COMPARATIVE STUDY ON THE METHODS FOR DETECTION OF LIQUEFACTION FROM STRONG MOTION RECORDS

M. V. Kostadinov, F. Yamazaki, M. ASCE, and K.Sudo
Institute of Industrial Science, University of Tokyo, Tokyo, Japan
mladen@iis.u-tokyo.ac.jp, *yamazaki@iis.u-tokyo.ac.jp*, *sudo@incede.iis.u-tokyo.ac.jp*

Abstract

Several records from liquefied-soil sites have been obtained during the recent big earthquakes in Japan and USA and a few methods for detection of liquefaction using recorded seismic motion were developed. In this study we propose an alternative method that simultaneously analyzes the instantaneous frequency contents of the horizontal and the vertical ground accelerations. We compare the performance of the all liquefaction detection methods by processing a common data set, including records from liquefied and non-liquefied sites in Japan, USA and Mexico. The results show that the occurrence of liquefaction could be reliably judged from the recorded acceleration time histories.

Introduction

During the latest big earthquakes in Japan and USA a number of records from liquefied-soil sites have been obtained. The records show that the frequency and amplitude of the horizontal acceleration alternate uniquely after the onset of liquefaction as a consequence of the pore-water pressure excess. Typically, the frequency drops under 1 Hz and the amplitude decreases comparing to that of the vertical acceleration. Ground motion parameters from the liquefied-site records were studied in order to capture the waveform alternation. Based on them, several methods for detection of liquefaction from the seismic records were recently proposed in Japan. These methods, however, focus mainly on the horizontal ground motion and may interpret as liquefaction-induced some records from soft-soil deposits or records with dominant surface waves, at which sites phenomenon was not observed. Besides, not all of the available records from liquefied-soil sites were processed.

In this study, after reviewing the recent methods for liquefaction detection from the seismic records, we propose a new method that simultaneously analyzes the instantaneous frequency contents of the horizontal and the vertical ground accelerations. We compare the performance of the proposed method with that of the other methods by processing a common data set of seismic records from liquefied and non-liquefied sites in Japan, USA and Mexico.

Review of Existing Methods for Liquefaction Detection Using Ground Motion Records

Method of Suzuki

The method (Nakayama *et al.*, 1998) uses the two horizontal acceleration components and considers following four parameters: peak ground acceleration (*PGA*), maximal spectral intensity (SI_{max}), which is obtained by rotating the direction of the horizontal acceleration, maximal horizontal displacement (D_c) and zero-crossing period ($T_{z,a}$). Occurrence of liquefaction is judged if all parameters exceed certain limit values: 1) $PGA \geq 100$

Ground Motion Parameters

Detection of Liquefaction	Amplitude Parameters	Frequency Parameters	Energy Parameters
Method of Suzuki	Peak horizontal acceleration, Max. horizontal displacement	Zero-crossing period	Spectral intensity
Method of Miyajima	Ratio of vert. to horizontal acceleration	Averaged predom. freq., Decrease rate of predom. freq.	Ratio of low-freq. portion to whole Fourier spectrum
Method of Ozaki and Takada			Ratio of filtered to non-filtered Arias intensity
Proposed Method	Peak horizontal velocity	Mean instantaneous frequency	

Figure 1. Ground motion parameters used in the liquefaction detection methods.

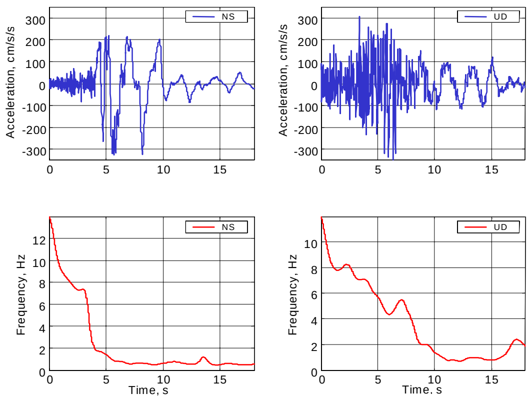

Figure 2. ***MIF*** **computed from the NS and UD components of the Higashi-Kobe bridge record**

cm/s^2, 2) $SI_{max} \geq 20$ cm/s, 3) $D_c \geq 10$ cm and 4) $T_{z,a} \geq 1$ s. The method of Suzuki is implemented into a new SI sensor, developed by Tokyo Gas Co., Ltd.

Method of Miyajima

This method (Miyajima *et al.*, 1998) analyzes the three components of an accelerogram. It evaluates the following four parameters (computation of some of them is modified as in Yamamoto *et al.*, 1999): the maximal ratio of vertical to horizontal acceleration amplitude ($A_{V,max}/A_{H,max}$), the ratio of low-frequency portion (up to 2 Hz) to the whole area of Fourier amplitude spectrum (R_L), the averaged predominant frequency ($F_{p,a}$), and the decrease rate of the predominant frequency ($\Delta F_{p,a}$). Liquefaction occurrence is judged using a point system. In case that any of the parameters exceeds a limit value, points are given as follows: $A_{V,max}/A_{H,max} \geq 2.0$ - 1 point, $R_L \geq 0.25$ - 1 point, $F_{p,a} \leq 1$ Hz and $\Delta F_{p,a} \geq 1$ Hz/s - 1 point, $F_{p,a} \leq 1$ Hz and $\Delta F_{p,a} < 1$ Hz/s - 0.5 points. If the sum of the points is less than 2.0, the possibility for liquefaction is judged as low. If the sum of points is equal or greater than 2.0 but less than 3.0, the possibility for liquefaction is judged as high. If the sum of points is equal to 3.0, the possibility for liquefaction is judged as very high.

Method of Ozaki and Takada

The method (Ozaki, 1999) processes the two horizontal acceleration components. It takes into account one parameter - ratio of Arias intensity of filtered to non-filtered acceleration time history (R_I). The filter used in this method is a low-pass filter with cutoff frequency of 1 Hz. Occurrence of liquefaction is judged according to the value of R_I as follows: $0 \leq R_I < 0.3$ - no liquefaction, $0.3 \leq R_I < 0.6$ - possible liquefaction, $0.6 \leq R_I \leq 1$ - liquefaction.

Description of the Proposed Method

The main feature of the liquefied-site records is not only that the high-frequency content vanishes in the horizontal components of the accelerogram, but also that it exists in the vertical one. Therefore, we suggest analyzing the instantaneous frequency behavior of both horizontal and vertical acceleration simultaneously. In our proposal, we consider the mean instantaneous frequency (*MIF*) defined as the ratio of the first to zeroth fre-

No	Site	Earthquake	Lique-faction	Record Type
1	Kawagishi-cho	1964 Niigata	L	S
2	Aomori-S (PHRI)	1968 Tokachi Oki	L	F
3	Hachirogata (PWRI)	1983 Nihonkai Chibu	L	F
4	Wildlife, GL	1987 Superstition Hills	L	F
5	Treasure Island	1989 Loma Prieta	LS	F
6	Kushiro-G (PHRI)	1993 Kushiro Oki	LS	F
7	Amagasaki Bridge	1995 Hyogoken Nanbu	LS	F
8	Amagasaki No. 3 P.P.	1995 Hyogoken Nanbu	L	F
9	Amagasaki-G (PHRI)	1995 Hyogoken Nanbu	L	F
10	Higashi-Kobe Bridge	1995 Hyogoken Nanbu	L	F
11	Kobe-JI-S (PHRI)	1995 Hyogoken Nanbu	L	F
12	Kobe-Dai8-G (PHRI)	1995 Hyogoken Nanbu	L	S
13	Port Island, GL	1995 Hyogoken Nanbu	L	F
14	Port Island, GL-16	1995 Hyogoken Nanbu	L	D
15	Port Island, GL-32	1995 Hyogoken Nanbu	LS	D
16	Rokko Island, B3, B1F	1995 Hyogoken Nanbu	L	S
17	JR Takatori Station	1995 Hyogoken Nanbu	LS	F
	Records from Liquefied Free-field Sites (Incl. 1 Downhole):			9
	Records from Liquefied Structure Sites:			3
	Records from Liquefaction-suspicious Free-field Sites (Incl. 1 Downhole):			5

L – Liquefied; LS – Liquefaction-suspicious

F - Free-field; S – Structure; D - Downhole

Table 1: Records from liquefied and liquefaction-suspicious sites.

Earthquake	Number of Records
1968 Tokachi Oki	2
1978 Miyagiken Oki	1
1983 Nihonkai Chibu	1
1985 Michoacan, Mexico City	5
1987 Superstition Hills	1
1987 Chibaken Toho Oki	5
1989 Loma Prieta	10
1993 Kushiro Oki	7
1993 Hokkaido Nansei Oki	4
1994 Northridge Earthquake	11
1994 Hokkaido Toho Oki	4
1994 Sanriku Haruka Oki	1
1995 Hyogoken Nanbu	10
1997 Kagoshimaken Hokuseibu	4
Records from Non-liquefied Free-field Sites (Incl. 4 Downhole):	66

Table 2: Earthquake events and corresponding number of records from non-liquefied sites.

quency moment of a time-frequency representation. As a time-frequency method, we use the short-time Fourier transform (STFT) spectrogram. In other words, we compute the mean frequency of the power spectrum of a moving window. We utilized the Hamming window of length 256 points for the acceleration records with a time increment of 0.01 s and a proportional rule was applied for different time increments in order to maintain similar frequency resolution. The window is moved stepwise within the time interval between the first and last exceeding of 40 cm/s^2 of the horizontal acceleration. We also employ in our method the peak horizontal ground velocity (*PGV*) as a measure of the ground shaking intensity that is related to the liquefaction-inducing stresses in the soil. Figure 1 summarizes the ground motion parameters employed in the methods for liquefaction detection. *MIF* of the NS and UD component of the Higashi-Kobe bridge record during the 1995 Hyogoken-Nanbu earthquake is shown on Figure 2.

The proposed method implements the following four steps:

1. *PGV* is calculated to select the potential liquefied sites. If *PGV* is equal or larger than 10 cm/s, step 2 is carried out. If *PGV* is less than 10 cm/s than “no liquefaction” is judged.
2. *MIF* is determined for the horizontal and the vertical ground acceleration components.
3. The total duration, satisfying the condition $MIF_H \leq 2/3$ Hz and $MIF_V \geq 3$ Hz is obtained, where the index *H* stands for any of the horizontal components and index *V* stands for the vertical component of the accelerogram. If this duration is equal or larger than 0.1 s than “liquefaction” is detected. Otherwise step 4 is performed.
4. The total duration, satisfying the condition $MIF_H \leq 1$ Hz and $MIF_V \geq 3$ Hz is ob-

tained, where the indices *H* and *V* have the same meaning as in step 3. If this duration is equal or more than 0.1 s, “liquefaction suspicion” is judged. Otherwise, “no liquefaction” is detected.

Common Data Set of Strong Motion Records

A common data set of seismic records is developed to compare the performance of the liquefaction detection methods as well as that of the individual ground motion parameters. In this study we concentrated on free-field records with *PGA* bigger than 150 cm/s^2 and *PGV* bigger than 15 cm/s, though some downhole and structure records are also presented. We classified the recording sites with respect to the liquefaction occurrence due to a particular earthquake in the following three groups:

1. *Liquefied sites*: there were evidences seen for liquefaction at the recording site.
2. *Liquefaction-suspicious sites*: there were no evidences seen for liquefaction at the recording site, but they were observed in its vicinity (up to 50 m) or cyclic mobility at the site was confirmed by an analytical study.
3. *Non-liquefied sites*: there were no evidences for liquefaction at the recording site and its vicinity (up to 50 m) or no conformation about cyclic mobility at the site.

The common data set consists of 74 free-field, 6 downhole and 3 structure ground motion records from Japan, USA and Mexico. For the purposes of the study, the records in the data set are divided in four categories: liquefied-site free-field (LF), liquefied-site structure (LS), suspicious-site free-field (SF) and non-liquefied-site free-field (NF). In total twelve liquefied-site records (LF and LS) and five suspicious-site free-field records are confirmed. The non-liquefied free-field records are sixty-six, including four downhole records. Table 1 shows the LF, LS and SF records and Table 2 displays the number of the NF records and the corresponding events. The values of *PGA* vs. *PGV* for all records in the common data set are plotted in Figure 3.

Comparison of Liquefaction Detection Methods

For the sake of comparison, we assumed that the different methods detect same levels of liquefaction occurrence. The levels are named “Level 1”, “Level 0.5” and “Level 0”. The relation between these levels and the outputs of the liquefaction detection methods is given in Table 3.

The judgments about the liquefied-site free-field records are shown in Figure 4. The method of Suzuki indicates the Port Island GL-16 record as Level 0 and the proposed method - as Level 0.5. This is due to the high-frequency content in the horizontal components that result in smaller $T_{z,a}$ and larger MIF_H values. The small value of the decrease rate of the predominant frequency causes the method of Miyajima to identify the Higashi-Kobe bridge record as Level 0.5. The method of Ozaki and Takada recognizes around half of the LF records as Level 1 and the rest as Level 0.5. Since this method uses one parameter, its thresholds might need additional adjustment.

Figure 5 displays the judgments about the records from liquefied structure sites. Both the method of Suzuki and the proposed method identify the Kawagishi-cho record as Level

	Level 0	Level 0.5	Level 1
Method of Suzuki	no liquefaction	*	liquefaction
Method of Miyajima	low possibility for liquefaction	high possibility for liquefaction	very high possibility for liquefaction
Method of Ozaki and Takada	no liquefaction	possible liquefaction	liquefaction
Proposed Method	no liquefaction	liquefaction suspicion	liquefaction

Table 3: Relation between the comparison levels and the method judgements.

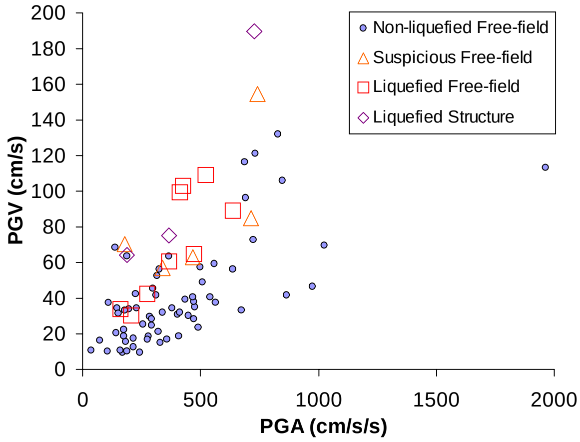

Figure 3. PGA and PGV of the records in the common data set.

0. While the former method estimates small D_c value, the latter method does not recognize it because the vertical acceleration component lacks of high-frequency content. The method of Ozaki and Takada detects all these records as Level 1. The method of method of Miyajima gives either Level 0.5 or Level 1 judgments.

The results about the suspicious-site free-field records are shown in Figure 6. Two of them - Port Island GL-32 from the 1995 Hyogoken-Nanbu earthquake and Kushiro-G from the 1993 Kushiro-Oki earthquake - are detected by the method of Suzuki as Level 0 again due to smaller $T_{z,a}$ value. The Treasure Island record is identified as Level 1 by the methods of Miyajima and the proposed one, as the Takatori station record by the method of Ozaki and Takada. Remaining four SF records are indicated as Level 0.5 by the methods of Miyajima and Ozaki and Takada. The Kushiro-G record, at which site cyclic mobility was confirmed is judged as Level 0.5 from all three-level methods.

Figure 7 depicts the detection of the non-liquefied-site free-field records. The methods of Suzuki and the proposed one recognize 90% of these records as Level 0 while the methods of Miyajima and Ozaki and Takada identify around 75 percent of them. The record at Tachibuya D. F. from the 1985 Mexico City earthquake is judged as Level 1 by the method of Ozaki and Takada though *PGA* at this site - 37 cm/s^2 - implies that the liquefaction occurrence is unlikely. It should be also noted that all methods interpret the record at Emeryville, 6363 Christie Ave from the 1989 Loma Prieta earthquake as Level 1 or Level 0.5. The record from this soft-soil site exhibits low-cycle acceleration with no frequency drop in the horizontal components but relatively high-frequency content in the vertical component and it is believed to reflect possible soil-structure interaction effect. The site was also close to area of considerable liquefaction.

Conclusions

A new method for judgement of soil liquefaction from the ground motion records was proposed and a comparative study on the performance of the different liquefaction detection methods was conducted. The comparison was done by processing a common data set of seismic records. Results show that all methods recognize more than 90 percent of the records from liquefied soil sites and distinguish at least two thirds of the

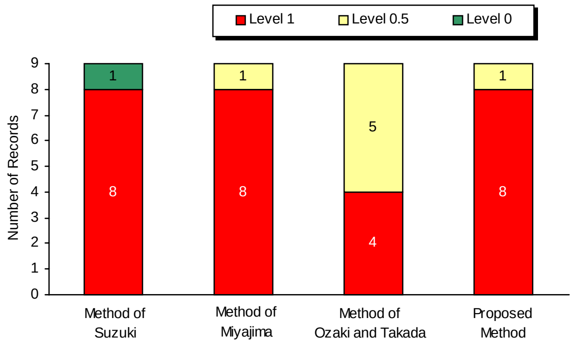

Figure 4. Detection of the records from liquefied free-field sites.

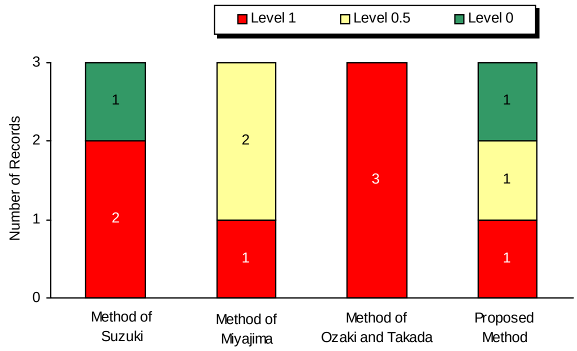

Figure 5. Detection of the records from liquefied structure sites.

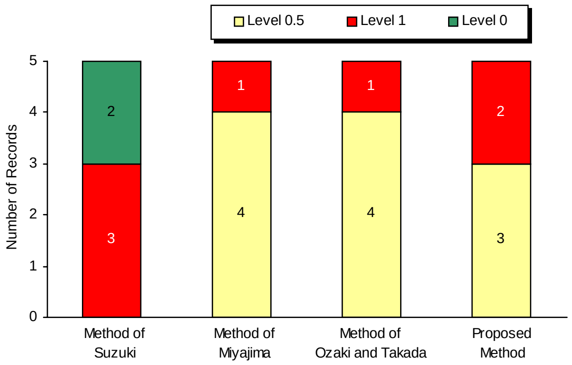

Figure 6. Detection of the records from suspicious free-field sites.

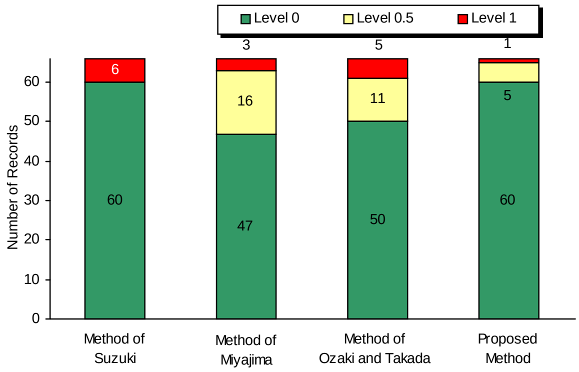

Figure 7. Detection of the records from non-liquefied free-field sites.

records from non-liquefied sites. Proposed method shows more efficient detection ability regarding the free-field records.

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