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DETECTION OF LIQUEFIED SITES USING SEISMIC GROUND MOTION RECORDS

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ABSTRACT: When a large earthquake occurs, buried pipes and harbor structures often suffer from serious damages. These damages are mainly caused by large ground deformation due to soil liquefaction. Hence, it is important to detect liquefied sites at an early stage. Many seismometers have been deployed in Japan and acceleration records at liquefied sites were obtained in recent earthquakes. In this study, a method to detect soil liquefaction using acceleration records is proposed based on a dataset including records at liquefied and non-liquefied sites. As for the records at liquefied sites, the predominant period of the horizontal components tends to be longer. On the other hand, the predominant period of the vertical component is not lengthened even at a liquefied site. To reveal these characteristics, the change of the predominant frequency over the time was calculated from the Fourier spectra and the zero-crossing period. The occurrence of liquefaction is judged by setting threshold values for the JMA instrumental seismic intensity and the predominant frequencies for the horizontal and vertical components.

KEYWORD: Detection of liquefaction, Fourier spectrum, JMA seismic intensity, Zero crossing period

1. INTRODUCTION

Large earthquakes, e.g. the 2004 Niigataken-Chuetsu earthquake and the 2007 Niigataken-Chuetsu-oki earthquake in Japan, cause various kinds of damages that affect the social and economic activities of the region. The damages of urban infrastructures, e.g. gas and water pipes and harbor structures, are related to large ground deformation due to soil liquefaction. Hence it is important to detect the occurrence of liquefaction at an early stage shortly after an earthquake occurs.

Many strong motion seismometers have been deployed in Japan and the acceleration records at liquefied sites were also obtained in the recent earthquakes. The records at liquefied sites show that the predominant period of the horizontal components tends to be longer. On the other hand, the predominant period of the vertical component is not lengthened even at liquefied sites. An example of liquefied records and that of non-liquefied records are shown in Fig. 1. These two seismic records were obtained in the 2007 Niigataken-Chuetsu-oki earthquake in Japan. The alteration of the horizontal acceleration is triggered by decreasing of the soil shear modulus as a consequence of the pore-water pressure buildup under the undrained condition. It is very costly to observe the pore-water pressure using pressure devices. But, it is much less costly to detect the occurrence of liquefaction using acceleration records. Such a method can utilize the data from existing accelerometers and identify the occurrence of the phenomenon immediately after an earthquake.

The ground motion parameters from liquefied sites were examined in previous studies [1,2] and some methods of liquefaction detection from strong motion records were proposed. Suzuki *et al.* [1]

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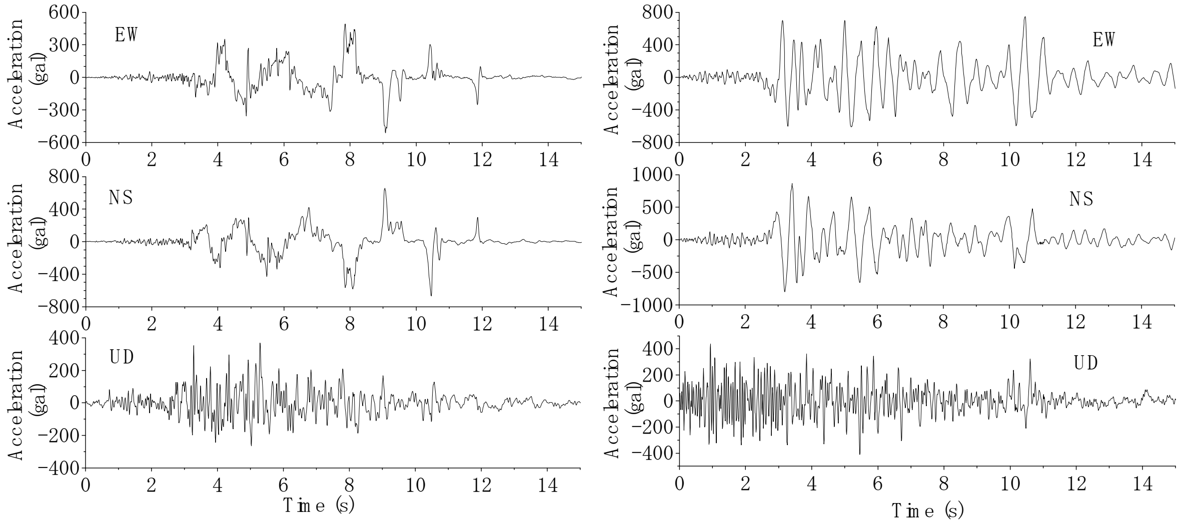
and Miyajima *et al.* [2] proposed the methods which judge the occurrence of liquefaction using the amplitude, frequency and energy parameters from acceleration records. However, these methods focus mainly on the predominant periods of the horizontal components, and thus the effects of surface waves which lengthen the period of seismic motion are difficult to remove. Kostadinov and Yamazaki [3] and Kiyono *et al.* [4] focused not only on the period of the horizontal components but also on that of the vertical component. Considering the predominant period of the vertical component, the effects of surface waves could be treated properly.

After these previous studies, the number of seismometers deployed in Japan have increased, and more ground motion records have been observed at liquefied sites than before. In this study, the accuracy of liquefaction detection methods is evaluated using newly observed data. In addition to that, a simplified method to detect soil liquefaction using acceleration records is proposed based on a dataset including records from liquefied and non-liquefied sites.



(a) Liquefied record at K-NET Kashiwazaki **(b) Non-Liquefied record at Nishiyama IC**

Figure 1. Examples of seismic motion records at liquefied and non-liquefied sites in the 2007 Niigataken-Chuetsu-oki, Japan earthquake

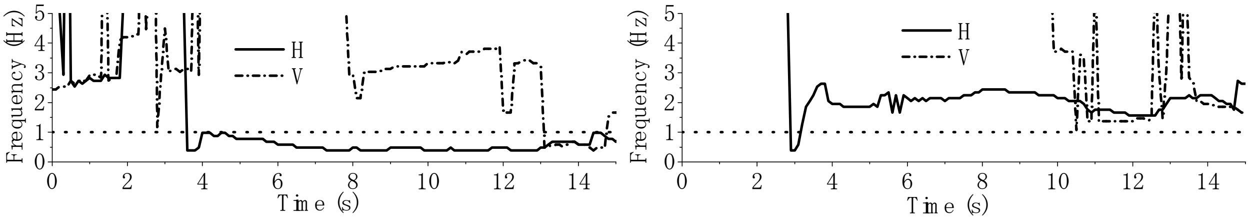
2. ESTIMATION OF PREDOMINANT FREQUENCY OVER THE TIME CALCULATED FROM RUNNING FOURIER SPECTRUM

This study calculates a running Fourier spectrum of the ground motion records to understand the predominant frequency with respect to time. Referring to Miyajima *et al.* [2], we estimated the predominant frequency at every 0.1 s, which indicates the maximum amplitude of the Fourier spectrum smoothed by a Parzen window of 0.4 Hz band width. The Fourier spectrum is calculated using an acceleration record of 2.5 s duration and the Fourier amplitude spectrum for the horizontal component, f_H, is defined as

$$f_H = \sqrt{f_{EW}\, f_{NS}} \tag{1}$$

in which f_{EW} and f_{NS},,are the Fourier amplitude spectra for two horizontal components.

Figure 2 illustrates the predominant frequencies over the time of acceleration records in Fig. 1. The predominant frequency for the horizontal component is smaller than 1.0 Hz in a main shaking at the



(a) Liquefied site (K-NET Kashiwazaki) **(b) Non-Liquefied site (Nishiyama IC)**

Figure 2. Examples of predominant frequencies over the time calculated from running Fourier spectra

liquefied site while that for the vertical component remains larger than 5.0 Hz. After the arrival of the surface wave (at 13 s in Fig. 2 (a)), the predominant frequency of the vertical component becomes as small as those of the horizontal component. The predominant frequency at the non-liquefied site is not smaller than 1.0 Hz even in a main shaking part.

Figure 3 shows the flowchart to detect of liquefied sites based on the predominant frequencies estimated from the running Fourier spectra. The JMA seismic intensity is introduced as an index to show the magnitude of ground shaking. Miyajima *et al.* [2] employed the peak horizontal ground acceleration (PGA), and Kostadinov and Yamazaki [3] utilized the peak horizontal ground velocity (PGV). Since the JMA seismic intensity is highly correlated with the products of PGA and PGV [5], the JMA seismic intensity was selected in this study. We assume that liquefaction occurs only at the site where the JMA seismic intensity is larger than or equal to 5.0.

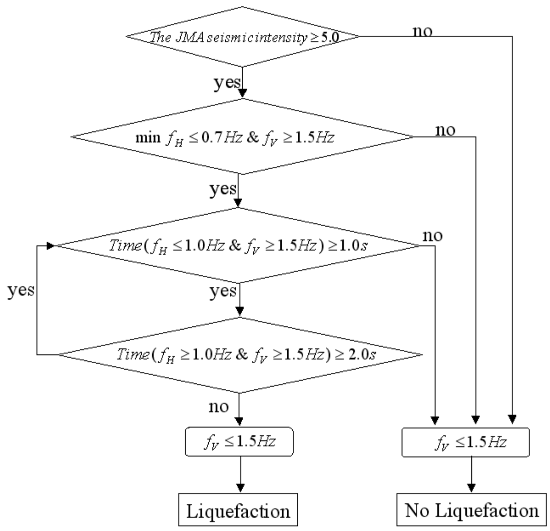


Figure 3. Flowchart to detect liquefied sites using the running Fourier spectra

As a rapid decrease in the horizontal predominant frequency is seen at the liquefied site (Fig. 2 (a)), it is assumed that the horizontal predominant frequency is smaller than 0.7 Hz at liquefied sites. The predominant frequency of the vertical component at the time was assumed to be larger than 1.5 Hz because the predominant frequency of the vertical component is not so small as that of the horizontal component as shown in Fig. 2 (a). Then, the duration in which the predominant frequency of the horizontal component is smaller than 1.0 Hz and that of the vertical component larger than 1.5 Hz is assumed to be longer than 1.0 s. The predominant frequency of the horizontal component sometimes gets smaller than 1.0 Hz for a short time even at non-liquefied sites. To avoid misleading, the duration will be investigated again if the horizontal predominant frequency becomes larger than 1.0 Hz before a judgment is made.

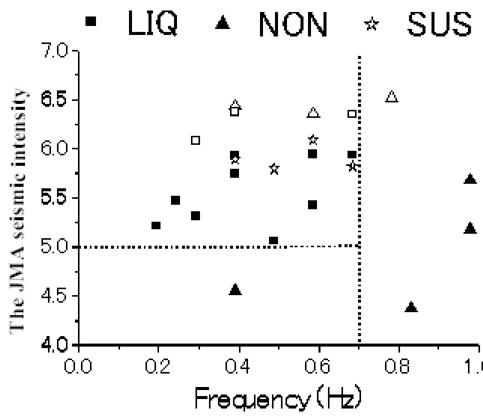


Figure 4. Relationship between the minimum horizontal predominant frequency and the JMA seismic intensity

Figure 4 shows the relationship between the minimum frequency of the horizontal component and the JMA seismic intensity for seismic motion records at liquefied and non-liquefied sites. The threshold values mentioned above were decided based on this plot. The minimum frequency of the horizontal component is determined when the vertical predominant frequency is larger than 1.5 Hz. Liquefied and non-liquefied records are selected from the dataset used by Kostadinov and Yamazaki [3] and some records from recent earthquakes are additionally considered. According to the figure, all the liquefied records show the minimum frequency of 0.7Hz or smaller. Moreover, the lower boundary of the JMA seismic intensity at liquefied sites is also seen to be 5.0 from the figure. The results of detection of liquefied sites are shown in Table 1 in the next chapter.

3. ESTIMATION OF THE PREDOMINANT PERIOD OVER THE TIME CALCULATED FROM ZERO CROSSING METHOD

In estimation of the predominant frequency by the running Fourier spectra, the extracted values are sometimes vague when the Fourier spectrum has multi-peaks in the amplitude (Fig. 5). In addition to that, the calculation process in the frequency domain is not suitable to conduct a real-time assessment.

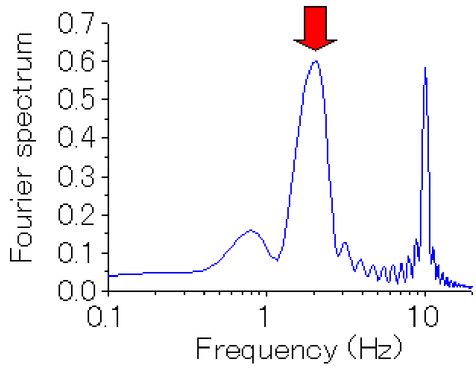


Figure 5. Fourier spectrum with multi-peaks in amplitude

To solve this problem and to simplify the calculation process, a zero crossing period is considered in this study. Figure 6 shows the schematic figure to extract a zero crossing period. From an acceleration time history, the times when the acceleration crosses the zero's line are extracted and the double length of each interval is defined as the zero crossing period in this study.

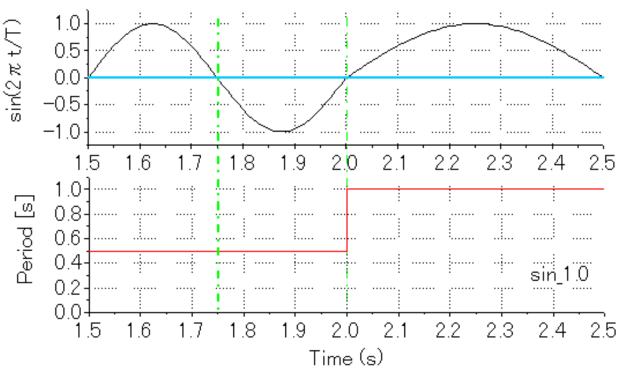
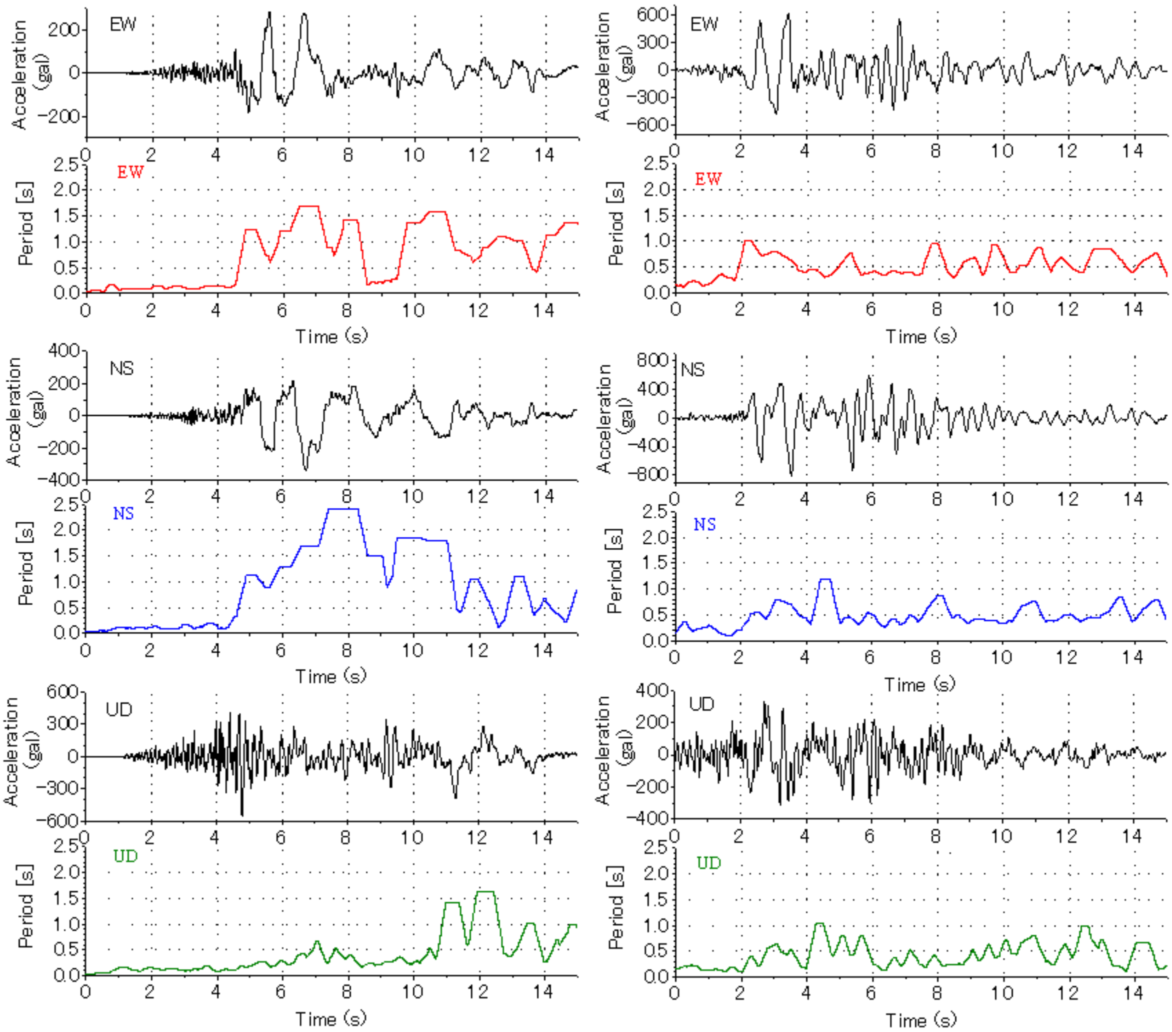


Figure 6. Schematic figure of the zero crossing period

Figure 7 shows the results for the liquefied and non-liquefied records in the 1995 Hyougoken-Nanbu (Kobe) earthquake in Japan. In the figure, the moving average is calculated for the period with the time window of 0.3 s. At liquefied sites, the period of the horizontal component tends to be longer in the main shaking while the period of the vertical component remains shorter than about 0.5 s. The vertical period becomes longer gradually after the arrival of the surface wave.

The occurrences of liquefaction are judged by the predominant periods of zero crossing following the flowchart in Fig. 8. If the predominant period of the horizontal component is longer than 1.5 s and that of the vertical component is shorter than 1.0 s, the seismic motion is considered to indicate the occurrence of liquefaction. Table 1 shows the results of detection of liquefied sites based on the two methods considered in this study. According to the results, all the liquefied sites were detected correctly. However, there still remains misjudgment in the results. As for the results of detection based on the zero crossing period, the duration time of the lengthened period of



(a) Liquefied site (Port-Island) **(b) Non-liquefied site (JMA Kobe)**

Figure 7. Examples of the zero crossing periods for liquefied and non-liquefied records in the 1995 Kobe earthquake

the horizontal component is not considered at this moment. The effects of duration will be taken into account in the near future.

4. CONCLUSION

In this study, the method to detect liquefied sites was proposed using a running Fourier spectra and zero crossing periods. Both of the horizontal and vertical components of ground motion records and the JMA seismic intensity are used in the proposed method. The both methods gave good estimation of liquefaction occurrence to some extent. In the future, the duration to the lengthened period of horizontal component estimated from the zero crossing periods will be considered properly to improve the accuracy of estimation.

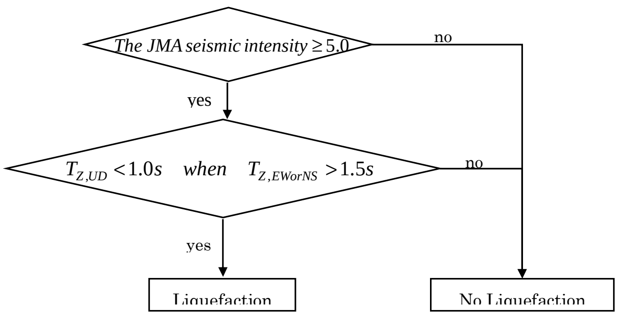


Figure 8. Flowchart to detect liquefied sites using zero crossing period

Table 1. Judgment of liquefied sites using acceleration records based on running Fourier spectrum and zero crossing period

Observation point	Earthquake	Report	Running Fourier Spectrum	Zero Crossing Period
Hachirogata	Nihonkai-Chubu Earthquake 1983	○	○	○
Wildlife	Superstition Hills Earthquake 1987	○	○	○
Higashi-Kobe Bridge	Hyogoken-Nanbu Earthquake 1995	○	○	○
Amagasaki	Hyogoken-Nanbu Earthquake 1995	○	○	○
Amagasaki No.3 P.P.	Hyogoken-Nanbu Earthquake 1995	○	○	○
Port Island	Hyogoken-Nanbu Earthquake 1995	○	○	○
Kobe-JI-S	Hyogoken-Nanbu Earthquake 1995	○	○	○
Nemuro, JMA	Kushiro-Oki Earthquake 1993	×	×	×
Suttsu, JMA	Hokkaidou-Nansei-Oki Earthquake 1993	×	×	×
Kushiro, JMA	Hokkaidou-Toho-Oki Earthquake 1994	×	×	×
Nemuro, JMA	Hokkaidou-Toho-Oki Earthquake 1994	×	×	×
Tomakomai, JMA	Hokkaidou-Toho-Oki Earthquake 1994	×	×	×
Urakawa, JMA	Hokkaidou-Toho-Oki Earthquake 1994	×	×	×
Hachinohe, JMA	Sanriku-Haruka-Oki Earthquake 1994	×	×	×
Kobe, JMA	Hyogoken-Nanbu Earthquake 1995	×	×	×
Osaka, JMA	Hyogoken-Nanbu Earthquake 1995	×	×	×
Akune, K-NET	Kagoshimaken-Hokuseibu Earthquake 1997	×	×	×
Kaseda, K-NET	Kagoshimaken-Hokuseibu Earthquake 1997	×	×	×
Miyagino, K-NET	Kagoshimaken-Hokuseibu Earthquake 1997	×	×	×
Ohkuchi, K-NET	Kagoshimaken-Hokuseibu Earthquake 1997	×	×	×
Sendai, K-NET	Kagoshimaken-Hokuseibu Earthquake 1997	×	×	×
Yonago, K-NET	Tottoriken-Seibu Earthquake 2000	△	○	×
Kohu, K-NET	Tottoriken-Seibu Earthquake 2000	×	×	×
Chokubetsu, K-NET	Tokachi-Oki Earthquake 2003	○	○	○
Ojiya, K-NET	Nigataken-Chuetsu Earthquake 2004	×	×	×
Kaguchicho, JMA	Nigataken-Chuetsu Earthquake 2004	×	×	×
Nagaokashisyo, K-NET	Nigataken-Chuetsu Earthquake 2004	×	×	×
Yamakoshishisyo, JMA	Nigataken-Chuetsu Earthquake 2004	×	×	○
Tohkamachi, K-NET	Nigataken-Chuetsu Earthquake 2004	×	×	×
Kariwa, JMA	Nigataken-chuetsu-Oki Earthquake 2007	○	○	○
Kashiwazaki, K-NET	Nigataken-chuetsu-Oki Earthquake 2007	○	○	○
Kashiwazaki IC	Nigataken-chuetsu-Oki Earthquake 2007	△	×	○
Kakizaki, JMA	Nigataken-chuetsu-Oki Earthquake 2007	△	○	×
Kakizaki IC	Nigataken-chuetsu-Oki Earthquake 2007	△	×	×
Nakanoshima, JMA	Nigataken-chuetsu-Oki Earthquake 2007	×	×	×
Nakanoshima IC	Nigataken-chuetsu-Oki Earthquake 2007	×	×	×
Nishiyamacho, JMA	Nigataken-chuetsu-Oki Earthquake 2007	×	×	○
Nshiyama IC	Nigataken-chuetsu-Oki Earthquake 2007	×	×	×
The first in Kariwa Kashiwazaki nuclear plant machine earthquake observation hut	Nigataken-chuetsu-Oki Earthquake 2007	△	×	×
Service Hall in Kariwa Kashiwazaki nuclear plant machine	Nigataken-chuetsu-Oki Earthquake 2007	△	○	○

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