RESPONSE ANALYSIS OF A PIPING SYSTEM IN THREE STORY BUILDING ON SHAKING TABLE

by

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Summary

This report describes the field experiment of a piping system in a three story building on the shaking table in Abiko Division of the Central Research Institute of Electric Power Industry. The response factors obtained both by the experiment on a shaking table and through analytical works are compared each other. It can be said that the fluctuation of response factors is significant to the design of equipment and piping systems.

1. Preface

Although the practical method of dynamic response analysis of piping systems was established, there are still several problems to be solved for improving the results of response analysis. The authors had been studied on the multi-input response problem of a bridged piping system for several years since 1966. In this study their effort was mainly concentrated to establish a practical method for evaluating the response of a bridged piping system through a kind of modal analysis techniques. They did their study by using an analog-computer and also checked theoretically. For their analysis, they employed one hundred pseudo-earthquakes and several historical earthqukes, for example, El Centro, Taft and others. Through this study they recognized the importance of the fluctuation of responses of piping systems to earthquakes.

For the further study of their practice they joined the studying team of the Japan Electrical Association in 1968. For first two years they

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* Member of ESR

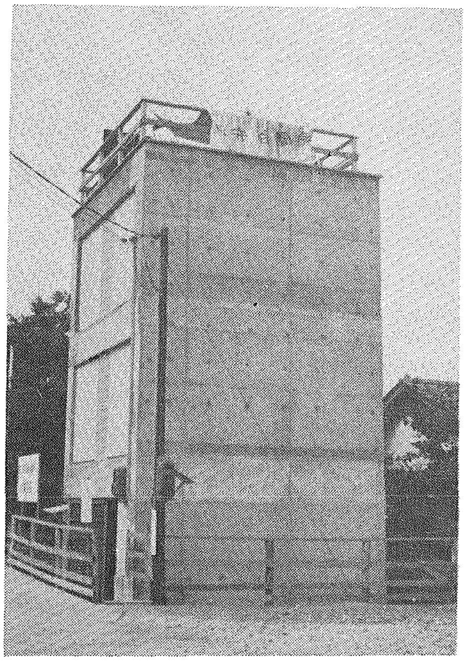

Fig. 1 Out Look of the Model Building at Nagano Site

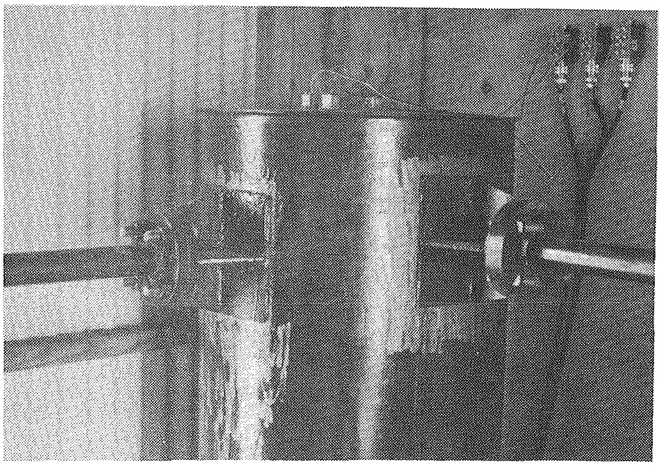

Fig. 2 A Part of a Vessel and Pipings

made the observation of the responses of a three-story model building, in which several types of equipment and pipings were mounted, to natural earthquakes. That building was built in Nagano City which had been intended to be affected by Matsushiro Earthquake Swam. Almost 60 records were obtained and analyzed (in Fig. 3).

The amplification factors, especially of the response of the piping system, were scattered very widely, and most of them did not coincide with those obtained through an analog computer. Such a discrepancy between the observations and simulations were considered to be caused by the lacks of the initial parts of each ground motion record. So the authors started the new project to reshake the three-story model including equipments and pipings on an electro-hydraulic shaking table and to record their response again to eliminate the effect of lacks of input data (in Figs. 4, 5, 6 and 7).

In this short article, the authors want to summarize their experiment which had been done for ten months since July of 1970 in Abiko City near Tokyo, and to review the results.

2. Field Experiment prior to the Experiment in Abiko

On some summer day of 1965, a seismograph suddenly observed many micro earthquakes. The number of earthquakes of everyday had been increasing very steeply. It was the beginning of Matsushiro Earthquake Swam. Since that day, August 3, 1965 and by July 15, 1968, that is, approximately for two years they had been recorded 687, 639 earthquakes, including 24 strong earthquakes, of which scales were over VII of MM.

Many experimental works in seismology and earthquake engineering fields had been done for those several years by using this swam. A studying comittee including some of authors was organized in the Japan Electric Association for studying the response of a structure, equipments and pipings to those earthquakes. It was said that the main purpose of this field experiment was to check the practice of response analysis through modal analysis method. And that the responses of the structure, equipment and pipings to an actual earthquake should be compared with the analytical results of their response to the records of underground and basement motions in each earthquake. A three story building was built in Nagano City near Matsushiro Area. This building was equipped with two pipings and a vessel system, a bridged single mass model and two two-degrees-of-freedom models. Their schematic drawing is the same as the other building which was built on a shaking table for reshaking shown in Fig. 8, except the two-degrees-of-freedom models. 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.

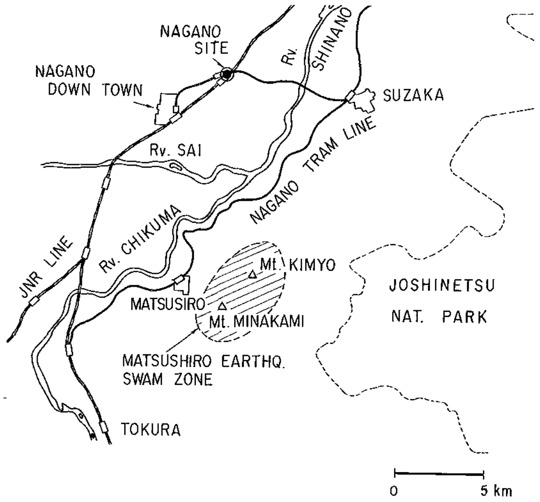

Fig. 3 Map of Nagano Site

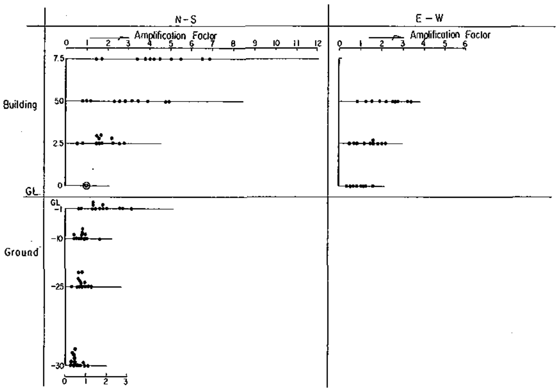

Fig. 4 Distribution of Amplification Factors of Model Building and Ground at Nagano Site

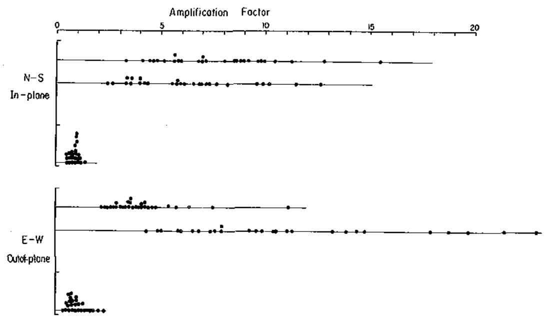

Fig. 5 Distribution of Amplification Factors of Piping at Nagano Site

The amplification factors of the acceleration of the third floor (3 FL) to the basement had been scattered from 1.4 to 6.9 as shown in Fig. 4. Those of the equipment and pipings were more scattered, for example, from 4.4 to 22.8 (outof-plane motions of the piping A, in Fig. 5). To make clear the cause of scattering of such amplification factors, an analog simulation for the responses of those systems to earthquakes was done. The study 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. 8), the mean ratio of calculated values to the observed is 0.56 and their standard deviation is 0.33. The reason of such low figures of 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. In Fig. 6 the extreme case is shown. In the first half second of actual record high frequency waves were observed, however it was smooth in the calculated curve. To the other type of earthquakes, sometimes they agreed with the calculated curves very well as shown in Fig. 7. In this case the wave form of the input earthquake is a moderate wave and does not contain sharp high frequency components.

The studying group discussed the discrepancy of such figures of response factors, and mentioned several reasons like the effects of non-linearity and so on. Also the corelation between the discrepancy of figures and the magnitude or the distribution of epi-centres of earthquakes was checked. Finally they concluded that the shallow earthquakes near the site, which means that the epi-centres of those earthquakes belonged to Matsushiro earthquake area, caused more discrepancy. This means that the lack of the first phase, which contains sharp P-waves, in the input data used for the analysis has the effects much on response factors.

Therefore they felt the necessity of a new project which the authors will report in this article, that is, checking of responses of the system: to exact input waves both for the actual system and simulated system.

3. Model

The series of model experiments was done on a large shaking table. The table 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 model consisted of a three story reinforced concrete building and equipment and piping systems as shown in Fig. 8. These configurations were almost similar to those in Nagano City which were described in the previous chapter. The building was a rahmen structure in the direction of shaking, and a rigid structure in the other direction.

Maximum capacity of the shaking table is 120 ton and shaken by hydraulic actuators, of which total vector force is 60 ton. As input

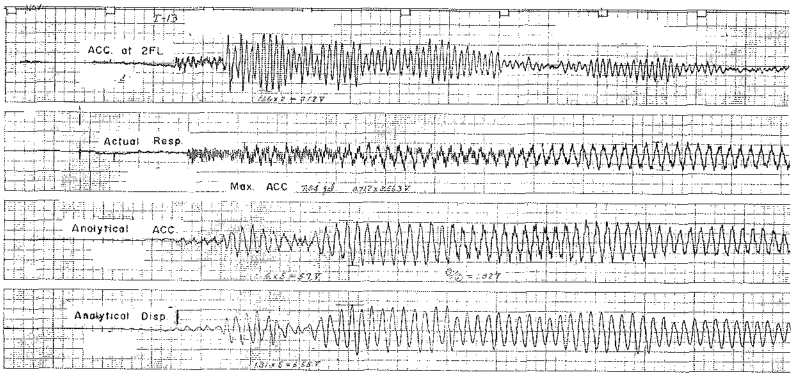

Fig. 6 Comparison of Actual Response to Analytical Result Outof Plane Vibration of Piping

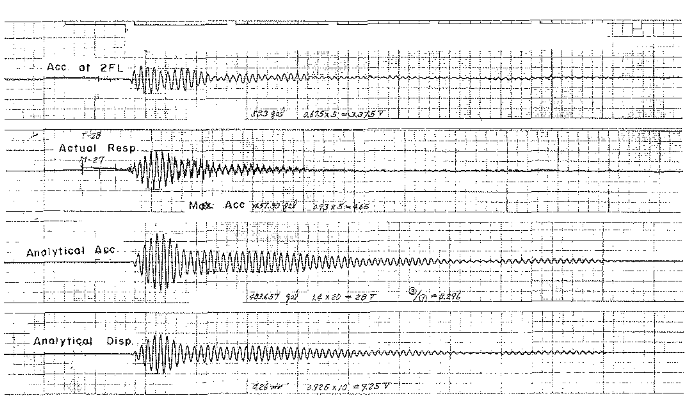

Fig. 7 Comparison of Actual Response to Analytical Result In-Plan Vibration of Piping

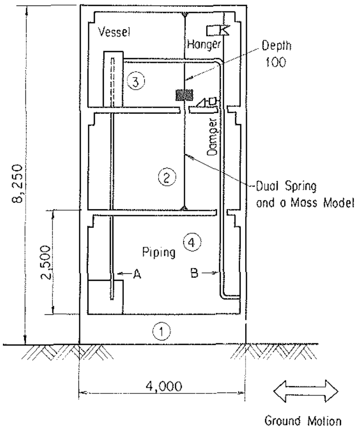

Fig. 8

Schematic Drawing of the Model Building

signals displacement waves, which are integrated through their hybrid computer, were used.

The accuracy of the acceleration on the table was kept to be as high as possible, but the authors could not satisfy completely. In Fig. 11, the results of five trials to the same input signal are shown.

The schematic configration of the model of equipment and pipings were as shown in Fig. 9. The piping system consisted of one cylindrical vessel and two Z shaped pipings. One was parallel to the direction of shaking and the other was vertical to that. The pipings mounted vibration eliminators (VE), constant force-type hangers (CH), wire mesh-type damper (MD) and dash pots (OD), but were not covered by thermal insulator. The model of equipment of this case was designed for checking the response analysis of a two input system. A flat steel bar hanged on the ceiling of the third floor and penetrated its floor to the second floor, and the lower end was fixed at the second floor. A weight (M) was mounted as shown in Fig. 9. Their vibration characteristics are shown in Table 1. It can be said that their values coincide with the theoretical values.

(Hz),〔%〕

Model	Structure	Pipings		Dual Spring and a Mass System
		Outof-plane (A)	In-plan (B)	
1st	(5.7) 〔1.8〕	3.12 (3.26) 〔0.186〕	5.34 (5.27) 〔0.076〕	(3.79) 〔0.108〕
2nd	(20.5) 〔1.5〕	6.75 (6.97) 〔0.121〕	14.92 (14.87) 〔0.091〕	(11.70) 〔0.070〕
3rd	(33.1) 〔1.3〕	16.18 (16.3) 〔0.089〕	21.67 (20.37) 〔0.174〕	(22.06) 〔0.057〕

Frequency, calculated by DYNAPS, (Freqency, observed), 〔critical damping ratio〕

Table 1. Vibrational Characteristics of Structure, Equipment and Pipings

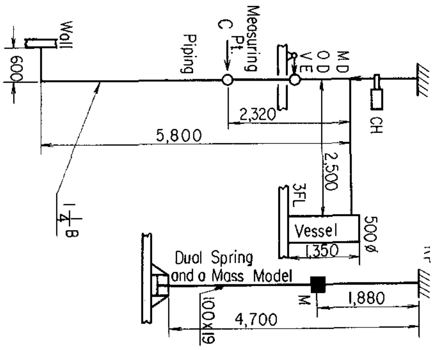

Fig. 9

Schematic Drawings of Piping and Equipment

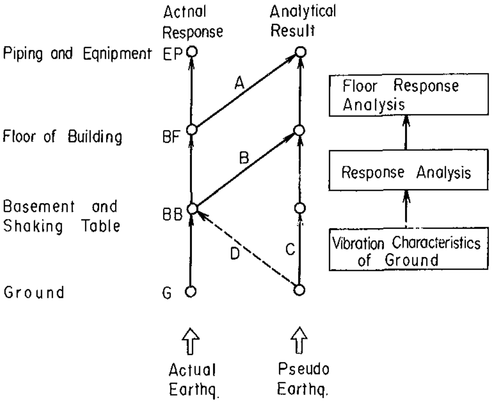

Fig. 10

Schematic Diagram of Response Analysis

4. Measurement and Analysis of Response of Equipment and Pipings

Comparisons of the responses obtained on the shaking table with analysis and simulation can be made in several ways as shown in Fig. 10. The comparisons through the routes A and B are important in engineering sense, and here the authors made comparisons through A, that is, to the results obtained by the floor-response technique. This time, they employed twenty local earthquakes which observed at Nagano site and, El Centro and Taft earthquakes. In Table 2 the conditions of experiments are shown in relation with their supporting condition and numbers of repetition of earthquakes. For the condition #10, the authors tried to shake the model by the same earthquake in ten times.

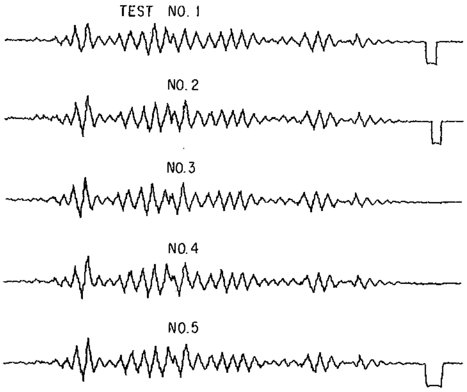

Fig. 11

Examples of Ground Acceleration of Shaking Table by an Identical Input Wave

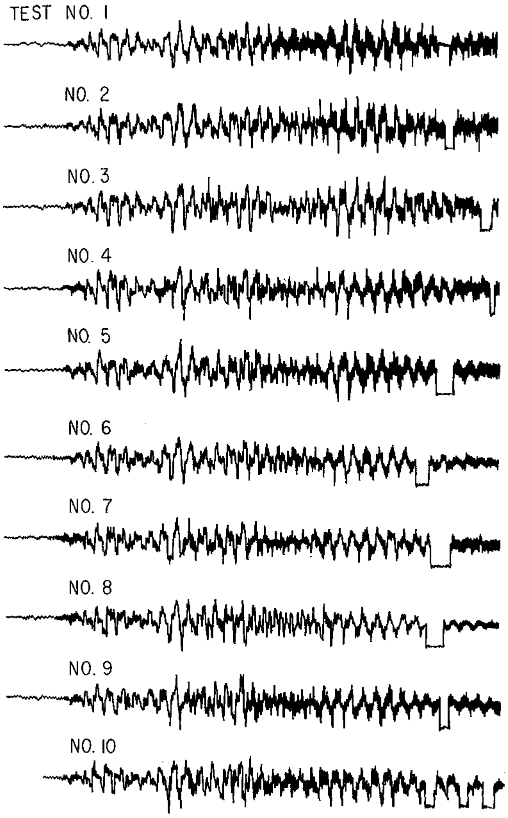

Fig. 12

Responses of Piping on Shaking Table to Ten Earthquakes Generated by an Identical Input Wave

4.1 Fluctuation of Response to the Identical Earthquakes

Some fluctuation of the responses to the ten identical earthquakes caused by the non-linearity of the system was expected, but the result was more than the authors had been expecting. Figures 11 and 12, show the wave forms of inputs and their responses. The differences between each earthquakes are not to be significant, but those of the responses are very large. As shown in Fig. 12, the effects on higher modes are strong. The patterns of the distribution of the maximum accelerations on the piping system are shown in Fig. 13. The disper-

Case	Dual Spring and a Mass System	Piping		Number of Trials
		Outof-plane	In-plane	
1	Mass (9 kg)	CH	MD*2	21
2	Mass (9 kg) + OD	OD		21
3	Mass (44 kg) + OD	CH + OD		17
4	Mass (44 kg)	NA*1		17
5		VE	MD*2	17
6			CH	22
7			OD	17
8			CH + OD	17
9			NA	17
10		CH	MD	10*3

*1 : No Attachment
*2 : Wire-mesh Type Damper
*3 : Trials by the Same Input Signal

Table 2. List of Conditions of the Experiment

Position	Average Acc. (gal)	Dispersion Factor
Roof Floor (RF)	113.9	0.01
Lower Supporting Point of Piping	71.7	0.01
OD point of Piping (pt. C)	229	0.09

Table 3. Average Response Accelerations and their Dispersion Factors to Ten Repetitions of an Earthquake

sion factors, that is, the ratio of standard deviation to mean, 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%.

4.2 Histograms of Response Factors

In Fig. 14, the examples of histograms of response factors --- amplification factors in each condition. Their tendencies are quite similar to those of the Nagano cases, that is, the response factors in each condition are scattered very widely. That to El Centro Earthquake sits near to average, and that to Taft Earthquake shifts to right side little bit in general. These data can be summarized into stochastic data as shown in Table 4. Dispersion factors 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 damping. And the lacks of the initial phase made the response curves of the both, the motion on the shaking table and the simulation by the analog computer, smoother than to actual earthquakes, and also made coincide each other better. So we can say that the disagreement of the response factors between the actual observed values and the analytical ones mainly came from the lack of the initial portion of the ground motion records.

	Condition of Appendage	Critical Damping Ratio %	Response Factor	
			Average	Disp. Factor
Dual Spring and a Mass System	+ Mass (9 kg)	0.1	9.79	0.51
	+ Mass (9 kg) + OD	8	2.91	0.31
	+ Mass (44 kg)	0.1	4.94	0.46
	+ Mass (44 kg) + OD	6	2.07	0.41
Piping Outof-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 4. Fluctuation of Response Factors of Equipment and Pipings

5. Scheme of Summing up Responses of Modes

Using floor response analysis technique, we can obtain the response of each mode to the motion of a single supporting point by the already known technique. If we assume that the input motions of both points are independent to each other, the response could be described(1) as

$$\ddot{z}(\xi, t) = \sum_{j=1}^{\infty} X_j(\xi) \left\{ \beta_{1j}\alpha_{b1}(t) + \beta_{2j}\alpha_{b2}(t) + \ddot{\varphi}(t) \right\} \tag{1}$$

where $\alpha_{b1}(t)$ and $\alpha_{b2}(t)$ are the accelograms of the both supporting points 1 and 2, $\ddot{\varphi}_j(t)$ is a response function of the j th mode obtained as the solution of eq. (2), $X_j(\xi)$ and ν_j are normalized mode function and circular eigen frequency of the j th mode respectively, and β_{1j} and β_{2j} are exciting coefficients to the motions of the both supporting points. The equation of motion of a piping system on a building is

$$\ddot{\varphi}_j(t) + 2\zeta_j\nu_j\dot{\varphi}_j(t) + \nu_j^2\varphi_j(t) = -\left\{ \beta_{1j}\alpha_{b1}(t) + \beta_{2j}\alpha_{b2}(t) \right\} \tag{2}$$

We put $H_{\ddot{z}}(s, \xi)$ as the transfer function through the system, then

$$\left| H_{\ddot{z}}(s, \xi) \right|^2 \doteqdot \sum_{j=1}^{\infty} X^2{}_j(\xi) \left| H_{\ddot{z}j}(s) \right|^2 \left\{ \beta_{1j}{}^2 \left| H_{\ddot{z}b1}(s) \right|^2 \right.$$

$$\left. + \beta_{2j}{}^2 \left| H_{\ddot{z}b2}(s) \right|^2 + 2\beta_{1j}\beta_{2j} \left[H_{\ddot{z}b1}(s) H_{\ddot{z}b2}(s) \right] \right\}, \tag{3}$$

where $H_{\ddot{z}b1}(s)$ and $H_{\ddot{z}b2}(s)$ are the transfer functions of both supporting buildings. Here the cross term between the i th mode and the j th mode are omitted, according to an ordinary scheme of random vibration theory. If we can assume the independency of the motions of both supporting points, eq. (3) can be reduced further to eq. (4).

$$\left| H_{\ddot{z}}(s, \xi) \right|^2 \doteqdot \sum_{j=1}^{\infty} X^2{}_j(\xi) \left| H_{\ddot{z}j}(s) \right|^2 \left\{ \beta_{1j}{}^2 \left| H_{\ddot{z}bi}(s) \right|^2 \right.$$

$$\left. + \beta_{2j}{}^2 \left| H_{\ddot{z}b2}(s) \right|^2 \right\} \tag{4}$$

From this equation Scheme A of eqs. (5) will be obtained as follow. In Fig. 15, a set of examples of response curves of the actual system and the analog simulation. In the case of Fig. 15, they agreed with each other very well.

The authors introduce the following five schemes to sum up the results of modal analyses of each mode in the case of the outof-plane vibration of the piping system.

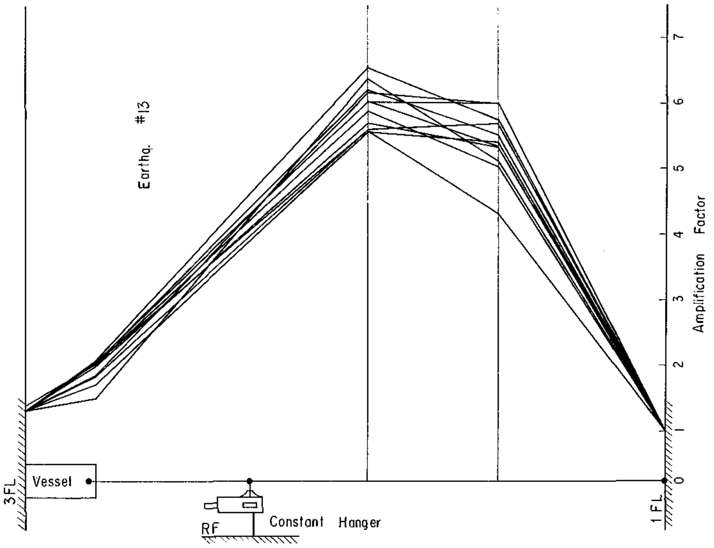

Fig. 13 Distribution of Maximum Acceleration of Piping to Ten Identical Earthquakes

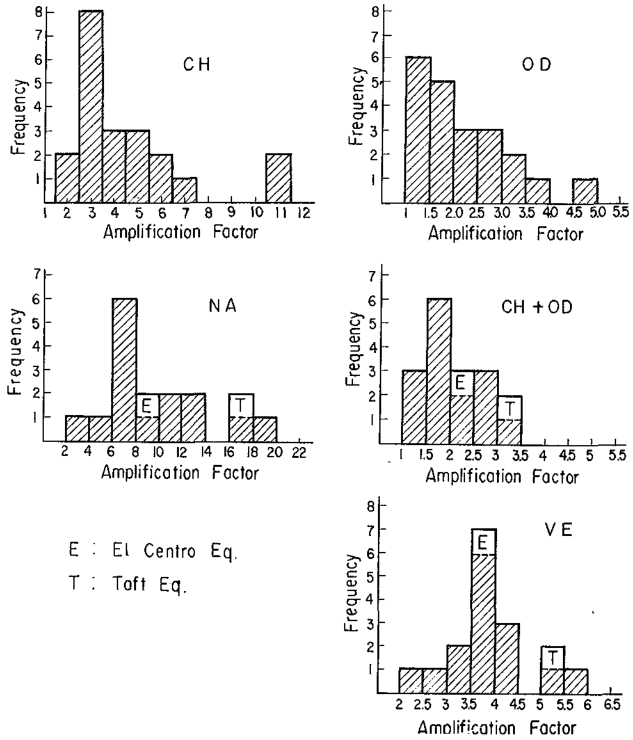

Fig. 14 Histograms of Amplification Factors of Piping

$$\text{Scheme A} = \sqrt{\sum_j \sum_r (x_{rj}^2 + y_{rj}^2)}$$

$$\text{Scheme B} = \sum_j \sum_r \sqrt{x_{rj}^2 + y_{rj}^2}$$

$$\text{Scheme C} = \sqrt{\sum_j [(\sum_r x_{rj})^2 + (\sum y_{rj})^2} \qquad (5)$$

$$\text{Scheme D} = \sum_j \sum_r (\,|x_{rj}| + |y_{rj}|\,)$$

$$\text{Scheme E} = \sqrt{\sum_r [(\sum_j x_{rj})^2 + (\sum_j y_{rj})^2}$$

where x_{rj} is the maximum response of the j th mode horizontal motion to a supporting point r and y_{rj} the maximum response of the j th mode vertical motion to a supporting point r. Scheme A is understood as "the root of sum of squares" and is reduced from eq. (4) directly. In the case described here, the supporting points 1 and 2 were on the first floor and the third floor of the building respectively, so the inputs to the piping system are correlated rather strongly in each mode. The phase relations between two inputs are determined by the relation of the eigen frequencies of the piping systems to those of the building. If the first mode of the piping systems resonates to the first mode of the building, then x_{11} and x_{21} should be added, but if to the second mode of the building, then $(x_{11} - x_{21})$ should be employed. But practically the authors applied this idea to Scheme C to neglect the phase relations to safety side or over-estimate. Scheme D is called the sum of absolute values and expected to give the upper-limit.

In Fig. 16 some results, the ratios of the actual data to analytical values, are shown. --- here, the authors used Runge-Kutta-Merson Method to integrate equations. For a dual spring and a mass system the analytical values are smaller than the actual values in general. For the piping system the results seem to be reasonable. Cases like the former example arise sometimes. The authors judge that they were caused by overestimating the damping coefficient of the system. Such an overestimation mainly comes from the flow of vibration energy in the whole system(2).

As a conclusion the authors judge that Scheme C is reasonable, but Scheme D, absolute sum, is too conservative.

But also we should pay our attention to the fact that the dispersion factors of every schemes are large and the same order.

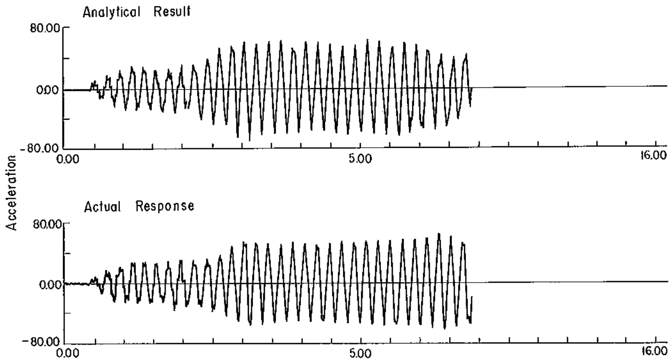

Fig. 15 An Example of the Response of Piping; Simulated Response and Actual Response

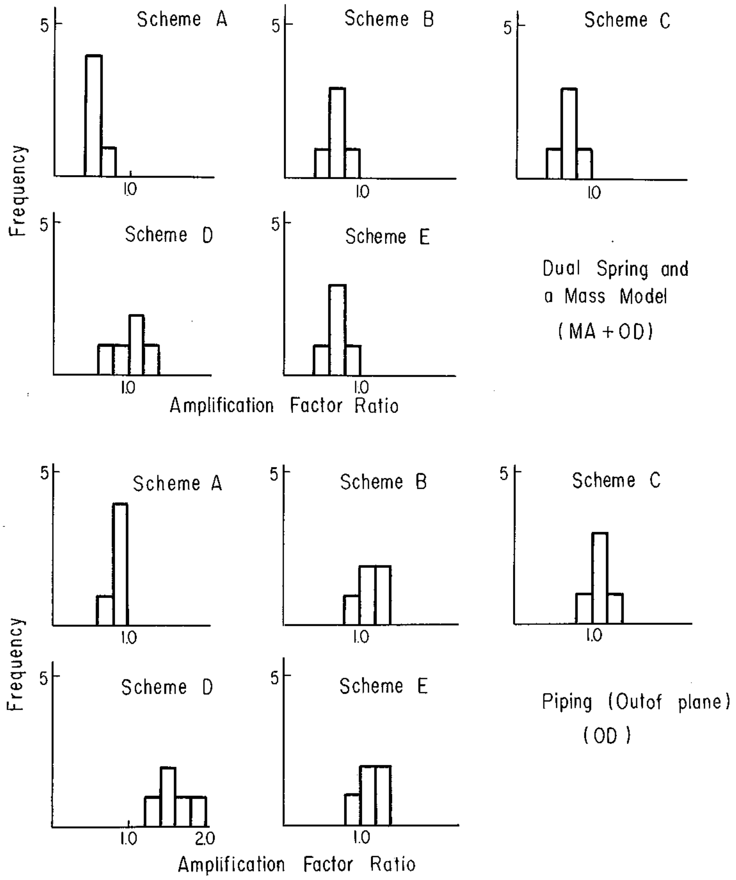

Fig. 16 Histogram of the Ratios of Simulated Response to Actual Response of Piping and Equipment

6. Acknowledgement

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Reference

(1) Shimizu, N. and Shibata, H.: J. of IIS, Vol. 21, No. 6 (1969. 6) p. 405.

(2) Yamamuro, M. and Shibata, H.: J. of IIS, Vol. 22, No. 8 (1970. 8) p. 362.

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