A NEW METHOD FOR FAST IDENTIFICATION OF LIQUEFIED-SOIL SITE FROM SURFACE ACCELERATION RECORDS

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ABSTRACT :

The methods for detection of soil liquefaction from seismic records are being developed recently. The developed detection methods make it possible to capture the alteration of the surface ground accelerations and then the occurrence of soil liquefaction can be indicated immediately after a earthquake happens. This kind of technique is useful in developing a system of seismic motion monitoring and the real-time disaster mitigation, and also provides a new approach to understand the mechanism of liquefaction. However, the existing detection methods generally result from the empirical estimation and there is shortage of the theoretical models. As a result, the soft sites by the methods are easily misdetected as the liquefaction sites and the misdetection have been explained reasonably.

In the paper a new method for fast identification of the liquefied-soil site from surface acceleration records is presented in terms of the concept of the frequency decrease rate. By analyzing the main factors influencing the self-vibration period in the liquefied sites the frequency decrease rate is employed to describe the variation of the acceleration history during the liquefaction. The liquefiable site is simplified as a double-degree-freedom model and the formula for calculating the reduction of horizontal natural frequency induced by liquefaction is attained. And then the lower limit of frequency decrease rate is derived and based on it, the fast identification method of site liquefaction from surface acceleration records is proposed. The reliability of the method is examined by the actual earthquake records and the results indicate that by using the approach presented in the paper, not only the liquefied sites and the stiff non-liquefied sites are identified, but also the soft non-liquefied sites are detected correctly.

KEYWORDS: Acceleration records; liquefaction identification; model; frequency decrease rate

1. INTRODUCTION

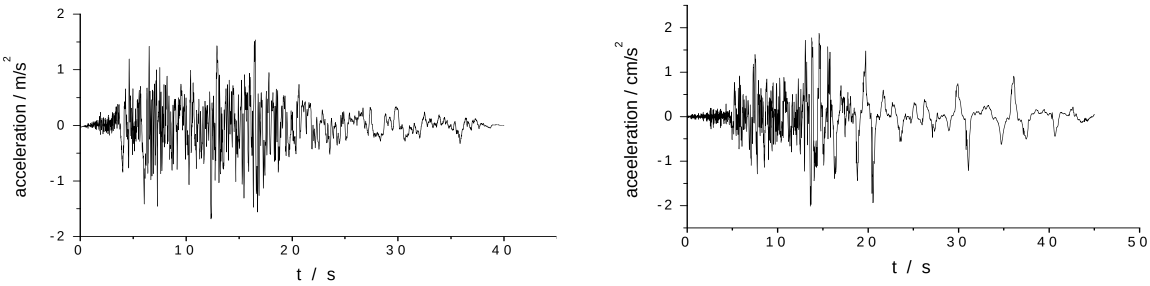
At present, many investigations on evaluating liquefaction potential have been conducted. But in recent earthquake, the liquefaction-induced damage still occurs. The possible reason is that even the liquefaction potential of the site can be predicted correctly, mitigation of the damage is still a difficult problem. For liquefiable site, soil improvement measure is usually taken in engineering. But it is recognized that soil improvement techniques are not economically feasible for mitigation of liquefaction-induced lifeline damages because of the large areas served. It is more practical to execute an emergency action immediately after an earthquake in order to minimize possible lifeline failures caused by the soil liquefaction. Essential element in the implementation of such a plan is the real-time identification of the liquefied sites and the identification methods may be achieved by surface strong motion records.

Recently some methods for detection of soil liquefaction from seismic records have been presented. The methods mainly focus on the horizontal ground motion, and the parameters include peak ground acceleration, spectrum intensity, predominant frequency, and so on. These methods, however, are basically the empirical methods from the limited records and lack of theoretical foundation. Especially they usually can not distinguish the liquefied site with the soft site.

Basing on a simple TDOF physical model, a fast identification method of liquefaction via relative decrement of instant frequency decent from the surface acceleration record is presented in this paper

2. INSPIRATION FROM RECORDS

The knowledge on the effect of liquefaction on ground motion can be acquired from earthquake records, such as Figure 1. The records are obtained on liquefied site and non-liquefied site in 1987 Superstition Hill Earthquake. From Figure 1, the frequency feature of acceleration alters after liquefaction occurrence. These changes can be found from other ground motion records (Kostadinov, Towhata, 2002). These phenomena indicate the frequency contents in the acceleration records have been influenced by the liquefaction.



(a) at non-liquefied site (b) at liquefied site

Figure 1 Surface acceleration records at liquefied and non liquefied site in 1987 Superstition Hills earthquake

The frequency of the seismic acceleration itself drops with time even on the non-liquefied soil layer and our knowledge on the effect of liquefaction on ground motion is not very rich so far because of limited seismic records on the liquefied soil layers. Therefore, using physical model may necessary approach for establishing a detection method of site liquefaction from seismic records.

3. THEORETICAL MODEL

3.1 Principle

The effect of liquefaction on ground motion has many forms in the surface ground motion including the horizontal and vertical acceleration, velocity, displacement, the time history of the frequency process etc. This is the reason for proposing different methods in the past researches.

According to our study on the soil layer response analysis, compared with the non-liquefied soil layers the most obvious change for the liquefied sites is in characteristic period of respond spectra. The numerical simulation indicates that for difference depth and thickness sand layer, the characteristic period prolongs 0.1s at least and 0.3s on average, i.e. the feature of site has been changed significantly due to liquefaction.

In our opinion, the physical nature of liquefaction in the site response is to change the horizontal self-vibration feature of the sites, and other changes in the surface ground motion are only the different apparent forms resulting from the physical nature. Meanwhile, the obvious change of the self-vibration feature on the liquefied site is the unique for all other type sites including soft soil layers. So the change in self-vibration feature could be the basic index and criterion for identification of the liquefaction. Furthermore, the absolute values of parameters such as the frequency change are used to be the threshold in the existing methods. But we think the absolute change is not always suitable for all cases, e.g., the time-frequency in soft soil layer is low usually. We think the relative change in the frequency should be mark for cases of liquefaction other than the absolute change.

3.2 Analytical Model

In this paper, the liquefiable site is simplified as a double-degree-freedom model showing in Figure 2. In the model, the first mass with the thickness H_L and weight m_1 represents the liquefiable soil layer. For the first mass, the initial shear stiffness is k_0 while is k_L after liquefaction. The second mass with the thickness H_d and weight m_2 stands for the non-liquefiable soil layer. Compared with the change due to liquefaction the shear stiffness of the second mass is supposed to keep constant value k_d. The reason of making the first mass to represent the liquefiable soil layer is that if the liquefaction occurs in the lower layer, the horizontal nature frequency of the model would be lower than that in the upper layer.

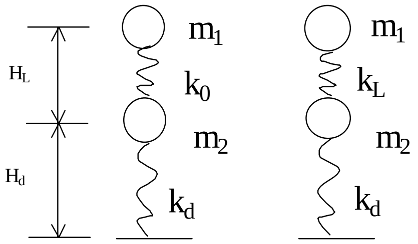


Figure 2 The simplified model for analysis

According to elastic dynamic theory, the horizontal nature frequency before liquefaction is

$$f_0 = \frac{1}{4\pi m_1 m_2}[(k_0 + k_d)m_2 + k_d m_1 - \sqrt{[(k_0 + k_d)m_2 + k_d m_1]^2 - 4m_1 m_2 k_0 k_d}\,] \tag{1}$$

After liquefaction, the horizontal nature frequency can be derived as

$$f_L = \frac{1}{4\pi m_1 m_2}[(k_L + k_d)m_2 + k_d m_1 - \sqrt{[(k_L + k_d)m_2 + k_d m_1]^2 - 4m_1 m_2 k_L k_d}\,] \tag{2}$$

Where

$$k_0 = \frac{G_0}{H_L} \qquad k_d = \frac{G_d}{H_d} \qquad k_L = \frac{G_L}{H_L} \tag{3}$$

G_0, G_L and G_d in Eq.(3) are the initial shear modular for liquefiable soil layer, the shear modular after liquefaction for liquefiable soil layer and the shear modular of the lower non-liquefiable soil layer, respectively. Frequency decreasing rate due to liquefaction can be defined as

$$\delta = (f_0 - f_L)/f_0 \tag{4}$$

Substituting Eq.(1)–Eq.(3) to Eq.(4) yields

$$\delta = 1 - \left[\frac{\lambda + \lambda^2 + p_0 p_L - \sqrt{(\lambda + \lambda^2 + p_0 p_L)^2 - 4p_0 p_L \lambda^2}}{\lambda + \lambda^2 + p_0 - \sqrt{(\lambda + \lambda^2 + p_0)^2 - 4p_0 \lambda^2}}\right]^{\frac{1}{2}} \tag{5}$$

where

$$\lambda = \frac{H_L}{H_d} \qquad p_0 = \frac{G_0}{G_d} \qquad p_L = \frac{G_L}{G_0} \tag{6}$$

Therefore, the frequency decreasing rate due to liquefaction can be determined by three factors, the thickness ratio λ between liquefiable and non-liquefiable layers, shear modular ratio p_L for the liquefiable soil layer before and after liquefaction, and initial shear modular ratio p_0 between the liquefiable and non-liquefiable soil layers. Because shear velocity could be expressed as $Vs=aH^b$ and the range of the parameter b is 0.2-0.45 investigated by other researches, the initial shear modular ratio p_0 could be expressed as

$$p_0=\frac{G_0}{G_d}=\left(\frac{a(\frac{2}{3}H_L)^b}{a(H_L+\frac{2}{3}H_d)^b}\right)^2=\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b} \tag{7}$$

Then, the frequency decreasing rate can finally be written as

$$\delta=1-\left[\frac{\lambda+\lambda^2+\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b}p_L-\sqrt{(\lambda+\lambda^2+\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b}p_L)^2-4\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b}p_L\lambda^2}}{\lambda+\lambda^2+\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b}-\sqrt{(\lambda+\lambda^2+\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b})^2-4\left(\frac{\frac{2}{3}\lambda}{\frac{2}{3}+\lambda}\right)^{2b}\lambda^2}}\right]^{\frac{1}{2}} \tag{8}$$

3.3 Lower Limit of Frequency Decrease Rate

Figure 3 shows the 3D curve of the frequency decreasing rate due to liquefaction according to Eq.(8) using b=0.2, i.e. the shear velocity increase most slowly with the depth. In the figure, X and Y coordinates are λ and $1/p_L$, separately, and Z coordinate represents δ, the frequency decreasing rate. In the figure, the range of p_L is 1/100-1/50(Yasuda 1991, Feng, 1988) and range of λ is 0.01-1.0.

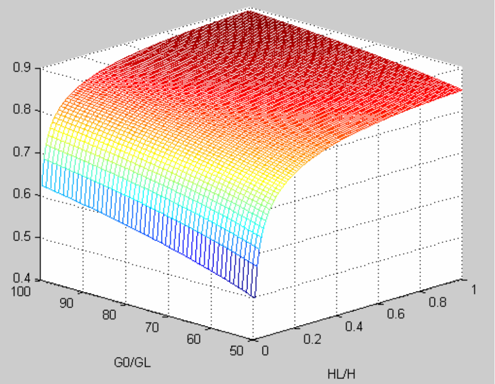


Figure 3 The frequency decreasing rate

It can be seen that δ increases with $1/p_L$, and λ, and the lower limit is δ=0.5, i.e. the liquefaction make the natural frequency of the site decrease by 50% at least.

4. IDENTIFICATION METHOD

As the medium of wave propagation, the nature frequency of the site determines the feature of the surface ground acceleration. The liquefaction influence on natural frequency feature of the site greatly and this alteration should control the frequency feature of the surface ground acceleration.

To detect liquefaction, the focus only can be placed on the duration around PGA. In this paper, duration of 30s around the time of PGA appearing is considered because the duration includes the entire effective incidence of the waves on the liquefaction process. The amplitudes less than 10% of PGA will be ignored because these small amplitudes show less contribution to the soil responses.

The PGA occurrence time is considered as the boundary to divide the acceleration history into two parts because liquefaction usually occurs after PGA appears. The average time-frequencies before the PGA and after the PGA are f_0 and f_L, separately. The PGA is included in the first part. The zero-crossing method is employed to determine the time-frequency because the method can supply unique solution. Then, the identification method can be summarized as follows:

(1) If the PGA less than 0.05g, the site will be judged as non-liquefaction.
(2) If the PGA more than 0.05g, the average time-frequencies of f_0 and f_L are calculated.

If $\frac{f_0 - f_1}{f_0} \geq 0.5$, occurrence of liquefaction is judged.

5. VALIDATION OF THE PROPOSED APPROACH

To verify the proposed method, 56 seismic records from 15 earthquakes are analyzed. The results show that the proposed approach can detect all liquefaction and non-liquefaction sites, especially the soft but non-liquefaction sites as shown in Table 1.

It can be seen from Table 1 that the frequency decreasing rate in the non-liquefied sites is less than 0.39 except one of 0.45. The averaged frequency decreasing rate for the non-liquefied sites is 0.14. The frequency decreasing rate in the liquefied sites is larger than 0.57 and the averaged frequency decreasing rate is 0.71. The boundary point 0.5 presented in the paper is reasonable.

Table 1 Results of liquefaction detection by the method of this paper

No.	Earthquake	Site and its classification	Damage investigation	Frequency decreasing rate	Proposed method
1	Niigata, Japan, 16/06/1964, M=7.5	Kawagishi-cho, (-)	Y	0.74	Y
2	Friuli, Italy, 05/05/1976, M=6.5	Tolmezzo, (-)	N	-0.53	N
3	Tabas, Iran, 16/09/1978, M=7.4	Dayhook, (-)	N	0.0001	N
4		Taba, (-)	N	-0.3	N
5	Victoria, Mexico, 09/06/1980, M=6.4	Cerro Prieto , (B)	N	0.11	N
6		Chihuahua, (C)	N	-0.02	N
7	Nihonkai-Chubu, Japan, 26/05/1983, M=7.7	Hachirogata, (-)	Y	0.68	Y
8	Superstition Hills, USA, 24/11/1987, M=6.6	Brawley, (C)	N	0.14	N
9		Calipatria Fire Station, (C)	N	0.11	N
10		EL Centro Imp., (C)	N	0.14	N
11		Parachute Test Site, (B)	N	0.17	N
12		Plaster City, (C)	N	0.29	N
13		POE Road, (-)	N	0.24	N
14		Superstition Mtn., (B)	N	0.03	N
15		Westmorland Fire Station, (C)	N	0.13	N
16		Wildlife GL, (-)	Y	0.57	Y
17	Loma Prieta, USA, 18/10/1989, M=6.9	Agnews State Hospital, (C)	N	0.17	N

18	18/10/1989, M=6.9	Aped2-Redhwood City, (D)	N	0.19	N
19		Corralitos , (B)	N	0.02	N
20		Gilroy Array #2, (C)	N	-0.38	N
21		Gilroy Array #6, (B)	N	0.25	N
22		Halls Valley, (C)	N	0.36	N
23		Hallister-Smith & Pine, (-)	N	0.01	N
24		Richmond City Hall, (C)	N	0.35	N
25		SF Intern Airport, (-)	N	0.19	N
26		Treasure Island , (D)	N	0.28	N
27	Northbridge, USA, 17/01/1994, M=6.7	Arleta-Nordhoff Fire Station, (C)	N	-0.02	N
28		LA-Baldwin Hills, (B)	N	0.30	N
29		LA-Century City, (B)	N	0.17	N
30		LA-Hollywood Storage FF, (C).	N	0.31	N
31		Leona Valley #6 , (C)	N	0.38	N
32		Newhall-Fire Station, (C)	N	0.35	N
33		Old Ridge Route, (B)	N	0.23	N
34		Tarzana, Cedar Hill, (-)	N	0.45	Y
35		Vasquez Rocks Park, (B)	N	0.34	N
36	Kobe, Japan, 16/01/1995, M=6.9	Kakogawa, (D)	N	0.23	N
37		KJMA, (B)	N	-0.09	N
38		Nishi-Akashi, (D)	N	0.20	N
39		Port island, (-)	Y	0.83	Y
40		Shin-Osaka, (D)	N	0.15	N
41		Takatazuka, (D)	N	-1.0	N
42		Takatori, (D)	N	0.31	N
43	Kocaeli, Turkey, 17/08/1999, M=7.4	Ambarli , (D)	N	0.30	N
44		Arcehk, (B)	N	0.17	N
45		Bursa Tofas, (-)	N	0.28	N
46		Duzce, (C)	N	0.29	N
47		Goynuk, (-)	N	0.06	N
48	Chi-Chi, Taiwan, 20/09,1999, M=7.6	Als, (B)	N	0.03	N
49		CHY002, (D)	N	0.02	N
50		CHY006, (C)	N	0.3	N
51		CHY008, (D)	N	0.2	N
52		CHY014, (C)	N	0.1	N
53		CHY024, (C)	N	0.04	N
54	Tangshan ,China, 28/07/1976, M=7.8	underground，(-)	N	0.26	N
55	Lijiang after shake, China, 05/02/1994, M=6.0	Ground，(-)	N	0.28	N
56	Longling after shake, China, 09/06/1997, M=6.2	Ground，(-)	N	0.24	N

6. CONCLUSION

A new method using the time-frequency decreasing rate for fast identification of site liquefaction from surface acceleration records is presented. The liquefiable site is simplified as a Two-degree-freedom model and the formula for expressing the reduction of horizontal natural frequency induced by liquefaction is attained. The lower limit of the frequency decreasing rate is derived and based on it, the fast identification method of site liquefaction from surface acceleration records is proposed. The reliability of the method is examined by actual earthquake records

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