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DYNAMIC CHARACTERISTICS OF LATERAL EARTH PRESSURES ON AN EMBEDDED FOUNDATION DURING EARTHQUAKES AND FORCED VIBRATION TESTS

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SUMMARY

The characteristics of earth pressures during forced vibration tests and earthquakes are studied on the basis of observations recorded on both sides of a large-scale shaking table foundation. It is revealed that the earth pressures on both sides of the foundation during earthquakes tend to be induced in phase for lower frequencies contained in the surface ground motions, and out-of phase for higher frequencies. It is noted that the in-phase phenomenon of the earth pressures can not be explained by a conventional assumption of vertical incidence of seismic waves. It is also revealed that the earth pressures are strongly related to the horizontal velocities of the foundation for rather lower frequencies, and to acceleration response for higher frequencies.

INTRODUCTION

Transmission of ground motions into a structure and resistance of the supporting soil for vibration of a superstructure are soil-structure interaction phenomena accompanying with generation of dynamic earth pressures on the foundation. The observation of earth pressures during earthquakes, therefore, would play a key role in understanding of the transmission mechanism of ground motions and resistance mechanism of the surrounding soil for a superstructure. The investigations of earth pressures during earthquakes have been conducted so far on the basis of theoretical, observational and experimental points of view. Above all, observations of earth pressures for actual structures or with use of model structures embedded in an actual soil have been providing valuable data in clarifying the generation mechanism of earth pressures on embedded foundations. Based on the observations, the frequency characteristics of earth pressures, the distribution of pressures on lateral sides of embedded foundations, phase characteristics of earth pressures induced on two opposite sides of the embedded foundation have been extensively studied. A detailed review about measurements of earth pressures during earthquakes has been presented by Ostadan and White [8].

It is worthwhile noticing that following distinctive features on the earth pressures have been observed and discussed on the basis of earthquake records.

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1. The observations include such that earth pressures on the opposite sides of the embedded foundation during earthquakes were induced in-phase, i.e. pull-and-pull or push-and-push phenomena were observed (Sakai et al. [9], Uchiyama et al. [11], Minowa et al. [6]). It is obvious that the fact cannot be explained by a conventional assumption of a vertical incidence of seismic waves.
2. As for the earth pressures examined in relation to responses of foundation, there have been presented some observations showing different tendencies. One is that the earth pressures on the sides of embedded foundations are strongly related to the velocity motions of the foundation (Matsumoto et al. [4], Sakai et al. [9]), the others are with acceleration motions of the foundation (Onimaru et al. [7]). There is also an observation showing that the earth pressure is caused by the relative motion between the structure and the surrounding soil (Kazama et al. [3], Ostadan et al. [8]).

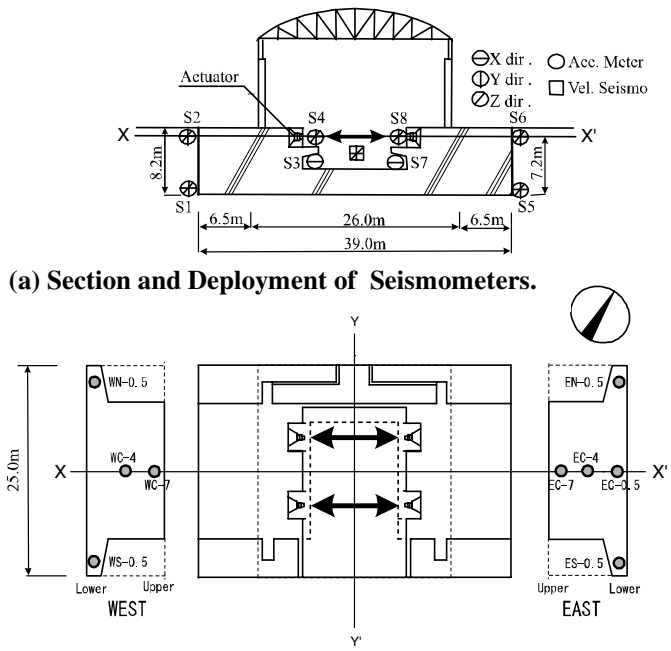
It should be noted that these phenomena are neither well documented nor explained from theoretical point of view. Some simplified models to predict the earth pressures on the rigid wall during earthquakes have been presented (Scott [10], Veletsos et al. [12], Veletsos et al. [13]). Unfortunately, these models fail to explain above described phenomena.

The observations of earth pressures induced by earthquake ground motions have been conducted on both sides of a large-scale shaking table foundation in Tsukuba. Simultaneous observations of free-field ground motions as well as the response of the foundation have been made (Iguchi et al. 2000, Iguchi et al. 2001). The dense earthquake observations around or on the shaking table foundation permit us to study the observed data of earth pressures in relation to the ground motions and to the response of foundation as well. Forced vibration tests have been also performed for the foundation to obtain the earth pressures during the excitations.

The objective of this paper is to analyze the records of the earth pressures observed on the lateral sides of the foundation during earthquakes and the forced vibration tests as well. Special emphasis is placed to extract above described phenomena on the basis of the observed data.

FOUNDATION AND EARTH PRESSURE MEASUREMENT

Figure 1 shows a large-scale shaking table foundation in National Research Institute for Earth Science and Disaster Prevention in Tsukuba. The size of the foundation is $25m \times 39m$ in plane and the base of the foundation is directly supported on firm sand at a depth of 8.2m. The section of the foundation and soil profile are shown in figures 1(a) and 2. The weight of the foundation and the shaking table is about 11,600tf (113.7MN) and 180tf (1.76MN), respectively. The total weight is approximately amount to 20,000tf including the weight of steel-made super-structure and almost corresponds to the excavated soil of the foundation. The fundamental frequency of the soil-foundation system is about 4.1Hz in the x-direction, which was observed by the forced vibration test. It has been confirmed that the foundation behaves as a rigid body within frequencies less than 10 Hz. The soil constants at the site were measured to a depth of about 40m as shown in figure 2, and more details may be found elsewhere (Minowa et al. [5]).
Figure 1(b) shows the location of earth pressure gauges deployed on the sides of the foundation. On each side of the foundation, five earth pressure gauges have been instrumented at different depths, but one installed on the west side was out of function and is omitted from the figure. The simultaneous observations of earthquake ground motions have been conducted at depths of 1m and 40m below the soil surface. We refer the ground motions recorded at the depth 1m to as surface ground motions. Regarding the foundation, the earthquake responses of the foundation have been observed at several points with accelerographs and a velocity seismograph as shown in figure 1(a). The horizontal response of the foundation is represented by seismograms recorded at the point S3, which is located almost at the center of the foundation.



(a) Section and Deployment of Seismometers.

(b) Plan and Location of Earth Pressure Gauges.

Figure 1. Large shaking table foundation and location of seismometers and earth pressure gauges.

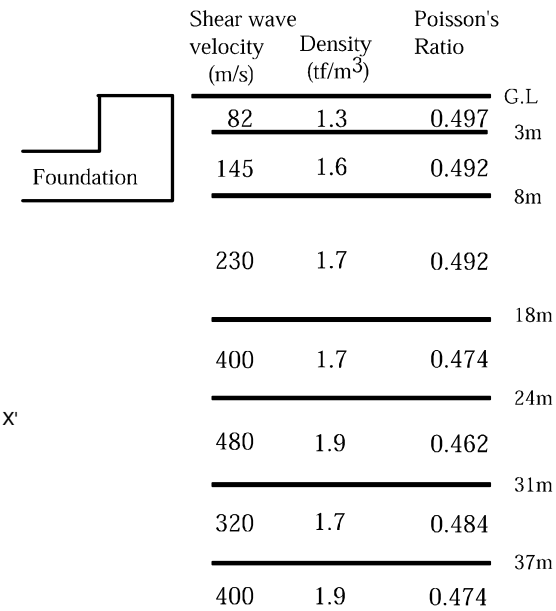


Figure 2. Soil profile and soil constants.

Earth pressure during forced vibration tests

The earth pressures have been measured during the step-sweep forced vibration tests. A harmonic excitation force was generated by driving a shaking table in the frequency range 1 to 20 Hz with a frequency step 0.2 Hz. The position that the excitation force was applied was at 1m below the foundation surface. Two levels of excitation tests were performed in the series of experiments: one level was the test conducted by driving the shaking table so as to generate the acceleration of about 100 gals on the foundation, which is equivalent to about 20tf of excitations, and the other was the test of about 500 gals throughout the frequencies.

There is no evidence of nonlinear phenomena such as separation of the lateral soil from the foundation as far as being judged from the recorded waveforms of the earth pressures.

Figures 3 and 4 show the frequency characteristics of earth pressures observed on both sides of the foundation. The results shown in figure 3 are the amplitude and phase characteristics of earth pressures normalized by unit horizontal displacement of the foundation. The results of earth pressures shown in figure 3 indicate that for lower frequencies less than 3：4Hz the amplitude of the earth pressure are almost constant and tends to increase for higher frequencies. As for the phase characteristics, it will be noticed that the earth pressures are induced in phase to the displacement motion of the foundation. This fact indicates that the seismic deformation method, which is widely used in the seismic response analysis of underground structures, may not be valid for higher frequencies. Similarly, figure 4 shows the characteristics of earth pressures normalized by unit horizontal velocity of the foundation. An inspection of these results shown in figure 4 reveals that the earth pressure varies with frequencies but the phases tend to be constant in higher frequencies more than 3：4Hz. It will be noticed that the earth pressures

are induced in phase to the velocity response of the foundation in the frequency range more than 3 : 4 Hz .

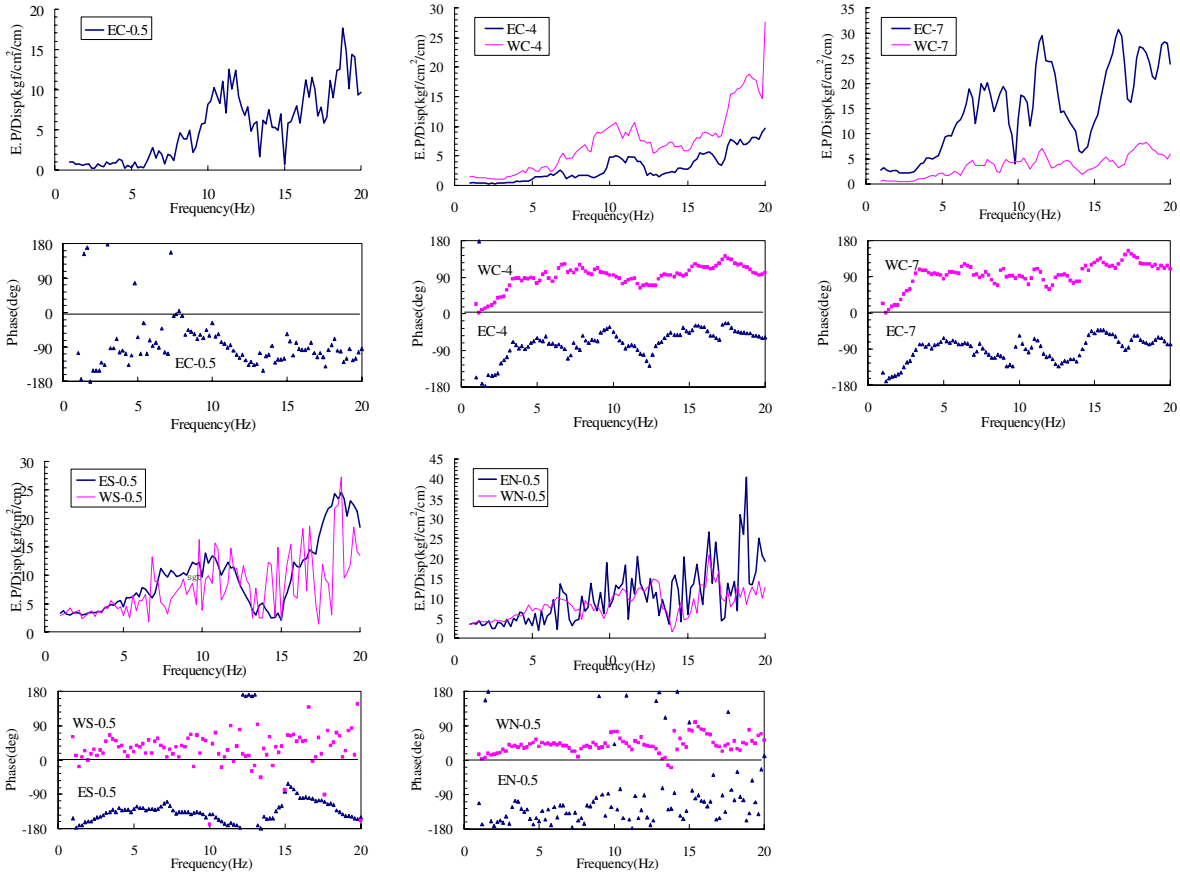


Figure 3. Amplitude and phase of earth pressures on both sides of foundation normalized by unit displacement of foundation.

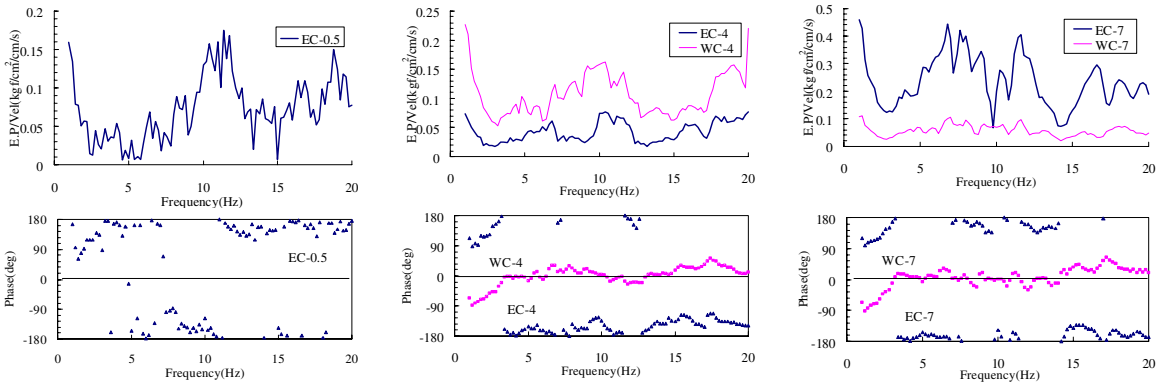


Figure 4. Amplitude and phase of earth pressures on both sides of foundation normalized by unit velocity of foundation.

The above mentioned frequencies $3:\ 4\,\mathrm{Hz}$ may be presumed as the fundamental frequency of two layering surface soil. The fundamental frequency can be approximated by means of a quarter-wave-length method, and will be given as follows with the soil constants shown in figure 2.

$$f_1 = \frac{1}{4}\left(\frac{H_1}{V_{s1}} + \frac{H_2}{V_{s2}}\right)^{-1} = 3.5\,\mathrm{Hz}$$

where H_1 and H_2 are the thickness of the first and the second layers of surface soil, and V_{s1} and V_{S2} are corresponding shear wave velocities. Thus, 3.5Hz may be considered to be the fundamental frequency of the two layered surface soil.

Earth pressure observation during earthquakes

The observations of earth pressures induced by earthquake ground motions have been conducted for six years from 1991 to 1996 and the records of about 30 earthquakes had been obtained. The details of the earthquake records may be found elsewhere (Iguchi et al. 2000, Iguchi et al. 2001). In order to analyze the characteristics of the earth pressures in relation to frequency component contained in the earthquake ground motions on the soil surface, the recorded earthquake motions was categorized into three groups (groups A, B and C). The grouping was made according to the predominant frequency components included in the earthquake acceleration motions (NS component) recorded on the soil surface; the earthquake ground motions including predominantly the lower frequencies less than 1Hz were categorized into group A; the earthquake motions with higher components (more than about 3 to 4Hz) were grouped into C, and group B is characterized by the motions having intermediate frequency components between groups A and C. In table 1 the earthquake parameters of the selected three records as the representative motions picked up from each group are shown. Figure 5 shows the normalized Fourier spectra of the representative motions chosen from the respective groups. The spectra are smoothed by using the Parzen window with a bandwidth of 0.1Hz.

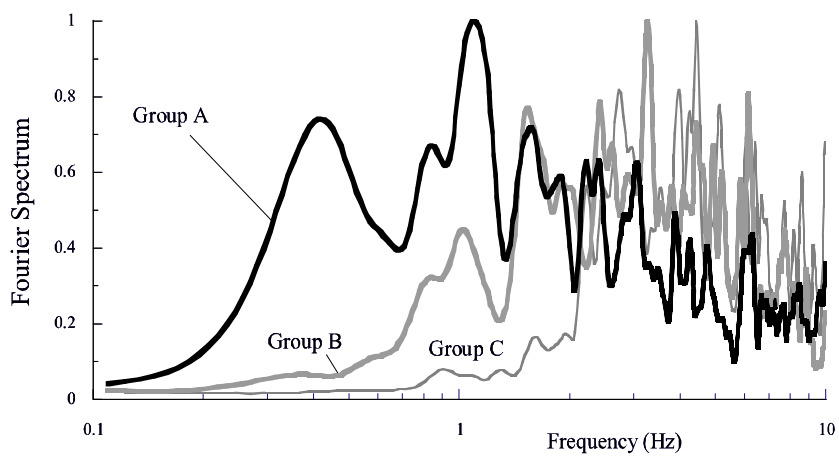
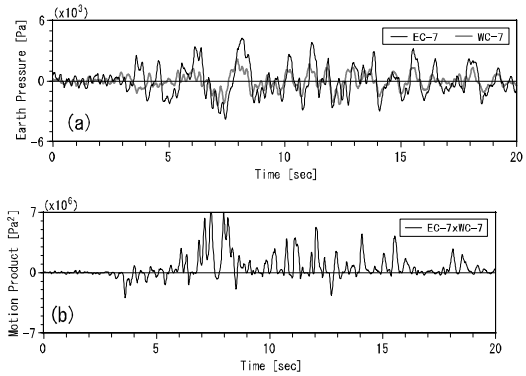


Figure 5. Normalized Fourier spectra of ground motions of Groups A, B and C.

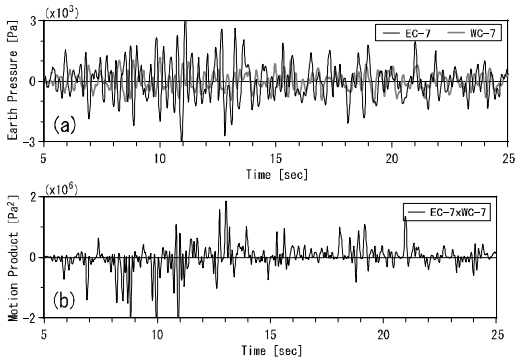
Table 1. Earthquake parameters

Eq. No	Date	Epicenter	Depth (Km)	Magnitude.	PGA (gal)	Group
3	1991 Oct 19	N36.08, E139.92	59	4.3	43.73	C
17	1993 Oct 12	N32.02, E138.24	390	7.0	27.15	B
30	1996 Sep 11	N35.07, E141.03	30	6.6	26.65	A



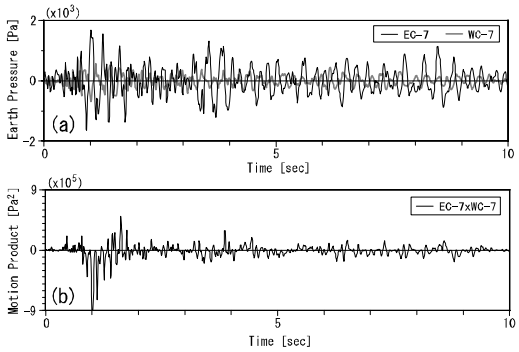
(a) Time histories (top) and motion product (bottom).

(Group A).



(b) Time histories (top) and motion product (bottom).

(Group B).



(c) Time histories (top) and motion product (bottom).

(Group C).

Figure 6. Time histories and phase characteristics of earth pressures induced on opposite sides of the foundation during earthquakes.

As for group B shown in figure 6(b), the earth pressures induced on both sides of the foundation are showing out-of phase in the primary portion of the time history and tend to shift to in-phase with progress of time. With regard to the motions of group C, which contains higher frequencies, out-of-phase and in-phase phenomena appear alternately throughout the whole time history as shown in figure 6(c). Summarizing the results shown in figures 6(a), (b) and (c), it may be noted that the phase characteristics of earth pressures induced on both sides of the foundation are strongly affected by frequency components

contained in the ground motions and tend to be induced in phase for the ground motions with lower frequencies.

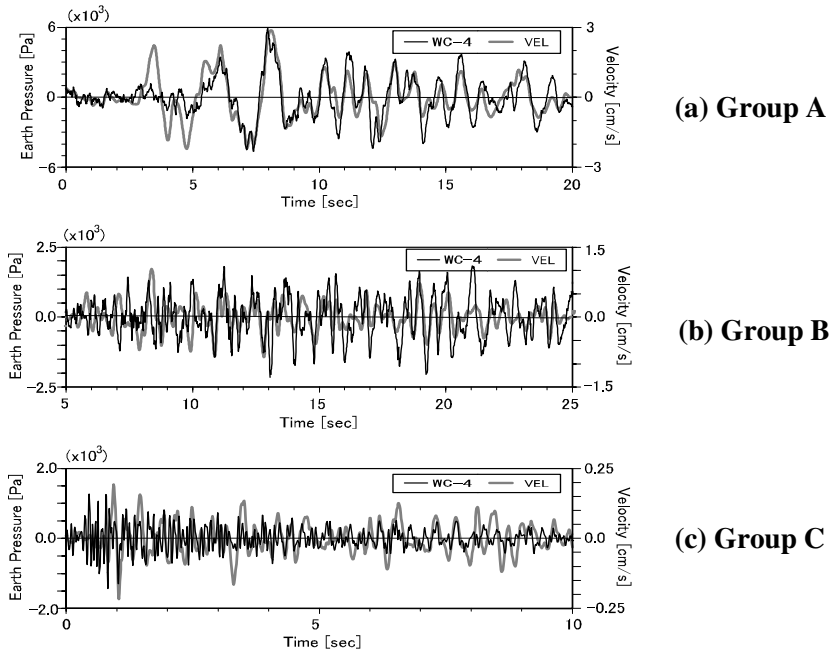


Figure 7. Time histories of earth pressures and velocity responses of foundation.

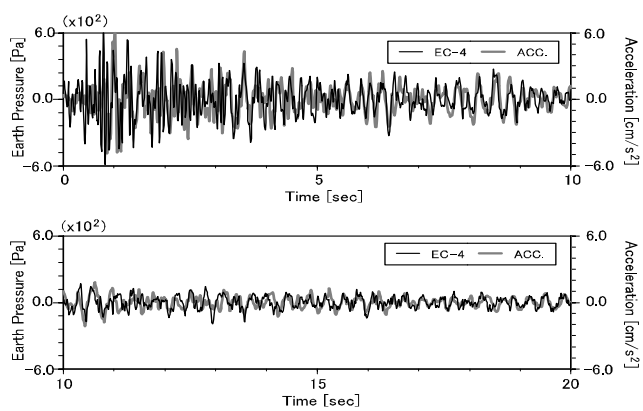


Figure 8. Time histories of earth pressure and acceleration response of foundation (Group C).

Another point to be discussed is what components of foundation motions are closely related to the earth pressures. Observed time histories of earth pressures and velocity response of foundation are shown simultaneously in figures 7(a), (b) and (c) for respective ground motions of groups A, B and C. It will be noticed that the earth pressures are closely correlated with velocity motions of foundation for group A and B. As for group C, on the other hand, the close correspondence between the two is not recognized as shown in figure 7(c). Figure 8 shows time histories of earth pressures and acceleration motions of the foundation from 0 to 10 sec (top) and 10 to 20 sec (bottom). A strong correlation between the earth pressures and acceleration motions of the foundation for group C is recognized. Finally, figures 9(a) to (e) show Fourier amplitude spectrum ratios of the earth pressures observed at different points to the velocity motions of foundation. The results are smoothed by use of Parzen window with a bandwidth of 0.2 Hz. It will be noticed that the spectrum ratios are almost constant for frequencies less than 4 : 5 Hz and tend to increase almost linearly for higher frequency. This fact indicates that earth pressures are induced in

accordance with velocity motions of the foundation for lower frequencies and to acceleration motions for higher frequencies.

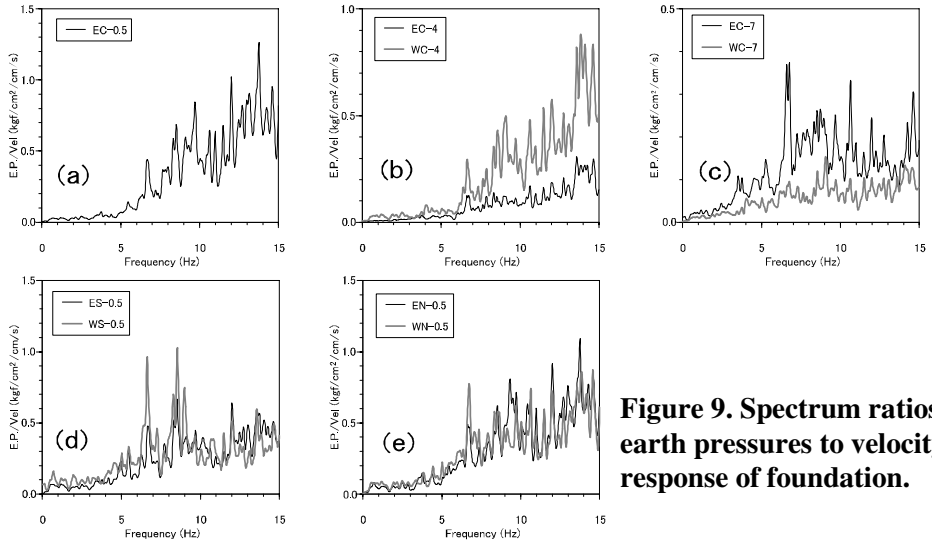


Figure 9. Spectrum ratios of earth pressures to velocity response of foundation.

CONCLUSIONS

The characteristics of earth pressures induced on the lateral sides of an embedded foundation during the forced vibration tests and earthquakes have been studied on the basis of observations. The studies have led us following conclusions.

1. The earth pressures during the forced vibration tests tend to be induced associated with the displacement motion of the foundation for frequencies lower than the fundamental frequency of the lateral soil. One the other hand, for frequencies more than the fundamental frequencies of the soil, the earth pressures tend to be induced in-phase to the velocity motion of the foundation.
2. The earth pressures induced by earthquake motions are strongly dependent on frequency component included in the ground motions.
3. The earth pressures are strongly related to the horizontal velocities of the foundation for rather lower frequencies and to acceleration response for higher frequencies.
4. A phenomenon that the earth pressures were induced in-phase on opposite sides of the foundation was observed for lower frequencies included in the ground motions. On the other hand, the earth pressures tend to be induced out-of-phase on the opposite sides of the foundation for high frequencies of ground motions.

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