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SEISMIC RESPONSE CHARACTERISTICS OF THE STRAINS OF IN-GROUND CYLINDRICAL TANKS

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SUMMARY

This paper describes the seismic response characteristics of the strains of in-ground cylindrical tanks. The earthquake observation has been carried out on an actual in-ground LNG storage tank. From the observed data, the circumferential components of the strains were expanded with finite Fourier approximation in circumferential direction. In the circumferential distribution modes, the axisymmetric mode or the sine mode is predominant. The latter mode is caused by the ring deformation mode. The FEM analyses lead to the following conclusions; (1) The sine mode is mainly caused by the SH body wave. (2) One of the earthquake ground motion components which cause the axisymmetric mode is the Rayleigh wave.

INTRODUCTION

It is important to understand the dynamic stress or strain on huge in-ground cylindrical tanks for aseismic design purposes. In order to measure the dynamic strain of the tank which is made of reinforced concrete, the earthquake observation has been carried out. The accelerations of the tank and the ground and circumferential component strains near the external side of the tank wall have been measured. The strainmeters are arranged at eight points along the circumference at equal interval. The relations between the tank strains and the ground motion components were studied using the earthquake observation data and Finite Element Method (FEM) analyses.

EARTHQUAKE OBSERVATIONS

The outline of the earthquake observation system, the tank and the ground is shown in Fig.1. The tank is 68.82 m in outer diameter and 35.5m in height. The thicknesses of the side wall and of the bottom plate are 2.2 m and 0.6 m, respectively. The earthquake observation site is composed of a banking, weak silt and firm mud stone. The shear wave velocity, Vs, of the ground is also shown in Fig.1. The examination were done for the two earthquakes shown in table 1.

EARTHQUAKE GROUND MOTIONS

The accelerations recorded at AG1, which is shown in Fig.1, during

IZUOOSHIMA KINKAI OKI and KANAGAWAKEN SEIBU earthquakes are shown in Fig.2. As for IZUOOSHIMA KINKAI OKI earthquake, the largest acceleration appears in the horizontal X component as indicated in Fig.2, whose evolutionary power spectrum (EPS) (Ref.1) is shown in Fig.3a. The peaks of EPS which range from 0.3 Hz to 5 Hz in frequency domain almost concentrate at about 13 seconds in time domain, and the dispersion characteristics of the surface wave(Ref.2) can not be found in this region. On the other hand, the traveling speed of the seismic wave in that region is more than 8.8 km/s, which is calculated by the arrival time differences of the maximum values of the X component accelerations at AG1, AG2 and AG3. From these two results, the X component of the ground motion at about 13 seconds is presumed to be an SH body wave which travels almost vertically from the bottom upward.

Fig.3b shows the EPS of the up-down component acceleration of KANAGAWAKEN SEIBU earthquake. In this EPS, the dispersion characteristics can be seen in the region from 40 to 50 seconds in time domain and from 0.3 to 0.7 Hz in frequency domain. The phase velocity of the earthquake ground motion in the region is 770m/s at 0.47 Hz, which is calculated by the EPS's peaks arrival time differences at the three points AG1 to AG3. The value of this velocity is between the phase velocities of the first and second modes of the Rayleigh wave calculated by FEM. But in the theoretical dispersion curves of group velocities, the 2nd mode only has a stationary value at around 0.47 Hz. Thus, the earthquake ground motion of the region is presumed as being the 2nd mode of Rayleigh wave.

OBSERVED TANK STRAINS

Fig.4 indicates the strain of the tank. The circumferential distribution modes of the strains were obtained by expanding the strains at 8 points with finite Fourier approximation in the circumferential direction. The strains at points 3-3 or 8-8 indicated in Fig.1 were, unfortunately not measured and these strains were estimated by means of Lagrange's interpolation formula using the measured strains. The absolute values of the strain coefficients are shown in Fig.5. As for IZUOOSHIMA KINKAI OKI earthquake, as shown in Fig.5a, the sine distribution mode (the harmonic number of finite Fourier approximation n=1) of strain is prominent at about 13 seconds. Fig.6a shows the strain distributions at the typical times indicated in Fig.4a with circles. In this figure, the solid and the dotted lines indicate the strains at GL-9.75 m and GL+3.075 m (shown in Fig.1), respectively. At about 13 seconds when the largest strain is generated, the strains of the semicircle of the tank are in tension and of the opposite semicircle are in compression. As for KANAGAWAKEN SEIBU earthquake, as indicated in Fig.5b, until around 25 seconds the axisymmetric (n=0) and sine (n=1) distribution modes of the strain are predominant, and after about 25 seconds only the axisymmetric distribution mode is predominant. Fig.6b shows the strain distributions at the typical times indicated in Fig.4b with circles. After about 25 seconds, it is noticed that the axisymmetrical mode is predominant. Besides, from Fig.5, the strain coefficients of n=2 and 3 are much smaller than those of n=0 and n=1 in the case of either of the two earthquakes.

ANALYSIS OF TANK RESPONSE TO BODY WAVE

The ground and tank coupled FEM model was used to analyze the earthquake response of the in-ground cylindrical tank. The model is an axisymmetric model subjected to an axisymmetric or an asymmetric dynamic load caused by the earthquake. Fig.7 shows the vertical section of the FEM model. On the boundaries the model is provided with the viscous dashpots proposed by Lysmer et al., which absorb wave effects emanating from the tank.

(1) Response to the SH body wave: The X component acceleration around 13 seconds

of IZUOOSHIMA KINKAI OKI earthquake was used for calculation, which is assumed to propagate vertically from the bottom upward. The calculated X component acceleration of the tank is indicated in Fig.8 in comparison with the observed one. Fig.9 shows the calculated circumferential component strain at 6-6 point shown in Fig.1 and compares it to the observed one. Fig.8 and 9 indicate that the calculated acceleration and strain by FEM model agree well with the observed ones. From the results it can be said that the strain of predominant sine distribution mode (n=1) is caused by an SH body wave propagating vertically from the bottom upward.
(2) Response to P body wave: As an example of P-wave propagating vertically from the bottom upward, the up-down component acceleration of KANAGAWAKEN SEIBU earthquake shown in Fig.2b was used. The calculated up-down component acceleration at AT1 and circumferential component strain are shown in Fig.10 in comparison with the observed values. The component of the observed strain is an axisymmetric component (n=0) of distribution mode. Fig.10 indicates that the calculated up-down component acceleration of the tank agrees well with the observed value. But the calculated strain is much smaller than actual strain. Thus it seems that the P-wave is not the cause of the predominant tank strain of the axisymmetric (n=0) distribution mode.

ANALYSIS OF TANK RESPONSE TO RAYLEIGH WAVE

As an example of a Rayleigh wave, the region from 0.3 to 0.7Hz in frequency domain and from 20 to 52 seconds in time domain of the epicentral and up-down component accelerations observed at AG1 for KANAGAWAKAN SEIBU earthquake were used. The earthquake response analyses to Rayleigh wave were carried out as follows: 1) The Rayleigh wave displacement modes are calculated of the typical five frequencies in the range 0.3-0.7Hz as eigenvalue problems. 2) The displacement modes needed to analyze for other frequencies are calculated by a linear interpolation of the five displacement modes calculated in advance. 3) As the ground motion in cylindrical coordinate system, the displacement mode of the n-th harmonic number are calculated by Fourier series expansion of the Rayleigh wave displacement. 4) The phase velocities used in calculation are the measured values. 5) The transient responses are calculated by the Fourier inverse transform of the steady state response same way as in Ref.4. The calculated circumferential component strain for the axisymmetric deformation mode is shown in Fig.11 in comparison with the observed strain of axisymmetric circumferential distribution component. Fig.11 indicates that the calculated and observed strains agree reasonably well with each other. The calculated epicentral and up-down component accelerations of the tank also agree well with the observed values.

CONCLUSIONS

The following conclusions may be drawn from the results of this work.
(1) The axisymmetric mode (the harmonic number of finite Fourier approximation n=0) or the sine mode (n=1) which is caused by the ring deformation are predominant in the circumferential distribution modes of the circumferential component strains.
(2) SH body wave causes the sine mode. Rayleigh wave is one of the earthquake ground motion components which causes the axisymmetric mode.

In the future, investigation of the following subjects should be continued: (a) Earthquake response characteristics of the strains of tanks constructed in soft ground. (b) The power of the surface wave components in strong earthquake ground motions. (c) Response characteristics of tank strains caused by Love waves and Body waves propagating obliquely from the bottom upward.

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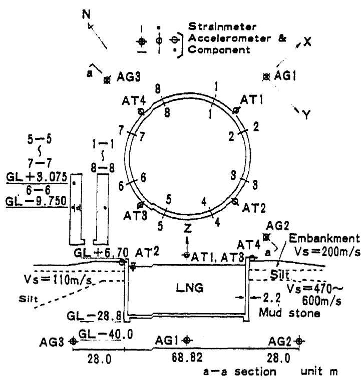

Fig.1 Schematic View of In-ground Tank and Arrangements of Pickups

Table1 Earthquakes

No.	Earthquake	Date	Magnitude	Intensity *	Max. Value Acceleration gal Horizontal	Vertical
A	IZUOOSHIMA KINKAI OKI	57.8.12	5.7	3	64.0	18.0
B	KANAGAWAKEN SEIBU	58.8.8	6.0	4	16.5	14.5

*in Japanese Scale in YOKOHAMA city

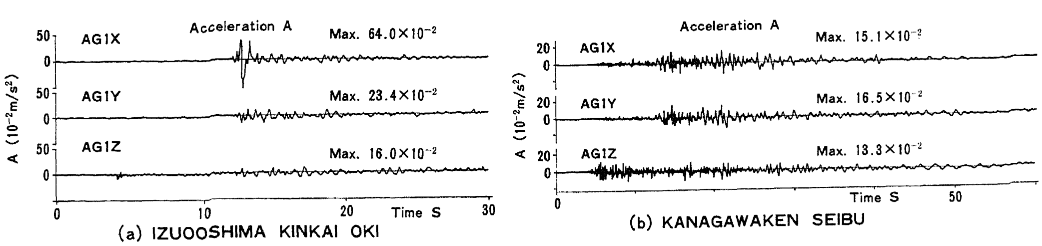

Fig.2 Observed Accelerations

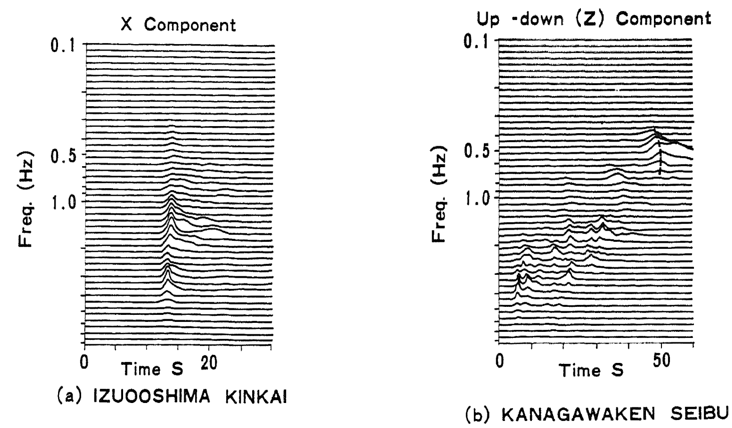

Fig.3 Evolutionary Power Spectra of
the Accelerations

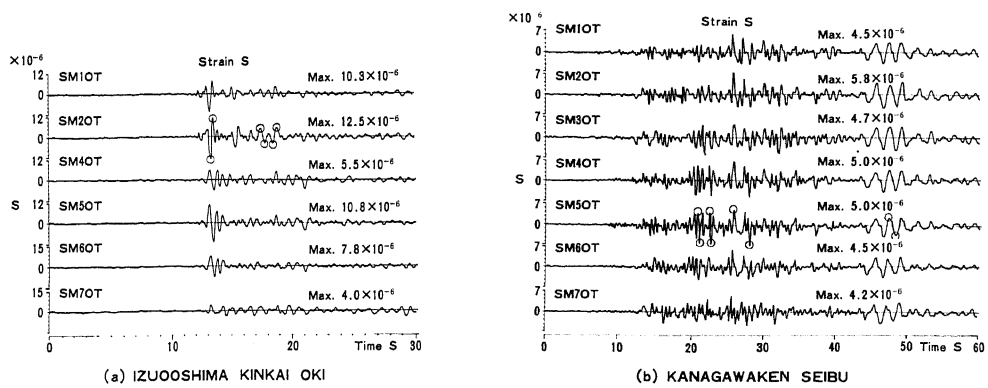

Fig.4 Observed Strains

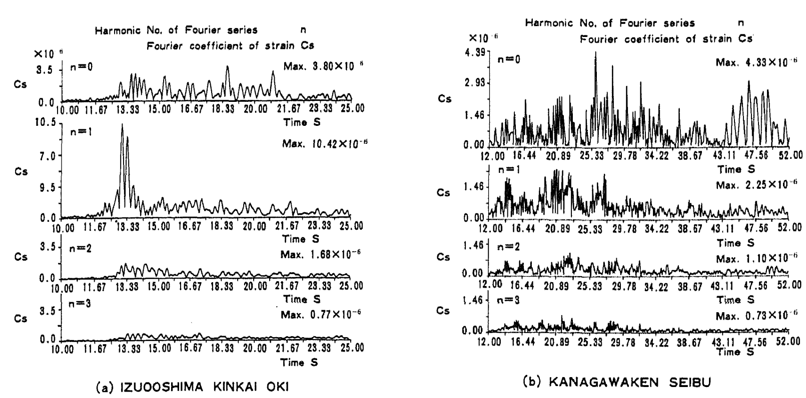

Fig.5 Absolute Values of the Coefficient
of Finite Fourier Approximation
for Strains

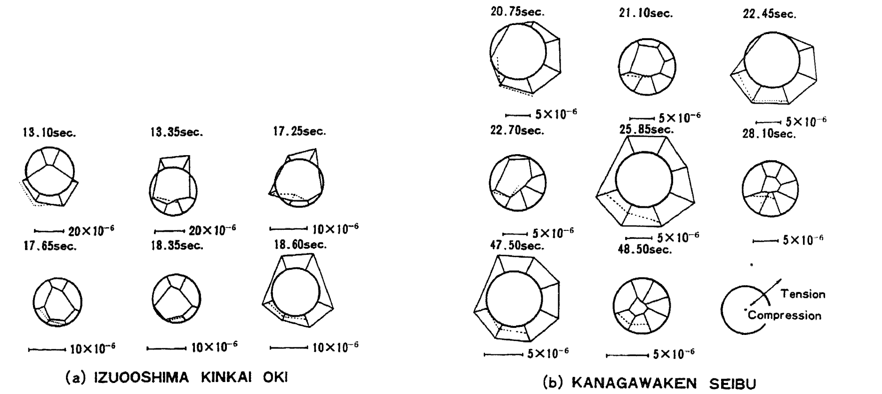

Fig.6 Strain Circumferential Distribution

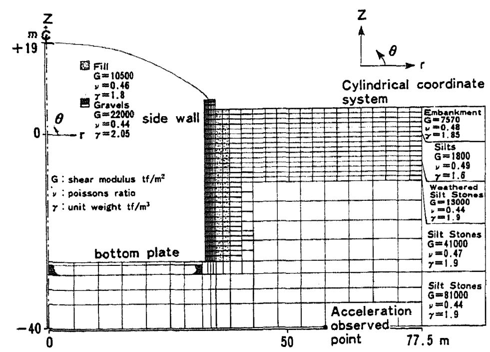

Fig.7 FEM Model of In-ground Cylindrical Tank and the Adjacent Soil

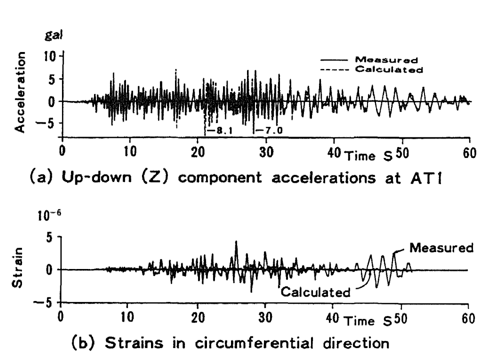

Fig.10 Response Acceleration and Strain Caused by P-wave

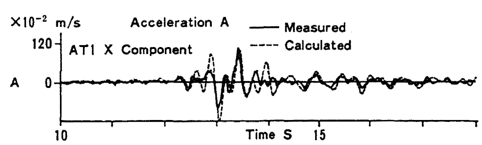

Fig.8 Response Acceleration Caused by SH Body Wave

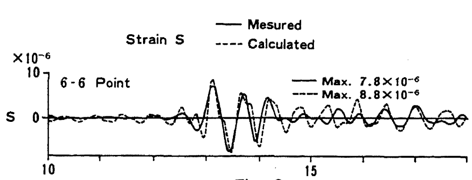

Fig.9 Response Strain Caused by SH Body Wave

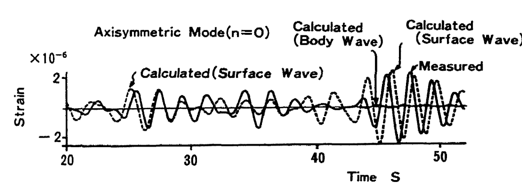

Fig.11 Response Strains Caused by Rayleigh Wave