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Stochastic model for response of slightly damped system obtained by long-term field observation

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ABSTRACT: This paper deals with the stochastic model for responses of slightly damped systems obtained by the observation project which has been done since 1972 in the Chiba Field Station, Institute of Industrial Science, University of Tokyo. This project aimes to clarify the behavior of equipment and piping systems, which are using in critical facilities such as nuclear power plants, petro-chemical engineering plants. In 1973 at 5WCEE, the authors presented their first report on the fluctuation of response factors of such systems obtained by the observation in the field station with results obtained by theoretical analysis and simulation. After several year observation, the authors found that some responses to particular earthquakes easily exceeded the 3σ range of other responses in their response factors, and also that the distribution form was changed year by year, it was not simple as one normal distribution. They tried to find the cause of their fluctuation. By the data obtained through the twenty year observation, they conclude that the stochastic model itself has been fluctuated.

1 INTRODUCTION

The authors have been interested in the stochastic characteristics of the response of slightly damped equipment and pipings for the safety analysis of nuclear power plants and other critical industrial facilities since 1969. At the 4th WCEE in Santiago de Chile in 1969, there were several papers which referred to a stochastic model and pseudo-earthquake ground motions generated from white noise type signal. The authors had observed high frequency resolution acceleration time history since 1962, but they had never successed to get good data by that time. And they noticed that it was a key to study on the responses of a piping bridged on two independent structures to pseudo-earthquakes by using an analog computer, and they noticed that the fluctuation of its response factors is significant for their design and safety evaluation(1)(2). Soon after this finding, Shimizu, one of the authors' group, tried to develop the method for theoretical analysis on the magnitude of the fluctuation. Therefore, the authors were started the project for the field observation on response factors of slightly damped elements of a chemical engineering complex model to natural earthquakes. The purpose was, of course, to obtain the data of response factors to evaluate the stochastic characteristics of them and to establish its stochastic model.

This project was planned to construct the complex model in Chiba-jikkenjo, so called, Chiba Field Station, Institute of Industrial Science, University of Tokyo, by the Grant of the Ministry of Education and Science, in 1969 and 70. They successfully developed this project, and they could obtained various fruits. And the project was developed to the "Engineering Array and Weakly Designed Structure Model Project" by the Earthquake Resistant Structure Research Group, so-called ERS, of the Institute in 1978. Also in 1978, there was an informal meeting for Seismic Probabilistic Risk Study was held in Berlin(3) in relation to the problem of Diablo Canyon Nuclear Power Station, California, U.S.A., and also the first phase of Seismic Safety Margin Research Project had been started. For these, the data obtained by the authors could gave some contributions, especially through the discussions on their paper(4) presented at the 3rd Conference on Structural Mechanics in Reactor Technology in 1975. Through such discussions, they could get the concept that the coefficient of variation is ranged 30 ∿ 50% in the dynamic response characteristics of structures. However, some data showed abnormally high response factors compare to the above stochastic model, and they reported this finding at the ASME PV&P Conf. in 1980 as Ref.[5]. This is one of starting points of this paper.

2 THE HISTORY OF MODEL STATION

In 1960, the draft of the Standard Aseismic Design Practice of Nuclear Power Plants(6)(7) in Japan had been completed as a part of the Safety Guideline. The dynamic design of primary coolant piping system was employed in it. For the dynamic response analysis of the piping systems, their dynamic characteristics and the design basis ground spectra or time history was necessary. The authors developed DYNAPS for its eigen-value analysis, and observed its damping coefficient at several conventional steam power plants(7). However, there were only several strong motion records observed by SMAC whose fold frequency was only 7.0Hz and displacement records. He tried to observed acceleration records which contained the higher frequency components up to at least 30Hz or 50Hz. In 1966, through the field survey on Matsushiro Earthquake Swam, Sato and Suzuki, members of the authors group observed the ground motions whose components were up to 70Hz during their field survey by using a force balance type acceleration pickups.

In 1970, the model plants of chemical engineering plants, which consisted of pipings, vessels, steel structures and a reinforced concrete building (Fig. 1) was completed in Chiba Field Station, University of Tokyo, approximately 50 km East of Tokyo. Fortunately our field station is located in a very high seismicity area in Japan. Since 1971, the authors have been continued the observation by now.

3 BRIEF EXPLANATION OF THE MODEL

The authors have never reported on the model in details. This model was planned to observe the response of typical elements of which a petro-chemical engineering plant or a nuclear power plant. In 1971, the first section has been built. It consisted of a hanged tank, a rigid tower type tank, a horizontal tank on a top of a structure and pipings with a reinforced concrete building embedded in soil with a 1 m^3 concrete block for recording free field ground motions. The Chiba Field Station is located approximately 50 km East from Tokyo, and on the way to Narita New Tokyo International Airport. It is near to the triple point consists from Pacific Ocean Plate, Southern Sea (Philippine Sea) Plate and Eurasian Plate, and near to three active nests. We usually feel one earthquake par week and twenty earthquakes are analyzable in each year in average.

The surface of the ground covered by 4 m thick Kwanto Loam stratum and then 4 m five sand stratum with thin volcanic clay layer. It is an area of a top of typical flat hills faced to Tokyo Bay, and it is approximately 1 km from the former coast cliff (Fig. 2). Seismicity of the area is very high as described in the previous section. A heavy wall tank, and a thin wall tank, a rectangular FRP tank had been build step by step to observe the response of a liquid storage tank and to establish the design practice. The thin wall tank was experienced the elephant foot-type bulging failure at the earthquake in Sept. 1980. The mechanism was reported in Ref.[8]. Additionally several other items of ground motions had been observed, that is, long period displacement motions for the design of sloshing phenomenon of liquid storage and torsional ground motions, and those results were summarized in Ref.[9].

The recording system was designed in 1969, therefore, all data are analog type, and recorded by oscilloscope on photographic paper. Afterwards, they were recorded by the analog type magnetic recorders. These equipment are triggered by two acceleration pickup on the concrete block to record the free field ground motions. The trigger level was adjusted in approximately 1.0 gal in horizontal. Such a low value was selected to catch the data as early as possible from the start of ground motions, because the authors hadn't any advanced recording system as it is very popular now. Also, the setting level of all recording devices was adjusted to 2 ∿ 10 gal in the peak horizontal ground motion to obtain analyzable data as much as possible, except SMAC Q-2, the Strong Motion Recorder for high frequency range. As the result, most of response records to more than 30 gal ZPGA were scale overed. Such earthquakes were observed once for one or two years in average. An automatic gain changer was not employed to avoid the disturbance of records by switching. On the other hand, the program to extrapolate the over scaled time history was used in some cases.

The dynamic characteristics of main items observed in 1972 were shown in Table 1. The authors check those values in this occasion (1992), and observed some changes. Most unexpected one is the lowering of damping ratio of the hanged tank from 3% to 0.9%. The authors hasn't evaluated the effect of this change to the stochastic distribution which is the subject of this paper.

4 SUMMARY OF DATA

The number of data, obtained last twenty years, is more than four hundred. Among these data, approximately 250 data are analyzable as shown in Table 1 and others. The peak ground accelerations on the free surface was reached to 350 gal. And several earthquakes were over MMI Intensity VI and two earthquakes exceeded 100 gal as in Table 2. Most of responses of the model structures were elastic range, but one buckling of 60 m^3 thin wall cylindrical tank model was observed(7). Typical wave forms are shown in Fig. 3, and data were recorded mainly the peak response values and response factors with other data.

One of the strongest earthquakes observed in the field station is Off-Boso Peninsula Earthquake in 12/17/1987. In the industrial area in Boso Peninsula, east of Tokyo Bay, various troubles were reported as the authors discussed in Ref.[10], and the peak ground acceleration was up to 600 gal, and two persons were killed. At the ground surface, 365 gal NS, 266 gal EW and 111 UD were recorded by SMAC Q-2 in Field Station. However, almost no significant damage was observed in this area. Some Japanese style porcelain coverings on roof of wooden structures jumped and slipped from their original position. And one steel wire to hang the cables for the authors' measuring system was broken, but some of its threads were rusted before the event. Anyway, no damage of all structures was observed in the area of Kwanto Loam, high acceleration up to 300 gal. However, if the value exceeded 400 gal some damage had been observed, and no collapsing of any building was reported.

We found that the fluctuation of response factors of the hanged tank was large, and didn't meet a usual stochastic distribution model as reported at US-South Asia Symposium on Eng'g. for Natural Hazard in 1977(11) and also in Ref.[5] in 1980, as shown in Fig. 4 from recent data. Since in 4WCEE, Santiago de Chile, in 1969, there were various reports on stochastic nature of response and pseudo-earthquake produced from Gaussian White noise has been used. And the authors recognized that the response fluctuation had been most significant for the seismic design of nuclear power plants in relation to their safety. Now, Seismic Probabilistic Risk (Safety) Study is one of the significant key issues for them, even though they assumed Gaussian-based distribution for this study as other studies. With their two year observation, the authors found that this assumption was doubtful in some cases, and they reported in their papers(5)(11).

They tried to study this subject with Okamura and Sakai, who have been specialized in Strength of Material and Stochastic Risk Analysis. They discussed and found that the distribution of response factors might be a log-normal distribution, and they presented this result in the papers(12)(13) with the authors.

5 THE PREVIOUS DISCUSSIONS

In the previous papers by the authors' group, which have been presented since 1972, there were 6 major points on the fluctuation of response factors of a slightly damped system as follows:

i) we should expect the fluctuation by the sampling effect, even if they belong to the same family.

ii) the result above-mentioned can be obtained by a stochastic theory and a simulation.

iii) the results obtained by the field observation at Chiba Field Station showed more fluctuation, and some values were abnormally high (in Fig. 4).

iv) it is difficult to explain these values by the difference of seismic sources, that is, the nests of earthquakes which could be divided into five major areas in the authors' case.

v) even ground motions from the same nest may give the large fluctuation in some cases.

vi) in the case, where the response factor was abnormally high, the wave form was either beating sinusoidal or pseudo-sinusoidal.

The authors have been tried to clarify their correlations to the regions of focus, magnitude, depth and so on, but it is difficult to conclude these relations(9). It should be mentioned that they have never discussed on the change of values caused by the nonlinear effect of the system in the previous reports which contains in the points above-mentioned and other such correlations. The system, whose responses have been mostly discussed, is the hanged tank, and it is connected with two parallel pipings and supported by four rods and four nonlinear springs so called, a vibration eliminator (Fig. 1).

There are two viewpoints to discuss on such fluctuations. The first one is that various factors should be considered as one stochastic model without discussing on the detailed mechanisms which may cause the fluctuation of response factors. The second one is, of course, that the mechanisms, which are bringing various response factors, should be clarified, and this is the study on the seismic response. The authors took mainly the first point in this study, even though they tried to analyze the mechanisms of inducing some abnormally high responses. The purpose of the response analysis is to predict the dynamic behavior of the structure for its design. There are many uncertainties on future earthquakes which may relate to the actual behavior of the structure which we concern. To know the adequacy of the behavior of the structure after the event, the highly sophisticated analysis may be necessary, but for the design, it is difficult to overcome such uncertainties at the design stage.

In this view point, the work which has been done is emphasized to overcome those uncertainties according to the design practice. Back to the abnormally high response factors which were observed in Chiba Field Station, the authors examined their stochastic distribution, and the relation to the ratio of the peak of the power spectral density at the eigen-frequency of the model tank to the total power. Those results couldn't clarify the mechanism of their fluctuation for the design analysis.

6 THE STOCHASTIC DISTRIBUTION

From 77 response factors, the authors discussed their distribution, and Okamura, one of co-author pointed out that its distribution might be a log-normal distribution in Ref.[12 and 13] with the authors. Starting from this, the authors tried to examine the distribution of response factors of several structures in Chiba Field Station. This study has been done the χ^2 testing to check the assumptions that the distribution would be normal distribution and log-normal distribution, and α is the risk for rejecting these assumptions. For the usual test α=0.05 or 0.10 is employed, and only checking the larger or smaller to these criteria to verify the adequacy of the assumption. The calculation was made with the following equation and numerical integration.

$$\alpha = P(\chi^2 > \chi_0^2) = \int_{\chi_\alpha^2}^{\infty} f_\phi \ (\chi^2) d\chi^2 \qquad (1)$$

where Φ is the degree of freedom, and divided by Starjes relation as Eq.(2) according to the number data. The degrees of freedom of divided data for each two years were decided based on the average number.

$$C = 1+3.32 \ \log_{10} n \qquad (2)$$

where C is the number of classes of the histogram, and $f_\phi(\chi^2)$ is obtained from the computer library.

To compare the result of numerical analysis on α, -log α is employed in the figure. If the value α is small, the distribution is quite different from normal or log-normal distribution, and the curve is going up in the figure.

Through the data on response factors of the hanged tank (NS and UD), the supporting structure (NS and UD), pipings (UD), the distributions of responses to earthquakes in early 1970's and several years around 1985 are far from the normal or log-normal distribution. Some examples are shown in Table 3 and Figs. 5(a) ∿ (e). As far as NS component, four peaks are observed in Figs. 5(a) and (b), this means, the distributions of the hanged tank and the supporting structure are off-normal four times for these twenty years, 1971 ∿ 90. On the other hand, UD Components have three peaks, and they shifted from the above four peaks. Therefore, it might be said that the changes of distributions of the horizontal component and the vertical component are independent. For the χ^2 testing, α=0.1 is the one criteria, and according to our results shown in Figs. 5(a) ∿ (d), those of some years, especially, early 1970's were off-normal distribution in general.

Broken line in Fig. 5(a) shows the result by employ the degree of freedom fitting to the individual number of data of every two years. The tendency is the same, but the details are different according to the selection of the degree of the freedom.

These results may be related to the activity of local seismic nests surrounding the Field Stations, and the authors' new finding but its mechanism hasn't been clarified. Also the authors examined the relation of the distribution to the regions of nests, and it is clear that earthquakes in two regions which may have some relation to local techtonics, or the wave path as shown in Table 4. The numbering of the regions in Table 4 is quoted from Fig. 2.

7 RELATION OF RESPONSE FACTOR TO RESPONSE SPECTRUM

We usually expect that an earthquake, which brought higher response factor, shows the higher response spectrum. According to response analysis by using a single degree of freedom system, the relation of the response factor which observed in the Field station to the ordinary response spectrum is not clear. As mentioned in a previous paper(5), the relation of local peak hights of the power spectral density (PSD) at the eigen-frequency is not correlated to the response factors actually observed. However, PSD of some earthquakes, which brought higher response factors to the hanged tank, have a fat peak, whose hight is not the highest, near to the eigen-frequency, 4.73Hz, of the hanged tank as shown the example in Fig. 6. The response spectrum (Fig. 7) of this earthquake, (11/12/1980, H=60 km, East coast of Boso-Pen.) has the second peak at T=0.211 sec (f=4.73Hz) but the value is considerably low to the actual response factor 28.2. The ground motions is shown in Fig. 8. In some other cases, the response spectrum is not so correlated to response factor well.

Once, Professor Kanai mentioned that an earthquake, which had a lot of punch in its motions, has (a) wide, fat peak(s) in its response spectrum. This feeling may be observed in the above-mentioned fact. As the authors mentioned in Chapter 4, beating sinusoidal waves or pseudo-sinusoidal waves, like obtained from random single by a filter, was dominant when the abnormally high response factor was observed, and these waves may have a diffused peak in PSD. In Fig. 6, this can be observed. But it should be mentioned that it is not clear how such waves of ground motions were induced in some particular cases from particular seismic nests.

8 CONCLUDING REMARKS AND ACKNOWLEDGEMENT

The estimation of response of a slightly damped structure is significant to its anti-earthquake design. However, there are many uncertainties, which have not known as their dynamic mechanism. To cover such uncertainties, we generally introduce a stochastic model. In this paper, the authors try to mention that the modeling in this sense has still some difficulty based on the data which have been obtained by their field works on the chemical engineering complex for more than twenty years.

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The authors like to express their gratitude for their supports. Mr. Otsuki designed the model in 1970 as the former technical assistant, and Dr. Sone, Kyoto Inst. of Technology, and other former graduate students were working for this project. The authors also express their gratitude for their cooperations.

Some part of original data were published, but it has never been distributed, therefore the authors hope to publish all data in the near future.

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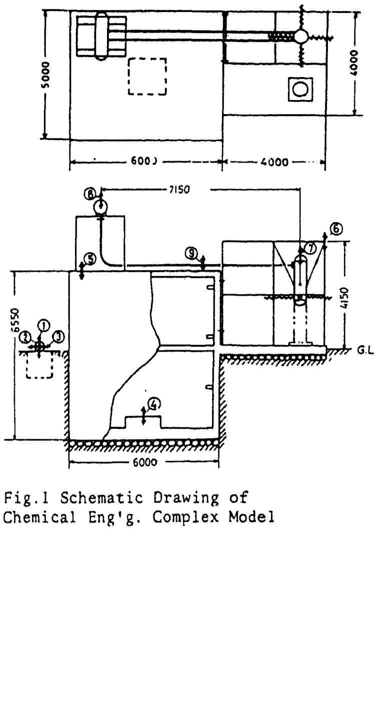


Fig.1 Schematic Drawing of Chemical Eng'g. Complex Model

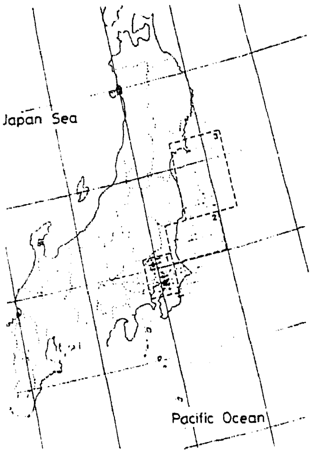


Fig.2 Map of Eastern Japan, Location of Field Station and Epi-Center Distribution and Areas

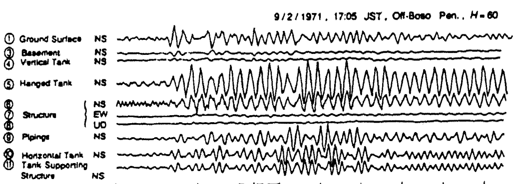


Fig.3 An Example of Recorded Chart of Responses and Ground Motions

Table 1 List of Items for Response Observation and Major Data

Item and Point	Hanged Tank (HT) NS	Hanged Tank (HT) UD	Structure NS	Structure UD	Pipings UD	Basement NS
Number of Data	271	158	230	140	185	225
Mean Resp. Factor	15.79	2.98	5.80	1.508	35.01	0.735
Standard Deviation Dispersion Factor	6.81 0.43	1.217 0.41	2.43 0.42	0.47 0.31	12.64 0.36	0.123 0.17
Upper Bound Value (+1σ)	36.3	6.63	11.1	2.92	72.9	1.094(+) 0.366(-)
Maximum Value of Data	69.0	10.3	20.4	3.88	79.9	1.48(+) 0.36(-)
Eigen-Frequency	4.73	16.67	21.2 13.7	24.0	11.42 10.93 5.50	---
Damping Ratio	1 (0.9)	---	0.5 2	---	0.1 0.2 1	---
α_N	0.017	0.551	0.013	0.006	0.138	0.330
Skewness	2.53	1.812	1.866	1.696	0.580	0.870

Table 2 Major Earthquakes Observed in the Period

Date	Time	Location	M	SMAC Q-II (gal) NS	EW	UD
9/25/1980	02:40	Mid-Boso Pen.	6.1	90.2	82.0	31.1
12/17/1987	11:08	Off-Boso Pen.	6.7	365	266	111

Table 3 An Example of Annual Change of Stochastic Values of Response Factor

Year	Number of Data N	Average Response Factor λ	Standard dev. σ	χ^2	Degree of Freedom	Risk for Rejecting Assumption α	Skewness	Average Acc. (gal)
'71~'90	271	15.79001 1.16604 14.65694	6.82806 0.16356 21.35926 10.05775	15.409 49.454	6 6	0.017 *	2.525	7.244
'71~'72	37	15.91930 1.18011 15.13941	5.20722 0.13849 20.82550 11.00582	1.503 3.148	3 3	0.681 0.365	1.041	3.267
'72~'73	50	16.61971 1.19869 15.80104	5.68641 0.13661 21.64209 11.53644	10.528 12.017	3 3	0.015 0.007	1.310	4.479
'73~'74	48	17.55121 1.20555 16.05289	9.63414 0.16916 23.69917 10.87359	12.366 27.560	3 3	0.006 *	3.447	6.266
'74~'75	34	15.75985 1.14011 13.80746	10.94091 0.20417 22.09468 8.62859	7.211 10.302	3 3	0.065 0.016	2.459	8.519
'75~'76	22	12.44487 1.06224 11.54206	5.49503 0.16447 16.85596 7.90339	4.269 7.136	3 3	0.234 0.068	1.503	2.435
'76~'77	28	13.73026 1.10344 12.68938	5.72777 0.17533 19.00063 8.47447	0.850 6.250	3 3	0.837 0.100	0.971	6.989
'77~'78	33	13.93183 1.12030 13.19168	4.56628 0.14920 18.59944 9.35622	1.348 1.445	3 3	0.719 0.695	0.515	8.987
'78~'79	25	16.63945 1.19275 15.58669	6.61560 0.15675 22.30172 10.88431	3.847 5.030	3 3	0.278 0.170	1.475	7.194
'79~'80	24	14.63467 1.18401 15.34654	7.28813 0.17360 22.88820 10.28985	4.707 2.224	3 3	0.195 0.527	1.200	10.917
'80~'81	32	16.24091 1.17981 15.10113	6.93966 0.16343 22.00082 10.36525	3.096 2.210	3 3	0.377 0.530	1.648	6.729
'81~'82	31	17.65854 1.20829 16.15451	7.33483 0.17219 24.01530 10.86674	3.260 4.852	3 3	0.319 0.183	1.747	5.954
'82~'83	29	14.38633 1.13006 13.49153	5.59638 0.15487 19.26326 9.44889	3.545 3.021	3 3	0.315 0.388	1.206	3.527
'83~'84	26	12.70402 1.08554 12.17693	3.72361 0.12871 16.41541 9.03284	4.769 4.167	3 3	0.190 0.244	0.411	8.976
'84~'85	27	15.12434 1.14518 13.96953	6.46892 0.17468 20.88498 9.34392	2.766 9.340	3 3	0.429 0.025	1.235	7.552
'85~'86	17	16.00261 1.22511 16.79237	7.15760 0.16506 24.55695 11.48285	3.085 8.651	3 3	0.555 0.034	0.830	5.560
'86~'87	24	17.91025 1.22786 16.89494	5.79813 0.15884 24.36110 11.72255	2.144 1.132	3 3	0.543 0.768	0.919	8.185

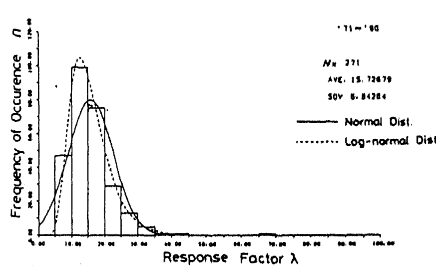
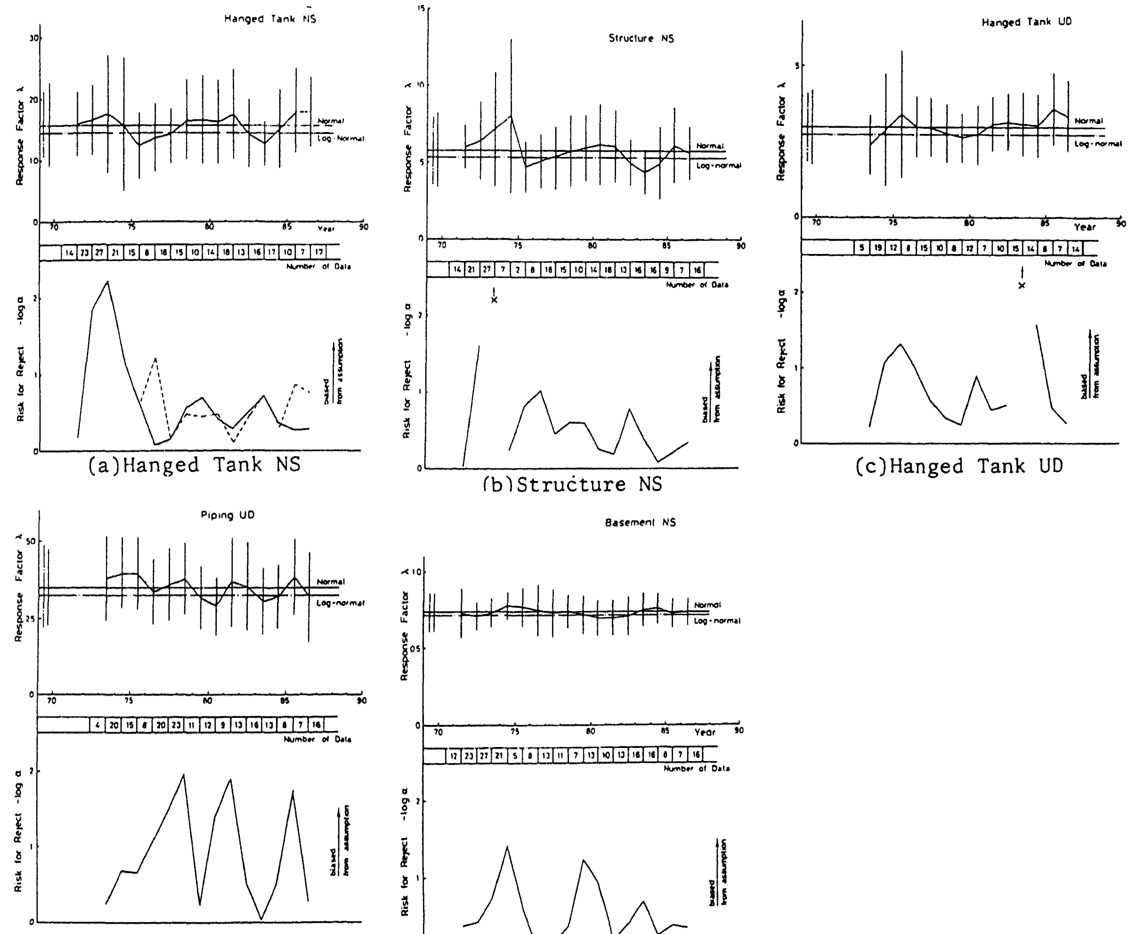


Fig.4 Frequency Distribution of Response Factor of Hanged Tank Observed in Chiba F.S. from 1971 to 90

Table 4 Variation of Stochastic Values according to Epi-Center Areas

Year & Area	Number of Data N	Average Response Factor λ	Standard dev. σ	χ^2	Degree of Freedom	Risk for Rejecting Assumption α	Skewness	Average Acc. (gal)
Area 1 '71～'90	104	15.81	7.09	42.773	10	*	0.7926	8.635
Area 2 '71～'89	28	15.58	7.17	17.271	4	0.0042	0.547	7.297
Area 3 '71～'87	19	15.73	3.99	0.904	4	0.930	0.0173	6.081



(a)Hanged Tank NS
(b)Structure NS
(c)Hanged Tank UD
(d)Pipings UD
(e)Ground Surface to Basement NS

Fig.5 Annual Change of Stochastic Values of Response Factors

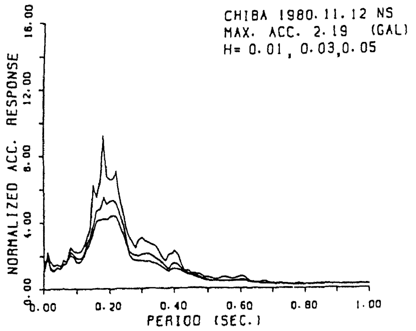


Fig.6 Response Spectrum of Earthquake (11/12/1980, NS)

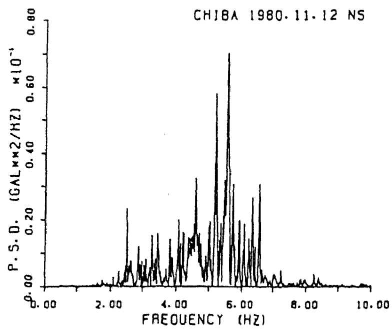


Fig. 7 P.S.D. of Earthquake (11/12/1980, NS)

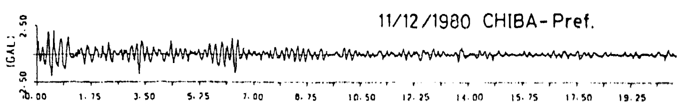


Fig.8 Wave-form of Earthquake (11/12/1980) at the Ground Surface