

STUDY ON SHEARING FORCES IN STRUCTURES
CAUSED BY MEDIUM EARTHQUAKES RECORDED
IN JAPAN

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1. SYNOPSIS

In this paper, several earthquake motions with the maximum accelerations of 10 to 100 gals recorded by the strong motion seismograph SMAC in Japan were analyzed by the analog computer SERAC, and the results were shown in the form of response spectrum. Moreover, various types of buildings were reduced to equivalent five degree of freedom shear type systems, and the shearing forces in these frames caused by the earthquake motions were calculated and examined in the elastic range.

This paper also gives a proposal of a simplified method for the preliminary design of earthquake resisting structures of high rise buildings, making use of the response spectrum of one degree of freedom system.

2. DISTRIBUTION OF STRONG MOTION SEISMOGRAPH

In Japan, many seismic vibrations have been recorded since the first installation of the strong motion seismograph of SMAC type in 1952. However, there has been no severe earthquake since then and most of the vibrations were the records of medium earthquakes which did not bring heavy damages.

The distribution of strong motion seismographs - both SMAC and DC type - in Japan in July 1963 is shown in the map. The total number of strong motion seismographs amounts to upwards of 120. The explanation of "SMAC" type A was reported by Dr. Takahashi at the First World Conference on Earthquake engineering in 1956. After that conference a more compact type has been developed and Type B and Type C are now being distributed commercially. Type C is a wall hanging type. The general mechanism of Type B and C is nearly the same with Type A.

The records obtained with these strong motion seismographs have been distributed by The Earthquake Research Institute, University of Tokyo. In this paper, the author has selected some of them for the purpose of analysis.

3. EARTHQUAKE RECORDS AND RESPONSE SPECTRA FOR ONE DEGREE OF FREEDOM SYSTEM

In this section are shown the results of the linear response of the one degree of freedom system to these actual earthquake motions, recently obtained by SMAC, by use of the analog computer SERAC. Detailed data of accelerogram

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records are shown in Table 1. In the course of analyses, natural periods of one degree of freedom systems are varied from 0.1 sec to 5.0 sec considering fractions of critical damping of 0.05 and 0.10 for each period. Earthquake records are converted into voltage values by a photo-electronic curve reader after optically enlarged and drawn on films. Then the voltages are applied to the computer as earthquake inputs. Fig. 1 shows the patterns of normalized earthquake inputs recorded by pen oscillograph.

In Fig. 2-1 to 2-8, results are shown in the form of shear force spectra which are the plots of the shear coefficient ratios α against the natural periods T . The shear coefficient ratio α is defined as the value of the shear coefficient q divided by the seismic coefficient of the ground k_0 , where the shear coefficient is the maximum shearing force divided by its own weight and the seismic coefficient of the ground is the maximum ground acceleration divided by the gravity acceleration. Therefore, it is considered that the shear coefficient ratio is nearly equal to the magnification factor of acceleration.

Fig. 2-7 and Fig. 2-8 show the shear force spectra for two kinds of earthquake recorded at the same site (Tokyo 101) on the different dates. The former corresponds to those of NS component and the latter EW. Two spectra for these two kinds of records are relatively similar to each other at rather short periods but somewhat different at long periods.

As the damping of the system increases with a constant natural period, the spectrum value decreases. In Fig. 6 is shown the relation between the spectrum value in unit of undamped one and the fraction of critical damping for El Centro (1940 NS) earthquake. Though the relation will naturally be varied in accordance with earthquakes, it appears that the spectrum value tends to decrease with the increase of fraction of critical damping in a form of hyperbola.

4. SHEARING FORCE DISTRIBUTION OF FIVE DEGREE OF FREEDOM SYSTEM CAUSED BY EARTHQUAKE MOTION

In order to design high rise buildings over 31m height to stand against earthquake motion in Japan, the shear coefficient has recently been used instead of the seismic coefficient. The shear coefficient of each story is defined as follows.

$$q_i = Q_{i \max} / \sum_{k=i}^N w_k \quad (1)$$

where $Q_{i \max}$ is the maximum shear force in the i -th story and w_i is the weight of the i -th story and N is the number of stories.

The shear coefficient for each story against earthquake varies according to the natural periods, mode shapes and dampings of buildings as well as the characteristics of earthquake motion.

To examine the characteristics of shear coefficients in buildings caused by earthquake, response analyses have been made for several kinds of building models and earthquakes by use of analog computer SERAC.¹⁾ The method of analyses is as follows.

Various frames in the projects of actual design of the buildings with the fundamental natural periods T_1 of 1.41 sec to 4.10 sec were reduced to the equivalent five degree of freedom systems. The list of these systems is shown in Table 2. On the other hand ideal five degree of freedom systems which have uniform distribution of mass and stiffness, having the fundamental natural periods of 0.5 sec to 4.0 sec, were considered simultaneously to compare with the actual building models. The fraction of critical damping of each system ζ_1 was taken as 0.05 for the first mode. Then these equivalent elastic vibratory systems were subjected to various earthquake motions and the shear coefficients for each of equivalent five stories were calculated by use of the analog computer SERAC. The analyzed earthquake motions are Tokyo 101 (NS, 1956 II), Tokyo 103 (NS, 1956 IX), Osaka 205 (NS, 1963 III), Nagoya 306 (NS, 1963 III), El Centro (NS, 1940 V) and Taft (EW, 1952 VII) earthquakes. For the detailed date of these earthquakes, the reader is referred to the third section.

In Figs. 7 and 8, the distribution of the shear coefficient along the height $\bar{\zeta}_i$ (ζ_i/ζ_1) is shown together with the base shear coefficient ratios α_i , which are the shear coefficients of the first story ζ_1 divided by the seismic coefficient of the ground k_0 . In Fig. 7 the stiffness distribution along the height \bar{K}_i (K_i/K_1 , K_i : spring constant) is also shown. From these figures it is seen that, though the shear coefficient distributions varies in accordance with the fundamental periods and earthquake motions, the shear coefficients in the uppermost story are relatively large when the fundamental periods of the systems are 1.5 to 2.0 sec. This is due to the large participation of higher modes in the responses. It is also seen that the shear coefficients in the upper part are comparatively smaller in the case of uniform models than in the case of actual building models, due to the difference of fundamental mode shapes between them.

5. EXAMINATION OF RESULTS

In this section, results of the shear coefficient response of building models are examined mainly on the base shear coefficient ratio and the types of the shear coefficient distribution, and a procedure for determining the design shearing force distribution is proposed.

Comparison of Base Shear in One and Five Degree of Freedom System

In Figs. 2-1 to 2-6 the base shear coefficient ratios α_1 are also plotted for the fundamental periods of the five degree of freedom systems. It is shown from these figures that the base shear coefficient ratios of five degree of freedom systems are generally smaller than, but almost equal to, the corresponding values for one degree of freedom systems. This fact may show that, in determining the design base shear coefficient, the shear force spectrum value of one degree of freedom system can be used with a slight erring on the safe side.

Types of Shearing Force Distribution

The type of shearing force distribution along the height of structures is considered to be decided by the combination of the fundamental mode of vibration and the higher modes, especially the second mode, of vibration.

It should be noted that the maximum shear force in each story does not occur simultaneously and the shear coefficient of each story has its characteristic combination of modes. If the dynamic constants of structures are to be previously known, the shear coefficients for earthquake motion will be predicted. However, from the point of view of the preliminary design of structures, a much simpler method to determine the design shear force distribution will be required. Thus, a method of obtaining the approximate shear distribution under several assumptions is shown in the following and the results are compared with those from the response.

The author assumes that the fundamental and the second modes of vibration correspond to the inverted triangular seismic coefficient distribution and the concentrated load at the top floor, respectively, and that the total shear coefficient distribution can be approximately expressed by the combination of these shear coefficient distributions for triangular and top load types in a specific ratio as shown in Figs. 3 and 4. The ratio of the both types of distribution is assumed to be related to the ratio of the maximum modal shears corresponding to the first and second modes. Namely, if the base shear coefficients for triangular and top load type distributions are designated by C_{BT} and C_{BP} , respectively, then the author assumes that the ratio C_{BT}/C_{BP} is the ratio of the maximum modal shear for the first mode at the lowest story to the maximum modal shear for the second mode at the middle point where the second normal mode crosses the ordinate. Thus, the ratio C_{BT}/C_{BP} is given as follows.

$$C_{BT}/C_{BP} = 1A \cdot 1q / 2A \cdot 2q \quad (2)$$

where $1A$ and $2A$ are the areas of lateral force diagrams and $1q$ and $2q$ are the values of shear force spectrum corresponding to the first and second natural periods, as shown in Fig. 3. The shear coefficient distribution is then obtained by adding those of triangular and top load type by the ratio of C_{BT}/C_{BP} .

In Figs. 9 to 10, the shear coefficient distributions calculated from these assumptions are compared with those obtained from direct dynamic analysis. (In this case, the values of sA are taken as $\sum m_i \cdot s \beta s u_i$, where m_i is the mass and $s \beta s u_i$ is the normalized normal mode. The values $1q$, $2q$ are obtained from spectrum curves for $h=0.05$ and $2q$ is modified by the relation, $(1 + 10_1h)/(1 + 10_2h)$, considering damping, where $2k/1k = \pi/2T$ and $1k = 0.05$.) Though both values (dynamically analysed and proposed) are not in very good agreement quantitatively, general trends seem to be identical to each other, considering the randomness of earthquake. It is seen that the correspondence between them is better in actual building models than in uniform models, because the assumed triangular shape of seismic coefficient distribution is much closer to the first modes of the former ones.

Procedure for Determination of Design Shear

In order to use the preceding method for the determination of the design shear, the values $1A/2A$ and $1q/2q$ have to be estimated in advance. In actual buildings the stiffness distribution \bar{K}_i along the height generally decreases with the height and the first mode shape will be close to the triangular type. For example, $1A/2A$ and $1q/2q$ values as well as the mode shapes for the five

degree of freedom systems of uniform mass and various stiffness distributions are shown in Fig. 5. It may be said that these values can be adequately presumed according to the kind of structure in the preliminary design process. For the estimation of spectral shear coefficient values q , standard spectra or some adequate earthquake spectra could be used.

Thus, the author proposes the next procedure to decide the design shearing force distribution:

- a. At first, decide the design base shear from the design foundation acceleration and the shear force spectrum using the period of fundamental mode.
- b. Next, divide this base shear in proportion to the ratio C_{BT}/C_{BP} which is shown in Equation 2.
- c. Calculate the shearing force in each story by combining the triangular and concentrated loads at the top in proportion to the C_{BT} and C_{BP} , respectively.

6. CONCLUSION

In this paper the authors studied the base shear and shear force distribution of the elastic structures which have several rigidity distributions along the height subjected to medium earthquakes in Japan.

At first the shear coefficient ratio spectra of one degree of freedom systems were shown and compared with the base shear coefficient ratios of five degree of freedom systems. Using these kinds of spectra, the design base shear coefficient will be inferred if the maximum acceleration of the foundation is assumed for the structure which has some fundamental period.

Here, the acceleration of foundation mentioned above is the ground acceleration influenced by the various factors such as the superstructure, the type of substructure and the interaction of soil and foundation. These factors will have to be considered carefully in determining the design seismic coefficient of the ground and the shape of the shear coefficient spectrum.

For the purpose of preliminary design of earthquake resisting structure, it is necessary to decide the seismic coefficient distribution or the shear coefficient distribution. If the shear coefficient spectrum and dynamic properties of structure are given, the modal analysis method can be used to determine the shear distribution in the elastic range. However, as this method is somewhat troublesome, the authors proposed a simplified method. Namely, the horizontal seismic coefficient is divided into two types - inverted triangular and top concentrated - according to some ratio which depends on the rigidity distribution and the shear coefficient spectrum. The results of the proposed method are compared with those of dynamic analysis by the analog computer SERAC, and for the preliminary design of structures this kind of method is verified to be a useful tool.

ACKNOWLEDGEMENT

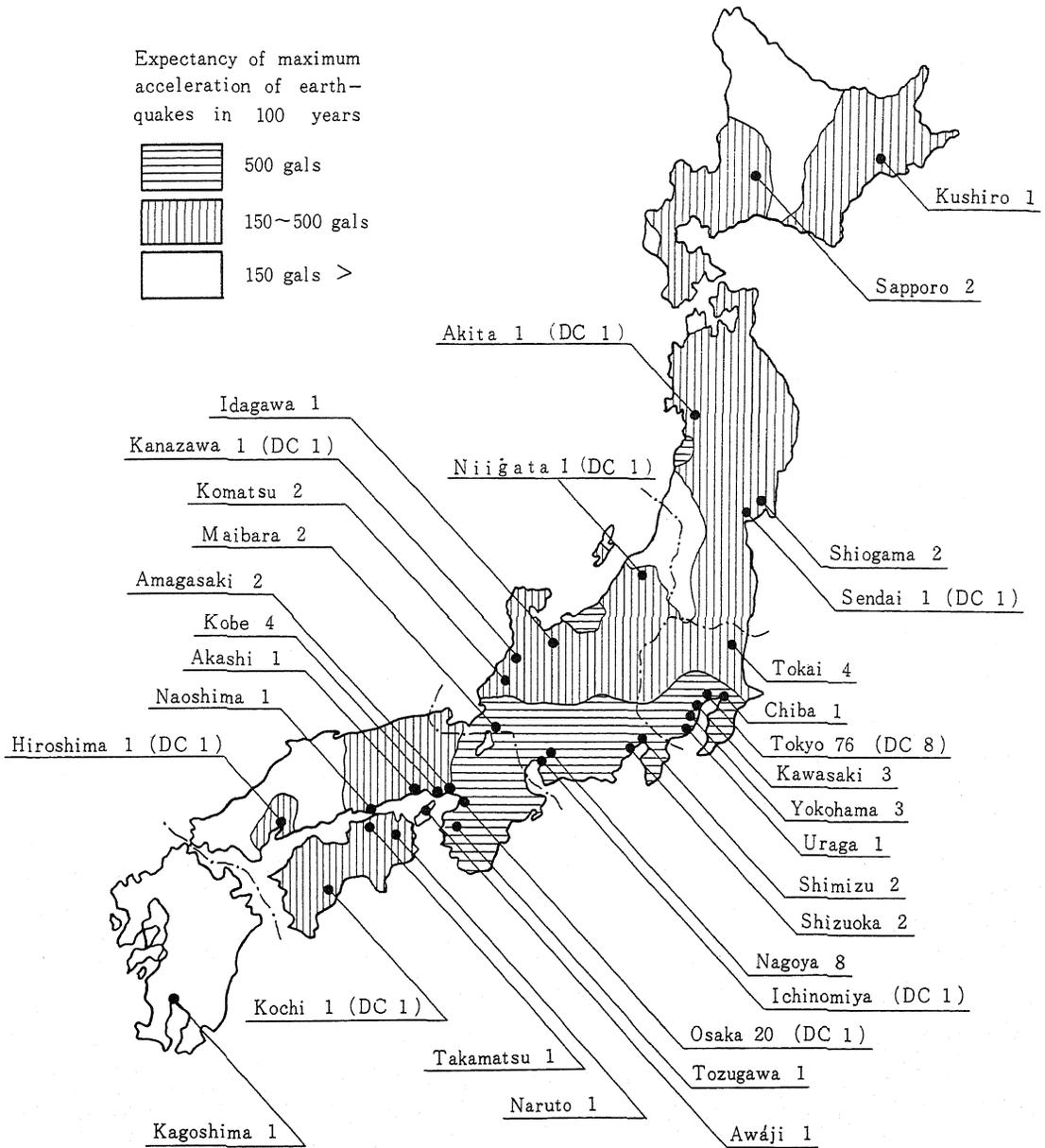
The authors wish to acknowledge the assistance received from Mr. H. Oka and Mr. Y. Matsushima, graduate students, University of Tokyo.

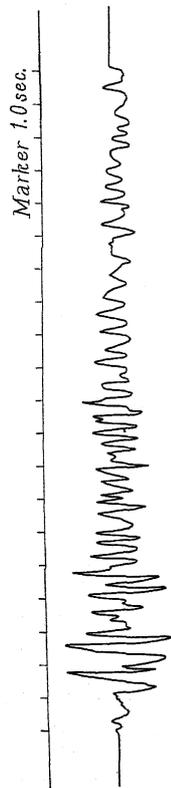
In the preparation of the acceleration records of El Centro (1940) and Taft (1952) Earthquake of U.S.A., Dr. K. Muto, Prof. Emeritus, University of Tokyo, allowed the authors to use the digital values of strong earthquake records which Prof. G. V. Berg, University of Michigan, kindly sent to him.

REFERENCE

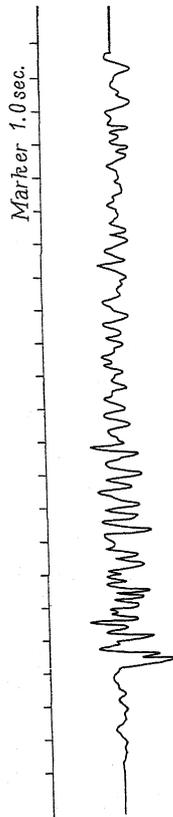
- 1) SERAC Report No. 1 - 5, Strong Earthquake Response Analysis Committee, c/o Faculty of Engineering, University of Tokyo

Distribution of "SMAC", "DC" Strong Motion Seismograph (July 1963)

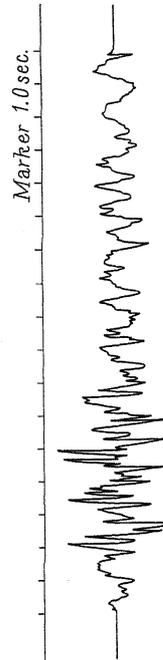




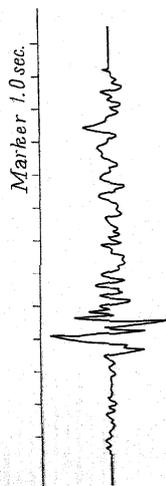
Tokyo, 101 (NS), 1956 IX 30, (0.04 g)



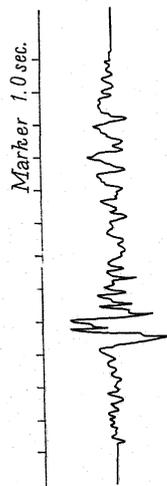
Tokyo, 101 (EW), 1956 IX 30, (0.05 g)



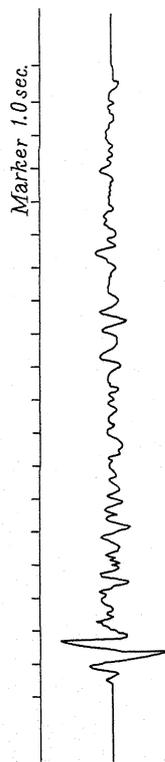
Nagoya, 306 (NS), 1963 III 27, (0.01 g)



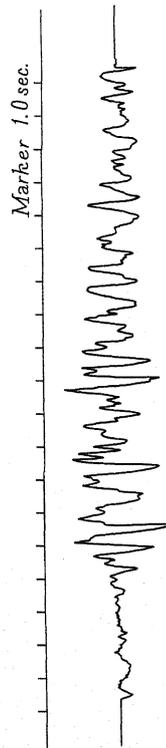
Tokyo, 101 (NS), 1956 II 14, (0.07 g)



Tokyo, 101 (EW), 1956 II 14, (0.06 g)



Tokyo, 103 (NS), 1956 IX 30, (0.05 g)



Ōsaka, 205 (NS), 1963 III 27, (0.02 g)

Fig. 1 Earthquake Accelerograms
Earthquake Data: District, Site Number
(Component), Date, (Max. Acceleration)

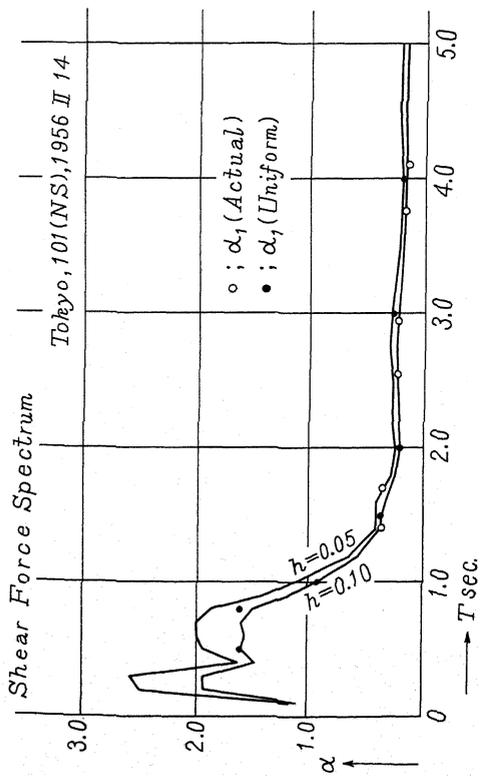


Fig. 2-1

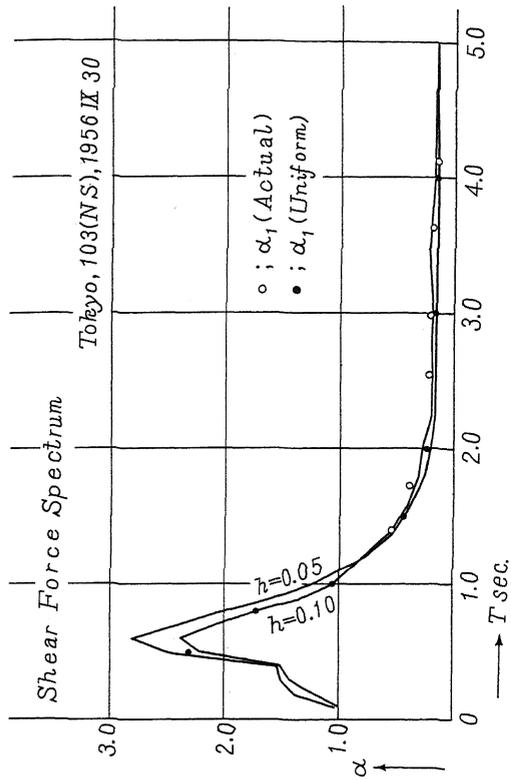


Fig. 2-2

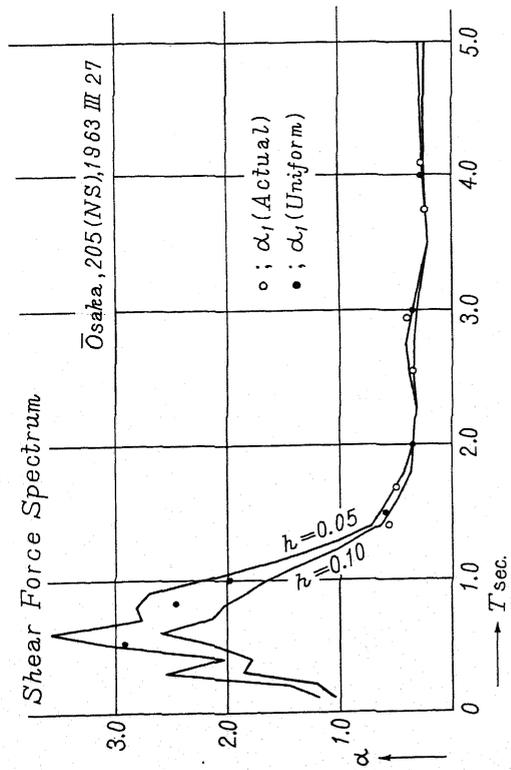


Fig. 2-3

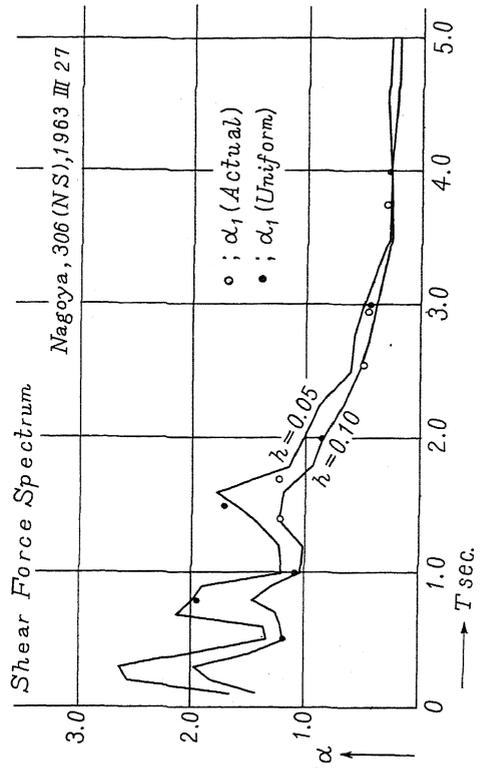


Fig. 2-4

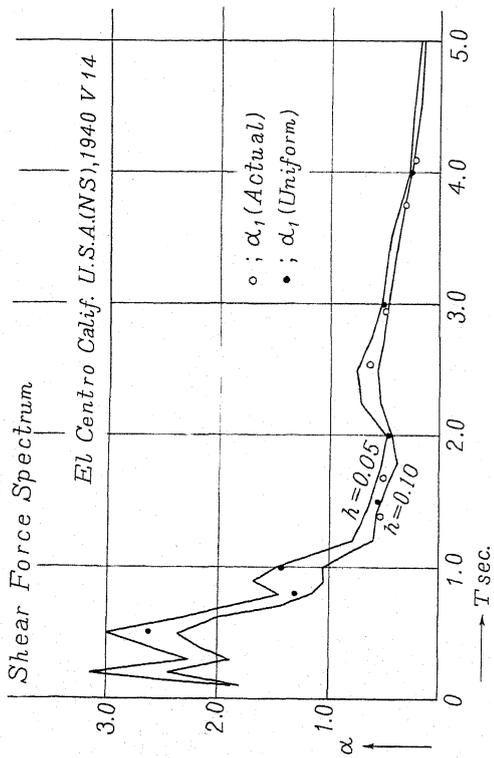


Fig. 2-5

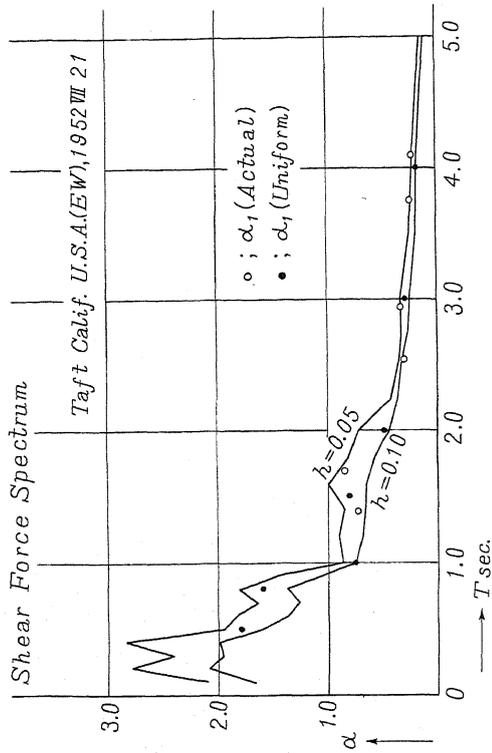


Fig. 2-6

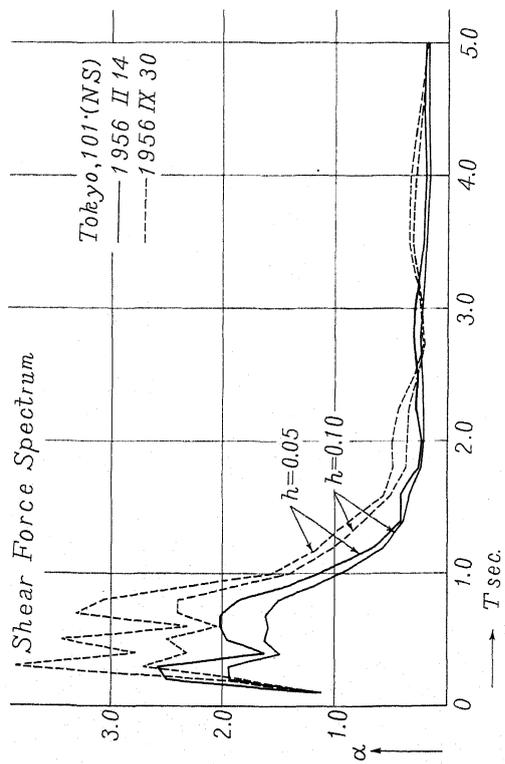


Fig. 2-7

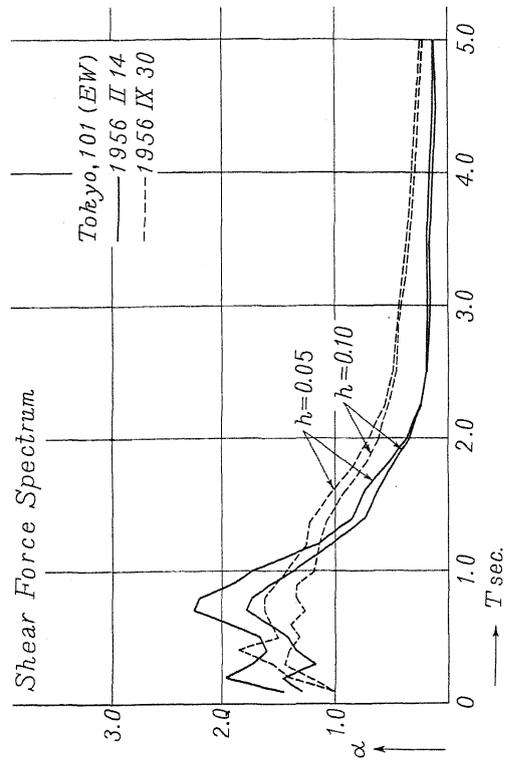


Fig. 2-8

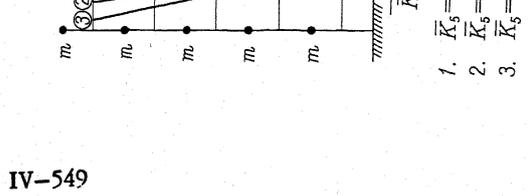
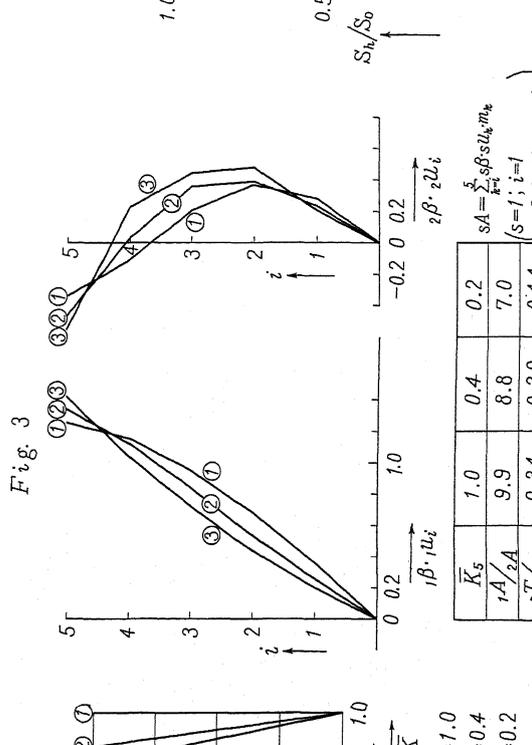
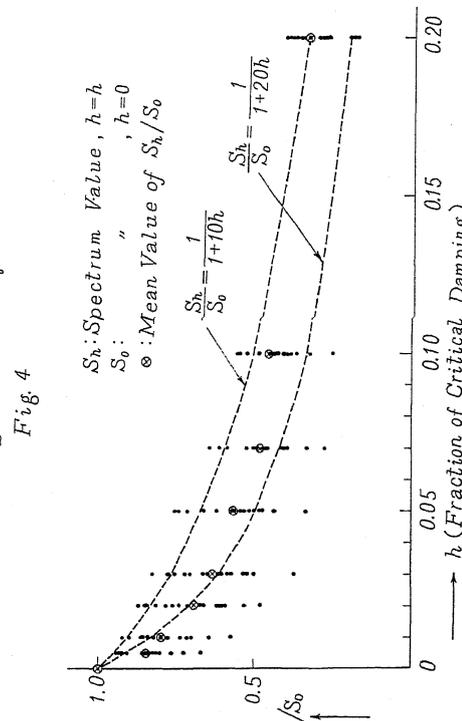
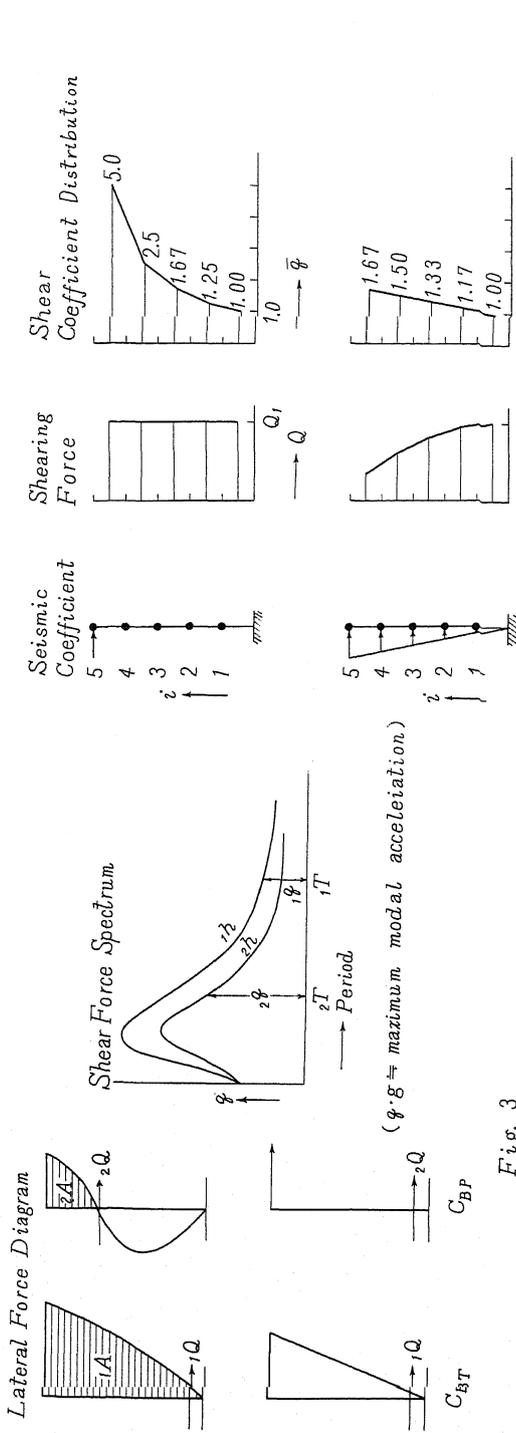


Fig. 4 Fig. 5 Fig. 6 Fig. 7 Fig. 8

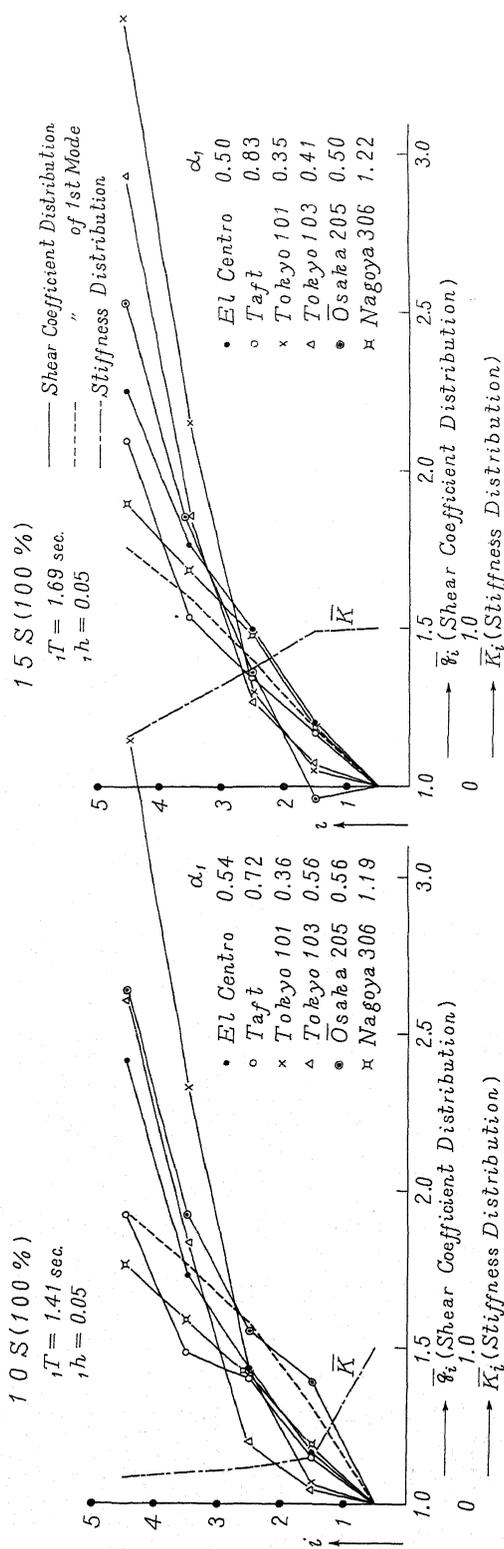


Fig. 7-1

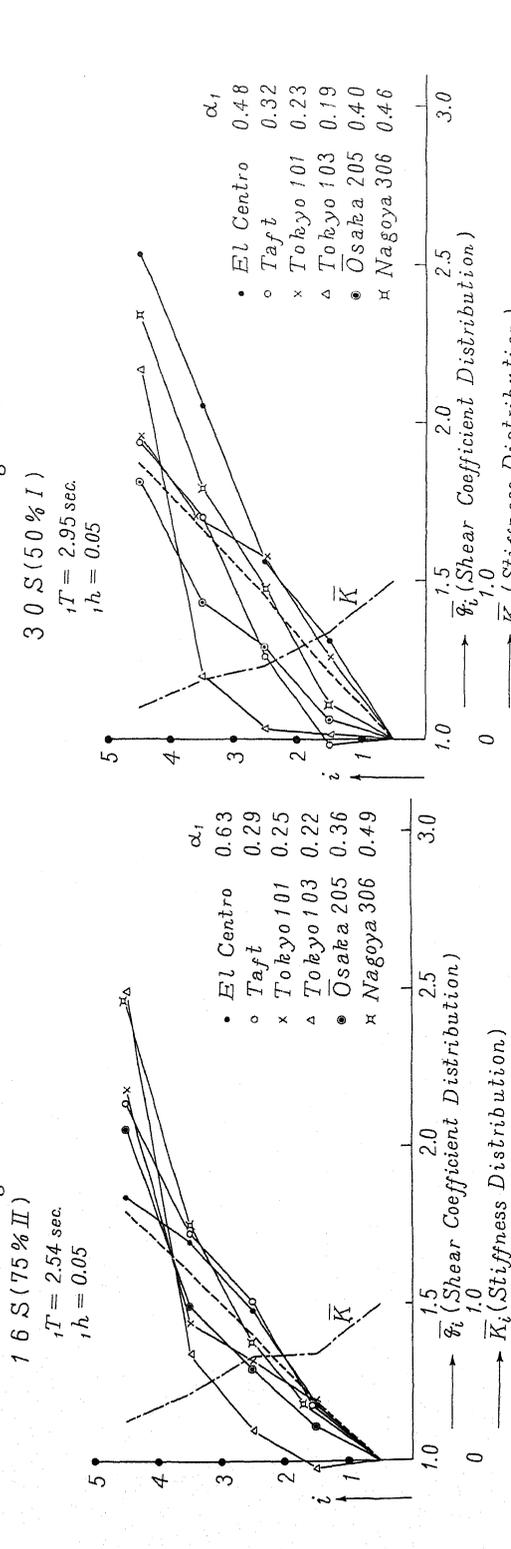


Fig. 7-3

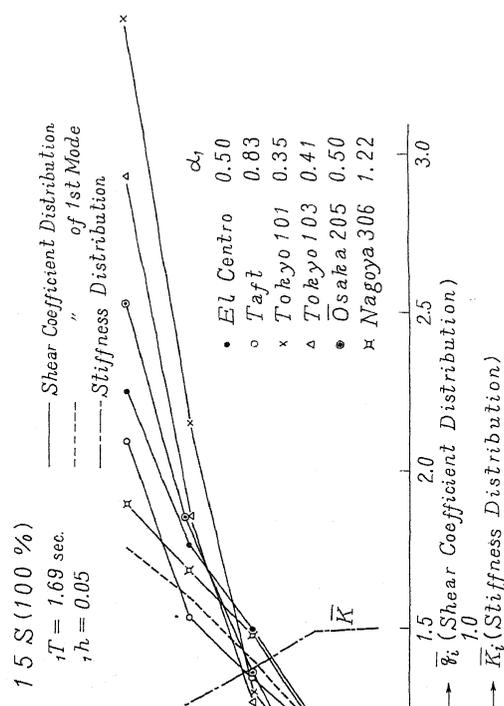


Fig. 7-2

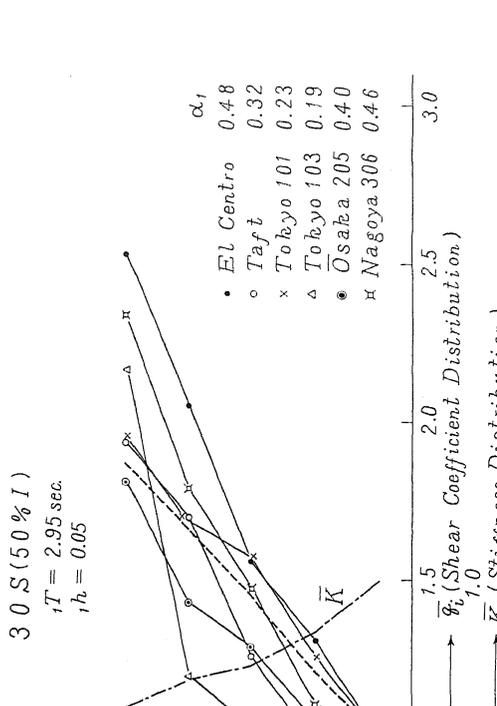


Fig. 7-4

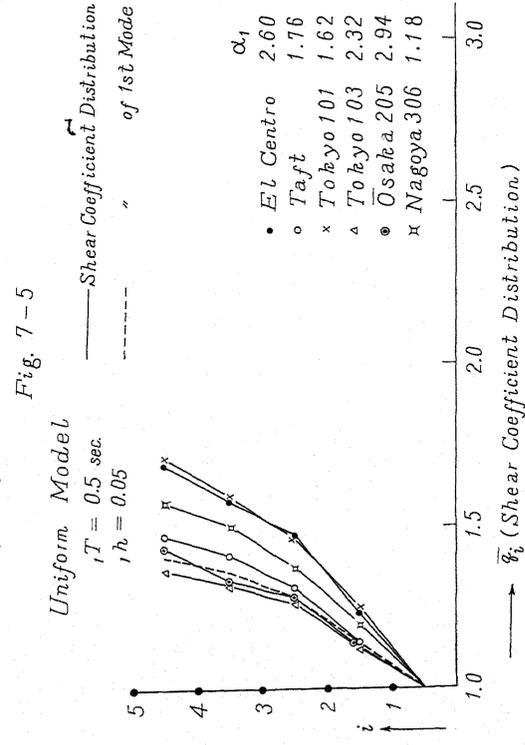
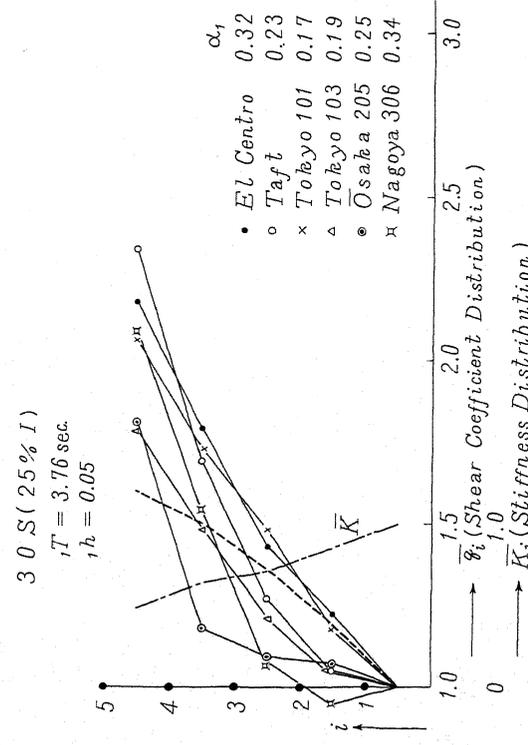
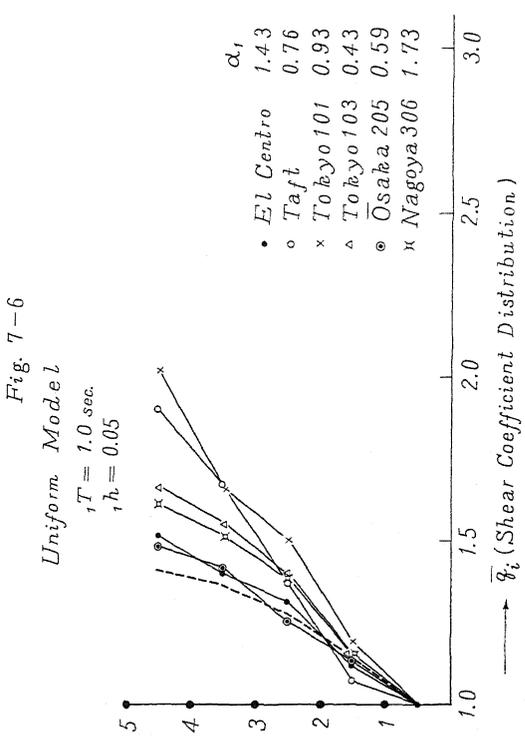
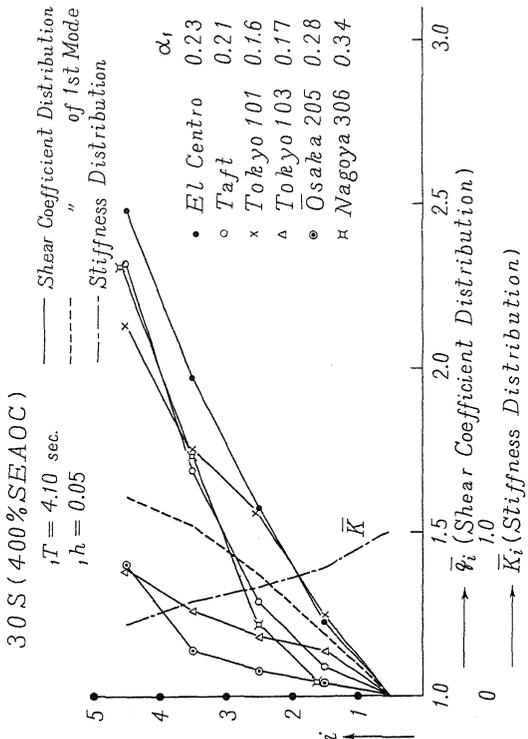


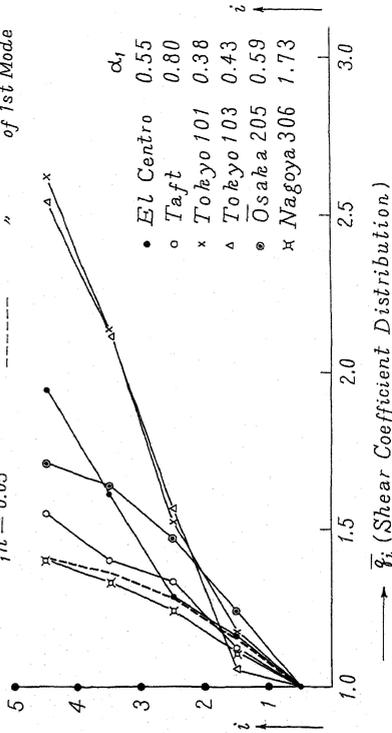
Fig. 8-2

Fig. 8-1

Uniform Model

$T = 1.5$ sec.
 $h = 0.05$

— Shear Coefficient Distribution
- - - " of 1st Mode

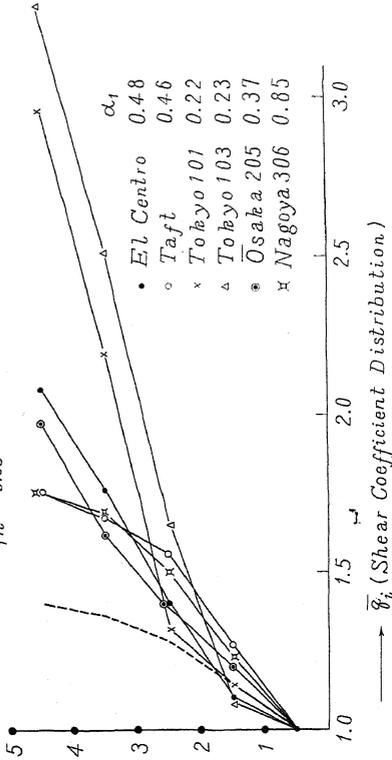


- El Centro 0.55
- o Taft 0.80
- x Tokyo 101 0.38
- Δ Tokyo 103 0.43
- Osaka 205 0.59
- x Nagoya 306 1.73

Fig. 8-3
Tokyo 101 $\epsilon \phi$.

Uniform Model

$T = 2.0$ sec.
 $h = 0.05$



- El Centro 0.48
- o Taft 0.46
- x Tokyo 101 0.22
- Δ Tokyo 103 0.23
- Osaka 205 0.37
- x Nagoya 306 0.65

Fig. 8-4
Tokyo 103 $\epsilon \phi$.

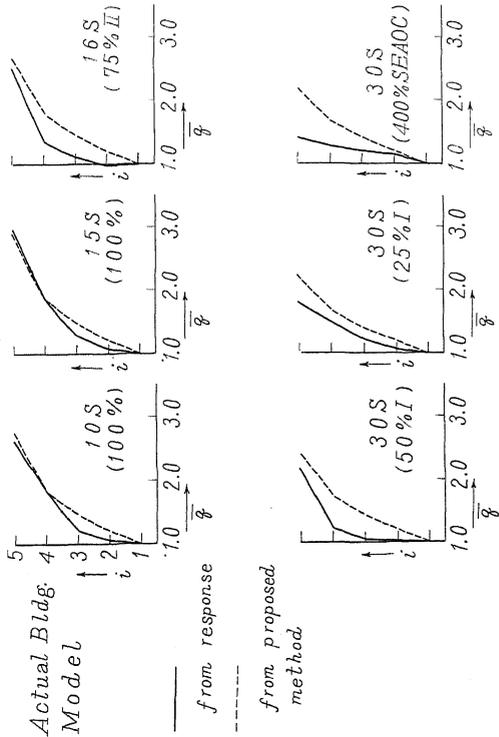
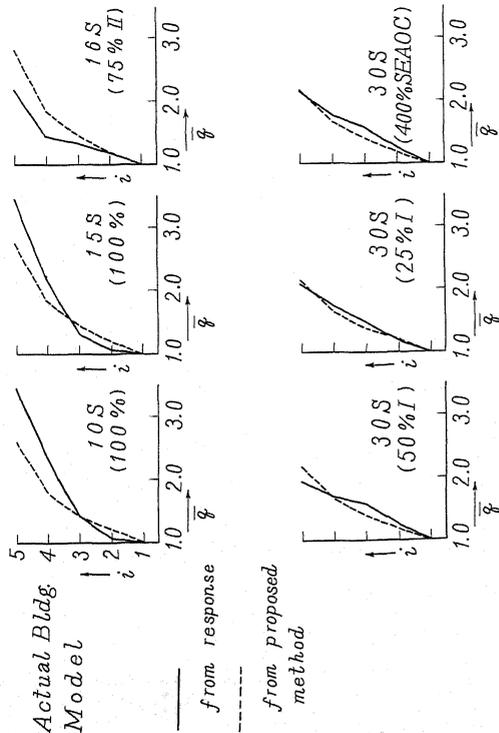


Fig. 9-1

Fig. 9-2

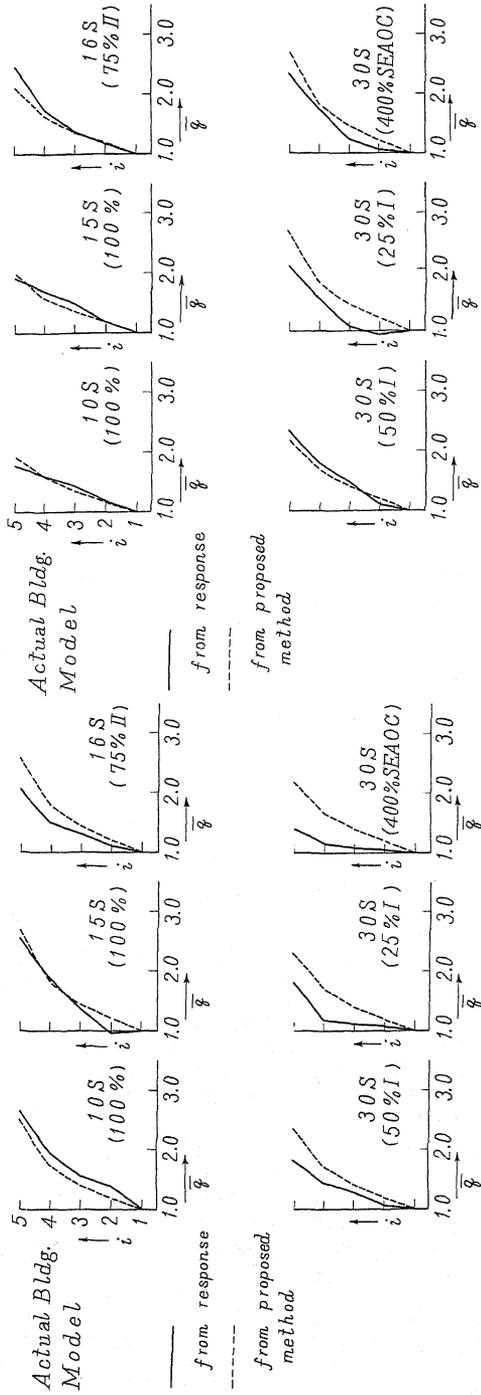


Fig. 9-3
Tokyo 101 Εφ.

Fig. 9-4
Tokyo 103 Εφ.

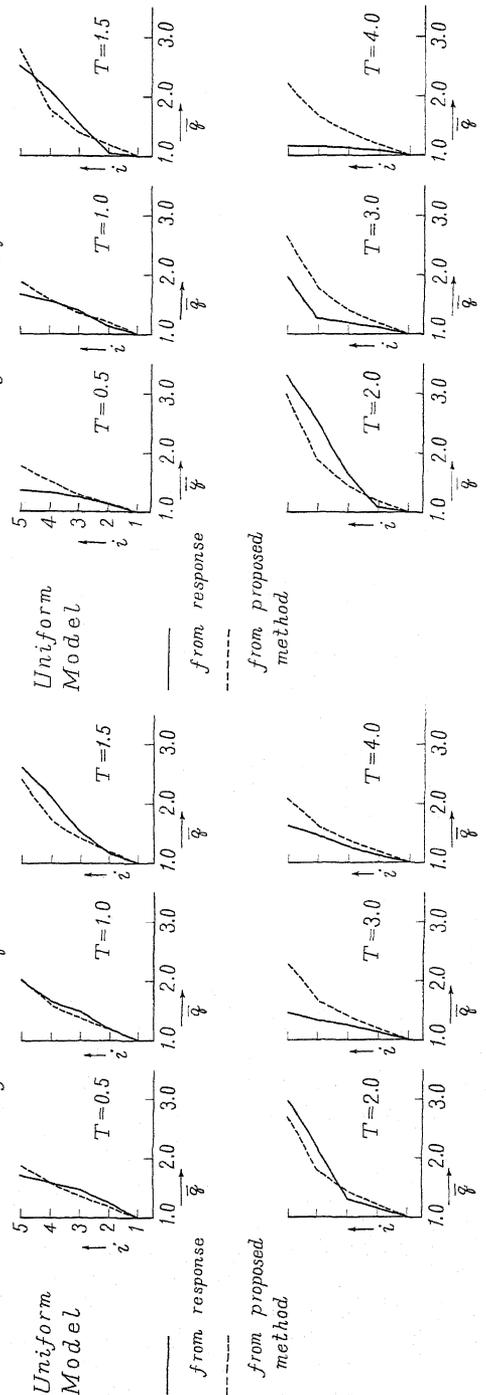


Fig.10-1

Fig.10-2

Table 1. Detailed Data of Earthquakes

District	Site	Date		Com- ponent	Max. Acc. (gal)	Du- ration (sec)	Distance from Epicenter (km)	Epicenter
Tokyo	101	1956	II 14	NS EW	74 61	10 10	20	35.7°N, 139.9°E Depth: 50km
Tokyo	101	1956	IX 30	NS EW	35 54	20 20	20	35.5°N, 140.2°E Depth: 70km
Tokyo	103	"	"	NS	49	20		"
Osaka	205	1963	III 27	NS	23	20	130	35.8°N, 135.8°E Depth: 20km
Nagoya	306	"	"	NS	12	20	130	"

Table 2. List of Frames in the Project of Buildings Used in the Response Analysis

Symbol	Designed by	Number of Stories	Structure	Design Seismic Force	Fundamental Period
10S (100%)	Obayashi Construction Co.	10	Steel Framed	100% of Japan Bldg. Code	1.41sec
15S (100%)	Mitsubishi Estate Co.	15	Steel Framed	100% of Japan Bldg. Code	1.69
16S (75%II)	Mitsui Group	16 + B4	Steel Framed	Base shear: 75% of Japan Bldg. Code Shear Coef. distribution: determined from response analysis	2.54
30S (50%I)	Mitsui Group	33	Steel Framed	50% of Japan Bldg. Code	2.95
30S (25%I)	Mitsui Group	33	Steel Framed	Base shear: 25% of Japan Bldg. Code Shear coef. distribution: determined from response analysis	3.76
30S (400% SEAOC)	Mitsui Group	33	Steel Framed	400% of SEAOC Code	4.10