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NEW TYPES OF GROUND MOTIONS FOR THE ANTI-EARTHQUAKE DESIGN OF NON-BUILDING INDUSTRIAL FACILITIES

by

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SYNOPSIS

Based on the authors' own observations of ground motions and responses of the models of a tower, pipings, vessels and storages during earthquakes, the characteristics of ground displacement in a range from 2 to 10 seconds, torsional ground velocity in vertical axis, and wide range ground acceleration motions are presented. The importance of these characteristics on the anti-seismic design of structures in the industrial facilities is also discussed.

INTRODUCTION

The authors have been continuing the observation of ground motions and responses of various items of a tower, pipings, vessels and storages in the Chiba Field Station, Institute of Industrial Science, University of Tokyo since 1972.[1] Following three items are different from widely observed items:

i) ground displacement motions in a range from 2.0 sec to 10.0 sec
ii) torsional ground velocity motions in vertical axis
iii) wide range ground acceleration motions.

These items have some particular relations to design conditions of various types of structures in industrial facilities, such as nuclear power stations, petro-chemical engineering plants, oil refinaries, oil storages, spherical tanks, various kinds of life-line systems and so on. As the author reported in the previous

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NOTE; Most part of this paper was presented at "International Workshop on Strong-Motion Earthquake Instrument Arrays" last May in Honolulu, Hawaii. There is no Proceedings for the collections of the papers presented in this meeting. And its summary was also presented at Japan National Symposium on Earthquake Engineering[7] recently. The last part of the paper for the Workshop, the report on engineering arrays related to industrial facilities in Japan are deleted.

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reports,[2] the mode of failure of such structures is the fundamental matter for their design. Many modes which we concern with are related to the ground motions which the author mentioned above. Some of the mechanisms of ground motions are not solved yet. Therefore, the author feels the necessity of observation networks through some industrial area as to collect ground motion records to cover these three items for their design.

In this short article the authors will discuss their features which they obtained through their observation briefly at first. Then they will raise what we should know about them, and what is the point related to the anti-earthquake design of structures in the industrial facilities.

SLIGHTLY LONG PERIOD GROUND DISPLACEMENT MOTIONS

EXPLANATION: As the authors will discuss the detail later, sloshing phenomenon of liquid storage is mainly governed by slightly long period ground motions, because the fundamental eigen period of sloshing of free surface liquid in a circular cross section vessel is nearly equal to the square root of diameter in meter. Therefore, that of 4 meter diameter is about 2 seconds, and that of 100 meter, maybe the largest class oil storage, is 10 seconds. To evaluate the safety of these storages, the ground displacement amplitude in such ranges is more significant than the peak ground acceleration.

In the case of the estimated record[3] of Kwanto earthquake-1923, it is said that the single maximum amplitude of ground motions might reach to 460 mm. This was done from the over-scaled record of Ewing type seismograph. Hall described the design criteria for Trans-Alaska Pipeline in his reports.[4] For the area affected by Magnitude 8.5 and 8 earthquake, the ground motion should be 22 in (66 cm) and that for structural design should be 12 in (30 cm) in the criteria. Such large ground displacement may cause fatal damage on storage tanks as we observed in the case of Alaska earthquake-1964 and Niigata earthquake-1964.

DATA AND RESULT OF ANALYSIS: The authors are employing two sets of a moving-coil-type pick-up and an operational amplifier as an integrator whose folding frequency is 0.1 Hz. All instruments set on a concrete foundation embedded in Kwanto Roam Layer with approximately 4 meter thickness. The size of the foundation is 1 meter cubic. Data were recorded in a data recorder triggered by a starter whose sensitivity is 0.5 gal in horizontal acceleration. Vibration characteristics of each earthquake are very variable as shown in Fig. 1. It is mainly depending on their nest, however, even from almost same epicenter area, they are very much different observed in the power spectral densities in (a), (b) and (c) in Fig. 1. The epicenters of earthquakes #812 and #862 are located in south-western part of Ibaragi-pref. and #864 is in southern part of the same prefecture. The distance between two areas is only 40 km. In Fig. 2, the ratio of peak of 0.40 Hz to the maximum peak on each earthquake makes a histogram. Their distribution is not uniform, however, the number of data is not enough to say what type of distribution is.

The relation between magnitude M and ground displacement in single amplitude Dg is shown in Fig. 3. If we decide the mean straight line only from the data, it becomes a solid line in the figure. If we consider on the data of three major earthquakes M = 7.9, 7.2 and 7.4, then the mean straight line will go up like a broken line. The author does not pay much attention on focal distance of each earthquake, because the decay constant of displacement waves is smaller than that of acceleration waves. Some data observed in Chiba show the relation of displacement to magnitude and epicenter distance in Fig. 4. Then he eliminates only three data marked X, the focal distance of those are over 200 km to decide the relation in Fig. 3. The reason why the solid line is more moderate is coming from the lack of data which are exceeding several mili-meters because of over scaling.

CONCLUDING REMARKS FOR THIS SECTION: The anti-earthquake design of storages, which have a free surface of liquid in it, depends on the design basis ground displacement rather than on the design basis ground acceleration. And it may be true for some high-rise flexible buildings. Even in a particular site, vibration characteristics of each earthquake are much different. The distribution of response factors is spread shown in Fig. 5. It comes from the fluctuation of vibration characteristics.

Duration of recording is also important. Usually the displacement record reaches to the maximum amplitude at 60 ∿ 90 seconds after triggering, while the acceleration record decays within a minute. And, sometimes it keeps such level more than ten minutes. So for this purpose the duration of recording should be over three minutes according to the author's experience.

TORSIONAL GROUND MOTIONS

EXPLANATION: If there are torsional component of ground motion, then the method of response analysis of structures should be changed. The authors have been observing torsional ground motions[5)] since 1972, using several moving coil type pick-ups which were designed by Furukawa, Chuo University. Nearly one hundred records have been obtained. The authors found some unexpected relation between the maximum horizontal acceleration α_{max} and the maximum torsional velocity τ_{max} that is $\tau_{max} \propto \alpha_{max}^2$ (in Fig. 6). If this be true, the effect of torsional ground motions would be more significant than that of ordinary horizontal accelerations for the design of light damped symmetric structures such as spherical tanks, high-rise steel buildings. The following five mechanisms are considered to obtain such torsional motion records.

i) cross-talk of instrument itself, especially between horizontal acceleration and torsional velocity

ii) dynamic behavior of the foundation supported with soil springs

iii) local effect of adjacent structures

iv) some effect of irregularity of strata and geographical configuration

v) torsional component of shear waves in uniform half-space continuous media.

All possibilities are considered at this moment, and the further study should be developed, especially under the cooperation of seismologists.

DATA AND RESULT OF ANALYSIS: As already mentioned, one of the feature obtained is the relation between the maximum horizontal acceleration α_{max} and the maximum torsional velocity τ_{max} as shown in Fig. 6. The order of torsional velocity is 10^{-5} rad/sec, that is, [mrad/sec]. The maximum record is 0.8 mrad/sec, while NS component of horizontal ground motions showed 30 gal. From 19 records the relation of Fig. 6 were obtained and its gradient can be said to be exactly 1/2. The data show some scattering, however, standard deviation are 1.29/0.775 under log-normal distribution, and such scattering is observed on other observation results on ground motions.

Cross-talk terms between horizontal acceleration components and torsional component depends on pick-ups. This means that the control of their production is not so well, however, most of them is the order of 0.5 mrad/sec per 10 gal. Also a peak is observed at 25 $\sim$ 30 Hz. According to the Fourier analysis of four components (in Fig. 7), in the frequency range up to 7 Hz, these four components possess common peaks in PSD. On the other hand, in the range more than 15 Hz, we can not observe any component in both horizontal components. The acceleration pick-ups are very wide range one, and almost flat up to 100 Hz, so he understands that the peaks of PSD of torsional ground motions higher than 11 Hz might be its own.

The absolute angles of such torsional velocity records are the order of 1 $\sim$ 15 $\times$ 10^{-6} rad. These values are obtained by integrating an analog integrator whose folding frequency is 0.2 Hz. The torsion of 10^{-5} rad means that 10 mm differential movement at two points 1 km apart from each other. It is very small angle, however, 0.8 mrad/sec at 20 Hz corresponds to almost 10 gal difference at two points 1 m apart. A response spectrum of such torsional waves has a similar shape to that of horizontal acceleration waves. In Fig. 8, two sets of curves show the difference of them. In this case those of torsional waves are more dominant in higher frequency range and less in lower frequency range.

CONCLUDING REMARKS IN THIS SECTION: The authors have not identify the mechanism of torsional motion from the five conceivable ones. If the relation of the square be true, the maximum torsional velocity would be 160 mrad/sec in the case of an earthquake of 300 gal in horizontal acceleration. This value of torsional motion has stronger effect on a symmetrical structure, for example, in a case of a structure whose radius of gyration is 5 m, then torsional response torque at the basement is almost 100 times compare to a unbalanced structure whose weight is the same and eccentricity is 5 m.

THREE-DIMENSIONAL GROUND MOTIONS AND THE RESPONSE

SIGNIFICANCE OF THREE-DIMENSIONAL GROUND MOTIONS TO RESPONSE ANALYSIS OF STRUCTURES: Three-dimensional response analysis of ordinary buildings may be less significant to those of industrial facilities. In the case of industrial facilities, the mechanisms of the three-dimensional response can be categorized into the following three items;

i) linear response of three-dimensional structure whose flexibilities to each direction are almost same, for example, piping system.

ii) stability of structure obtained by the gravity force, for example, over-turning of non-anchored block or pile of graphite bricks in a nuclear reactor core, and other rocking phenomenon.

iii) sloshing problems of free liquid surface.

Additionally, for equipment and vessels mounted on a flexible floor of the building, the response of such floor is also important, however, this analysis can be made separately to two other components usually.

According to the authors, observation results, the vibration characteristics of a vertical component have not much different than horizontal components. The response factor to the flexible system like pipings has large value and is scattered as shown in Fig. 9. Also sliding of non-anchored structure is a very important problem for the anti-earthquake design of industrial facilities as well as those of embankments and slopes.

DATA AND RESULT OF ANALYSIS: The model plant in the Chiba Field Station consists of a complex, shown in Fig. 10, and two cylindrical tanks, both 4 m in diameter. The site area has a very high seismic activity. We usually expect analizable earthquakes, that is more than 1 gal on the ground surface twice a month. However, the maximum value of the horizontal acceleration is 40.6 gal and most of them were less than 10 gal. Although a strong motion recorder SMAC-Q (Akashi) is also mounted on the same block, it operated only several times, the difference of both reading values were usually less than 10%.

The ratio of the maximum vertical acceleration to that of horizontal accelerations is the most important point for the design criteria. In some areas of Japan, the higher acceleration values in the vertical component are observed rather frequently. The records obtained at the place near to the source may be direct reflection of source mechanism, therefore, if the fault movement is near to vertical movement, vertical records near to the fault may be dominant. In the author's case, this tendency is not clear as shown in Fig. 11. Marks, which have no area such as ×, †, Λ, ---, show nearfield earthquakes whose epicenter distance is less than 50 km. We can find no difference between two categories of earthquakes. The gradient of line is 0.881, this means the vertical ground acceleration is not exactly proportional to the horizontal ground acceleration. However, the standard deviation is 1.34/0.746, therefore the relation above-mentioned has not established exactly. The ratio of the vertical ground acceleration to the horizontal one is 0.453, that is, almost 1/2 as usually said. Although the authors expected a some difference between near-field earthquakes and others, they could not find it.

Analysis on the principal axes of ground motions are done. This idea was presented by Penzien and Watabe in 1975.[6] There might be several way, and the author calculated the principal axes of the covariance function matrix at $\tau = 0$. Fig. 12 shows notations on the direction of one of the principal axes. Usually the third axis, whose value is the smallest, is considered as P-wave component in almost all period. So, if ψ_3 is nearly zero, then the vertical component consists from mainly P-wave component. The authors made this analysis on the data at the Tukuba Station, National Disaster Prevention Center in Ibaragi-pref. mainly, and some other famous historical records and Chiba's ones. One of the example at Tukuba, shown in Fig. 13, clearly shows the tendency of $\psi_3 \doteqdot 0$. This case is a near-field earthquake. The maximum value of the third principal component value σ_3 of this earthquake is almost one half to other two components at the surface as shown in Fig. 14. However, in a deep well the third component σ_3, which was defined as the corresponding component of σ_3 at the surface, was not the smallest as shown in Fig. 15. In the case of offshore earthquakes near to the area above-mentioned, the third component σ_3 usually less than one third of other components as shown in Fig. 16. Some data are summarized in Table 1. The ratio of vertical component to vector sum of horizontal components is between 1/2 and 1/3. Direct ratio of the maximum reading values is larger than the ratio of the principal values $\sigma_3 / \sqrt{\sigma_1^2 + \sigma_2^2}$. In a well of GL-40, the third component is more than one half sometimes as observed in Table 1. It is a problem to be solved which type of such ratio is significant for the design criteria.

Some earthquakes make several peaks on principal values and ψ_3 run up to a certain angle like the result of Kern County earthquake-1952 in Fig. 17. Some other earthquakes observed in the Chiba Field Station have very distinct peaks. It seems to be that such peaks are the result of successive shocks.

We have many examples of sliding phenomena of non-anchored very heavy equipment during strong earthquakes. The authors observed sliding of 5000 KL 80%-full oil storage slided to sideway about 15 cm in Tokachi-oki earthquake-1968. And also he observed three package boilers slided more than one meter in Olive View Hospital in San Fernando earthquake-1971. According to experiment on a shaking table, the existence of vertical ground motion, especially higher frequency components, is very significant. An experimental result on a small oil storage model is shown in Fig. 18.

SOME PROBLEMS IN RESPONSE ANALYSIS FOR DESIGN: The authors like to mention the following two problems. One is unexpected failure of equipment as observed in San Fernando earthquake-1971. The other is abnormally high response factors observed in Chiba Field Station.

As the authors described in the previous section, three package boilers moved more than one meter. Also three sets of motor and pump were failed. Especially two of the motors were broken at anchor bolts and also coupling to pumps. One motor was kicked off from its foundation. It has never been clear the failure mechanism. A specialist of aero-space dynamics and fracture said that it might be force momentum fracture, if the maximum velocity exceeded 100 kine. The value of the maximum velocity is sometimes more important for the criteria of such mode of fracture.

An example of abnormally high response factor is shown in Fig. 19. This is data observed on a tank hanged by four rods and supported by spring-type vibration eliminators. Some statistical data of response factors of the several models are shown in Table 2. According to Fourier analysis of each record, they have many peaks in PSD as shown in Fig. 7. For example, the hanged tank of the case of Fig. 19 has the eigen-frequency of 4.73 Hz, and the dominant peak of 4.71 Hz appears very often. The authors estimate such abnormal response factors come from a pseudo-resonance phenomenon.

CONCLUDING REMARKS: Wide dynamic range, and also wide frequency range are necessary to obtain enough informations for the analyses which the authors discussed in the previous several sections. The authors are using a force-balance type pick-ups for acceleration measurement. The frequency range of such pick-ups is spreading from DC to 100 Hz. The problem of wide dynamic range has a some difficulty. He has not solved yet. Wide dynamic range A-D converter, more than six digits, may be available, so the numerical recording might be one idea. And anothers are the use of a logarithmic amplifier.

On the other hand an idea to obtain the broader frequency range is describing the ground motions by a state vector, such as (*displacement, acceleration*). This method also brings the wider dynamic range in general. This idea originally comes from a way of controlling a hydro-dynamic shaking table.

For the analysis of huge structures like nuclear power plant buildings, a common-bed type foundation of petro-chemical industries, very large oil storages, the multi-pick-up system may be necessary to decide the effective ground motions. This has never studied from such a view point.

ACKNOWLEDGEMENT

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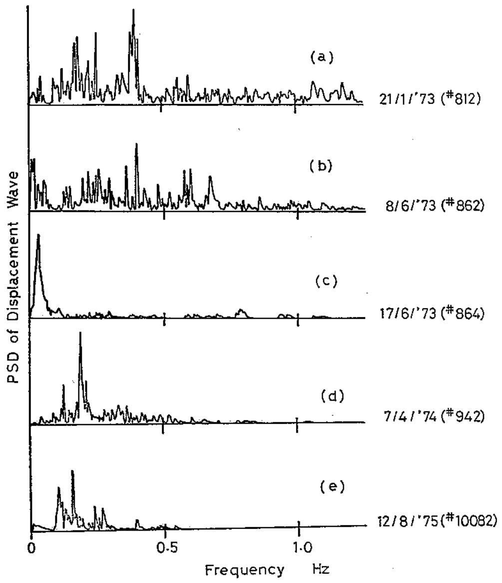


Fig. 1

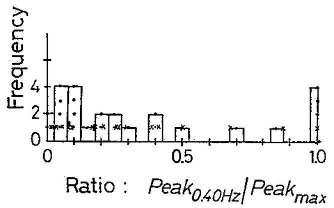


Fig. 2

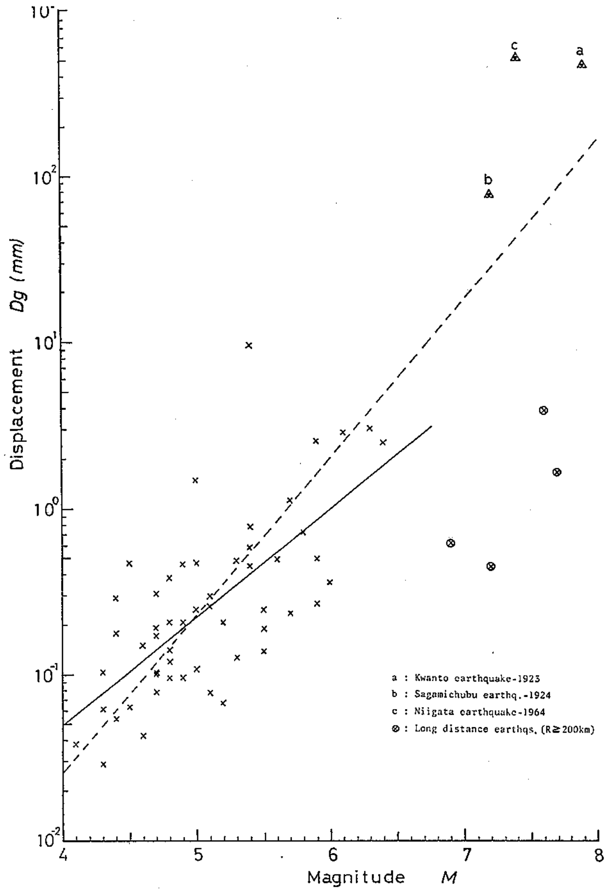


Fig. 3

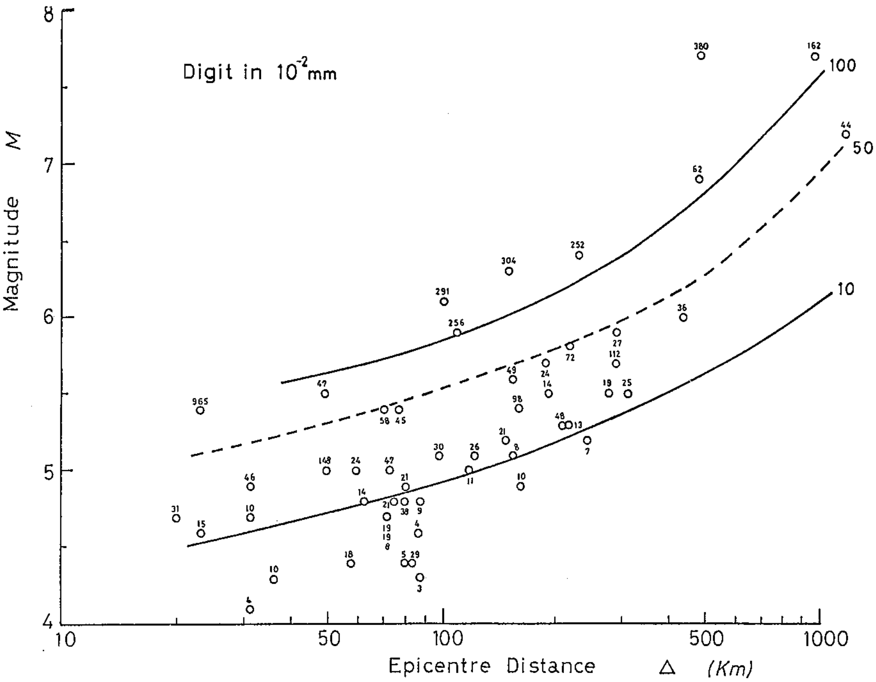

Digit in 10⁻²mm
Magnitude M
Epicentre Distance Δ (Km)
100
50
10

Fig. 4

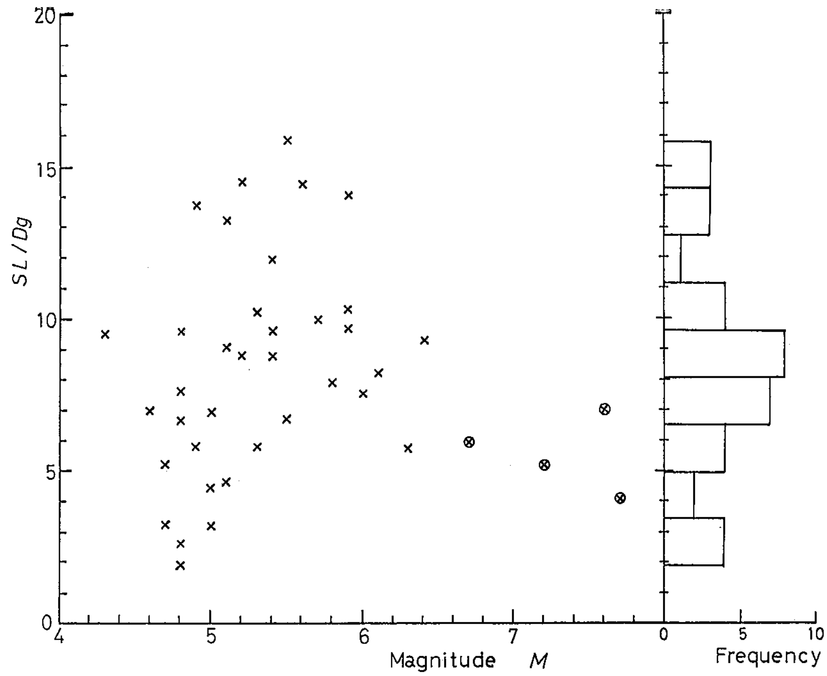
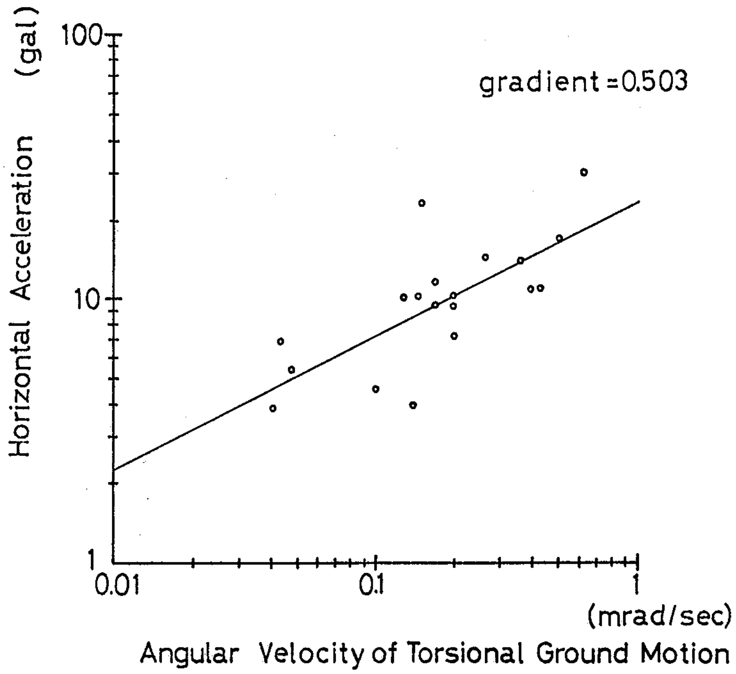
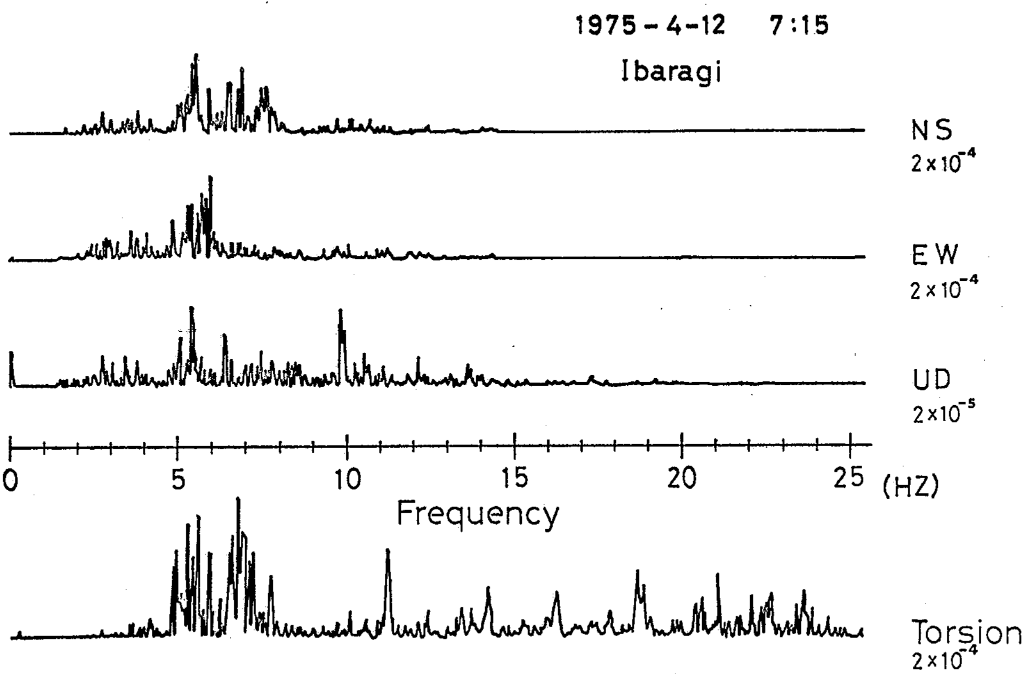

SL / Dg
Magnitude M
Frequency

Fig. 5



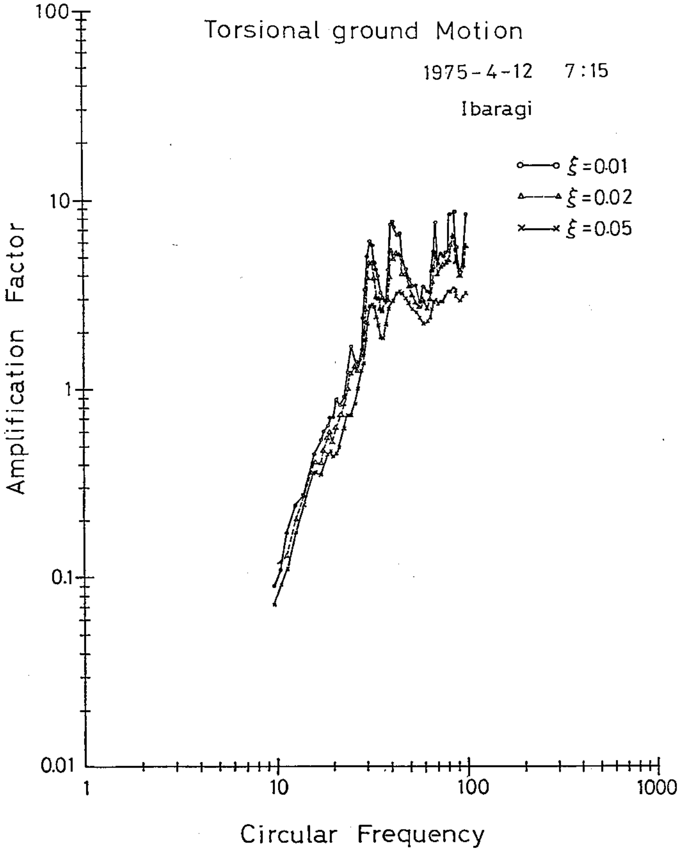
100
10
1
Horizontal Acceleration (gal)
gradient =0.503
0.01
0.1
1
(mrad/sec)
Angular Velocity of Torsional Ground Motion

Fig. 6



1975-4-12 7:15
Ibaragi
NS
2×10⁻⁴
EW
2×10⁻⁴
UD
2×10⁻⁵
0
5
10
15
20
25
(HZ)
Frequency
Torsion
2×10⁻⁴

Fig. 7


Torsional ground Motion
1975-4-12 7:15
Ibaragi
ξ=0.01
ξ=0.02
ξ=0.05
Amplification Factor
Circular Frequency
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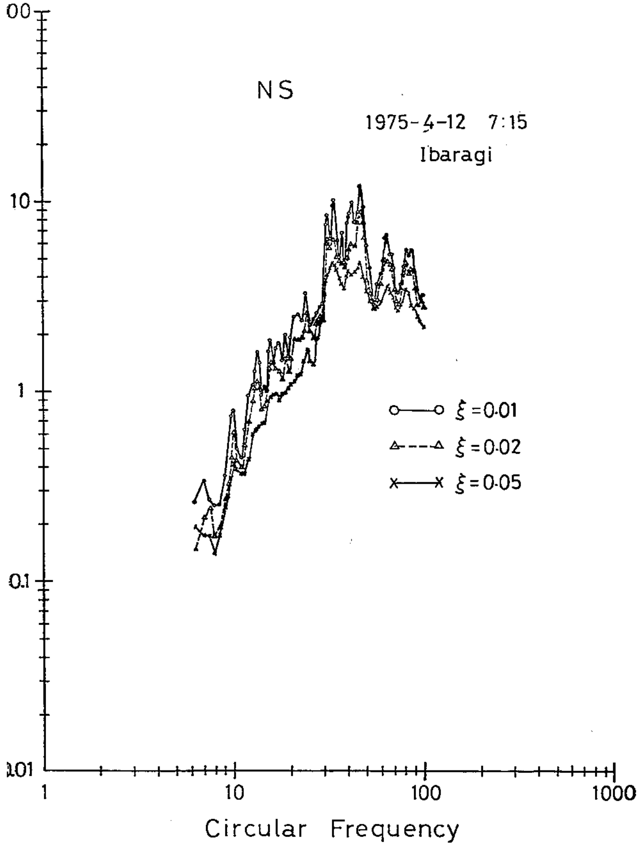
10
1
0.1
0.01
1
10
100
1000

Fig. 8(A)


NS
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Ibaragi
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10
100
1000

Fig. 8(B)

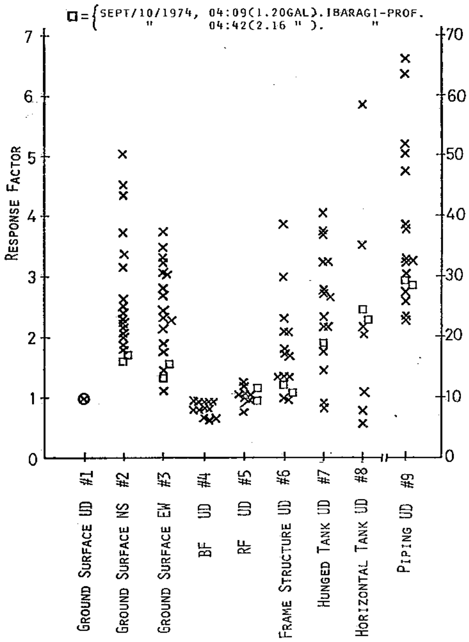

Fig. 9

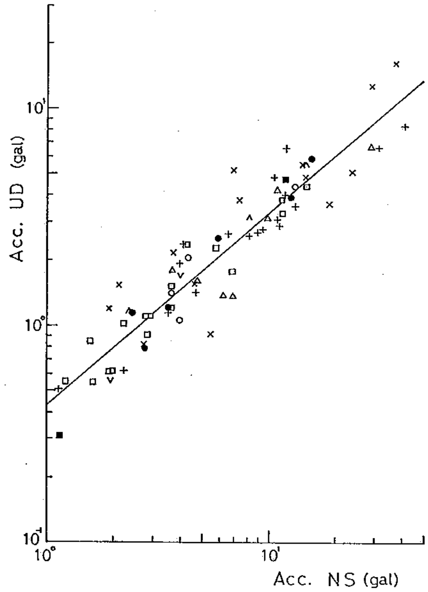

Fig. 11

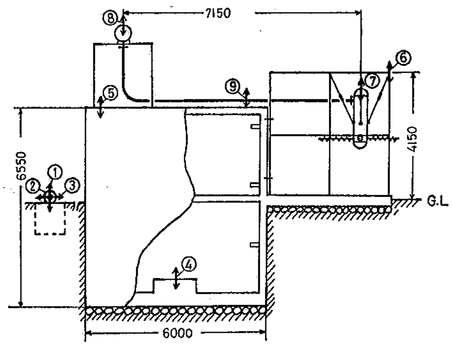

Fig. 10

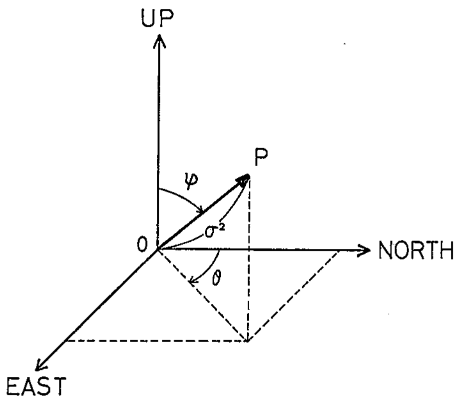

Fig. 12

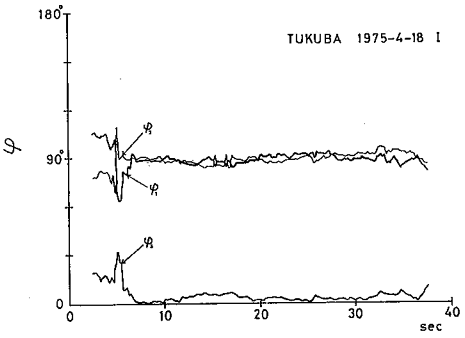

Fig. 13

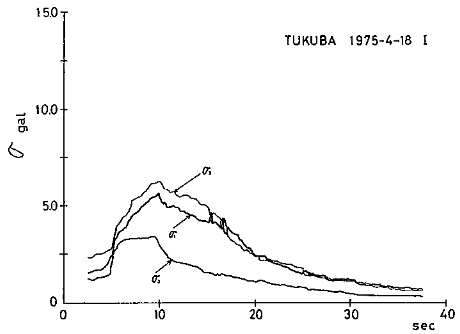

Fig. 14

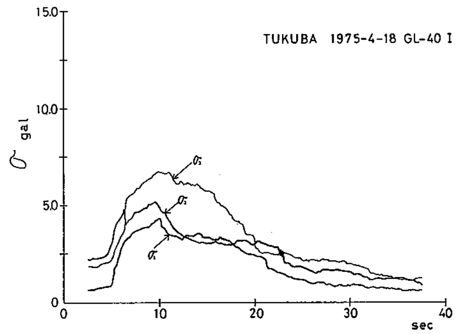

Fig. 15

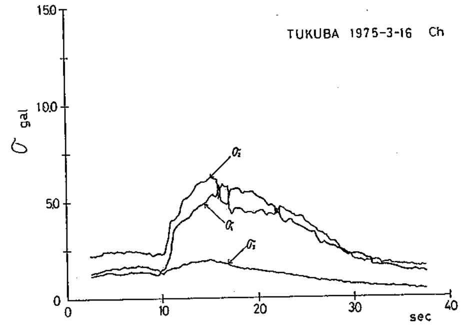

Fig. 16

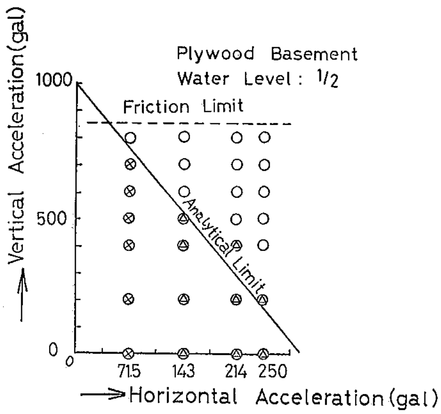

Fig. 18

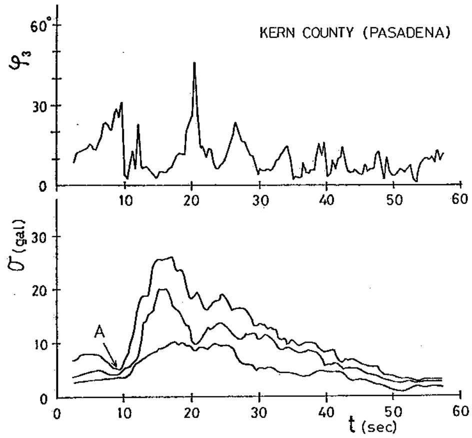

Fig. 17

Table 1. Comparison of Vertical Component to Horizontal Components

Earthqs.	Date	$\sigma_3 / \sqrt{\sigma_1^2 + \sigma_3^2}$	UD / $\sqrt{(EW)^2 + (NS)^2}$
Chiba #1	'75-4-12	0.144	0.131
#2	'75-4-12	0.251	0.280
Tukuba #1	'75-3-30	0.340	0.385
(Surface) #2	'75-4-18	0.387	0.496
#3	'75-2-08	0.347	0.389
#4	'75-3-16	0.229	0.246
Tukuba #2	'75-4-18	0.996	0.668
(GL-40) #4	'75-3-16	0.657	0.702

Table 2. Response Factor and Statistics

[ ] Abnormal Data are Omitted

	Hanged Tank (HT)	Pipings (P)	Saddle-type Tank (PT)	Self-standing Tank (VT)
Number of Data	77	57	58	58
Mean	16.97 [15.01]	22.86	5.87	1.344
Dispersion Factor	0.492 [0.262]	0.345	0.538	0.248
Upper Bound Value of 3σ	41.0	46.4	15.6	2.34
Maximum Value of Data	69.0	166	14.7	2.98
Eigen Frequency	4.73	7.59 [5.50]	4.72 6.38	----
Damping Ratio (%)	3	2,(1)	2, 1	----