Effects of subsurface liquefaction on earthquake ground motion at surface

Influence de la liquéfaction de la subsurface des sols sur la propagation sismique à la surface

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ABSTRACT: The earthquake-related risk management of lifeline operation requires that the onset and extent of subsurface liquefaction are detected immediately after an earthquake. This goal is achieved by deploying many accelerometers in the area of possible liquefaction and collecting records through a wireless network. This paper attempts to develop a measure to interpret the collected data of surface motion and to assess the thickness of liquefied layer. For this purpose, both analysis of earthquake records and shaking table tests on model ground were carried out. It was shown that the thickness of liquefied layer can be assessed by using the maximum acceleration and the spectrum intensity at the surface.

RESUME: La gestion des réseaux d'utilités soumis au risque sismique exige que l'intensité et l'étendue de la liquéfaction sub-surface des sols soient détecteés immédiatement après la liquéfaction sub-surface des sols soient détecteés immédiatement après le séisme. Le but est atteint en déployant de nombreux accéléromètres dans la zone de liquéfaction potentielle, et en collectant les données par un réseau sans fil. Le présent article vise à développer une méthode pour interpréter les données collectées de mouvements de surface et pour évaluer l'épaisseur du niveau liquéfié. Dans ce but ont été réalisées des analyses d'enregistrements de séismes ainsi que des expériences sur plateau vibrant avec des sols reconstitués en laboratoire. Il est ainsi démontré que l'épaisseur du niveau liquéfié peut être estimée en connaissant l'accélération maximum et le spectre d'intensité à la surface.

1 INTRODUCTION

The seismic liquefaction in loose sandy subsoil is one of the most important earthquake hazards to embedded lifeline facilities. Although densification of sand is an effective measure against liquefaction in principle, the vast area of a lifeline operation makes the overall densification difficult. It is consequently argued to initiate immediately after an earthquake such necessary emergency actions as stopping gas supply and seeking for alternative networks. Since the emergency action requires information about the extent of liquefaction to be known as precisely as possible, a new measure is proposed here by which the earthquake motion records are interpreted to detect both the onset and the extent of subsurface liquefaction. This measure has become possible with the aid of a recent installation of a wireless earthquake observation network which can collect and report the data concerning the ground motion.

2 ANALYSIS OF PAST EARTHQUAKE RECORDS

Analyses were made of ground motion records observed at the surface during past earthquakes. It was aimed to detect a feature of the records which indicates the effects of subsurface liquefaction. Although a design value of the maximum acceleration at the surface has been widely used in prediction of liquefaction potential, the observed maximum acceleration is considered to be inappropriate in the present study because it does not tell anything about the number of loading cycles that plays an important role in onset of liquefaction. It seemed better that more attention is paid to the large displacement amplitude at the surface which is induced by a significant softening in liquefied subsoil.

The present study attempts to make use of the spectrum intensity, abbreviated as *SI* here, together with the maximum acceleration, called A_{max} in this text. This idea is benefited by the fact that new seismographs are easily available to detect quickly both *SI* and A_{max}. *SI* is obtained by averaging the relative velocity spectrum of a seismic motion over the range of natural periods of 0.1 to 2.5 seconds with a critical damping ratio of 20%. Fig.1compares *SI* and the maximum velocity of ground motion, V_{max}, for the horizontal records cited in Table 1. Note that this V_{max} as well as the amplitude of displacement, D_{max}, were obtained by integrating with time the original acceleration records for their harmonic components of periods shorter than 10 seconds. Fig.1 shows that *SI* is reasonably equal to V_{max}, whether or not

Table 1 Earthquake motion records employed for present study (site name, earthquake name, and year).

Records at sites of liquefaction Kawagishi-cho, Niigata, 1964; Wildlife, Superstition Hill, 1987 (Holzer et al., 1989); Aomori Harbor, Tokachi-oki, 1968; Port Island, Kobe, 1995 (observed by Development Bureau of Kobe City).
Records near liquefied areas Akita Harbor, Nihonkai-chubu, 1983; Kobe Harbor, Kobe, 1995 (CEORKA).
Records without effects of liquefaction El Centro, 1940; Hachinohe, Tokachi-oki, 1968; Kaihoku Bridge, Miyagi-ken-oki, 1978; Owi, Chiba-Ibaragi, 1980; Sunamachi, Chiba-toho, 1987; Amagasaki, Kobe, 1995 (CEORKA).

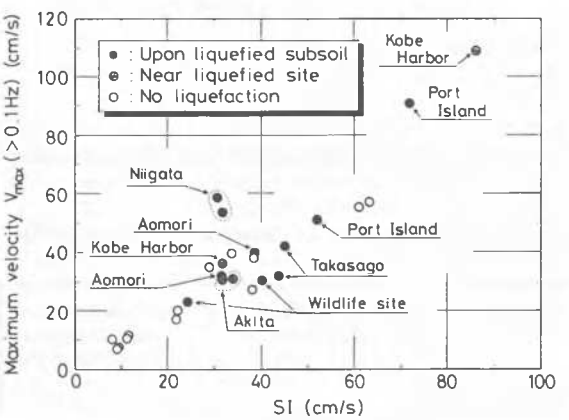

Fig.1 *SI* and V_{max} values of observed records (two horizontal records from one site).

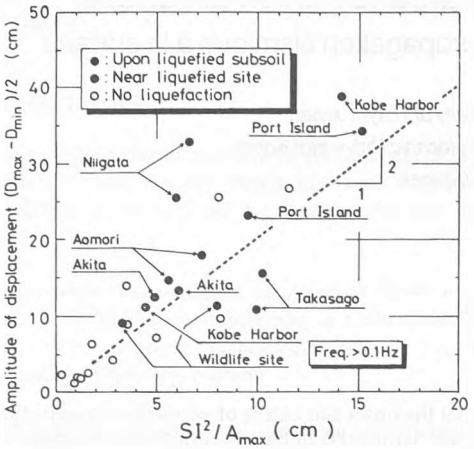

Fig.2 Relationship between displacement, SI, and A_{max}.

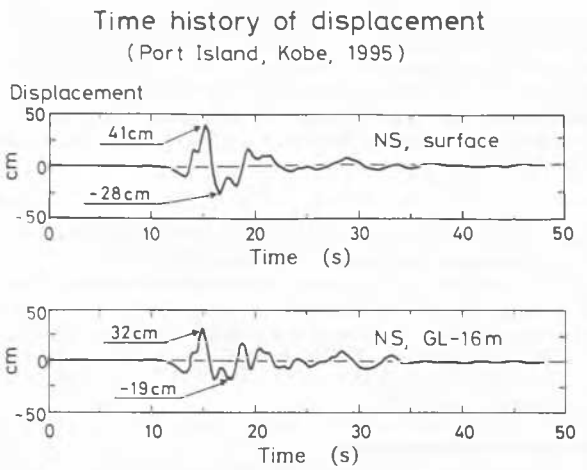

Fig.3 Time history of NS displacement at Port Island.

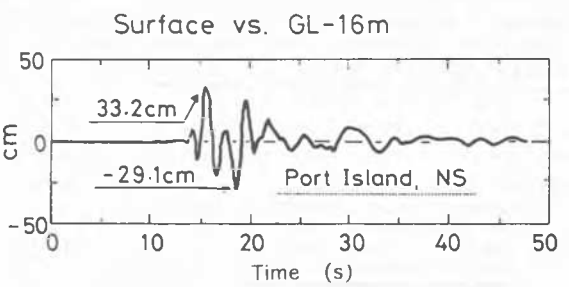

Fig.4 Assessed deformation in liquefied layer of Port Island.

Table 2 Surface displacement and deformation in liquefied layer.

Records		Amplitude of surface displacement (m)	Amplitude of shear deformation in liquefied layer (m)
Wildlife	NS	0.114	0.107
	EW	0.091	0.069
Port Island	NS	0.345	0.312
	EW	0.233	0.188

Note: the amplitude of displacement is defined by *(positive maximum - negative minimum) / 2*.

liquefaction occurred in the subsoil. It is interesting that SI values at sites of liquefaction is greater than *0.2*m/s. This fact does not achieve the goal of the present research, however, because similarly large SI values were obtained at unliquefied sites as well.

The large displacement amplitude at the surface can be detected by combining SI or the maximum velocity with the maximum acceleration. Firstly, a harmonic motion, which is a *sin* function of time, has a following relationship between the amplitudes of displacement, velocity, and acceleration;

$$D_{max} = V_{max}^2 / A_{max} \tag{1}$$

The velocity amplitude on the right-hand side of this equation was replaced by SI as validated by Fig.1 and SI^2/A_{max} was compared in Fig.2 with the displacement amplitude of the original motion. There seems to be a relationship of

$$D_{max} = 2 \times SI^2 / A_{max} \tag{2}$$

which is similar to Eq.1, whether or not liquefaction occurred in the subsoil.

It seems reasonable that the softening and a large amplitude of deformation in liquefied subsoil increase the amplitude of displacement at the surface. The extent of subsurface liquefaction, therefore, can be detected by assessing the large deformation in the liquefied subsoil from the surface displacement amplitude. With this idea in mind, the surface displacement amplitude and the deformation of liquefied layers at Port Island and Wildlife Site were compared (see Table 1). This type of study is possible only at these two sites where both the surface motion as well as the motion at the bottom of loose sandy deposits were recorded. By integrating twice the surface and the bottom acceleration records, the displacement histories were derived. Their difference directly gives the extent of shear deformation in the liquefied subsoil.

Fig.3 reveals the time histories of displacement in NS direction at Port Island. Fig.2 demonstrates the time history of shear deformation in liquefied sand which is the difference between two histories in Fig.3. Although the maximum displacements in Fig.3 are compatible with each other, the maximum value in their difference in Fig.4 is still large, approximately equal to the maximum surface displacement. Table 2 summarizes all the studies for four records to demonstrate that the surface displacement amplitude is a good approximation of the shear deformation in the liquefied layer. Therefore, it is reasonable to say that the assessment of surface displacement amplitude (Eq.2) helps detect the large shear deformation in a liquefied subsoil.

3 SHAKING TABLE TESTS

A series of shaking table tests were carried out to study in more detail the nature of SI on liquefied subsoil. Fig.5 displays the configuration of models which measured mostly 4 m in length and 0.55 m in thickness of sand. The model ground was prepared by raining Toyoura sand in water to achieve a relative density of 30 to 40%. For more details, refer to Towhata et al. (1996).

One of the test results is illustrated in Fig.6, where time histories of SI, surface and base accelerations, and excess pore water pressure are presented. The time history of SI was obtained by using the acceleration of the first t seconds; t varing from 0 to the whole duration of shaking. It is seen that i) the pore pressure started to rise at around 3 seconds, ii) the maximum surface acceleration occurred at 4 seconds, at which SI attained the ultimate maximum value as well, and iii) the pore pressure attained 100% liquefaction at 5 seconds.

The amplification of motion, which is a ratio of the surface motion and the bottom motion, achieved the maximum at around 4 seconds. It seems that the subsoil became softer as pore pressure developed thereby the natural period of the model deposit increasing. At about 4 seconds, this elongated period matched with the period of the input motion and the maximum amplification (resonance) occurred. The further pore pressure increment erased the stiffness of sand completely and the surface motion disappeared after 4 seconds.

Fig.7 compares the development of SI and excess pore water pressure. The testing frequency and the shape of models did not affect the test results. It appears that the onset of liquefaction is

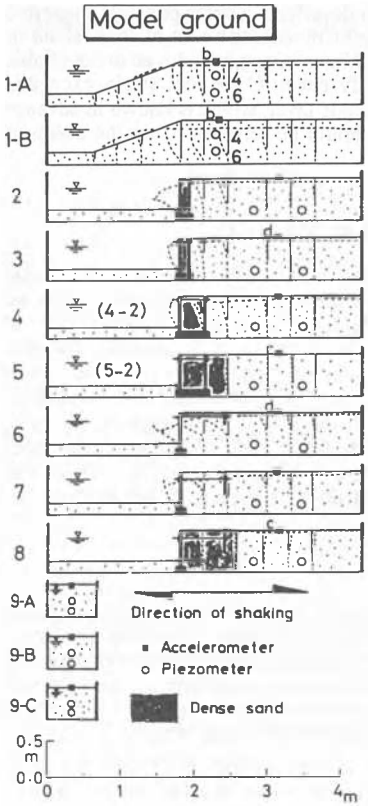

Fig.5 Configuration of model ground.

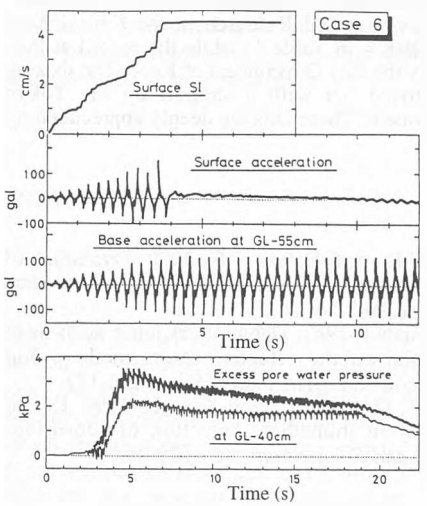

Fig.6 Typical results of model test with sheet pile wall.

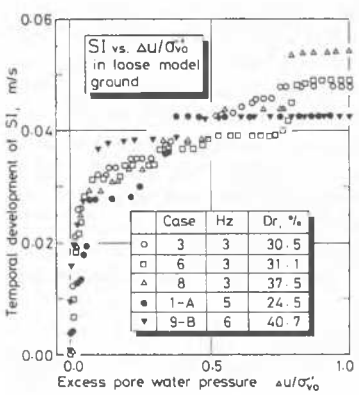

Fig.7 Relationship between developments of *SI* and excess pore pressure.

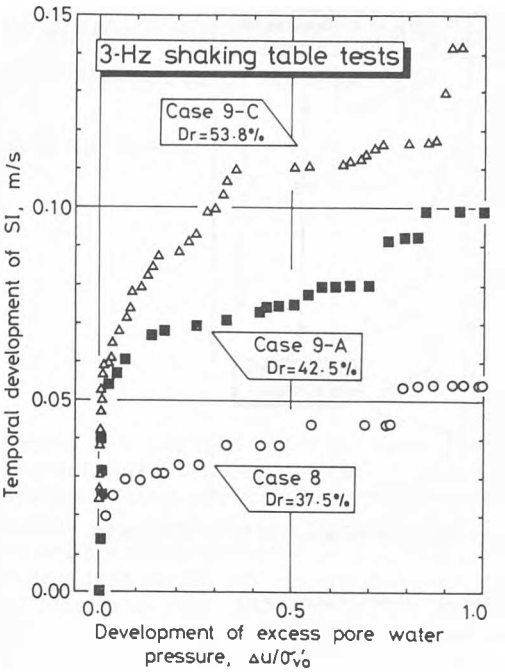

Fig.8 Effects of density of sand on development of *SI*.

always associated with *SI=0.04* to *0.05*m/s. This *SI* is, however, much smaller than the field experience of *0.2 m/sec* at liquefied sites. (Fig.1). Moreover, the *SI* versus pore pressure relationship is affected by the density of sand, as illustrated in Fig.8. Therefore, *SI* alone cannot be a good sign of subsurface liquefaction, as asserted before.

4 ASSESSMENT OF THICKNESS OF LIQUEFIED LAYER

The present study employs and assesses the thickness of liquefied subsoil as an indicator of the extent of liquefaction. The shaking table tests exhibited that A_{max} and *SI* are attained at resonance which is slightly before the complete liquefaction. The idealized amplitude of lateral displacement at resonance, d, is given by a sinusoidal function of depth, *z*;

$$d = D_{max} \cos\frac{\pi z}{2H} \tag{3}$$

where *H* is the thickness of a liquefied layer. Hence, the maximum shear strain, γ, in a liquefied layer is derived at the bottom; *z=H*. By using Eq.2,

$$\gamma = \frac{\alpha d}{\alpha z}(z-H) = \left(\pi SI^2\right)/\left(HA_{max}\right) \tag{4}$$

This strain occurs at resonance as stated above which is slightly prior to complete liquefaction. Therefore, the value of γ is large but not significantly large. The present study considers that this γ is equivalent with a double amplitude of axial strain of $\varepsilon_1 = 0.025$ *(=2.5%)* in cyclic undrained triaxial tests. The undrained condition requires $\varepsilon_3 = -0.0125$ and the value of shear strain is derived as $\gamma = (\varepsilon_1 - \varepsilon_3) = 0.01875$. This is substituted in Eq.4 and the thickness of liquefied layer is assessed;

$$H = \left(\pi SI^2\right)/\left(0.01875 A_{max}\right) \tag{5}$$

Towhata et al. (1996) extended this idea to a situation in which there is an unliquefied crust at the surface.

Figure 9 illustrates the estimated thickness of liquefied layer at Kawagishi-cho site in Niigata. The loose deposit of sand down to the depth of 12m liquefied. This agrees with the range of high excess pore water pressure(Fig.10) which was suggested by a

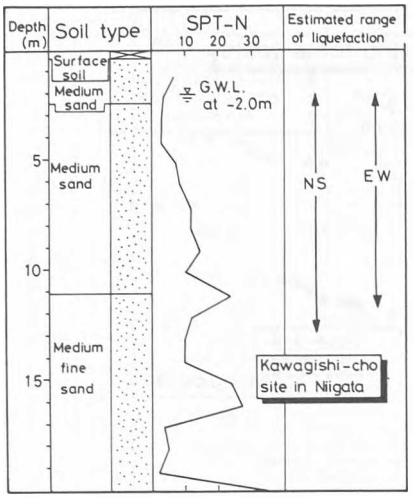

Fig.9 Assessed thickness of liquefied layer in Niigata.

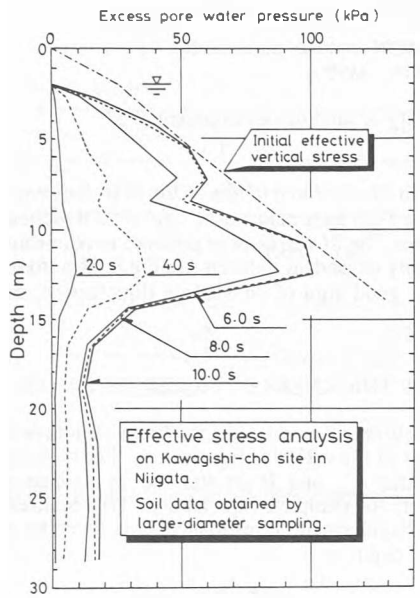

Fig.10 Excess pore water pressure shown by numerical analysis.

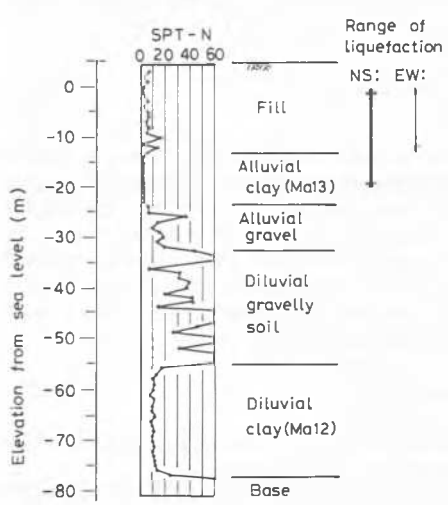

Fig.11 Assessed thickness of liquefied layer in Port Island.

numerical analysis based on the effective stress principle suggested (Ishihara et al., 1982). Fig.11 reveals the case of Port Island in Kobe. The assessed range of liquefaction includes an unliquefiable clay layer (Ma13) probably because the real strain exceeded *0.01875*. Thus, an unliquefiable layer, which is known in advance in available boring logs, should be removed from the assessed range of liquefaction.

5 MINIMUM *SI* FOR LIQUEFACTION

The significant discrepancy in *SI* values of field and model Liquefaction is caused by the scale. The scale effects can be studied briefly by using Eq.5 that was derived independent of the scale. The thickness of liquefied layer, *H*, indicates the idea of scale. Since A_{max} is similar in both field and model, SI^2 is proportional to the scale. When the field deposit is, for example, 10 to 30 times larger than the model, *SI=0.04m/sec* in loose model deposits is equivalent with *0.13* to *0.22m/sec.* in the field. This seems to agree with *SI* at liquefied sites in Fig.1. When the field *SI* is less than this critical value, liquefaction is unlikely.

6 CONCLUSIONS

A series of shaking table tests as well as an analysis of earthquake motion records were carried out in order to develop a measure by which the extent of field liquefaction is immediately detected. This goal was achieved by using the maximum acceleration and the spectrum intensity, and the assessed thickness of liquefied layer matches reasonably with the field experience.

7 ACKNOWLEDGMENT

The earthquake motion records at Kobe Harbor and the Amagasaki site were recorded and supplied for research by the Committee of Earthquake Observation and Research in the Kansai Area which is called CEORKA in Table 1. while the record at Port Island was supplied by the City Government of Kobe. The shaking table tests were carried out with a support by the Tokyo Metropolitan Government. These aids are deeply appreciated by the authors.

REFERENCES

Holzer,T.L., Youd,T.L., and Hawks,T.C. 1989. Dynamics of liquefaction during the 1987 Superstition Hills, California, earthquake. *Science*, 244: 56-59.

Ishihara,K. and Towhata,I. 1982. Dynamic response analysis of level ground based on the effective stress method. *Soil mechanics - transient and cyclic loads*, Wiley, 133-172.

Towhata,I., Park,J.K., Orense,R.P., and Kano,H. 1996. Use of spectrum intensity in immediate detection of subsurface liquefaction, *Soils and Foundations*, 36(1) 29-44.