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Quantitative Identification of Near-Fault Ground Motion using Baker's Method; an Application for March 2011 Japan M9.0 Earthquake

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Abstract

Some ground motions recorded in the direction of fault rupture show large long-period pulses in their velocity time history. There are several studies which have proposed different possible configurations of those pulses. However, to quantitative classify a new record as a near-field (or near-fault) ground motion, there is only one method proposed by Baker (2007). Before this study, such a classification had been done by visual observation of records. In this report, Baker's method will be reviewed. This method will be used to find out whether recent destructive earthquake in Japan (M9.0) on March 11, 2011 is a near-fault ground motion or not.

Introduction:

Earthquake is a shear dislocation of earth at a fault which starts at a point and spreads at a velocity about the shear wave velocity (Somerville, 1997). If there is a chance to have a seismometer along the forward rapture direction of fault, recorded velocity may show a large long-period pulse. Seismologists call this pulse-like record as a "near-fault" ground motion. Since the response of structures for this kind of records is different, mainly shows higher demands, this is also of interest of earthquake engineers (Alavi and Krawinkler 2001, PEER Report 2002-02, Akkar et. al. 2005, Hall et. al. 1995, Kallan and Kunnath 2006, Amiri 2008).

Near-fault records can be found in the fault-normal component of ground motion within 25km range. Directivity and fling effect are main causes of these records. Directivity is accumulated energy propagating toward a site which usually has two-side pulse in the velocity time history. Fling is a permanent displacement of fault which has one-side pulse in the velocity record. Figure 1 illustrates the forward and backward directivity for Landers earthquake. One example of fling effect is also shown.

Several studies have proposed different types of features to represent pulse-like near-fault effect (Alavi and Krawinkler 2001, Bray and Rodriguez-Marek 2004). But main question is which record is a near-fault record. We need a quantitative method to distinguish this kind of records from far-field records. Before Baker's quantitative method (Baker 2007), classification of near-fault motion was a personal judgment of a seismologist. Two above-mentioned characters, large long-period pulse recorded within 25km range, represent quality of records not quantity. In this report, Baker's method will be reviewed then this method will be applied to find out whether recent destructive earthquake in Japan on March 11, 2011 can be classified as a near-fault motion or not.

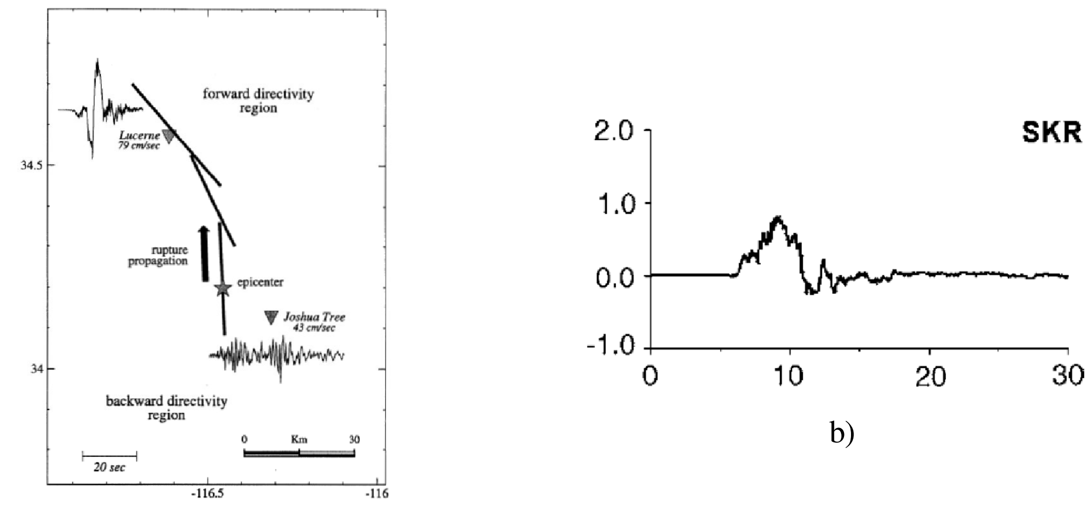


Figure 1- a) forward and backward directivity effect in 1992 Landers earthquake (after Somerville, 1997), b) an example of near-fault ground motion caused by fling-step (after Kallan and Kunnath 2006)

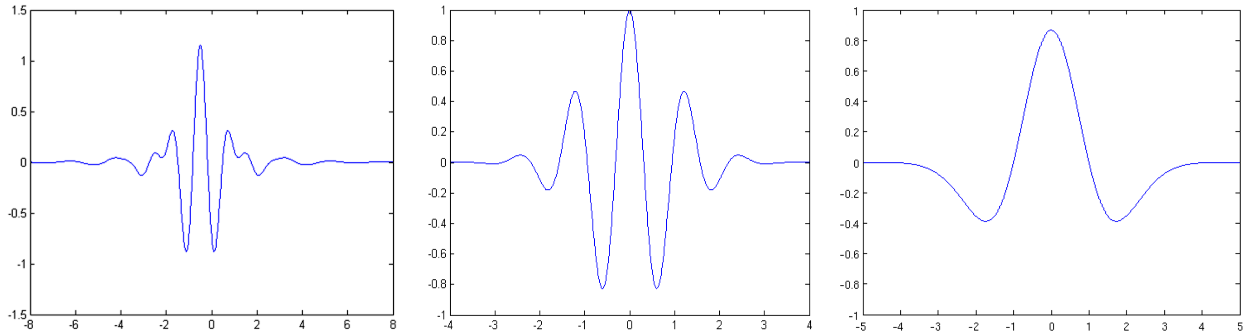
Baker's Method:

Baker proposed a quantitative identification of near-fault ground motion using wavelet analysis (Baker 2007). Summary of his study is as follows: (1) decompose original velocity signal by wavelet analysis, (2) calculate pulse indicator, (3) calculate pulse late arrival time and (4) check PGV of original record. Period of pulse can also be obtained by this method. A short review of these steps will be provided.

1- Wavelet Analysis

Any signal can be decomposed by Fourier transformation technique into its constituent frequencies. This transformation decomposes a function into harmonic functions. Each harmonic function in the time domain has only one amplitude and one phase in frequency domain. On the other hand, each harmonic in time domain is represented only by one point in frequency domain. Wavelet was proposed to conquer this defect and cover a range both in time and frequency domains. Wavelet is a short-time pulse in time domain which can be used to transfer a signal from time domain into frequency instead of SIN or COS. Wavelet transformation uses a mother wavelet in which transformation of each mother wavelet is not only one point in frequency. However, it coves a range in frequency. Equation (1) is mathematical representation of wavelet transformation in which $\emptyset(.)$ is mother function. Figure 2 illustrates some mother functions.

$$\emptyset_{s,l}(t) = \frac{1}{\sqrt{s}}\emptyset(\frac{t-l}{s})$$
$$C_{s,l} = \int_{-\infty}^{+\infty} f(t)\,\emptyset_{s,l}(t)dt \qquad (1)$$



a) Mayer **b) Morlet** **c) Mexican Hat**

Figure 2- Some Mother functions for Wavelet Analysis (Wikipedia)

Wavelet analysis can be carried out by continuous or discrete analysis. Main advantage for continuous analysis is that it's independent to time windowing. By means of Wavelet Toolbox of MATLAB, decomposed velocity signal of 1979 Imperial Valley earthquake at Brawley Airport is shown in Figure 3. I decomposed this signal by a Daubechies wavelet of order 4 in 10 levels. One of these decomposed signals has the largest amplitude (d_8). Baker named this one as the main extracted pulse and the difference between the original and extracted pulse is residual. Figure 4 compares original and extracted velocity signal of 1971 San Fernando earthquake at Pacoima Dam.

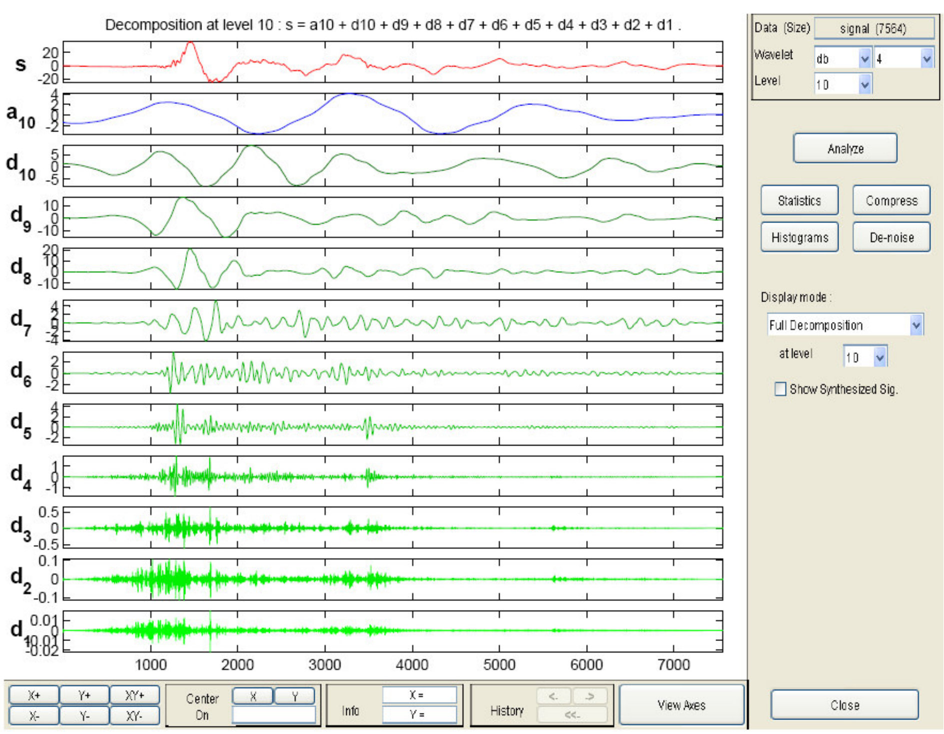


Figure 3- Decomposing Velocity Signal of 1979 Imperial Valley earthquake at Brawley Airport

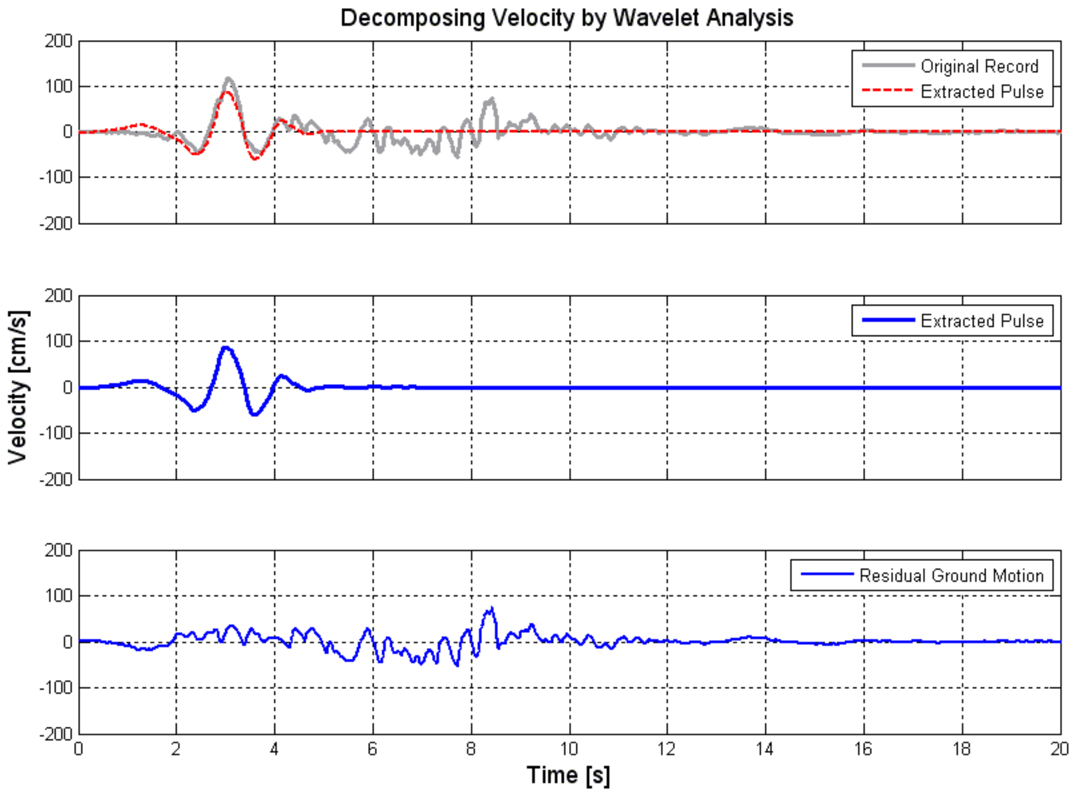


Figure 4- Comparing Original and Extracted Velocity Signal of 1971 San Fernando earthquake at Pacoima Dam

2- Pulse Indicator

We have decomposed an original velocity signal into main pulse and residual signal. Next step is to use these data and provide an indicator for pulse-like ground motion. Baker considered 402 records (all fault-normal ground motions in the Next Generation Attenuation (NGA) ground motion library (http://peer.berkeley.edu/nga) with magnitudes greater than 5.5 and recorded within 30 km of an event were selected) and manually classified them as pulse-like (124 records), non-pulse-like (190 records) and ambiguous (84 records) records. He tries different ways to find a relation between original pulse and extracted pulses. Finally, he found that two predicator variables, PGV ratio and energy ratio, can be a good representative of pulse indicator. Figure 5 shows energy ratio versus PGV ratio of mentioned records. Then, by means of logistic regression, he defined pulse indicator (PI) as follows:

$$PI = \frac{1}{1 + e^{-23.3+14.6(PGV\ ratio)+20.5(enegy\ ratio)}} \tag{2}$$

where PGV ratio is the peak ground velocity (PGV) of the residual record divided by the original record's PGV and energy ratio is the energy of the residual record divided by the original record's energy (where energy can be computed as the cumulative squared velocity of the signal, or, equivalently, as the sum of the squared discrete wavelet coefficients).

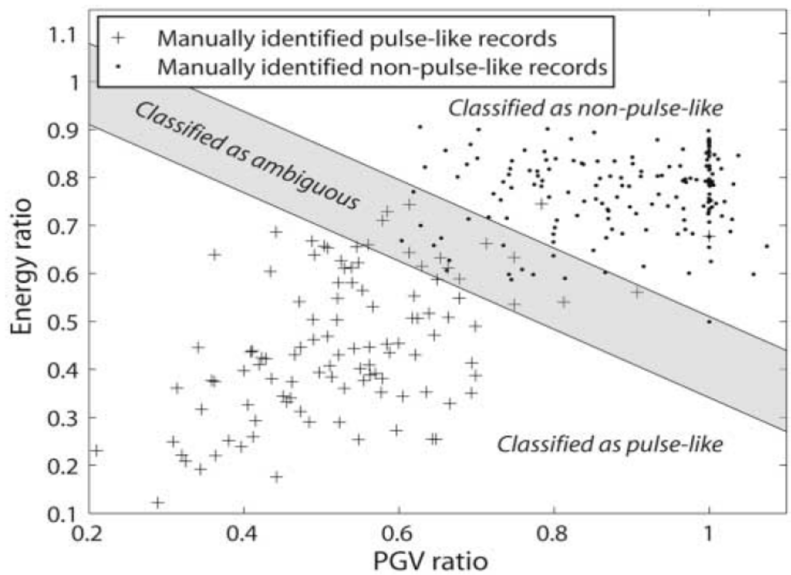


Figure 5- Scatter plot of the predictor variables used for classification (Baker 2007)

Pulse indicator takes values between 0 and 1, with high values providing a strong indication that the ground motion is pulse-like. Records with score above 0.85 are classified as pulse-like.

3- Exclude the Late-Arriving Pulses

Desired near-fault ground motions have pulses arriving early in their velocity time history. He proposed using cumulative squared velocity (CSV) of original and extracted pulses in which 10% of total CSV of extracted pulse ($t_{10\%,pulse}$) should reach before 20% of total CSV of original signal ($t_{20\%,original}$). Otherwise, signal should be excluded.

4- PGV should be greater than 30cm/s

Since the motion may be very simple for far-field records, it is possible to have a velocity time history as a pulse where soil inelastic properties will filter motions. To exclude these far-field pulse-like motion, Baker proposed to put a limit of PGV>30cm/s on records.

Summary of Baker's Method:

To quantitatively classify a given record as near-fault, pulse indicator of that record should be greater than 0.85, pulse should arrive early in time history of velocity where CSV of $t_{20\%,original} > t_{10\%,pulse}$ and PGV should be greater than 30cm/s. by this method, he classified 98 records as near-fault motion detailed in Appendix 1. Figure 6 shows appropriate factors for 1979 Imperial Valley earthquake recorded at Brawley Airport. For 1971 San Fernando earthquake at Pacoima Dam station (upper left abut.), PI is 0.97 and PGV is 116 cm/s.
Baker's source codes in MATLAB are available online on his website (http://stanford.edu/~bakerjw/).

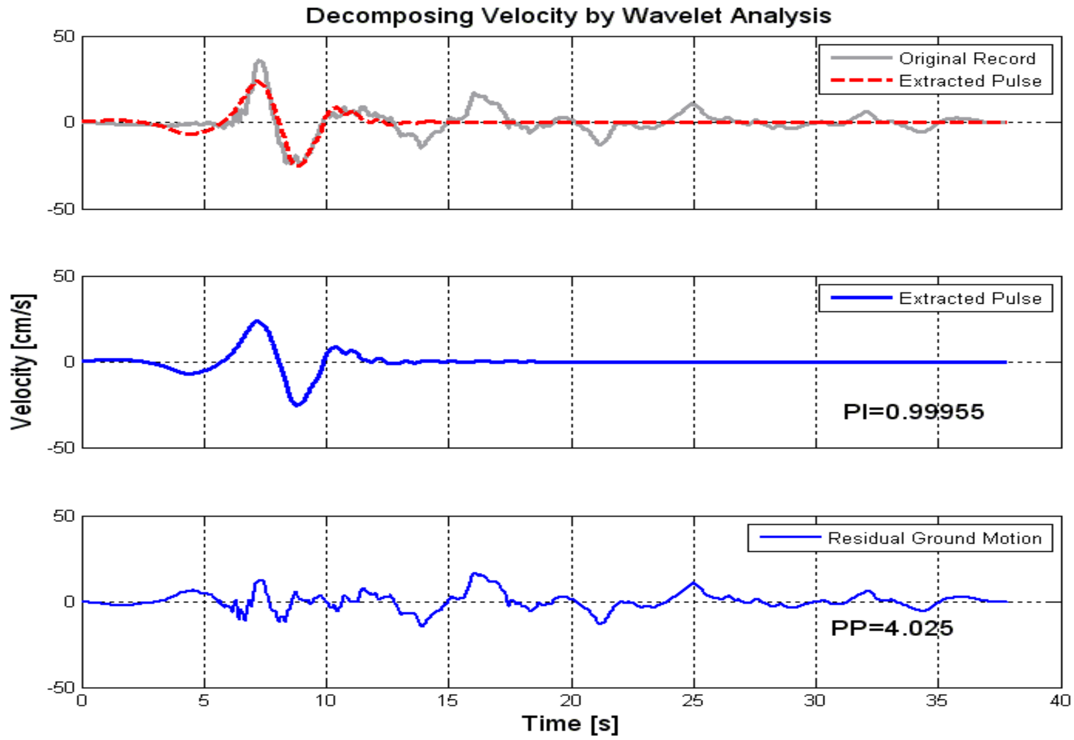


Figure 6- Pulse Indicator and Pulse Period for 1979 Imperial Valley earthquake recorded at Brawley Airport

Application of Baker's Method on Japan Earthquake M9 in March 2011:

On March 11, 2011 a destructive earthquake hit west coast of Japan with a magnitude of 9. USGS shake map and aftershock pattern are shown in Figure 7. About 1024 stations in Japan recorded this earthquake and all ground motion data is also available online at http://www.k-net.bosai.go.jp/. Figure 8 shows epicenter of this earthquake and all sites' location which have recorded this event. It would be a good try to use Baker's method to find out whether recorded ground motions are near-fault type or not. Since we have a huge database and time is limited, I only worked on 4 stations. First station is famous Sendai record located 175km away from epicenter. By means of USGS aftershock pattern, we can estimate the width and length of rapture. As mentioned before, near-fault effect can be only seen in the fault-normal component of records in the forward direction of rupture of fault. 3 other stations have chosen to be in the direction of rupture length illustrated in Figure 9. All records have been corrected by a linear baseline correction with Buttereworth bandpass filter (Freq1=0.1, Freq2=25, Order 4) by SeismoSignal (Seismosoft 2011). Figures 10-14 show the results by Baker's method. This method indicates that selected records are not near-fault ground motions since pulse indicators are about zero. Luca et. al. (2011) has reported that selected records in their study are not near-fault ground motions using Baker's method.

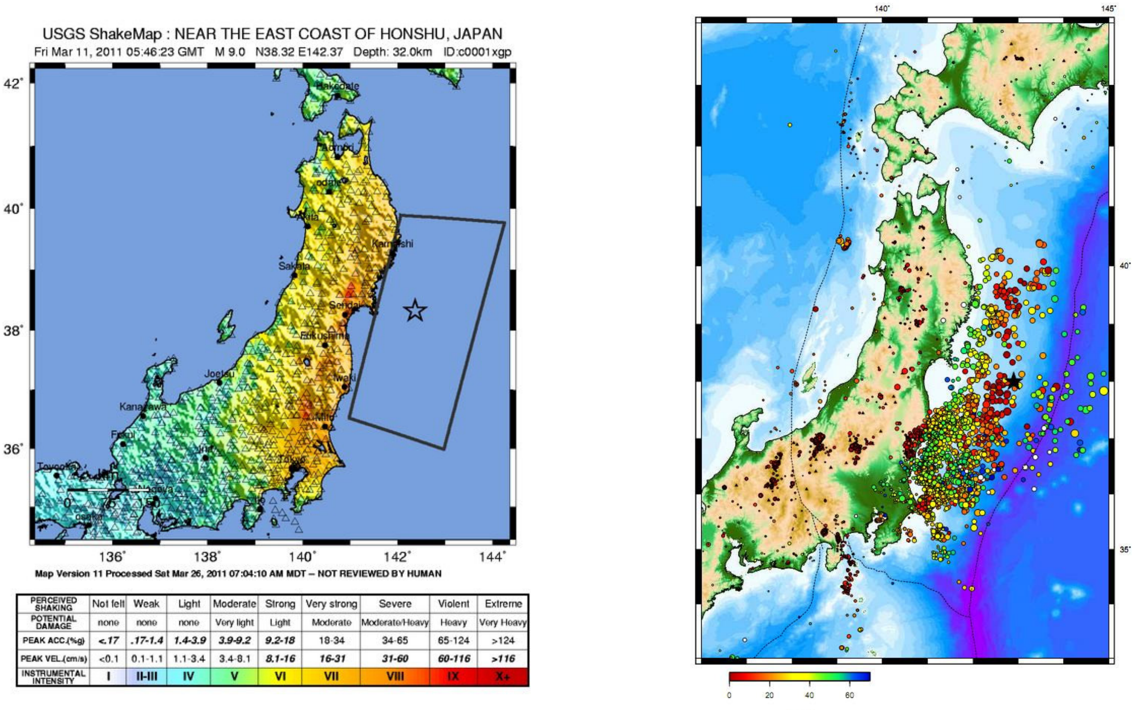
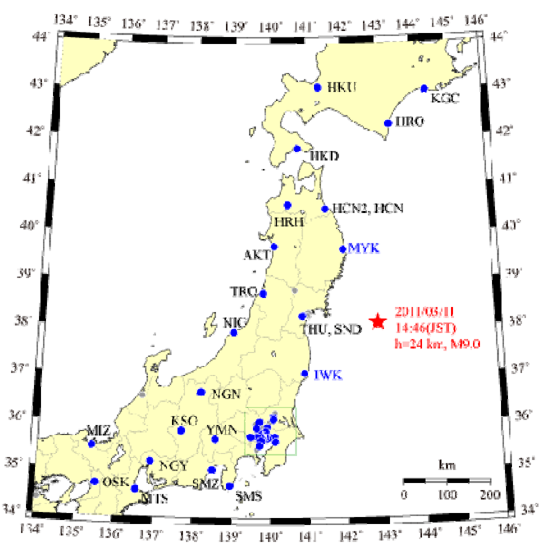


Figure 7- Shake Map and Aftershock Pattern for March 2011 Sendai Earthquake in Japan

http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/c0001xgp/

BRI strong motion: http://smo.kenken.go.jp/



http://smo.kenken.go.jp/smreport/201103111446

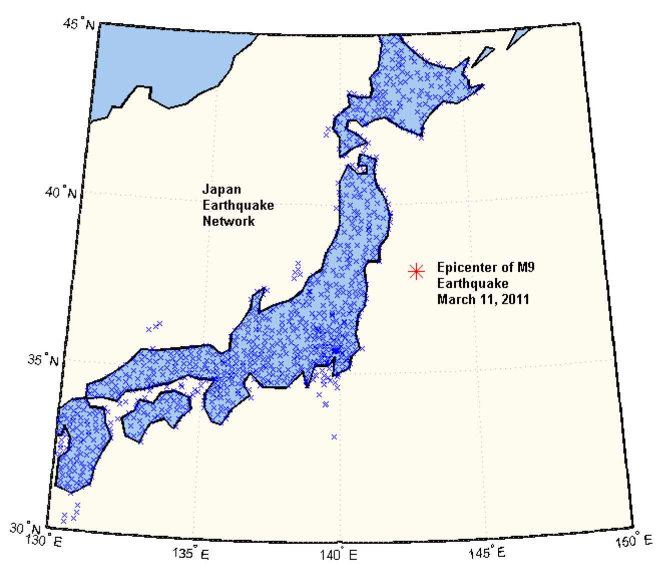


Figure 8- a) Epicenter and Some Stations in BRI Database b) Epicenter and all Stations of k-net Database

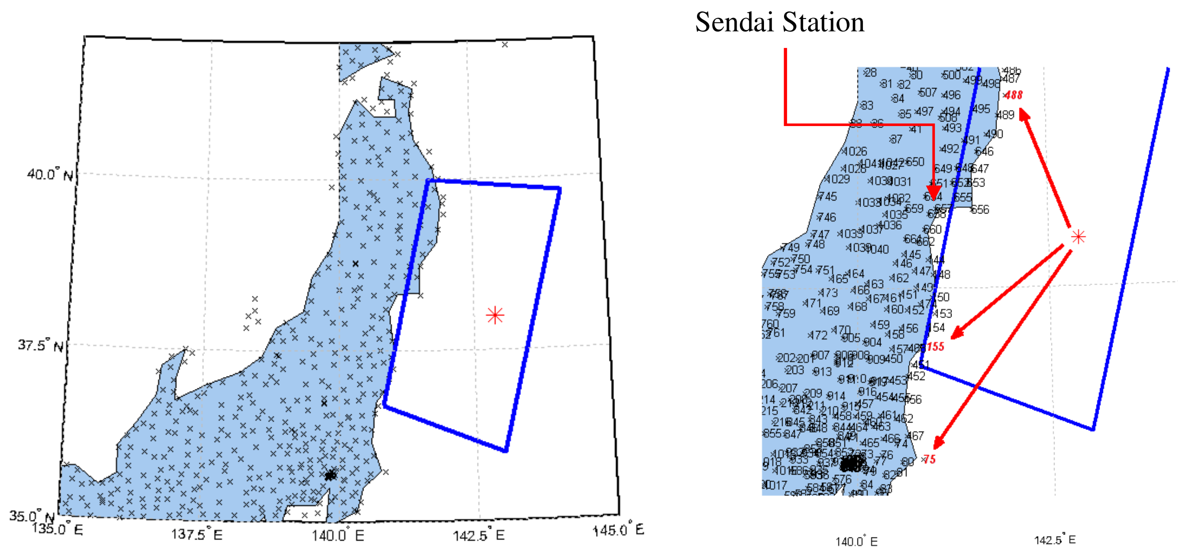


Figure 9- Methodology for Selecting the Other Records in K-Net Data Base
No. 75: CHB005 (Chohshi), No. 155: FKS012 (Nakoso), No. 489: IWT007 (Kamaishi)

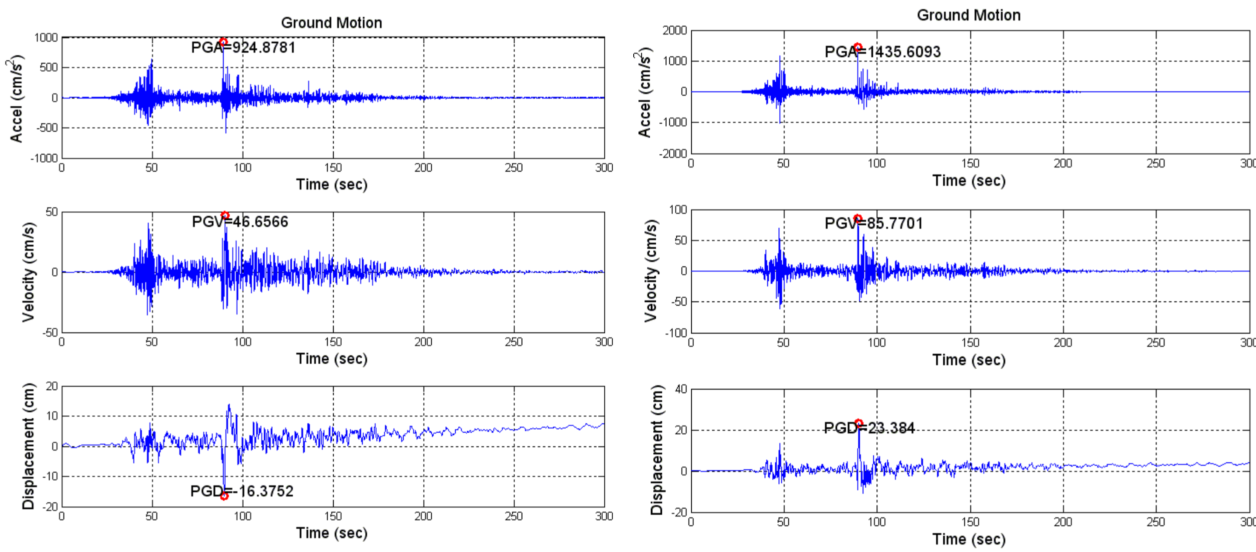


Figure 10- Ground Motion Recorded at Sendai Station, March 2011 Japan Earthquake M9
(Left is E-W Component and Right is N-S Component)

Note that high PGA is due to recording the motion on the first floor of a building. It means that this is the response of structure not free-field ground motion. Displacement time history also indicates that we should use better filtering technique.

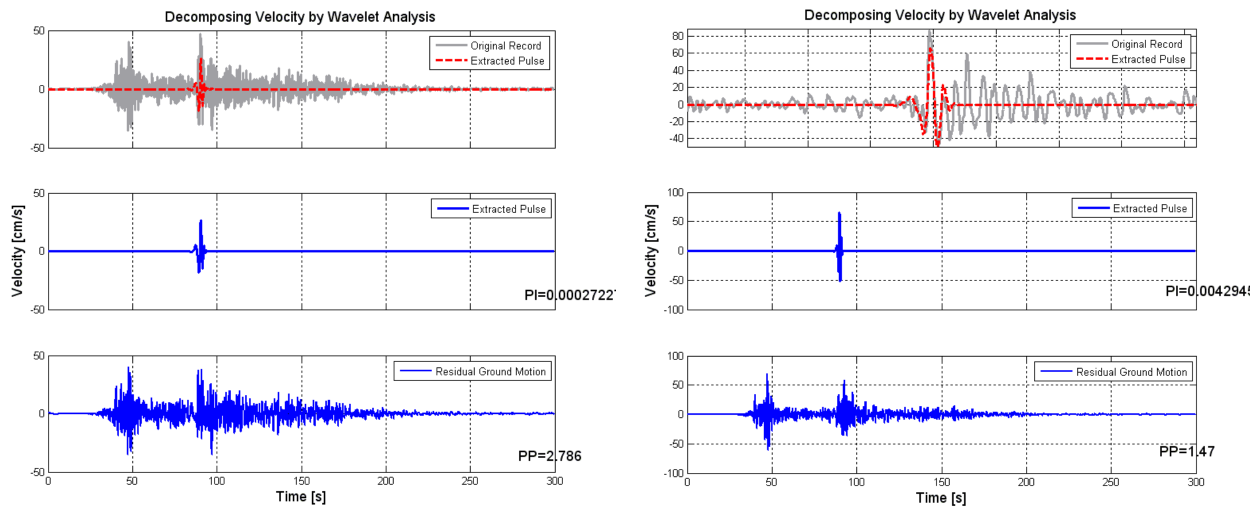


Figure 11- Near-Fault Classification of March 2011 Japan Earthquake M9, Sendai Station (Left is E-W Component and Right is N-S Component)

Note: N-S acceleration is zoomed in time to see the pulse

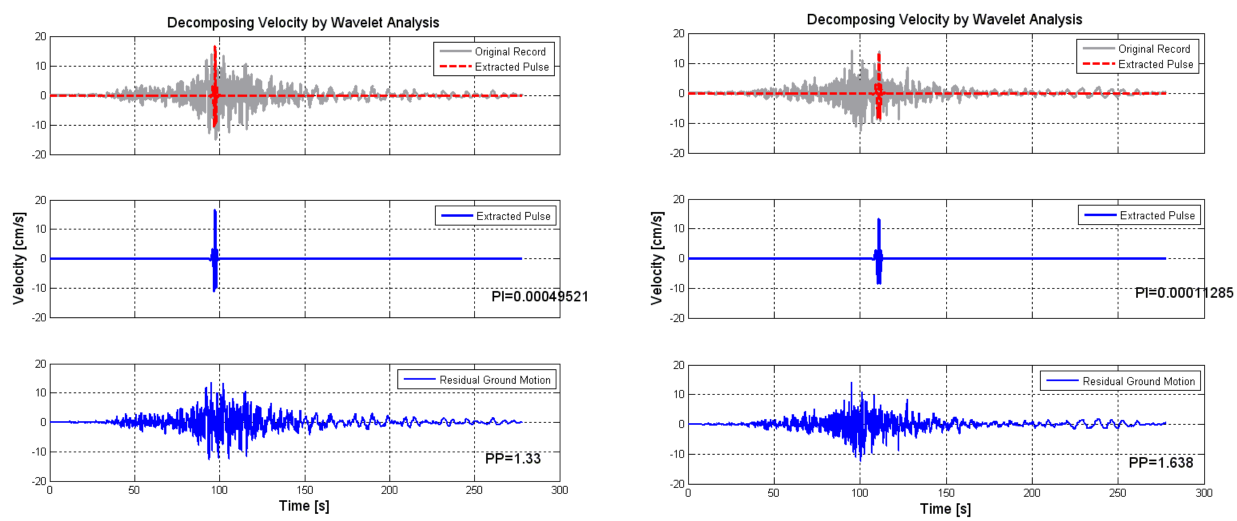


Figure 12- Near-Fault Classification of March 2011 Japan Earthquake M9, Chohshi Station (CHB005) (Left is E-W Component and Right is N-S Component)

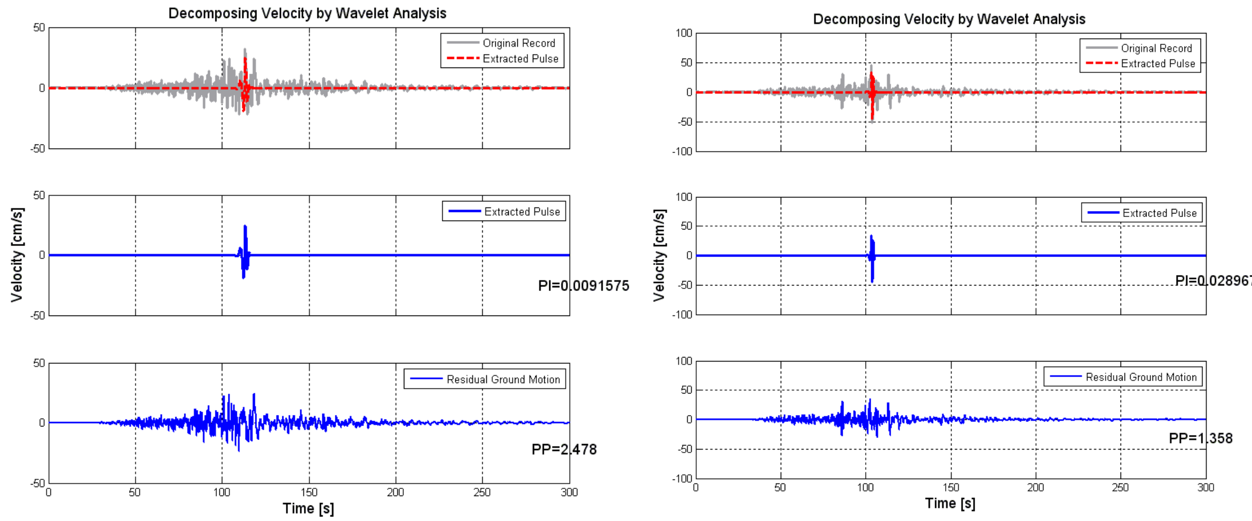


Figure 13- Near-Fault Classification of March 2011 Japan Earthquake M9, Nakoso Station (FKS012) (Left is E-W Component and Right is N-S Component)

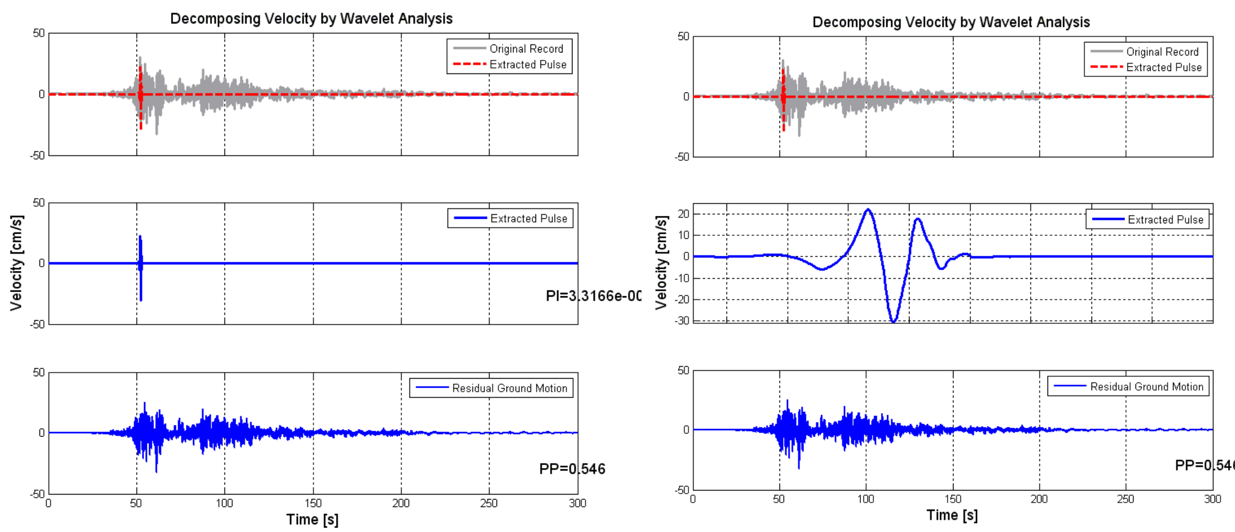


Figure 14- Near-Fault Classification of March 2011 Japan Earthquake M9, Kamaishi Station (IWT007) (Left is E-W Component and Right is N-S Component)

Conclusion:

Baker's quantitative method for classification of near-fault ground motions has been reviewed. If desired ground motion meets 3 conditions (1) pulse indicator greater than 0.85, (2) pulse should arrive early in time history of velocity where CSV of $t_{20\%,original} > t_{10\%,pulse}$ and (3) PGV should be greater than 30cm/s, then this record is a near-fault ground motion. This method has been implemented to find out whether records of recent destructive earthquake M9 in Japan (March 11, 2011) is a near-fault or not. 4 stations have been chosen in the direction of fault rupture where basically, the chance of having pulse-like wave is high. Analyses show that these records are not near-fault ground motions by Baker's method.

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