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5-4-14 DYNAMIC CHARACTERISTICS OF LARGE STRUCTURE 'JOYO' DEEPLY EMBEDDED IN QUATERNARY GROUND AND EVALUATION OF EMBEDMENT EFFECT

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SUMMARY

Forced vibration test (FVT) and earthquake observation of a large structure were performed which is deeply embedded in quaternary ground. Dynamic behavior of 'JOYO' under FVT showed some characteristics due to deep embedment. Dynamic stiffnesses and dampings of base and side grounds were obtained using FVT data, which were used in earthquake response analysis. FVT simulation by half-space theory with some modifications brought sufficient result. Earthquake response analysis using mass-spring system revealed the followings, that is, the calculated responses mostly agreed with observed ones, provided that the recorded motion at the underground which has the same depth as the foundation was used as an input wave.

INTRODUCTION

It is one of the important subjects for aseismic design of reactor buildings constructed on/in quaternary grounds to grasp earthquake response characteristics and to examine the aseismicity of deeply embedded structures.

From such viewpoint, ground survey, FVT and earthquake observation of deeply embedded large structure 'JOYO' were performed. In this paper, dynamic behavior of JOYO under FVT is characterized, the method to evaluate complex dynamic reactive coefficients of ground using FVT response curves is devised and certified and applicabilities of theoretical methods to simulate dynamic behaviors of the structure under FVT are examined.

Then, dynamic behaviors of the structure during earthquakes are summarized and earthquake response analysis by mass-stick model is performed with the attention to the effect of side ground stiffness and what should be taken as input waves.

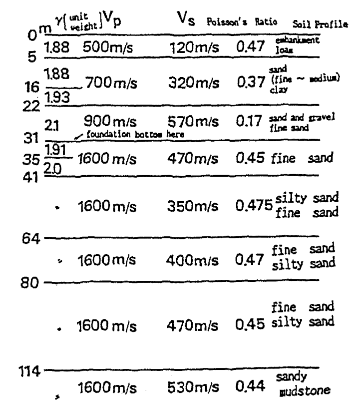


Fig.1 Ground Structure Obtained from Seismic Prospecting

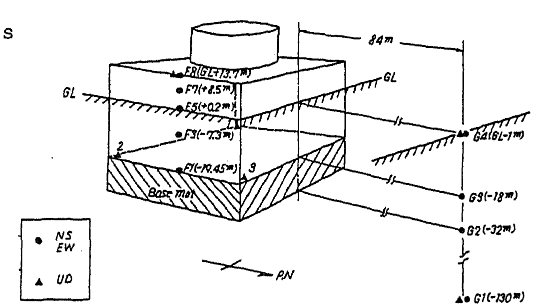


Fig.2 Arrangement of Eqk. Observation Points

FORCED VIBRATION TEST AND ITS ANALYSIS

Outline of FVT The site ground mainly consists of sand and sandy gravel up to the depth of 114m, underlain by sandy mudstone (Fig.1). The oscillated structure is 50mx55m in plane, 58.5m in height, about 170 kilotons in weight and is embedded more than 50% of total height in sandy ground (Fig.2). It mainly consists of accessory building, reactor bldg. and containment vessel. So, design model consists of 3 sticks and the foundation (Fig.3). The exciter was installed on the roof of accessory bldg. and the structure was oscillated both horizontally and vertically

Table 1 From Various FVTs on R/B

Varieties of Excited R/B	Dimension of Foundation	Total Height	Embedment Depth		Shear Wave Velocity	1st Natural Values		Displacement Ratio of 1st Mode		
			Embedment Depth	Percentage		Natural Frequency	Modal Damping	Sway	Rotation	Building Deformation
A	70 m x 70 m	80.7 m	25.2 m	31%	470 m/s	2.8 Hz	15%	12%	60%	28%
B	75.5 m x 75.5 m	75.3 m	17.5 m	23%	410 m/s	2.7 Hz	29%	13%	66%	21%
C	52.3 m x 50 m approx.	62.8 m	16.0 m	25%	1220 m/s	5.6 Hz	7%	6%	15%	79%
D	φ20 m	40.6 m	16.5 m	41%	500 m/s	6.7 Hz	25%	8%	62%	30%
E (JOYO)	49 m x 54 m	58.5 m	31.8 m	54%	465 m/s	4.3 Hz	56%	28%	65%	7%

with the exciting eccentric moment varied several steps from 2.9 to 154kg·m.

Measured points were arranged so as to be able to get horizontal and rotational behaviours of all grids in design model. The total number of measured points came up to 120 components in each of horizontal and vertical FVT. Reappearance of the phenomena in the different trial of FVT was certified with standard point measured at every trial. In addition, it was made clear that phenomenon was linear within the above mentioned exciting force.

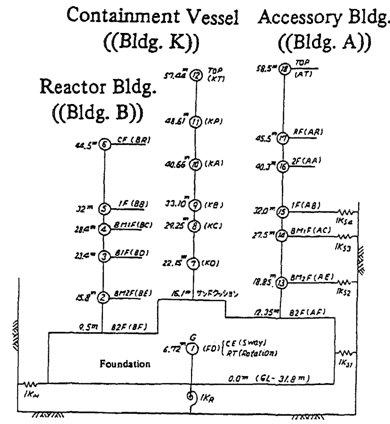


Fig.3 Design Model

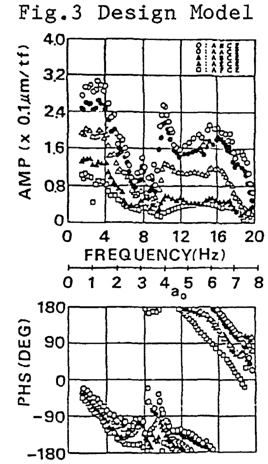


Fig.4 Response Curves from Horizontal FVT

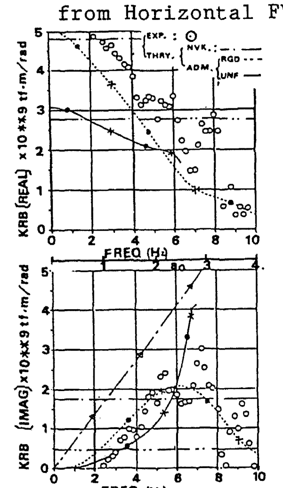


Fig.5 Reactive Coefficients K_{RB} - Exp. & Cal.

Dynamic Characteristics of Deeply Embedded Structure under FVT Horizontal and rotational displacement response curves of each grid in horizontal FVT and vertical displacement response curves of each grid in vertical FVT were successfully got, including both amplitude and phase lag (Fig.4). It is usually more difficult to get response curves of good quality in vertical FVT than in horizontal FVT from viewpoint of grasping SSI characteristics, as structural rocking and floor deformation are apt to occur, both of which often play interfering role to get good response curves in vertical FVT, but here in JOYO, also vertical FVT was successful. After applying data reduction method, the following may be pointed out as dynamic characteristics of deeply embedded structure under FVT. (1).In horizontal FVT, the 1st mode was predominant, which showed coupled sway-rotational mode with the responses of all grids almost the same phase (Fig.4), and rotation was the main in the 1st mode shape. When compared with other excited buildings, modal damping of JOYO is the largest, and bldg. deformation ratio is the smallest (Table 1), both of which are the dynamic characteristics of deeply embedded structure in quaternary ground. (2).In vertical FVT, the structure also behaved rigidly, and the 1st natural frequency was 3.2Hz, which was lower than that from horizontal FVT, which is worthy of note as the characteristics of deeply embedded structure. The 1st modal damping was also very large (74%), and the 1st mode was definitely predominant.

Evaluation of Complex Dynamic Reactive Coefficients in Case of Embedded Structure The method to calculate dynamic reactive coefficients of the ground from response curves obtained from FVT, with mass, rotational moment of inertia and height of each floor known, and without using element stiffness of the structure, is, for example, written in Ref.5), in case of surface foundation. On the other hand, when embedded deeply, 4 unknown reactive coefficients exist, that is, K_{HB}, K_{RB}, K_{HS} and K_{RS}, (Subscripts mean the followings. H:Sway, R:Rotation, B:Base, S:Side)

So, solutions couldn't be obtained only from two equilibrium equations relating to sway and rotation of total system. The method was devised[1)] to calculate 4 reactive coefficients directly from FVT response curves in case of embedded structure, introducing the following assumption, that is, the complex ratios of $K_{HB}:K_{HS}$, $K_{RB}:K_{RS}$ are assumed after theory. Owing to these assumptions, 4 unknown reactove coefficients can be directly calculated out from horizontal FVT response curves (Fig. 5). Recalculation of response curves was performed with obtained reactive coefficients given to the structure model. Experimental response curves were well simulated covering principal frequency range of excitation (Fig.6). Thus the above-mentioned method to evaluate reactive coefficients directly from FVT response curves was proved to be valid enough. The same method was applied to vertical FVT, and better result was obtained.

<u>Application of Theoretical Methods to Simulate Structural Behavior under FVT</u> The method developed by M. Novak[4)] and elastic half-space theory by H. Tajimi[5)] (VAT for short, hereafter) with necessary modification[1)] were applied to simulate dynamic behavior of the structure under FVT. In both applications, the analysed system was transposed to the structure and a uniform side layer both underlain by elastic half-space. Tajimi's stratification correction method[5)] was used in this transposition. In applying modified VAT, contact pressure distribution and contribution coefficient from both sides α were tried parametrically. Thus, applying theoretical methods, reactive coefficients of both base and side grounds were obtained (Fig.5), which agreed approximately with those from experiments especially when contact pressure distribution was assumed rigid and α=2. Response analysis during FVT with theoretically obtained reactive coefficients given brought approximate agreement with experiment from the viewpoint of

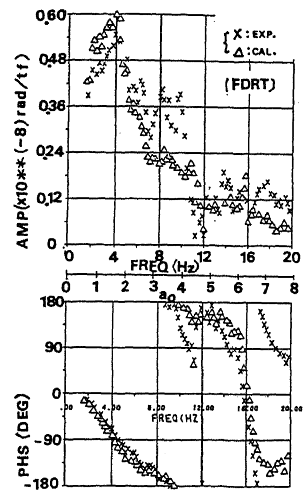
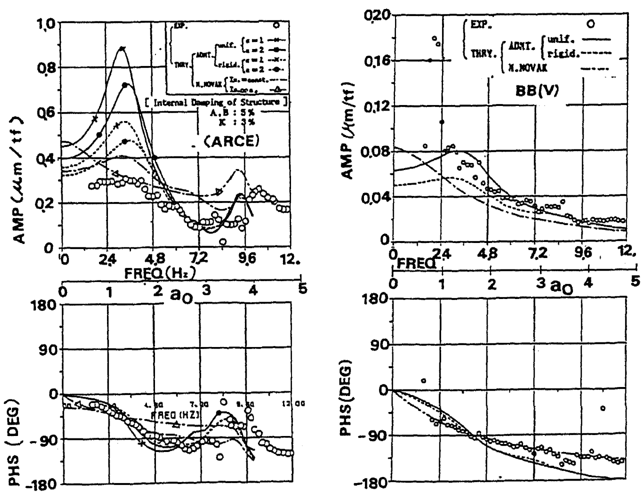


Fig.6 Recalculated Response Curves - Exp. & Cal.



(1) Horizontal FVT (2) Vertical FVT

Fig.7 FVT Simulation by Modified Half-space Theory

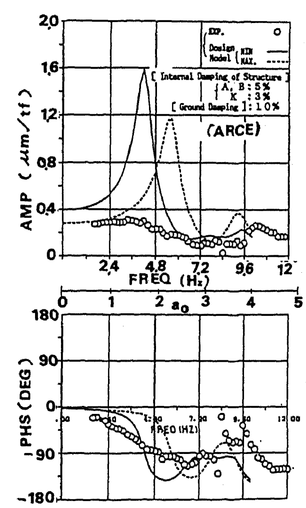


Fig.8 FVT Simulation with Design Condition

resonant frequency and amplitude (Fig.7(1)). The situation was similar also for vertical FVT case (Fig.7(2)). Thus theoretical methods based on elastic half-space theory were proved to have good applicability.

Table 2 List of Observed Earthquakes

Eq.No.	Time occurred	Epicenter Location	Latitude	Longitude	Focal Depth (km)	Magnitude	Epicentral Distance (km)	Hypocentral Distance (km)	Max. Acc. on the Ground Surface (gal)	Remarks
01	85/07/29 03:06:05	FUKUSHIMAKEN OKI	37° 3.9′	141° 14.5′	52	4.7	107.9	119.5	5.10	
02	85/07/29 04:33:42	FUKUSHIMAKEN TŌBU	37° 18.5′	140° 41.5′	90 △	5.5	116.6	146.9	17.78	Anal.
03	85/09/09 20:09:36	IBARAGIKEN OKI	36° 22.3′	140° 58.7′	41	3.7 △	39.6	56.9	5.65	
04	85/10/04 21:26:04	IBARAGIKEN NANBU	35° 52.1′	140° 9.5′	78	6.1	56.7	96.1	34.06	Anal.
05	85/10/13 02:22:07	IBARAGIKEN OKI	36° 40.2′	141° 19.1′	44	5.0	81.7	92.6	13.95	Anal.
06	85/10/17 22:06:34	SAITAMAKEN TŌBU	35° 52.1′	139° 52.5′	67	4.5	75.6	100.6	6.88	
07	85/10/26 15:14:48	IBARAGIKEN NANBU	36° 10.7′	140° 23.1′	69	4.3	18.2	71.3	6.18	
08	85/11/19 01:09:05	IBARAGIKEN OKI	36° 38.7′	140° 59.5′	51	4.2	57.5	76.8	7.18	Anal.
09	85/11/22 13:17:09	IBARAGIKEN NANSEIBU	36° 01.9′	139° 58.6′	52	4.9	58.3	77.9	8.60	Anal.
10	85/12/21 20:21:34	IBARAGIKEN HOKUBU	36° 30.4′	140° 32.0′	56	3.6 △	27.1	62.2	5.10	
11	86/01/11 02:52:19	IBARAGIKEN OKI	36° 41.9′	141° 13.6′	46	4.3	76.9	89.5	8.27	Anal.
12	86/02/12 11:59:40	IBARAGIKEN OKI	36° 25.0′	141° 05.0′	44	6.1	50.1	66.6	51.32	Anal.
13	86/02/12 12:47:18	IBARAGIKEN OKI	36° 23.3′	141° 02.2′	44	4.1	45.1	63.0	6.55	
14	86/02/14 10:25:55	IBARAGIKEN OKI	36° 23.7′	141° 10.3′	42	4.5	57.0	70.7	4.18 △	
15	86/03/02 16:10:10	MIYAGIKEN OKI	38° 28.2′	142° 18.9′	33	6.0	290.2 △	291.3 △	6.87	
16	86/04/05 09:29:54	MIYAGIKEN ENGAN	36° 29.0′	140° 39.0′	56	3.9 △	25.8	61.7	9.30	
17	86/05/05 22:27:37	FUKUSHIMAKEN OKI	36° 55.2′	141° 31.4′	78	4.9	113.0	136.9	11.48	
18	86/05/15 02:11:59	FUKUSHIMAKEN TŌBU	37° 31.9′	140° 43.4′	83	4.9	141.5	163.5	10.63	
19	86/06/24 11:52:57	BŌSŌHANTŌ OKI	34° 49.4′	140° 43.2′	73	6.5	160.4	175.2	15.53	
20	86/07/10 11:10:47	IBARAGIKEN CHŪBU	36° 12.9′	140° 35.9′	81	4.8	6.7	81.3	27.85	

Consideration on Design Condition Applying design condition, structure responses during excitation were calculated and compared with experimental responses (Fig.8). In design, ground stiffnesses had value ranges, so both cases were tried where all coefficients take maximum values, and where all are minimum. Damping constants in design were 5% for concrete structure, 1% for steel structure and 10% for SSI. As is shown in Fig.8, 1st natural frequencies from experiment and from design may be looked upon as equivalent, but maximum amplitude from design condition was far larger than that from exp., indicating that damping constant for SSI in design (=10%) was fairly conservative.

EARTHQUAKE OBSERVATION AND ITS ANALYSIS

Outline of Observation As is shown in Fig.2, observed points were arranged both in/on the ground and in the structure. Observed points in/on the ground were about 84m off from the structure wall, and 4 points G_1~G_4 were set up (G.L.-130m, -32m, -18m, -1m each). G_1 is in the bedrock consisting of sandy mudstone, G_2 is as deep as foundation bottom and G_4 is almost on the ground surface. Those in the structure were F_1 on the foundation (-19.45m), F_3(-7.3m), F_5(0.2m), F_7(8.5m) and F_8 on the roof (13.7m). Vertical components at the corner of the foundation were also observed to detect foundation rotation. Total observed components were 24. Observation started Jul. '85 and about 20 seismic records were got during about a year. Table.2 shows list of observed earthquakes, magnitudes of which are mostly 4~5 which often have their epicenters off the coast of Ibaraki-Pref. 4 of them have larger magnitude than 6. Maximum acceleration on the ground surface was 51gals at Eqk. No.12, and 2nd largest was 34gals at Eqk. No.4. Others are not so large but dynamic range of measurement system is 100dB, so records are accurate enough as a whole.

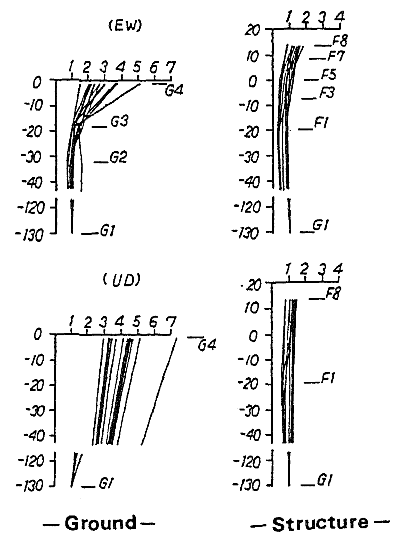


Fig.9 Max.Acc. Distribution (Normalized at G1)

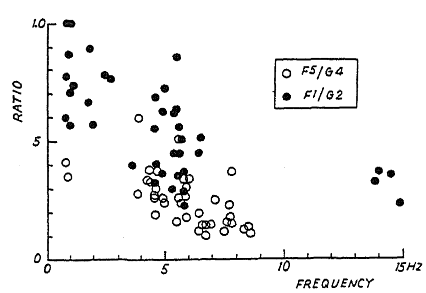


Fig.10 Max.Acc. Ratio between Str./Gr. (Same Level)

Some Characteristics from Observation Fig. 9 shows distribution of amplification factor when maximum acceleration at bedrock (G_1) is set 1. Maximum acceleration of horizontal component in ground was amplified mainly at the shallower region than -18m, and on the ground surface, amplification ratio was about 2~3 against bedrock. On the contrary in the structure, only a bit of amplification was recognized above the ground, but almost no amplification was observed under the ground.

Also in vertical component, there was some amplification in ground, but almost no in the structure. Fig.10 shows maximum acceleration ratio between structure and ground (horizontal component). The ratio is all less than 1.0, and it decreases as frequency increases, which is so-called 'low-pass filtering effect'. Similar phenomena were observed at other large structures[2)3)]. The studies in the past by the authors[2)3)] revealed that it was caused by the impedance ratio between the ground and the foundation. The 7 earthquakes were selected in which maximum ground surface accelerations were large enough, Fourier spectra of them were got and transfer functions between observed points were got as the average of Fourier spectral ratio. Transfer function between roof and foundation (F8/F1) had its spectral peaks around 4, 8, 10Hz, which are well coincident with those from FVT. Fig.11 shows 2 transfer functions F1/G4 and G2/G4, where G4 is ground surface, F1 is foundation and G2 is in the ground which is as deep as foundation bottom. Both have similar tendencies against frequency except the range higher than 10 and a few Hz, starting around 1.0 at low frequency range, decreasing quickly as frequency increases, and remaining around some constant value far less than 1.0. This similarity suggests that the behaviours of embedded foundation during earthquakes could be estimated approximately from the underground motion which is as deep as the foundation.

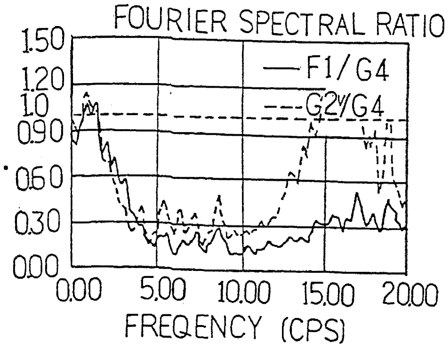


Fig.11 Transfer Functions: Foundation & Underground against Grd.Surface

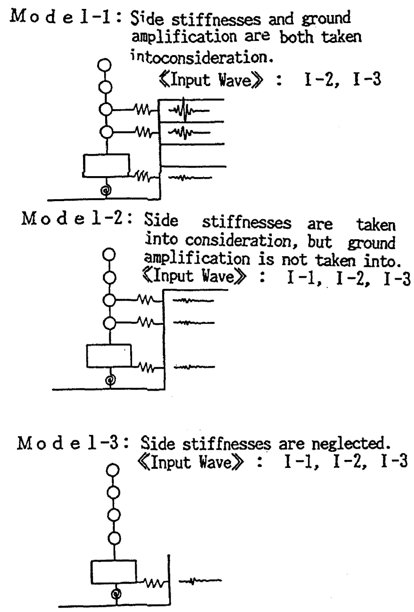


Fig.12 Three Kinds of S-R Models

<u>Earthquake Response Analysis</u> Simulation analyses for dynamic behavior during earthquakes were performed using mass-spring system in order to examine what is the effect of input and model variation paying attention to embedment effect. Eqk. No.2,4, 12 in Table.2 were used for the analysis. As model variation, 3 types of models were tried (Fig.12). In Model-1, embedment side stiffnesses and ground amplification were both taken into account. In Model-2, side stiffnesses were taken into account but ground amplification was not, that is, input waves from the side stiffnesses were the same as that from the base. In Model-3, side stiffnesses were neglected. As to not only embedment side stiffnesses and dampings but base stiffnesses and dampings both for sway and rotation, the evaluated values directly from FVT response curves were used. Then as input waves, also 3 kinds were tried. As I-1 input, the wave recorded on the ground surface (G4) was used. As I-2, the wave recorded at G2 was used which was as deep as the foundation. As the last one, I-3 was the calculated wave at the foundation bottom level which was looked upon as open to the air. So 8 sorts of simulations were performed with models and input waves variation combined, except the combination of Model-1 and I-1, as the case is not realistic. Nodal data and member properties of the structure model were taken from design model with slight modification, so that the structure behaviors under FVT may be simulated well by it.

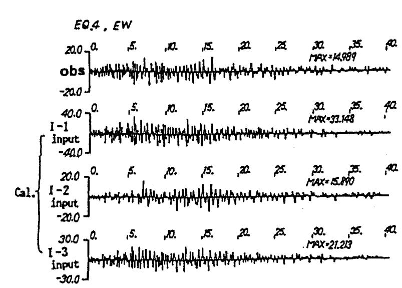


Fig.13 Waves at Roof(M-3, EQ.4, EW) - Obs. & Cal.

Result from Earthquake Response Analysis Fig.13 shows an example of calculated waves (at the Roof(F8)) with Model-3 and input wave varied, in which the result from I-2 input was the best as far as maximum acceleration is concerned. Wave forms look more or less similar with observed wave. Fig.14 shows the results from all the cases, with the calculated max.acc.at the roof divided by observed one in the y-axis and with input wave variation in x-axis. It shows that roof response with I-1 input > that with I-3 input > that with I-2 input ≒ observation irrespective of models and earthquakes. Fig. 15 shows difference of calculated responses due to model variation in the case of I-2 input, in which clear distinction due to model variation could not be recognized. So, from the investigation performed here, the following may be concluded, that is, what should be taken as an input wave is more influential on the estimation of responses of deeply embedded structure during earthquakes than what should be taken or not as side gound stiffnesses, and that the recorded motion in the underground which is as deep as structure foundation may be the most suitable as an input wave in the cases where the structure is embedded and the structural mass-stick model is such as that in this paper. And it is useful for design purposes to know that even a simple mass-spring system might roughly estimate dynamic behaviors of embedded structures during earthquakes so long as recorded motion in the underground as deep as structure foundation is used as an input wave.

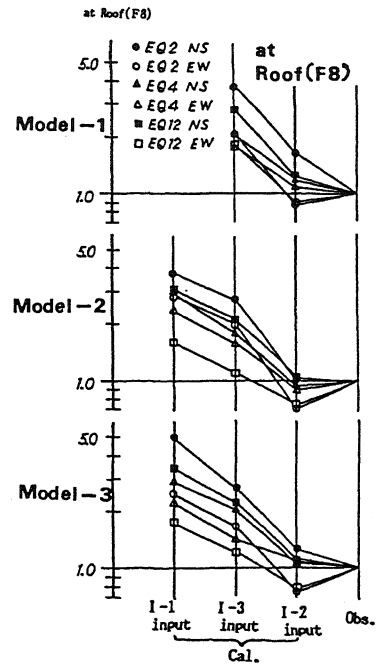


Fig.14 Max.Acc. Ratio due to Model & Input Variation

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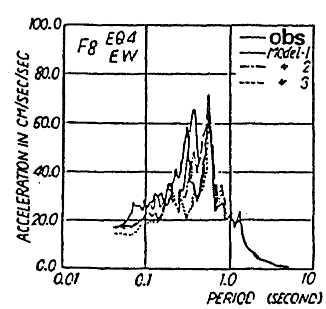
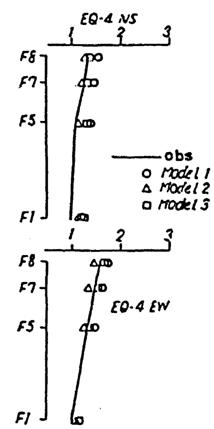


(1) Acc. Response Spectra



(2) Max.Acc. Distribution

Fig.15 Influence of Model Variation (I-2 Input)