRPC. Stations CBGS and SHLC did not show any asymmetry in the waveforms despite >0.1g accelerations. Hence waveform records at stations HVSC, PRPC, CCCC, CBGS, and SHLC as well as WTMC are chosen. We use waveform records for all the earthquakes greater than M3.0 with the epicenters located within 1.5 degree radius.

To quantify the degree of asymmetry in vertical acceleration waveforms, Aoi et al. [4] proposed a metric based on positive and negative envelopes. Here, we slightly modify the metric and define a similar quantity as follows:

$$Fs = \frac{|S^+| - |S^-|}{\max(|S^+|, |S^-|)} \tag{1}$$

where S^+ and S^- are the positive and negative envelopes, respectively, which are estimated from the linear interpolation of their peak values. Note that these envelopes are different from symmetric envelope obtained from the Hilbert transform.

Fry et al. [1] proposed a different metric defined by the positive and negative peak values of vertical accelerations, as follows:

$$Fp = \frac{|P^+| - |P^-|}{\max(|P^+|, |P^-|)} \tag{2}$$

where P^+ and P^- are maximum values of the positive and negative peaks, respectively.

Fs may be biased by asymmetrical background noise before or after earthquake-induced AsVA. *Fp* focuses only on the maximum value independent of frequency content and may be biased by transient phenomena unrelated to the overall waveform asymmetry. To partially remedy these biases, we define another metric that accounts for several significant waveform peaks:

$$Fh = \frac{|H^+| - |H^-|}{\max(|H^+|, |H^-|)} \tag{3}$$

where H^+ is the average of positive peak values exceeding 50% of the maximum value. H^- is the average of negative peak values, and the same number of negative peaks as in H^+ is used to calculate H^-.

Fig.2 shows the histograms corresponding to *Fs*, *Fp*, and *Fh* for waveform records obtained from stations WTMC, HVSC, PRPC, CCCC, CBGS, and SHLC. Colored histograms in Fig.2 indicate earthquake waveforms exceeding the PGA of 0.1g (blue) and 0.4g (red), respectively. Histograms for station WTMC show clear shift in the positive direction for larger PGAs. This is consistent with the characteristics predicted by the flapping effect. The classical trampoline effect cannot explain the positive shift in the histogram for data not exceeding 1g. Similar positive shifts are also visible for metrics *Fp* and *Fh* (Fig.2). Station PRPC and CCCC show similar trends as in station WTMC. This suggests that strong motion records at PRPC and CCCC may be contaminated by the flapping effect. On the other hand, CBGS and SHLC show no clear differences among the background and colored histograms. Histograms for station HVSC do not show clear positive shift, but the data exceeding 0.4g is in the positive range in terms of *Fp* and *Fh*. More precise discussion for the records at station HVSC is needed.

Overall these metrics and corresponding histograms may enable to detect and identify strong-motion stations prone to the flapping effect when acceleration records with the PGA>0.4g are available. However, in practice, many strong-motion stations have not yet experienced such large accelerations. Once large accelerations are generated by nearby earthquake sequences in the future, these metrics would be useful in not only identifying the occurrence of AsVAs but also quantitatively assessing whether observed AsVAs represent the actual ground shaking or contaminated by the elastic flapping effect.

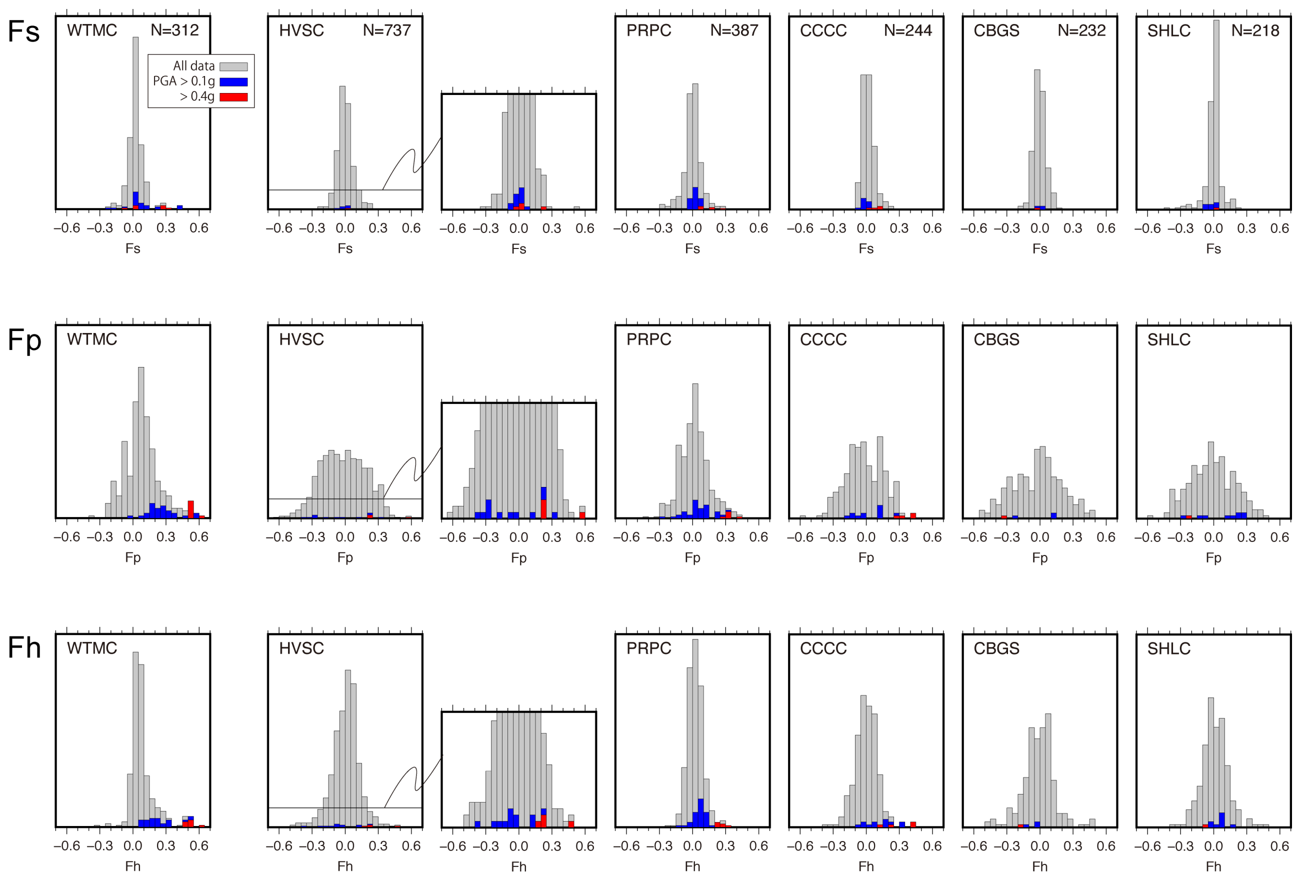

Fig. 2 – Histograms of AsVA quantifications: *Fs* (top), *Fp* (middle), and *Fh* (bottom). Gray background represents all data, while blue and red colored histograms are for the data exceeding 0.1g and 0.4g of PGA, respectively.

4. Conclusions

Extremely large, asymmetric, vertical accelerations (AsVA) have been observed at strong motion stations during recent earthquake events. The mechanism responsible for the AsVA with the peak value of 3.2g recorded at seismic station WTMC during the 2016 Kaikoura earthquake is flapping effect, that is, the local elastic bouncing of a foundation slab on which the sensor was installed. This suggests that large acceleration records with AsVA cannot simply be used as input motion for engineering applications.

In order to assess the occurrence of AsVAs and further test the applicability of the elastic flapping effect, we quantitatively evaluate the presence of AsVAs using acceleratin records at strong motion stations in Christchurch and Waiau. Acceleration records at stations HVSC, PRPC, CCCC, CBGS, and SHLC as well as station WTMC are utilized in the analysis. We propose three metrics, namely *Fs*, *Fp*, and *Fh*, to quantify the degree of waveform asymmetry. Histograms of these metrics for station WTMC show a clear shift in the positive direction with increasing PGAs. This is consistent with the characteristics predicted by the flapping effect. Station PRPC and CCCC show similar trends as in station WTMC. This suggests that strong motion records at stations PRPC and CCCC may be contaminated by the flapping effect. These proposed metrics may be useful in identifying the occurrence of AsVAs and assessing whether AsVAs are caused by the elastic flapping effect.

5. Acknowledgements

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6. References

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