A Proposal for Method for Detection of Soil Liquefaction Using Strong Motion Records

by

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ABSTRACT

Since the 1964 Niigata earthquake, several records from liquefied-soil sites have been obtained. The records show that the frequency and amplitude of the horizontal acceleration alternates uniquely after the onset of liquefaction as a consequence of the pore-water pressure excess. The ground motion parameters from these sites were studied and several methods for detection of liquefaction from the seismic records were developed. 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. In this study, we propose a new liquefaction detection method that simultaneously analyzes the instantaneous frequency content of the horizontal and the vertical ground acceleration. The performance of the method is examined by processing a data set of 83 strong motion records from liquefied and non-liquefied sites.

INTRODUCTION

Since the 1964 Niigata earthquake, several strong motion records from liquefied-soil sites have been obtained. The records exhibit specific alternation of the horizontal ground acceleration after the liquefaction onset - its frequency abruptly drops off under 1 Hz and its amplitudes decrease comparing to that of the vertical acceleration (Figure 1). This alternation is triggered by the excess of the pore-water pressure, as a consequence of the undrained cyclic loading in loose saturated soils. An adequate description of the alternation can be used as a method for detection of liquefaction from the seismic records. Such a method can operate data from a seismometer network and identify the occurrence of the phenomenon immediately after an earthquake. It can also function as a standalone liquefaction sensor in combination with an accelerometer. Liquefaction has been recognized as the main reason for collapse of earth dams and slopes, failure of foundations, superstructures and lifelines and its early detection might be of great interest.

A practical approach to capture the alternation of ground motion is to calculate appropriate ground motion parameters and compare their values with limit ones that correspond to soil liquefaction. The advantages of this approach are that the alternation is expressed in terms of physically meaningful quantities and that computations are simple. The disadvantage is the incompleteness of the alternation description. The ground motion parameters from liquefied-soil sites were examined in a number of studies and a few methods for liquefaction judgment from the strong motion records were proposed (Nakayama *et al.*[1], Miyajima *et al.*[2], Ozaki[3]). These methods, however, focus mainly on the horizontal ground motion and may interpret as liquefaction-induced some records from soft-soil deposits or

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records with dominant surface waves, at which sites phenomenon was not observed. An example is the record at SC&T from the 1985 Michoacan, Mexico City earthquake, shown in Figure 2.

In this study, a new detection method is proposed, based on simultaneously analyzing of the horizontal and vertical acceleration. The method is examined by processing a data set of 83 seismic records from liquefied and non-liquefied sites in Japan, USA and Mexico.

DESCRIBTION OF THE 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. The instantaneous frequency behavior of a given signal i.e. how the signal frequency changes over the time is the subject of the joint time-frequency analysis. Taking the Fourier transform within a moving window, known also as short-time Fourier transform (STFT) is the simplest among the variety of time-frequency representations (Qian and Chen[4]). Its square, named STFT spectrogram is the most used time-dependent power spectrum. Another popular time-frequency methods are Wigner-Ville distribution and its derivatives - Cohen's class distributions.

In our proposal, we consider the mean instantaneous frequency (*MIF*) defined as

$$MIF(t) = \frac{\int_0^{f_N} fP(t,f)df}{\int_0^{f_N} P(t,f)df} \tag{1}$$

where $P(t,f)$ is a bilinear time-frequency representation of the acceleration time history, f_N is the Nyquist frequency, t stands for the time and f for the frequency. As a time-frequency representation, we use the STFT spectrogram. In other words, we compute the mean frequency of the power spectrum of the moving window. Because it is a weighted average of all frequencies present at a given moment, *MIF* can quantify the frequency alternation in the ground acceleration records from the liquefied sites. The advantage of using *MIF* is that it can be computed from different time-frequency representations, depending on the specific application.

We utilized the Hamming window of length 256 points for the acceleration records with a time increment of 0.01 s. For different time increments, the window length is changed proportionally in order to maintain similar frequency resolution (i.e. 128 points for time increment of 0.02 s). The window is moved stepwise within the time interval between the first and last exceeding of 40 cm/s^2 of the horizontal acceleration. Having the *MIF* computed, we detected the time instants at which it has relatively low value in any of the horizontal acceleration components and relatively high value in the vertical acceleration component. We consider the total time of this state (represented by the number of the time instants, multiplied by the time increment) as an indicator for soil liquefaction. This procedure is expected to distinguish well the liquefied-site records from those from non-liquefied sites. Figure 3 shows the *MIF* of the Higashi-Kobe bridge record during the 1995 Hyogoken-Nanbu earthquake.

In addition to *MIF* we 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. *PGV* is defined as the maximal value of the vector sum of the two horizontal ground velocity components. In their study, Midorikawa and Wakamatsu[5]

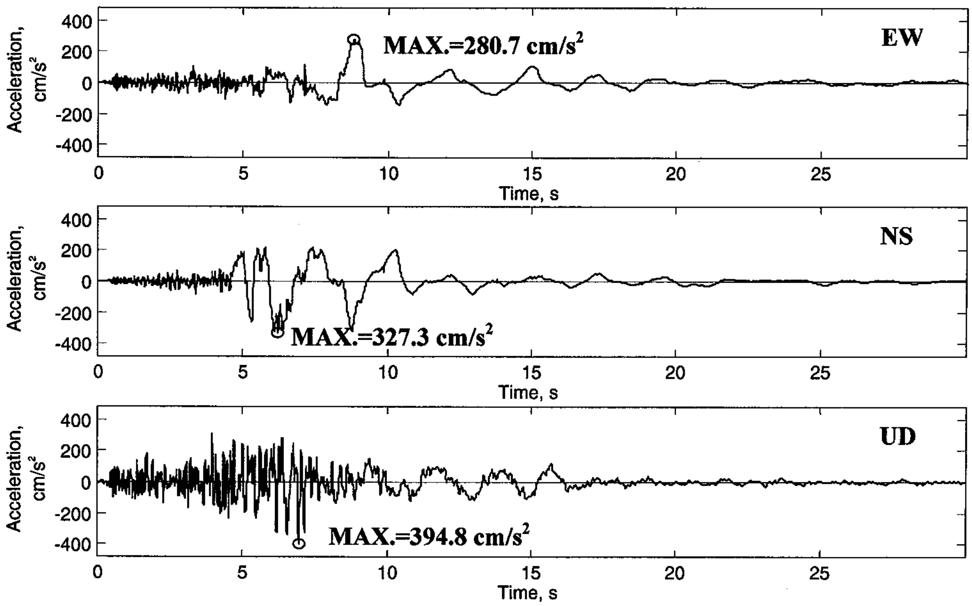

Figure 1. Acceleration record from Port Island GL during the 1995 Hyogoken-Nanbu earthquake. The site was heavily liquefied.

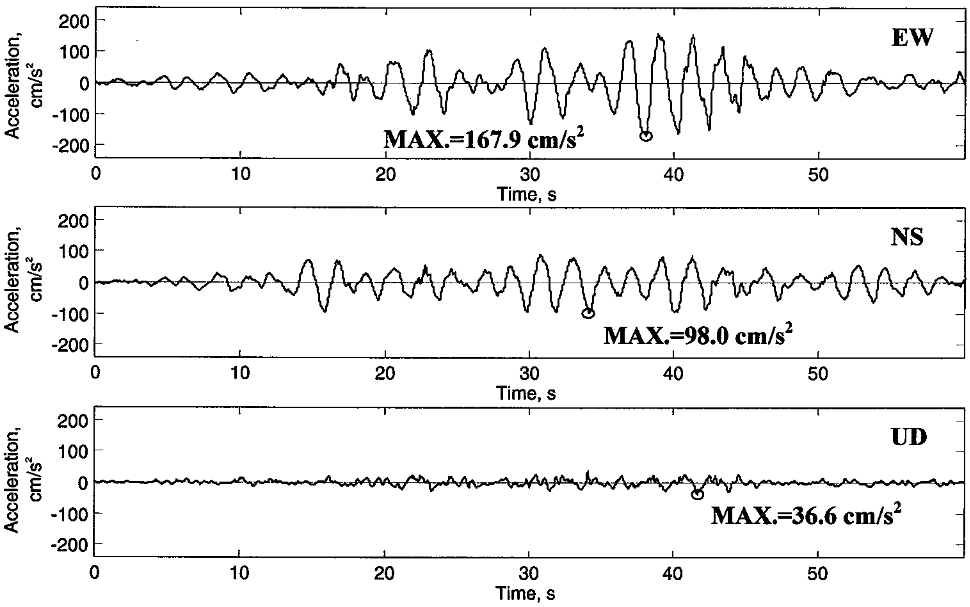

Figure 2. Acceleration record from SC&T during the 1985 Michoacan, Mexico City earthquake. No liquefaction occurred at the site.

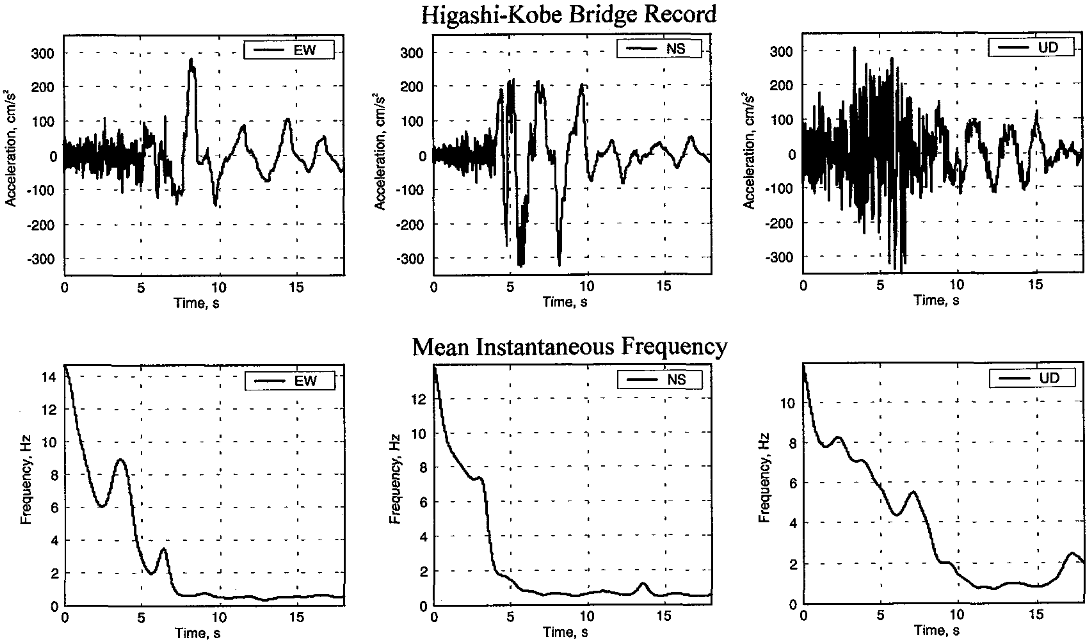

Figure 3. Mean instantaneous frequency of the Higashi-Kobe bridge record during the 1995 Hyogoken-Nanbu earthquake.

calculated the intensities of the ground motion at liquefied sites during past earthquakes by semi-empirical method, taking into account the fault size and the soil profile at the site. They concluded that *PGV* is better correlated with the occurrence of liquefaction than *PGA* and suggested that soil liquefaction is likely to occur when *PGV* exceeds 10-15 cm/s, which is supported by the observations (see Table 1). *PGV* is obtained through integration of the ground acceleration time history. We used integration by Fourier transform after filtering the original acceleration components with a band-pass filter between 0.05 Hz and 33 Hz.

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, "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 obtained, 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.

DATA SET OF STRONG MOTION RECORDS

To examine the performance of the proposed method for liquefaction detection a data set of seismic records is developed. Free-field records with *PGA* bigger than 150 cm/s^2 and

PGV bigger than 15 cm/s are mainly presented in the data set, though there are some downhole and structure records.

The fact whether a record is from a liquefied site or not is judged from a report about the site condition after a particular earthquake. Liquefaction occurrence is proved by field evidence like sand boils, ground fissures filled with sand, large permanent displacements or vertical settlements of the soil, uplifting of pipelines or tanks, tilting of buildings, some foundation failures etc. Seed *et al.*[6] pointed out that the liquefaction evidence take different forms for different soils and suggested to consider two phenomena - "liquefaction" and "cyclic mobility". The former involves very large deformations while the latter involves limited amount of cyclic strain in the soil. Depending on the soil profile, however, some liquefaction evidence such as sand boils may not be observed on the surface, when liquefaction occurs in depth.

In accordance with the above consideration, 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 evidence 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 evidence for liquefaction at the recording site and its vicinity (up to 50 m) as well as no conformation about cyclic mobility at the site.

The data set consists of 74 free-field, 6 downhole and 3 structure ground motion records from Japan, USA and Mexico. American records are obtained from the Earthquake Strong Motion CD-ROM, National Oceanic and Atmospheric Administration[7] and from the Internet site of California Strong Motion Instrumentation Program (CSMIP). The early Japanese data are also obtained from the mentioned CD-ROM and the rest are provided by various national organizations and institutes, including Japan Meteorological Agency (JMA), Port and Harbour Research Institute (PHRI), Ministry of Transport, Public Works Research

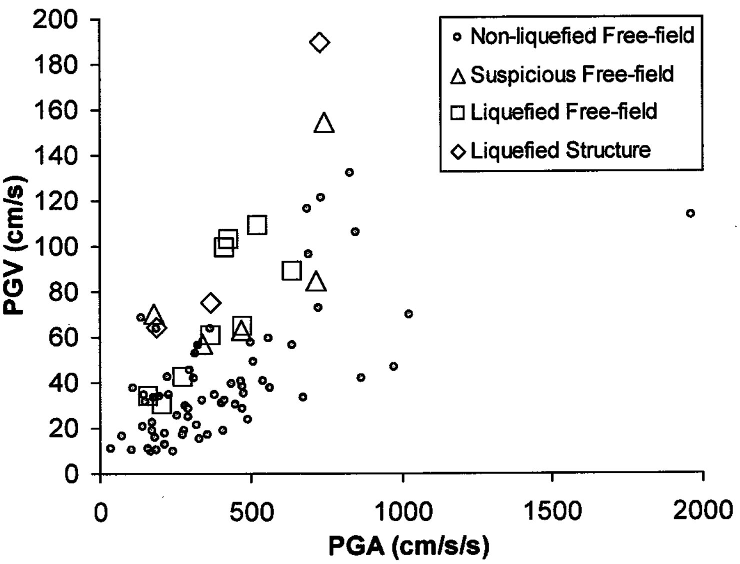

Figure 4. *PGA* vs. *PGV* for all records in the dataset

Table 1. Seismic records used in this study and corresponding detection for liquefaction

No	Site	PGA, (cm/s^2)	PGV, (cm/s)	Record Type	Liquefaction occurrence	Record Group	Detection	Reference for liquefaction
	Niigata Earthquake 1964/06/16							
1	Kawagishi-cho	186.06	65.1	S	LIQ	LS	0	8)
	Tokachi-Oki Earthquake 1968/05/16							
2	Aomori Harbor	275.91	39.9	F	LIQ	LF	1	9)
3	Hachinohe Harbor	312.76	39.1	F	NON	NF	0	
4	Muroran Harbor	229.62	35.7	F	NON	NF	0	
	Miyagiken-Oki Earthquake 1978/06/12							
5	Shiogama Harbor	316.12	53.6	F	NON	NF	0	
	Nihonkai-Chibu Earthquake 1983/05/26							
6	Akita-S	222.42	37.4	F	NON	NF	0	
7	Hachirogata	177.36	72.9	F	LIQ	LF	1	10)
	Michoacan, Mexico City Earthquake 1985/09/19							
8	C. de Abastos Frigorifico	109.68	38.3	F	NON	NF	0	
9	Caleta de Campo	140.14	20.7	F	NON	NF	0	
10	SC&T	187.61	63.6	F	NON	NF	0	
11	Tacubaya, D.F.	36.97	10.4	F	NON	NF	0	
12	Tlahuac Bombas	137.90	68.6	F	NON	NF	0	
	Superstition Hills Earthquake 1987/11/24							
13	Wildlife GL	206.60	30.6	F	LIQ	LF	1	11)
14	Wildlife GL -7.5	175.52	22.0	D	NON	NF	0.5	
	Chibaken-Toho-Oki Earthquake 1987/12/17							
15	Chiba Array, IIS	329.33	15.5	F	NON	NF	0	
16	Katsuura (KT552), NIED	257.34	25.4	F	NON	NF	0	
17	Kisarazu (KT521), NIED	403.56	30.9	F	NON	NF	0	
18	Mobara, Stokogyo	475.65	35.3	F	NON	NF	0	
19	Narashino, Takenaka ED	242.63	9.1	F	NON	NF	0	
	Loma Prieta Earthquake 1989/10/18							
20	Agnew, Agnews State Hospital	178.44	31.6	F	NON	NF	0.5	
21	Capitola, Fire Station	541.69	41.1	F	NON	NF	0	
22	Corralitos, Eureka Canyon Rd.	634.07	56.6	F	NON	NF	0	
23	Emeryville, 6363 Christie Ave	255.53	45.2	F	NON	NF	0.5	
24	Foster City, Redwood Shores	297.60	46.9	F	NON	NF	0.5	
25	Gilroy #1, Gavilan College	436.07	39.2	F	NON	NF	0	
26	Hollister, South St and Pine Drive	364.93	62.5	F	NON	NF	0	
27	Santa Cruz, UCSC/Lick Lab.	491.95	22.1	F	NON	NF	0	

Table 1. (Continued)

No	Site	PGA, (cm/s^2)	PGV, (cm/s)	Record Type	Lique-faction occur-rence	Record Group	Detection	Reference for liquefaction
28	Saratoga, Aloha Ave.	497.30	56.3	F	NON	NF	0	
29	SF, International Airport	378.08	34.3	F	NON	NF	0	
30	SF, Presidio	195.59	34.4	F	NON	NF	0	
31	Treasure Island	158.72	34.3	F	SUS	SF	1	12)
	Kushiro-Oki Earthquake 1993/01/15							
32	Hanasaki-F	169.96	9.7	F	NON	NF	0	
33	Kushiro, JMA	1024.07	71.2	F	NON	NF	0	
34	Kushiro-G	467.82	62.1	F	SUS	SF	0.5	13)
35	Kushiro-GB	280.85	19.5	D	NON	NF	0	
36	Nemuro, JMA	216.10	12.8	F	NON	NF	0	
37	Tokachi-M	408.76	19.3	F	NON	NF	0	
38	Urakawa, JMA	281.82	29.4	F	NON	NF	0	
39	Urakawa-S	322.09	21.2	F	NON	NF	0	
	Hokkaido-Nansei-Oki Earthquake 1993/07/12							
40	Hakodate-F	144.85	33.2	F	NON	NF	0	
41	Hakodate-FB	71.01	16.4	D	NON	NF	0	
42	Hakodate-M	151.79	32.4	F	NON	NF	0	
43	Suttsu, JMA	216.65	16.0	F	NON	NF	0	
	Northridge Earthquake 1994/01/17							
44	LA, Bell Postal Facility, Ground	272.63	17.4	F	NON	NF	0	
45	LA, Griffith Observatory	291.94	28.5	F	NON	NF	0	
46	LA, Sepulveda Canyon, Ground	470.11	28.3	F	NON	NF	0	
47	LA, Wadsworth VA Hosp., South	471.31	39.2	F	NON	NF	0	
48	Newhall, LA County Fire Station	731.84	119.1	F	NON	NF	0.5	
49	Pasadena, 535 South Wilson Ave.	161.80	10.9	F	NON	NF	0	
50	Tarzana, Cedar Hill Nursery	1965.20	114.7	F	NON	NF	0	
51	Topanga, Fire Station, Ground	358.81	17.7	F	NON	NF	0	
52	Santa Monica City Hall, Ground	866.34	41.7	F	NON	NF	0	
53	Sylmar County Hospital	827.35	131.2	F	NON	NF	0	
	Hokkaido-Toho-Oki Earthquake 1994/10/04							
54	Kushiro, JMA	561.31	37.6	F	NON	NF	0	
55	Nemuro, JMA	414.02	31.4	F	NON	NF	0	
56	Tomakomai, JMA	105.45	10.4	F	NON	NF	0	
57	Urakawa, JMA	181.06	15.4	F	NON	NF	0	
	Sanriku-Haruka-Oki Earthquake 1994/12/28							
58	Hachinohe, JMA	673.32	31.9	F	NON	NF	0	

Table 1. (Continued)

No	Site	PGA, (cm/s^2)	PGV, (cm/s)	Record Type	Lique-faction occur-rence	Record Group	Detection	Reference for liquefaction
	Hyogoken-Nanbu Earthquake 1995/01/17							
59	Amagasaki Bridge GR-2	340.68	57.4	F	SUS	SF	1	*
60	Amagasaki-G	499.56	61.5	F	LIQ	LF	1	14)
61	Amagasaki No.3 P.P., KE	366.00	58.9	F	LIQ	LF	1	15)
62	Gen. Tech. Research Inst. GL, KE	687.51	58.1	F	NON	NF	0	
63	Higashi-Kobe Bridge	411.52	99.2	F	LIQ	LF	1	16)
64	Inagawa GR-1, PWRI	467.95	41.1	F	NON	NF	0	
65	Kobe, JMA	847.88	105.3	F	NON	NF	0	
66	Kobe-Dai8-G	726.63	189.4	S	LIQ	LS	0.5	17)
67	Kobe-JI-S	583.30	110.9	F	LIQ	LF	1	18)
68	Kobe University, CEORKA	324.24	57.2	F	NON	NF	0	
69	JR Nishi Akashi Station	506.99	47.8	F	NON	NF	0	
70	Port Island GL	426.54	103.2	F	LIQ	LF	1	19)
71	Port Island GL -16	636.79	88.4	D	LIQ	LF	0.5	20)
72	Port Island GL -32	713.22	85.0	D	SUS	SF	0.5	20)
73	Port Island GL -83	723.22	72.9	D	NON	NF	0	
74	Rokko Island City, B3, B1F	386.03	74.8	S	LIQ	LS	0	18)
75	Shin Kobe S.S., KE	688.11	102.6	F	NON	NF	0	
76	Tadaoka, CEORKA	293.16	24.7	F	NON	NF	0	
77	JR Takarazuka Station	690.44	97.6	F	NON	NF	0	
78	JR Takatori Station	742.74	156.8	F	SUS	SF	0.5	18)
79	Yotsubahsi GR-1, PWRI	362.33	30.5	F	NON	NF	1	
	Kagoshimaken-Hokuseibu Earthquake 1997/05/13							
80	Akune (KGS004)	173.46	18.5	F	NON	NF	0	
81	Miyanojoh (KGS005)	976.57	46.8	F	NON	NF	0	
82	Ohkuchi (KGS003)	187.45	10.3	F	NON	NF	0	
83	Sendai (KGS007)	340.30	32.2	F	NON	NF	0	

* Contacted PWRI

Record Type: F - free field; S - structure; D - downhole

Liquefaction Occurrence: LIQ - liquefied site; SUS - liquefaction-suspicious site; NON - non-liquefied site

Detection: 1 - liquefaction; 0.5 - liquefaction suspicion; 0 - no liquefaction

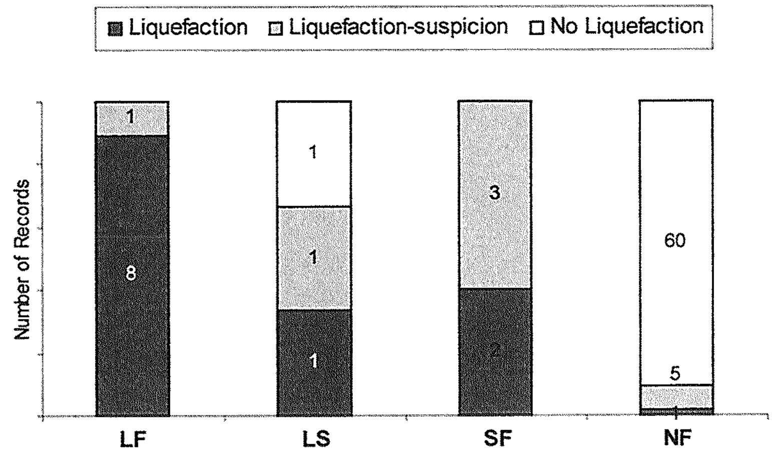

Figure 5. Detection of liquefaction for different record groups

Institute (PWRI), Ministry of Construction and Kyoshin net (K-net), National Research Institute of Earth Science and Disaster Prevention.

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[8)-20)] (the information about Amagasaki bridge was collected by contacting PWRI). The record from Treasure Island during the 1989 Loma Prieta earthquake was classified as SF although the observations of liquefaction were "within 100 m" of the seismic station (Darragh and Shakal[12)]). The sudden amplitude decrease in the horizontal acceleration around 15 s from its beginning is associated with the liquefaction onset (Jarpe *et al.*[21)]). We also included the downhole records GL-16 m and GL-32 m at Port Island from the 1995 Hyogoken-Nanbu earthquake in the LF and SF category respectively, taking into account the analytical studies that estimate the possible liquefied layers in depth at that site (Yamazaki *et al.*[20)]). This collection of records from liquefied sites is probably the most complete one examined by now. The non-liquefied free-field records are sixty-six, including four downhole records from some liquefied, suspicious and non-liquefied sites. Table 1 shows all records in the data set and the corresponding values of *PGA* and *PGV*. Figure 4 shows the *PGA* vs. *PGV* for all records in the dataset. Note that it was the 1995 Hyogoken-Nanbu earthquake, after which most of the liquefied-site records were obtained.

A comment on the structure records is needed. This type of records is not used in the preliminary damage assessment, but we put it into consideration because all three sites were liquefied or liquefaction-suspicious. The Kawagishi-cho record is the first ever one obtained from a liquefied site. The seismometer was placed in the basement of a four-story apartment building with a shallow foundation, next to the three tilted buildings at that site. The instrument at Kobe Dai 8 is installed on a quay wall and perhaps followed closely the movements of the ground. The seismometer at Rokko Island is located in the basement of a forty-story building, founded with piles of depth 12 m. There are more instruments at the upper levels of this building, but their records follow the structure response.

EXAMINATION OF THE PROPOSED METHOD

The results of the detection are showed in Table 1 and summarized in Figure 5. Proposed method indicates eight of the LF records as liquefied and one - Port Island GL-16 - as liquefaction-suspicious. This is due to the high-frequency content in the horizontal components that result in larger MIF_H values.

Regarding the liquefied-site structure records, the proposed method identify the Kawagishi-cho record as non-liquefied. The method does not recognize it because the vertical acceleration component lacks of high-frequency content. The reason for that lack may be an effect of soil-structure interaction or an inability of the employed SMAC-A seismometer to record high frequencies. The Kobe-Dai-8 record is identified as liquefaction-suspicious and Rokko Island - as liquefied.

Three of the suspicious-site free-field records are judged as liquefaction-suspicious and the other two - the Treasure Island and Amagasaki bridge records - are identified as liquefied. Note that the Kushiro-G record, at which site cyclic mobility was confirmed is judged as liquefaction suspicious.

Proposed method recognizes nearly ninety percent of the NF records as non-liquefied. Five NF records are judged as liquefaction-suspicious and one as liquefied.

CONCLUSIONS

A new method for detection of liquefaction from the ground motion records was proposed and examination of its performance was conducted. The examination was carried out by processing a data set of 83 seismic records that were divided in four categories: liquefied-site free-field, liquefied-site structure, suspicious-site free-field and non-liquefied-site free-field. Results show that the proposed method indicates all liquefied and liquefaction-suspicious free-field records and distinguishes nearly ninety percent of the non-liquefied free-field records.

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