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OBSERVATION AND NUMERICAL SIMULATION OF DYNAMIC EARTH PRESSURE

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ABSTRACT

In order to investigate dynamic characteristics of earth pressure acting on underground walls of embedded structures, earth pressure and acceleration of a building and the surrounding ground were observed at an actual nuclear power plant site. From the observation data, correlation between dynamic earth pressure and seismic ground behavior was confirmed. There is close correlation between dynamic earth pressure and velocity response in regard to peak values. Relative displacement between the building and ground corresponds quite well to dynamic earth pressure. A simulation analysis on the observation results was carried out using 2-D FEM. A suitable input motion for analysis was estimated by averaging time histories which computed from records of the array observation. Calculated acceleration responses and dynamic earth pressure are in good agreement with observation results. The overall behavior of the building and the ground was visualized from the observation data. It can be seen clearly that the earth pressure is induced due to the fact that the building restrains the deformation of the ground.

KEYWORDS

observation of dynamic earth pressure; seismic array observation; dynamic characteristic of earth pressure; soil-structure interaction; simulation analysis; 2-D FEM

INTRODUCTION

At the design stage for embedded structures, earth pressure acting on underground walls must be taken into consideration as a load. In Japan, a method that was developed on the basis of limit state of soil supported by retaining walls is commonly used in the evaluation of dynamic earth pressure. Behavior of dynamic earth pressure acting on an embedded building may differ from that estimated by this method. However, data obtained from observations of earth pressure during earthquakes is limited. In order to estimate dynamic earth pressure in a simple and rational manner, it is necessary to glean observation data and to investigate the data.

Therefore, earth pressure acting on an embedded building and the acceleration of ground and building have been observed at an actual nuclear power plant site. the correlation between the dynamic earth pressure and the earthquake motion of the ground and the building was investigated. A simulation analysis on the observation results using two dimensional FEM was carried out and the applicability of FEM for estimation of dynamic earth pressure was studied. In order to see a condition of occurrence of dynamic earth pressure, the overall behavior of the building and the ground was visualized from the observation data.

Dynamic earth pressure described here means fluctuating earth pressure during earthquakes or the difference between earth pressure during an earthquake and at rest.

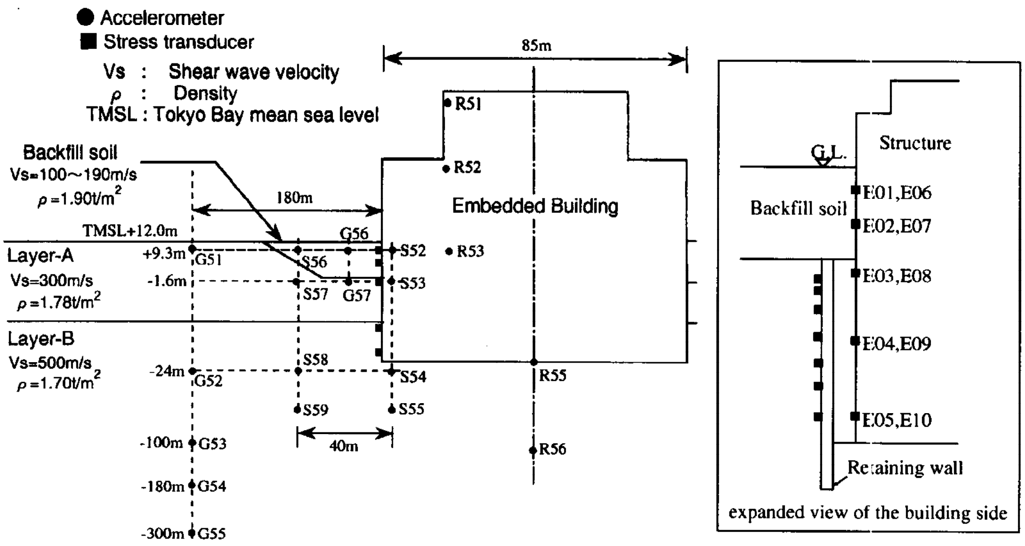


Fig.1. Profile of site and location of measuring meters

OUTLINE OF SEISMIC OBSERVATION

Site profile and location of seismometers are illustrated in Fig.1. Surface layer (Layer-A) is quaternary soft mudstone whose thickness is about 20m and Layer-B under Layer-A is Neogene mudstone. The shear wave velocity of Layer-A and Layer-B are about 300m/s and 500m/s respectively. The reinforced concrete building is embedded to a depth of G.L.-36m which is standing on Layer-B. The surface stratum around the building is backfill soil with a thickness of 12m.

Earth pressure gauges are installed on the underground wall. The accelerometers are placed both in the building and in the peripheral ground. The feature of this observation is that the accelerometers in the ground are arranged in a grid pattern on the vertical plane. From this arrangement, we can directly grasp the ground deformation during earthquakes. At a point about 180m from the building, accelerometers are vertically installed in order to observe the dynamic characteristics of the ground only.

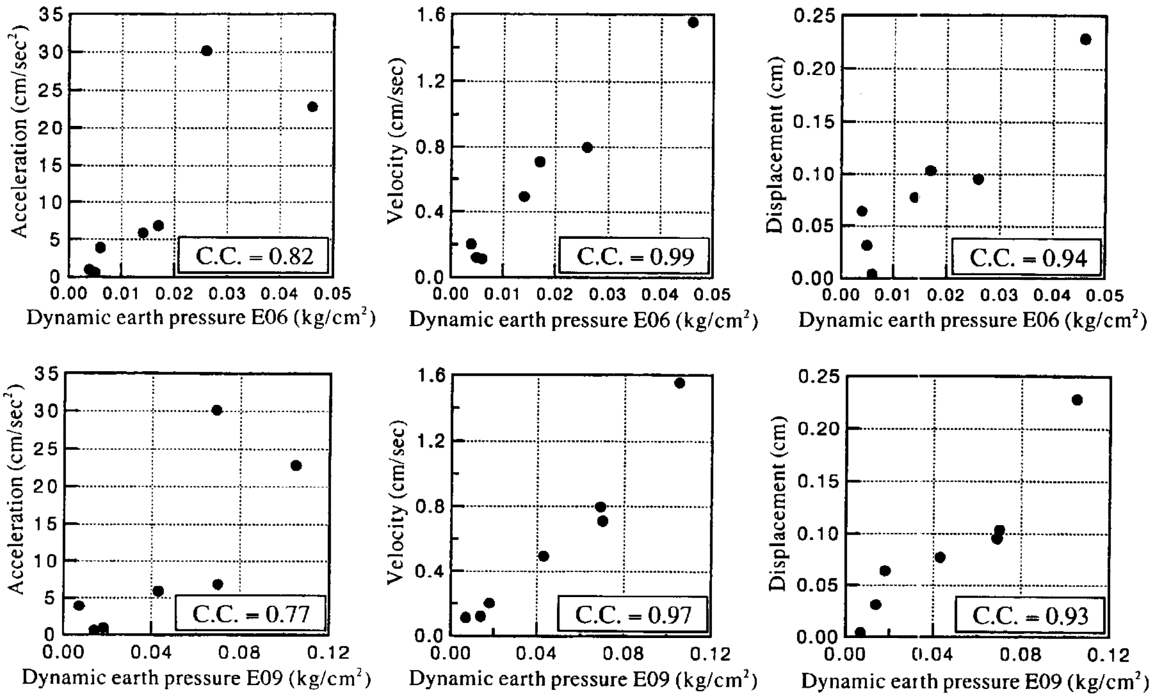
OBSERVED DYNAMIC EARTH PRESSURE

Observed earthquake

Earthquake observation started in 1989 when the building was completed. Many earthquakes have been observed but many earthquakes were small and obtained data is noisy. We have obtained only 5 useful records as shown in table 1. During earthquake No.8, 30 gal for the maximum peak acceleration was recorded on the ground surface. It is the largest record on the ground surface among the records obtained to date. We reported the study of earthquakes No.2-No.8 earlier (Hirota et al., 1992). After that, new large earthquake data (earthquake No.9) were taken. During earthquake No.9, the largest earth pressure in the observation data was recorded. We will discuss characteristics of dynamic earth pressure, adding the data of earthquake No.9.

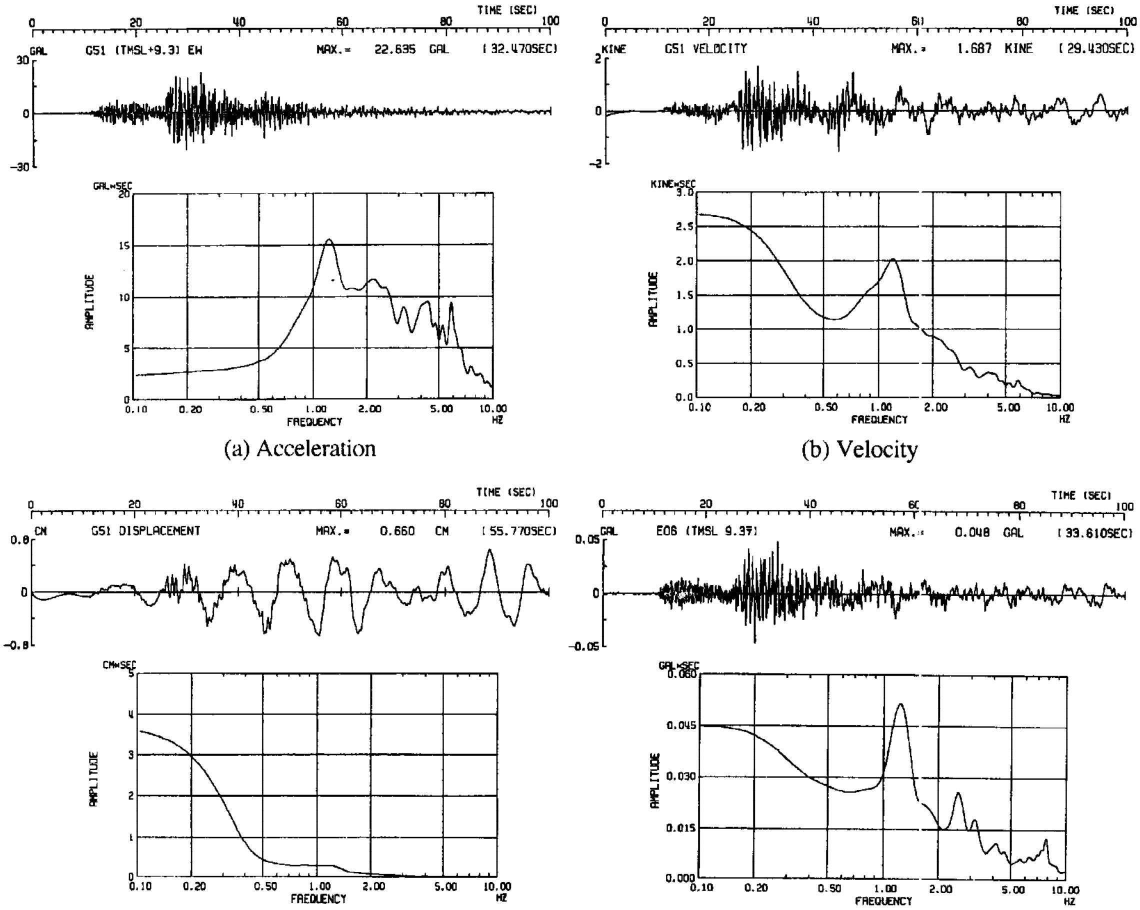
Table 1. Observed earthquake data

No.	Event	Date	Magnitude	Focal Depth (km)	Epicentral Distance (km)	Peak acceleration on the ground surface (cm/sec^2)	Maximum earth pressure (kg/cm^2)
2	MID NIIGATA PREF	05/27/89	3.1	12	4	8.64	0.0239
4	FAR E OFF SANRIKU	11/02/89	7.1	0	472	0.783	0.0346
7	NEAR IZU-OSHIMA ISLAND	02/20/90	6.5	6	301	1.0	0.0226
8	MID NIIGATA PREF	12/07/90	5.4	14	27	30.2	0.0805
9	OFF NOTO PENINSULA	02/07/93	6.6	25	118	22.6	0.2550



C.C. ; Correlation Coefficient

Fig.2. Correlation between earthquake response and dynamic earth pressure



(a) Acceleration

(b) Velocity

(c) Displacement

(d) Dynamic earth pressure

Fig.3. Comparison of acceleration, velocity, displacement and dynamic earth pressure in regard to waveform and Fourier spectra

Maximum value correlation between ground motion and dynamic earth pressure

It is both important and useful to estimate maximum value of earth pressure from seismic level. Maximum value of ground surface response is considered as an index of seismic level at the site. Regarding peak value of time history, correlation between dynamic earth pressure (E06,E09) and seismic response (G51) is examined. Figure 2 shows the correlation between acceleration and dynamic earth pressure, velocity and dynamic earth pressure, and displacement and earth pressure. The axis of ordinates is the maximum value of acceleration or velocity or displacement and the axis of abscissas is the maximum value of dynamic earth pressure. The value indicated by a dot is peak value observed during each earthqukae. These figures show the positive correlation of dynamic earth pressure with acceleration, velocity, and displacement. However, the values indicated by dots scatter and the level of the scattering is different for each relation.

Correlation coefficients were calculated for each relation and presented in the figures. Correlation coefficient between velocity and dynamic earth pressure is 0.97 or 0.99. These values are closer to 1.0 than in the other correlation. Correlation coefficient between acceleration and dynamic earth pressure is 0.82 or 0.77 which are farther from 1.0 than in the other correlation. There is close correlation between dynamic earth pressure and velocity response in regard to peak values.

In order to examine the reason why dynamic earth pressure and velocity are in close correlation, time histories and Fourier spectra of acceleration, velocity, displacement (G51) and earth pressure (E06) are compared in Fig.3. Amplitude of low frequency range increase in this order, acceleration, velocity, displacement. Dynamic earth pressure tends to increase in the low frequency range and its shape of Fourier spectra and waveform is similar to that of velocity. Due to the fact that dynamic earth pressure and velocity have similar frequency characteristics, there is close correlation between dynamic earth pressure and velocity response in regard to peak values.

Relative displacement between building and ground and dynamic earth pressure

When considering that earth pressure occurs on the boundary between a building and ground, it can easily be anticipated that the relative displacement of the ground and the building in a horizontal direction will correspond well to the dynamic earth pressure. We reported on this relationship concerning earthquake No.8 earlier (Hirota *et al.* 1992). A clearer relation has been obtained for earthquake No.9. Figure 4 shows the superposition of the relative displacement wave between the ground and the building, and the earth pressure wave. The waveforms presented are those of the main shock part of earthquake No.9 and are standardized by their peak value. The relative displacement was obtained as a difference between the ground displacement at a point located 40m from the building and the building displacement. The displacement was calculated by integration of the acceleration. In this calculation, a frequency range lower than 0.4Hz was eliminated due to the fact that measurement noise is amplified in the low frequency range. This figure indicates that the relative displacement and the earth pressure correspond quite well to each other.

Through the measurement for the actual building,the following correlations are made clear.

(1) Magnitude of dynamic earth pressure is closely related to intensity of velocity response.
(2) Dynamic earth pressure is closely related to relative displacement between ground and building.

It was known that soil strain is in close correlation with velocity response and relative displacement can be regarded as soil strain. It can be considered that these correlations are arrived at for the same reason. Soil deformation surrounding a building plays important role in the occurrence of dynamic earth pressure. Therefore in order to evaluate the dynamic earth pressure, responses of both the building and the ground must be precisely estimated.

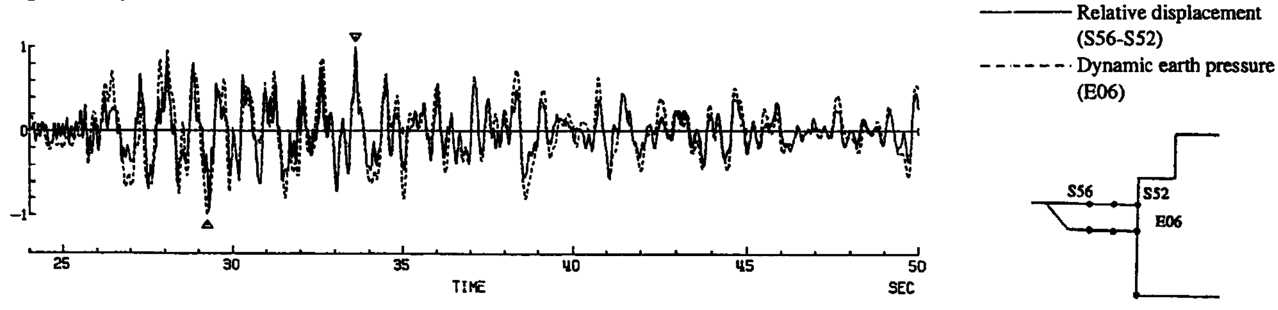


Fig.4. Comparison of dynamic earth pressure and relative displacement

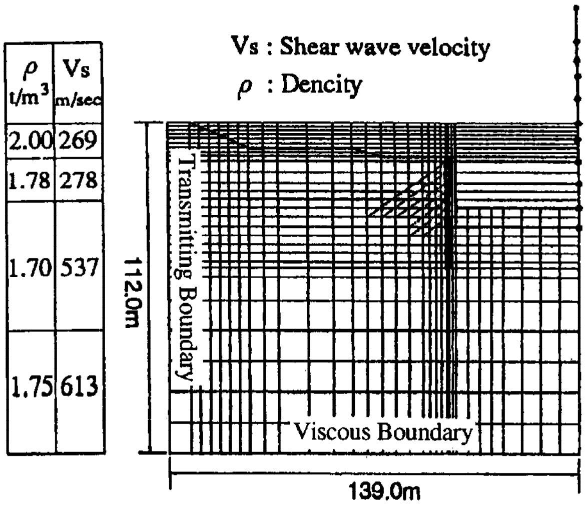


Fig.5. 2-D FEM model

SIMULATION ANALYSIS OF DYNAMIC EARTH PRESSURE

Since seismic records were obtained for the behavior of the ground and the building, the simulation analysis was carried out using the two dimensional FEM. The analytical result was compared with the measurement result.and the applicability of FEM for estimation of dynamic earth pressure was studied. Earthquake No.9, during which the largest earth pressure to date was observed, was the subject of the simulation.

FEM model

The outline of the analytical model was shown in Fig.5. The building and the peripheral ground were modeled. The ground part is modeled with plane strain elements and the building is modeled with a lumped-mass model. The underlaying halfspace is simulated through viscous dampers at the lower boundary. The side of the FEM model is connected to lateral transmitting boundaries allowing for dissipation of energy as radiation damping.

Estimation of input seismic motion for FEM model

Input motion estimated from observation data was applied at a lower boundary of the FEM model.. An incident wave at the base of the model as input motion was computed with the one dimensional wave propagation theory using the records of the vertical array observation located 180m from the building.

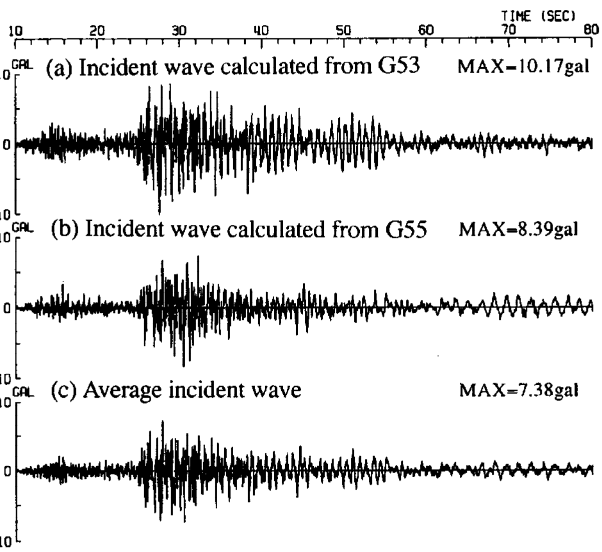


Fig.6. Calculated incident waves and an average incident wave

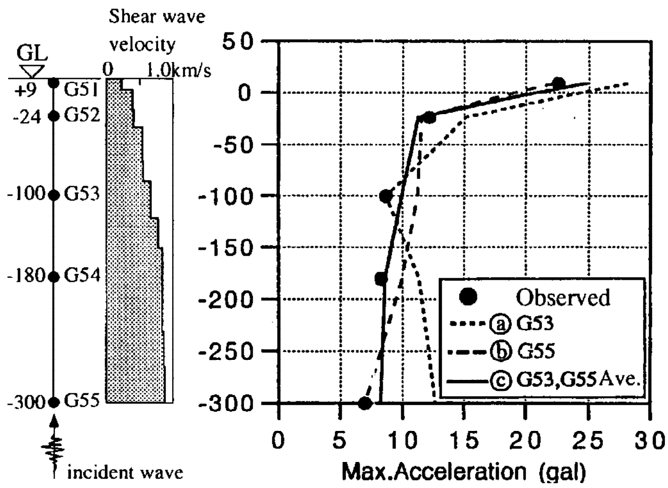


Fig.7. Comparison of maximum acceleration obtained from the observation and calculated from the three incident waves(Fig.6)

In the vertical array, seismic records were obtained at different depths. From each record, the incident wave can be computed. Figure 6 (a) and (b) shows incident waveforms calculated from the records observed at G53 (GL-100m) and G55 (GL-300m). The two waveforms do not agree with each other, but an actual incident wave must be the same. Because observed data must include noise or non-vertical traveling wave, calculated incident waves do not coincide. Therefore, in order to estimate a correct incident wave, we calculated an average wave (Fig.6 (c)) of incident waves obtained from G53 and G55. By taking an average, it was expected that the influence of noise was reduced.

In order to confirm the accuracy of the average incident wave, responses of the vertical array were calculated. The average incident wave and incident waves calculated from G53 and G55 are inputted in a soil model of the vertical array. Calculated peak values are compared with the observation ones in Fig.7. Distribution of peak acceleration obtained from average wave corresponds well to the observed distribution on the whole. A suitable input motion was successfully obtained by taking an average of time histories which were computed from records of the ground array.

Acceleration response

For the acceleration response, analytical results are compared with observation results. Typical results are presented in Fig.8 Figure 8 (a) shows the comparison of the acceleration waves at the ground level of the building. Figure 8 (b) shows the vertical distribution of the maximum acceleration values. The analytical results correspond quite well to the results obtained from the actual measurement.

Dynamic earth pressure

Comparison of the earth pressure acting on the side walls of the building between the analytical results and the observation results is shown in Fig. 9. The observation results are averaged values at two observation points at the same depth: one point at the center of the building and the other at its end. Figure 9 (a) compares the earth pressure wave recorded from the observation with that obtained from the calculation. Figure 9 (b) shows the comparison of the spectra. Although a slight difference between the two waves is found in the details, the overall shapes of the two results correspond well to each other. Figure 9 (c) shows the distribution of the maximum earth pressure. The calculated values are slightly smaller than the observed values in deeper part. However, the calculated values correspond well to the earth pressure observed on the retaining wall . Even when taking into account the dispersion of the earth pressure values due to the fact that the earth pressure is easily subject to local influences, it can be cosidered that the analytical values correspond quite well to the observation values as a whole.

OVERALL BEHAVIOR OF THE GROUND AND THE BUILDING

We try to visualize the overall behavior of the building and the ground in the two dimensional vertical in-plane from the grid pattern observation array using Earthquake Engineering Visualization software called EODAS (Shiomi *et al.*, 1992).

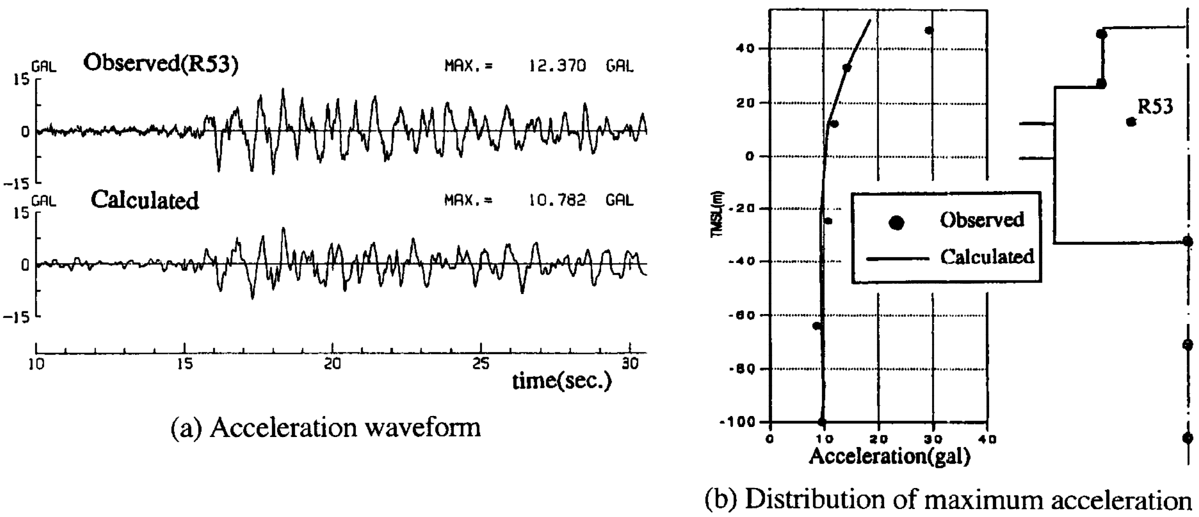
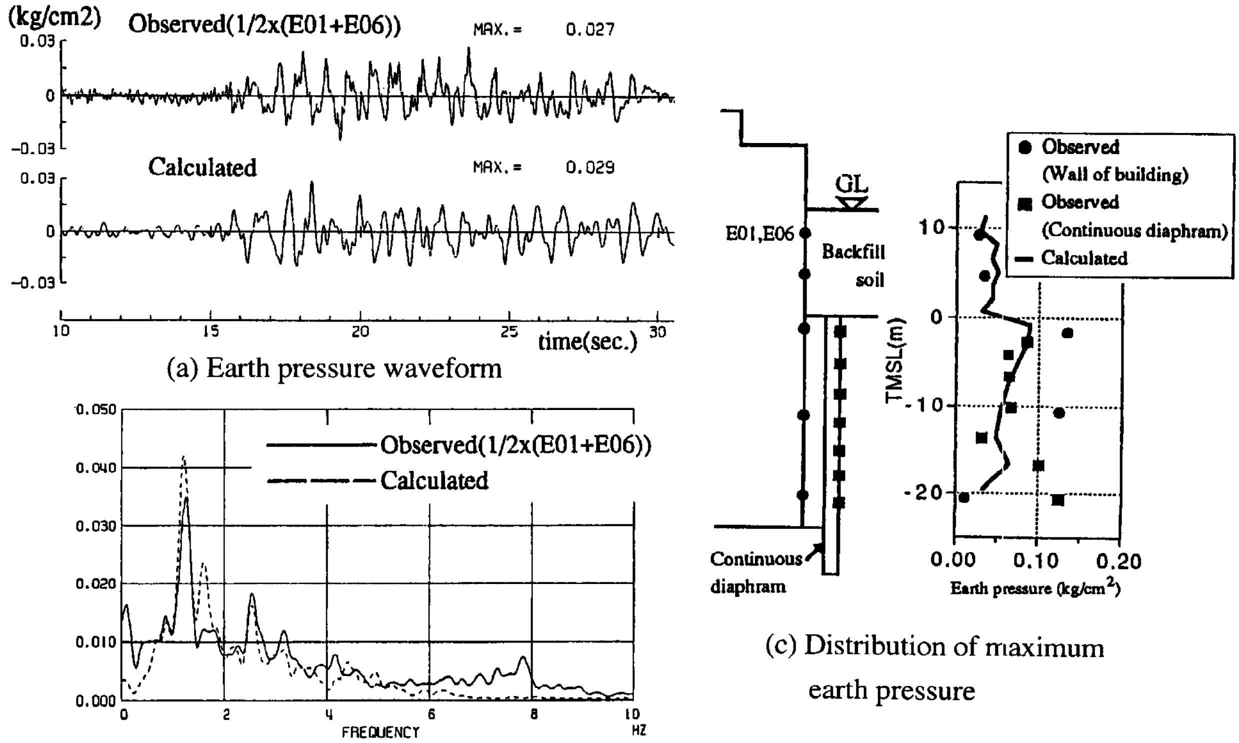


Fig. 8. Comparison of acceleration between observed and calculated by FEM



(a) Earth pressure waveform

(b) Fourier spectra

(c) Distribution of maximum earth pressure

Fig.9. Comparison of earth pressure between observed and calculated by FEM

The movement is obtained by integrating the observed acceleration. The configuration of the soil-structure-model is prepared in the same way as FEM and the observation data are inputted as the deformation of the nodes. The deformations of node without the observation data are interpolated with observation data. The analytical overall behavior was obtained in the same manner.

Figure 10 illustrates the comparison between the observed overall behavior and the analytical behavior. Dynamic earth pressure is presented by a flag along the building. Both results from the observation and the analysis can be seen corresponding well to each other as a whole. The ground is moving in shear mode. The building dynamic deformation is smaller than surface ground deformation and the building restrains the shearing deformation of the surrounding ground. In this case, the ground pushes against the building. The ground does not support the deformation of the building The earth pressure acts on the loading side for the building.

CONCLUSION

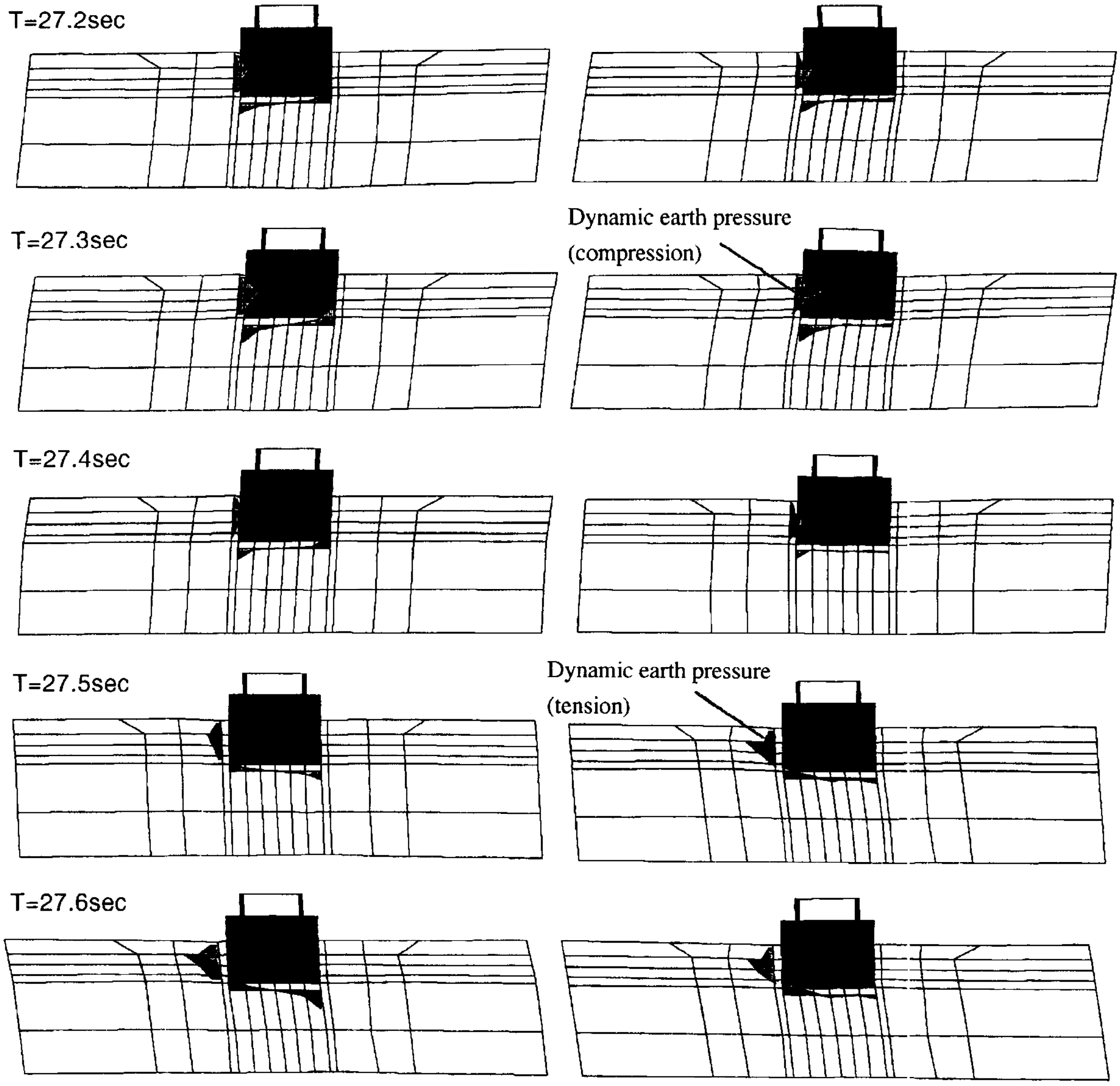
The following points have been made clear as a result of the investigations:

(1) There is close correlation between dynamic earth pressure and velocity response in regard to peak values, and dynamic earth pressure is in close correlation with the relative displacement of the ground and the building. It was confirmed from actual measurements that the earth pressure depends upon the interaction between the behavior of the ground and that of the building.

(2) In consequence of the simulation study on the observation for Earthquake No.9 using the two dimensional FEM, not only the acceleration response but also the dynamic earth pressure can appropriately be estimated. Applicability of FEM for estimation of dynamic earth pressure is confirmed.

(3) As a result of the visualization of the behavior of the ground and the building on a vertical in-plane during Earthquake No.9, the earth pressure is induced due to the fact that in this case the building restrains the displacement of the surface layers. This indicates that the earth pressure acts on the loading side for the building.

The aforementioned investigation was obtained from limited seismic observations for one building only. Through the accumulation of data gleaned by continuing observations in the future, a more general conclusion will be formed concerning the dynamic characteristics of the earth pressure.



(a) Calculated by FEM (b) Observed

Fig.10. Overall behavior of the building and the ground
(Displacement is magnified 10,000 times.)

Grid pattern array observation in the vertical plane is a unique attempt. So obtained data should have much useful information. We will try to apply the observed data for the investigation about not only dynamic earth pressure but also soil-structure interaction.

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