

ON FLUCTUATION OF RESPONSES OF A STRUCTURE

by

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SYNOPSIS

This paper involves the observation of the responses of a three-story building and piping model to actual earthquakes, the response analysis of the identical model on a big size shaking table, the stochastic nature of ground motions, the stochastic analysis of response factors of a piping system bridged between two buildings to a set of pseudo-earthquakes by an analog simulation and the theoretical estimation of the fluctuation or the relative dispersion factor of response factors. They are discussed in several points of view, and evaluated in relation to the response analysis for the design.

§1 Introduction

Nowadays for the design of important structures such as nuclear reactors, we usually make response analysis in a sense of time-history of earthquake records. If we can get the records which were observed at the specific site, and if can obtain the response of the structure which we are designing, will it be shaken in the same way as the response which we have obtained?

In this paper the authors would like to insist that there may be some discrepancy between the results of the analysis and what we will meet in a future earthquake. Such a fluctuation of the responses of a structure to earthquakes comes from several causes.

- 1) the distribution of sources of earthquake wave
- 2) the average of pathes of wave from its source to a site, and their deviation⁽¹⁾
- 3) the fluctuation of responses to a particular set of earthquake records in stochastic sense
- 4) the differences of initial conditions for each earthquake, especially those come from some nonlinearities of the real system.

The authors will discuss mainly the items (3) and (4). And in addition to such causes, there may be another discrepancy which comes from the estimation errors of the vibration characteristics of a structure itself, or those of its foundation, however the authors will not discuss anything about it in this paper.

At the beginning of this study, the authors experienced that the response factors of the models of a structure, pipings and equipment constructed in Nagano to Matsushiro Swam were scattered very much. We design

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a structure from the result of dynamic response analyses to several earthquakes, or sometimes to a single earthquake, for example, El Centro Earthquake. The maximum acceleration of a structure which we obtained through dynamic response analysis to a specific earthquake record would not predict the exact value of the maximum response to a future earthquake, even if the future maximum ground acceleration will be equal to that used for the analysis. Because the future earthquake is only a sample from a family of earthquakes in a stochastic sense, and some fluctuation or discrepancy should be expected between the average response and a sampled value.

We usually employ relative dispersion factor σ/m , which means the ratio of standard deviation to its mean. Hereafter, the authors will use this value to express the stochastic nature of the response. For example, some reported the σ/m of the response factors to about fifty earthquakes observed in Japan is near to 50%. The authors obtained the result that the σ/m of the response factor of a bridged piping between two buildings to one hundred pseudo-earthquakes is approximately 23% in the worst condition as they will discuss in section 3. The latter says that the reliability of response calculation is so low that a single result of simulation has an error exceeded by 70% of the mean value according to 3σ law.

§2 Non-stationality of Earthquake Records

Non-stationality of earthquake records is very deeply related to the fluctuation of responses to them.

Here the authors took the following assumption:⁽²⁾⁽³⁾

$$\chi(t) = \varphi(t) \chi_0(t) \quad (1)$$

here $\varphi(t)$ is a slowly changing function of time and $\chi_0(t)$ is a band limited and filtered white noise. The $\chi(t)$ is a some type of earthquake records, but at this moment it is not stated whether acceleration, velocity or displacement. To generate pseudo-earthquake, the nature of $\varphi(t)$ was examined in two ways. At first a lag window type filter was used for smoothing the data expressed in power domain or $y = [\chi(t)]^2$. A large number of repetition of this operation gives $\varphi^2(t)$, under the criterion that $[\chi_s(t)]$ has Gaussian distribution.

Secondly for the simplicity of generating $\varphi(t)$ on an analog computer, the authors also took the following form as Shinozuka⁽³⁾ and others,

$$\varphi(t) = a \cdot (e^{-\alpha t} - e^{-\beta t}) \quad (2)$$

And a technique to determine the co-efficients α and β from earthquake records were developed. This method also uses $[\alpha^2(t)]$ and fits $\varphi(t)$ in $E[\alpha^2(t)]$ for a set of earthquake records in a stochastic sense (Fig. 1). In Fig. 2 the mean power spectra of natural earthquakes and those of estimated models of $[\chi_0(t)]$ are compared, and also the standard deviation is shown. The details of these techniques were reported in the authors' previous report.

§3 The Evaluation of Response-Fluctuations to Pseudo-earthquakes by Analog Computer⁽⁵⁾⁽⁶⁾

As the authors already presented, the fluctuation of responses to a set of one-hundred pseudo-earthquakes is greatly large. In this repost,

the result is shortly reviewed.

The model is a piping system bridged between two independent buildings. And pseudo-earthquakes were generated from a low-frequency noise oscillator. After band limiting and filtering, they were chopped into one-hundred records, of which duration was 20 seconds when the dominant period T_g of ground is one second. The authors used these chopped stationary waves, and also the non-stationary waves which obtained by multiplying the stationary ones by $\mathcal{V}(t)$ as the sets of pseudo-earthquakes, and adding to these, they used four natural earthquakes as shown in Fig. 3.

The discussion in this section is limited to the acceleration response of the middle point of the piping system. The histograms in Fig. 3 show the response factors of the piping system to the 100 stationary and non-stationary pseudo-earthquakes under the worst condition, that is, $T_b = T_{b1} = T_{b2} = T_{m1}$, where T_{m1} is the fundamental natural period of the piping system. The response factors to natural earthquakes under the same condition are also indicated on the abscissa. These histograms say the mean value of response factors to the non-stationary inputs is about 70% of that to the stationary ones. The relative dispersion of response factors is almost 30%, and is not so much affected against changing the parameters except in the range of rigid buildings, that is, $T_b < T_g$ ⁽⁶⁾ in Fig. 4.

§4 Theoretical Analysis of the Fluctuation of Response Spectra ⁽⁷⁾⁽⁸⁾

The way of the authors' theoretical analysis depends on the evaluation of mean wave energies (or mean powers) of input and output records which continue for a certain finite duration T_i . It is assumed that the input acceleration waves $I_i(t)$ and the output or response waves $I_o(t)$ of the system are of finite length but stationary, and they belong to Gaussian Process. Also the assumption that the square of response factor λ is proportional to the ratio of output mean wave power to input one within the finite duration T_i is adopted, that is,

$$\lambda^2 = \int_0^{T_i} I_o^2(t) dt / \int_0^{T_i} I_i^2(t) dt \quad (3)$$

The distribution of the value χ corresponding to the square root of the mean wave power is obtain from Rice's approximate formula, then

$$\chi^2 = \left(\frac{m}{\sigma^2}\right) \int_0^{T_i} I^2(t) dt \quad (4)$$

And the degree of freedom n of generalized χ^2 type distribution is

$$n = m^2/\sigma^2 - 1 \quad (5)$$

As the joint probability distribution ⁽⁹⁾⁽¹⁰⁾ of χ_i and χ_o is easily obtained under the assumption of their independence from each other, the probability distribution of $\lambda^* = \chi_o / \chi_i$, that is proportional to λ in eq. (3) and the ratio is \mathcal{K} , is

$$f(\lambda^*) d\lambda^* = \begin{cases} \frac{2 \Gamma(n_i + n_o + 2)}{\Gamma(n_i + 1) \Gamma(n_o + 1)} \frac{\lambda^{*2n_o + 1}}{(1 + \lambda^{*2})^{n_i + n_o + 2}} ; \lambda^* \geq 0 \\ 0 ; \lambda^* < 0 \end{cases} \quad (6)$$

Through these calculations, the statistical properties of response

factors are obtained as follows:

$$\left\{ \begin{array}{l} \text{mean} \quad \quad \quad : \bar{\lambda} = \kappa \alpha_1 \\ \text{standard deviation} : \sigma_{\lambda} = \kappa \sqrt{\alpha_2 - \alpha_1^2} \\ \text{relative dispersion} : d_{\lambda} = \sqrt{\alpha_2 - \alpha_1^2} / \alpha_1 \end{array} \right. \quad (7)$$

where α_1 and α_2 are the 1st and the 2nd moments of λ^* and these values can be introduced from eq. (6) as the relation including Gamma function of n_i and n_o .

The interpretation of n_i and n_o is not obvious here, but the authors understand that they correspond to the ratio of the duration of waves to a kind of time constants of input- and output-waves, that is, relative length of those waves. If T_i is large, or n_i and n_o are small, the non-stationarity of the response or the fluctuation becomes weak.

Of a multi-degrees-of-freedom system, the parameter n_o decreases along with increase of its degrees-of-freedom. Because at that situation the variance of the output waves increases, that is, the wave form approaches to sinusoidal one, therefore from eq. (5) n_o becomes large. An example of numerical calculation from such relation is shown in Figs. 4 and 5, and the tendencies of relative dispersion against the parameters of the system both of analog simulation and the theory are well agreed with each other.

The assumption that χ_i and χ_o are independent from each other seems to be ridiculous, because the output-wave is a consequence of the input. By introducing a co-efficient μ , the correlation co-efficient of a normalized mean power of input-wave and that of output-wave,

$$\mu = \frac{\overline{\chi_i^2 \chi_o^2} - \overline{\chi_i^2} \cdot \overline{\chi_o^2}}{\sqrt{\{(\overline{\chi_i^2})^2 - (\overline{\chi_i^2})^2\} \{(\overline{\chi_o^2})^2 - (\overline{\chi_o^2})^2\}}} \quad (8)$$

the joint probability can be written in the same as in eq. (6). The eqs. (7) can be rewritten by using the followings:

$$\alpha'_1 = \left[1 - \frac{\mu}{4 \sqrt{(n_i+1)(n_o+1)}} \right] \alpha_1, \quad (9)$$

$$\alpha'_2 = \left[1 - \frac{\mu}{\sqrt{(n_i+1)(n_o+1)}} \right] \alpha_2.$$

The μ is usually high for rigid structures, and decreases for flexible structures except the resonance situation.

§5 Field Experiment of a Piping System in Three Story Building in Nagano⁽⁹⁾

The detail of this experiment was reported in the Bulletin of ERS⁽¹¹⁾. A studying committee including some of authors was organized in the Japan Electric Association in order to study the response of a structure, pipings and equipment to a large number of earthquakes originated in Matsushiro area (Fig. 6). It was said that the main purpose of this field experiment was to check the practice of response analysis through modal analysis method. A model building was built in Nagano City near the area of epi-centers. The building is a three story reinforced concrete, and a rahmen structure in a direction and rigid wall structure in another direction (Fig. 13).

This building was equipped with a two pipings and vessel system, a dual spring and single mass model and two models of two-degrees-of-freedom system. Their schematic drawing in Fig. 7 is the same as the building which was built on a shaking table for reshaking in Abiko as described in Section 6, except equipping no two-degrees-of-freedom model. The piping system consisted of one cylindrical vessel and two Z shaped pipings, one of which was parallel to the direction of the rigid walls and the other was parallel to the rahmen structure. The pipings were mounted, with a constant force-type hanger and other mechanisms to support, but were not covered by thermal insulator. The model of equipment for this case was designed for checking the response analysis of a two-input system. Their abbreviations and the vibration characteristics are shown in Tables 1 and 2.

About sixty records had been obtained over the period from January 1968 to March 1969. Their responses were checked by the simulation technique which was used as the usual dynamic analysis method in design procedure. The amplification factors of the acceleration of the third floor (3FL) to the basement were scattered from 1.4 to 6.9. Those of the pipings and equipment were more scattered, for example, from 4.4 to 22.8 (out-of-plane motions of the piping A). To make clear the cause of scattering of the amplification factors, an analog simulation for the responses of those systems to earthquakes was done. The study has raised another problem, that is, the calculated values of responses are fairly lower than the observed ones. Even for the responses of a dual spring and single mass model (2 in Fig. 7), the mean ratio of the calculated values to the observed is 0.56 and their standard deviation is 0.33. The reason of such low figures of the calculated values was estimated as the lack of the first phase of earthquake records used for the analog simulation due to the delay of the starter. The first phase, which contains sharp P-waves, of ground motion, has the strong effects on response factors. Therefore the necessity of a new project that the authors will report in this paper was discussed, that is, checking of responses of the system to exact input-waves both for the actual system and the simulated system.

§6 Response Analysis of a Piping System in Three Story Building on Shaking Table

The series of model experiments was done on the large shaking table, which is equipped in Abiko Division and is operated by Dr. Tsutsumi and other staffs of the earthquake resistant structure group of civil engineering laboratory of the Central Research Institute of Electric Power Industry. The configurations of the model were almost similar to those in Nagano City which were described in the previous section. The building was shaken in a direction of rahmen structure. As input signals, displacement waves, which were made by integrating acceleration waves by their hybrid computer, were used. The accuracy of the acceleration waves at the shaking table was kept to be as high as possible, but it was not satisfactory completely. The comparison of the responses obtained on the shaking table with those of analysis and simulation can be made in several ways. The comparison between direct response method from basement to equipment and floor response method is important in engineering sense, and here the authors made this through the floor response method. For the comparison, they employed twenty local earthquakes which were observed at Nagano site and, El Centro and Taft Earthquakes. For a condition, the authors

tried to shake the model by the same earthquake record in ten times. Some fluctuation of the responses to the ten identical earthquakes caused by the nonlinearity of the system was expected, but the result showed much more fluctuation than the authors had been expecting. The differences between each earthquakes reproduced on the table are not significant, but those of the responses are very large. The effects on higher modes are strong. The patterns of the distribution of the maximum acceleration on the piping system are shown in Fig. 9. The relative dispersion factors have the very significant values to the piping system as shown in Table 3. The value of the building was only 1%, but that of the piping systems was 9%.

In Fig. 9, the examples of histograms of response factors --- amplification factors in each condition are shown. Their tendencies are quite similar to those of the field experiment cases, that is, the response factors in each condition are scattered very widely. Those to El Centro earthquake sit near to average, and those to Taft earthquake shift to right hand side little bit in general. These data can be summarized into stochastic data as shown in Table 4. The relative dispersions are large and have a tendency to depend heavily on the damping values. It can be understood that the slight differences between each resonance condition affected more strongly on their response factors in the case of lower value of damping. And the lack of the initial phase of records made the response curves of the both, namely the motion of the model on the shaking table and the simulation by the analog computer, smoother than those to actual earthquakes, and also made them coincide with each other better. So we can say that the disagreement in the response factors between the actually observed values and the analytical ones mainly came from the lack of the initial portion of the ground motion records.

Using floor response analysis technique, we can obtain the responses of each mode to the motion of a single supporting point by using the already known techniques⁽¹²⁾. The authors introduce the five schemes to sum up the results from modal analyses of each mode in the case of the out-of-plane vibration of the piping system.

In Fig. 11 some results, the ratios of the actual data to analytical values, are shown --- here the authors used Runge-Kutta-Merson Method for integrating the equations. For the dual springs and single mass system the analytical values are smaller than the actual ones in general. For the piping system the results seem to be reasonable, but the cases like the former example occur sometimes. The authors have judged that they are caused by overestimating the damping coefficient of the system. Such an overestimation mainly comes from the flow of vibration energy in the whole system⁽¹³⁾.

Finally the authors consider that Scheme C is reasonable. Here Scheme C means the way of summing up as $\sqrt{\sum_j [(\sum_r x_{rj})^2 + (\sum_r y_{rj})^2]}$, where x_{rj} and y_{rj} are the maximum responses of the j th mode motion to a supporting point r horizontally and vertically respectively. But Scheme D, absolute sum, is too conservative. However the authors would like to draw our attention to the fact that the relative dispersions calculated from every schemes are large and of the same order.

§7 Observation of the Responses of Chemical Plant Model to Natural Earthquakes

In Chiba Field Station, 50Km away from Tokyo to east, the authors are observing the response of a chemical engineering plant model to natural earthquakes including long period displacement wave and torsional ground motion. The model plant consists of a rigid RC structure, steel frames, pipings, a tower and storages in Fig. 12.

The examples of responses at several points on the model plant against 21 earthquakes which were observed in the period from Sept. 1971 to March 1972 are shown in Fig. 10. EQ# 1 was a very peculiar earthquake comparing to the others, that means the response factors at the point #5, #9 and #12 are quite high (in Table 5). The mean response factors and their relative dispersions to the earthquakes of 21 records are shown in Table 6. The latter values fall on the range concluded from the analog simulation and the theory in the previous sections. Here we can tell a tendency that the relative dispersion factor increases along with the number of the degrees of freedom of system except the pipings.

Torsional vibration of ground was observed during an earthquake (its intensity being MM=5) in February 1972. The authors have only two records, so at this moment they can not discuss anything about it from the viewpoint of fluctuation.

58 Conclusion and Acknowledgement

The results of response analysis to natural earthquakes and the pseudo-earthquakes of finite length were examined, and the authors showed that the relative dispersion factor of the systems such as pipings usually falls upon the range from 0.2 to 0.4, and it depends on the degrees of freedom of the system. Of rigid system it is smaller than that of a resonated or a flexible system, but of the latter systems it is almost constant.

The value of 30% relative dispersion means that the reliability of response analysis is so low that a single result of computation might have an error exceeding 90% of the mean value according to 3σ law. That is, the accuracy of the response analysis to one or two earthquakes is not so high, comparing with those of response factors obtained by a smoothed response curve. The tendency of moving mean value obtained from the data from two pseudo-earthquakes to 100 ones shows that the mean value may be said to be relatively stable for the case when the number of earthquakes used for analysis exceeds 20. There is a tendency that the relative dispersion tends to increase as increasing the complexity of the system.

The above-mentioned facts are supported by the theory; the analog simulation and the experiments. And also the result of the vibration experiment shows the possibility of existense of the fluctuation caused by nonlinearity of the system, even if the system were subjected to the identical earthquake. The accuracy of response analysis required for design should be strictly limited by those facts, and the authors would like to point out that the response analysis on time-history base to a few earthquake records is less significant than that generally expected. If we use pseudo-earthquakes or a set of natural earthquake records for the purpose of aseismic design, at least ten records should be analyzed.

The study reported in Sections 3 and 4 was done as the work of members of the ADN (Aseismic Design of Nuclear Facilities) group in the Japan Society of Mechanical Engineers, and also those in Sections 5 and 6 were done as the members of the studying group in the Japan Electric Association. These studies were supported by the Agency of Science and Technology. And

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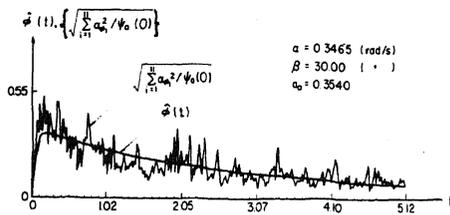


FIG. 1 POWER OF 11 ACCELERATION RECORDS AND ESTIMATED SHAPING FUNCTION

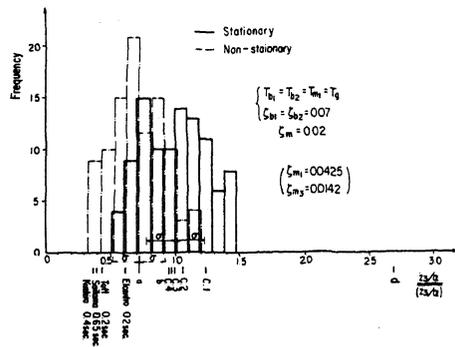


FIG. 3 HISTOGRAMS OF RESPONSE FACTORS OF BRIDGED PIPING TO 100 PSEUDO-EARTHQUAKES (ref. TABLE 7)

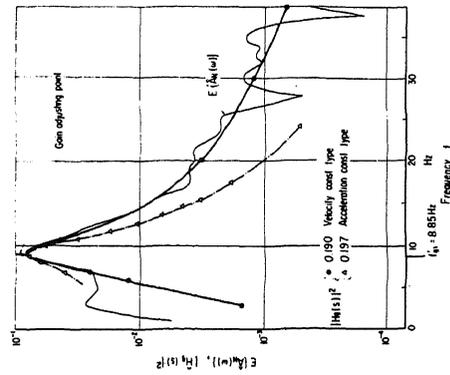


FIG. 2 MEAN POWER SPECTRA OF 11 RECORDS AND ESTIMATED MODEL

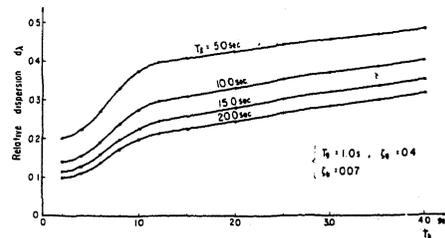


FIG. 4 RELATIVE DISPERSION FACTOR OF SINGLE DEGREE-OF-FREEDOM SYSTEM

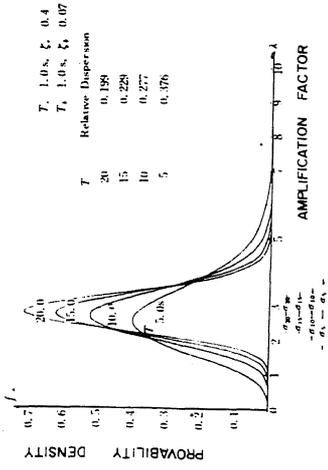


FIG. 5 PROBABILITY DENSITY FUNCTION OF RESPONSE FACTOR FOR TIME DURATION OF INPUT-WAVE

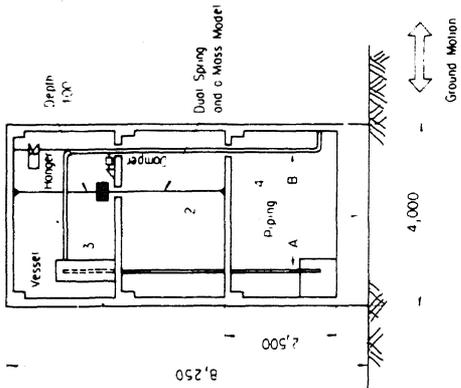


FIG. 7 SCHEMATIC DRAWING OF MODEL IN NAGANO

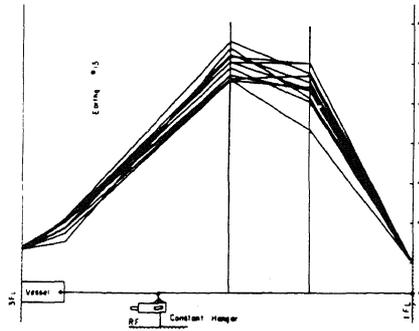


FIG. 8 DISTRIBUTION OF RESPONSES OF PIPING TO TEN IDENTICAL EARTHQUAKES ON SHAKING TABLE

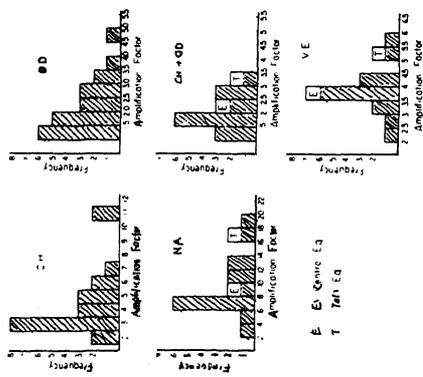


FIG. 9 HISTOGRAMS OF RESPONSE FACTORS OF PIPING

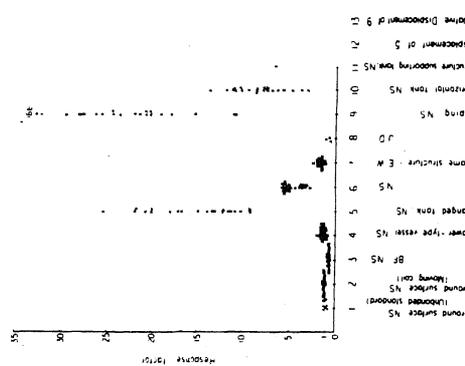


FIG. 10 DISTRIBUTION OF RESPONSE OF MODEL PLANT IN CHITBA TO NATURAL EARTHQUAKES

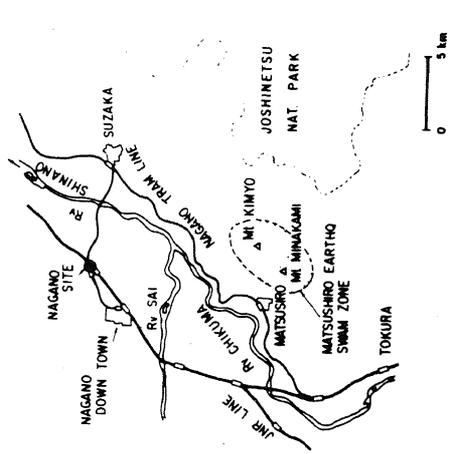


FIG. 6 MAP OF MATSUSHIRO AND NAGANO CITY AREA

Table 1, Vibration Characteristics of the Model in Abiko (Hz), [%]

Model	Mode	Pipings		Dual Spring and Mass System
		Out-of-plane (A)	In-plane (B)	
1st 2nd 3rd	(5.7) [1.8]	3.12 (3.26) [0.186]	5.34 (5.27) [0.076]	(3.79) [0.108]
	(20.5) [1.5]	6.75 (6.96) [0.121]	14.92 (14.87) [0.091]	(11.70) [0.070]
	(33.1) [1.3]	16.18 (16.3) [0.089]	21.67 (20.37) [0.174]	(22.06) [0.057]

Frequency; by DYNAPS, (Frequency; observed) and [Critical Damping Ratio]

Table 2, Abbreviation of Condition for Piping Supports

- VE: Vibration Eliminator
- CH: Constant-force-type Hanger
- MD: Wire-mesh-type Damper
- OD: Dash-pot-type Damper
- NA: No Attachment Condition

Table 7, Abbreviation of Scheme of Summing Up the Responses of Modal Analysis in Fig. 3

- a: Mean of Results of Simulation to Non-stationary Input
- b: Mean of 1st mode of Simulation to Stationary Input
- c1: Absolute Sum of 1st, 3rd and 5th modes from the Table of Theoretical Response Factor
- c2: Root of Sum of Squares of 1st, 3rd and 5th modes from the Table of Theoretical Response Factor
- c3: Root of Sum of Squares of 1st and 3rd modes
- c4: 1st mode only
- d: Response to Sinusoidal Input

Table 3. Average and Relative Dispersion of Acceleration Responses to Ten Identical Earthquakes on Shaking Table

Position	Average Acceleration (gal.)	Relative Dispersion Factor
Roof Floor (RF)	113.9	0.01
Lower Supporting Point of Piping " OD " point of Piping	71.7 229	0.01 0.09

Table 4. Fluctuation of Response Factors of Equipment and Piping

	Condition of Attachment	Critical Damping Ratio %	Response Factor	
			Mean	Rel. Disp.
Dual Spring and Single Mass System	Mass(9kg)	0.1	9.75	0.51
	Mass(9kg)+OD	8	2.91	0.31
	Mass(44kg)	0.1	4.94	0.46
	Mass(44kg)+OD	6	2.07	0.41
Piping Out-of-plane (A)	NA	0.2	6.32	0.38
	CH	3.3	3.01	0.34
	OD	25	1.50	0.16
	CH+OD	17	1.39	0.19

Table 5, Examples of Response Distribution of Chemical Engineering Plant Model in Chiba

Earthquake No.	Date	Time	Epi-center		Acc. (gal.)					#5				
			#1	#2	#3	#4	#5	#6	#7		#8	#9	#10	#11
EQ.#1	Sept. 2, 1971	17.05	Chiba-pref.	4.85	----	3.42	6.97	100						
				1	----	0.705	1.43	20.6						
EQ.#11	Nov. 11, 1971	06.39	Ibaragi-pref.	3.23	3.66	2.17	3.86	29.7						
				1	1.13	0.672	1.19	9.20						

#12 Hanged Tank (Disp.)		#6	#7	#8	#9	#10	#11	#12(μ)	#13(μ)
		23.6	5.22	3.28	805	38.2	32.1	156	----
		4.86	1.07	0.667	166	7.87	6.62		

#13 Pipings (Relative Disp.)		#6	#7	#8	#9	#10	#11	#12(μ)	#13(μ)
		12.2	5.03	---	49.0	20.6	---	16.7	34.9
		3.78	1.56	---	15.2	6.37	---		

Table 6, Average, Standard Deviation and Relative Dispersion of Responses of Chemical Engineering Plant Model Structure in Chiba

Position	#2 Ground Surface		#3 BF	#4 Tower-type Vessel		#5 Hanged Tank	
	NS	UD		NS	UD	NS	UD
Number of Earthquakes	15		19	21	21	21	21
Mean of Response Factor	1.13		0.68	1.34	1.34	1.34	14.86
Standard Deviation	0.077		0.086	0.28	0.28	0.28	4.16
Relative Dispersion	0.068		0.125	0.21	0.21	0.21	0.28

Frame Structure	#9 Piping		#10 Horizontal Tank	
	NS	UD	NS	UD
21	16	3	20	20
4.48	1.66	0.78	22.09	8.60
1.17	0.34	0.25	5.90	3.04
0.26	0.21	0.32	0.27	0.35

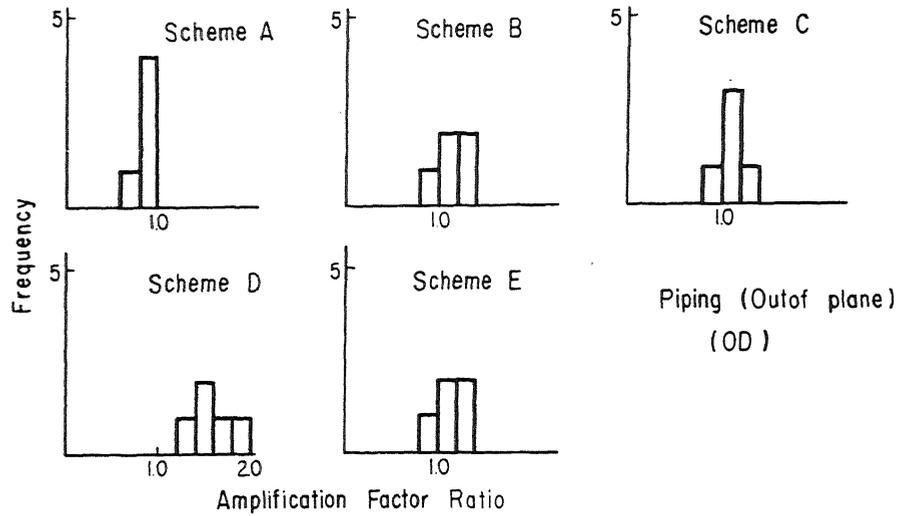


FIG. 11 HYSTOGRAMS OF RATIO OF SIMULATED RESPONSE TO ACTUAL RESPONSE FOR PIPING

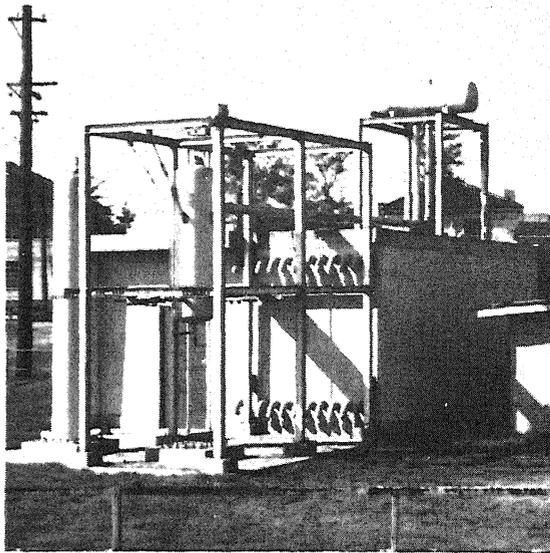


FIG. 12 PHOTO OF CHEMICAL ENGINEERING PLANT MODEL IN CHIBA FIELD STATION

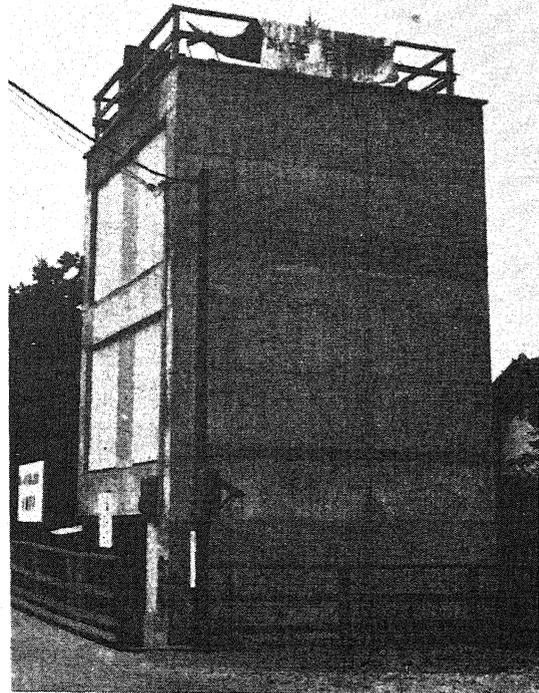


FIG. 13 PHOTO OF THREE STORY BUILDING MODEL BUILT IN NAGANO CITY