EXPERIMENTAL PROJECT OF SOIL-STRUCTURE INTERACTION USING THE FOUNDATION OF NUPEC LARGE VIBRATION TABLE - VIBRATION OF FOUNDATION AND GROUND, DYNAMIC EARTH PRESSURE AND WAVE PROPAGATION -

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SUMMARY

This project research was conducted as a joint research by Nuclear Power Engineering Test Center (NUPEC) and Central Research Institute of Electric Power Industry (CRIEPI) to demonstrate the applicability of some analysis methods to dynamic interaction between a large-scale foundation and sand-and-gravel ground by obtaining measured values. The behavior of the foundation and that of the surrounding ground of the large vibration table located in Tadotsu-cho, Japan, during exciting and natural earthquakes were examined. At the same time, simulations were made using the 2-D and 3-D vibration analysis methods. The calculated results and the measured results were collated with each other to demonstrate the applicability of the analysis methods.

PERFORMANCE OF THE VIBRATION TABLE AND SIZE OF THE FOUNDATION

The performance of the vibration table is as shown in Table 1. The foundation of the vibration table is a box-shaped reinforced concrete structure with a projection in the center, measuring 90.9 m × 44.8 m × 21 m and weighing 150,000 tons (Fig. 1).

GROUND UNDER THE FOUNDATION OF THE VIBRATION TABLE

The foundation has been built on an diluvial deposit of 161 m thick formed on granite bedrock. The ground is a well-compacted almost horizontal diluvial sand and gravel ground, with some cohesive soil layers scattered within (Fig. 2).

The shearing wave velocity (Vs) of the gravel layer at GL-21m directly below the foundation is 330 m/sec, and Vs increases together with the depth. The standard penetration N value (S.T.P.N value) of the ground was 40 to 50. Sand and gravel materials were used in back filling of the surrounding area of the foundation, and the back fill was compacted by sand compaction piles.

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LAYOUT OF INSTRUMENTS AND DATA RECORDING

In order to measure accelerations of the foundation and of the surrounding area during earthquake, servo type accelerometers were installed for 30 channels altogether; 4 accelerometers on the foundation and 8 accelerometers on the surrounding area (Fig. 3). The recorder used was equipped with a 12-bit A/D converter and a binary gain amplifier. This measuring system was capable of recording of earthquakes from 10 mgal to 1 gal and over. In addition to them, 18 accelerometers of 36-ch type were temporarily installed on the foundation and 19 accelerometers of 39-ch type on the ground surface so as to measure the behavior of the ground and in turn to make measurement during exciting of the vibration table (Fig. 4). 43 bottom earth pressure gauges and lateral earth pressure gauges [3] installed beforehand during construction were used to measure dynamic earth pressure during exciting.

ANALYSIS METHODS USED IN SIMULATIONS

The following methods were used to simulate the behavior during exciting:

① Dr. Tajimi's theory based on the assumption that circular footing rests on the elastic half space [7];
② 2-D F.E.M. complex dynamic analysis method (program name: BES-I)[4];
③ 3-D F.E.M. complex dynamic analysis method (program name: TB3D-I)[4]; and
④ Tajimi's thin layered method by application of 3-D point load solution.

Further, the following methods were used to simulate the behavior during earthquake:

⑤ Multiple reflection theory [5]; and
⑥ 3-D F.E.M. complex dynamic analysis method (program name: TB3D-II)[6].

The model of 2-D F.E.M. complex dynamic analysis method (BES-I) developed by CRIEPI was provided with lateral pseudo three dimensional dampers so as to achieve three dimensional effects (Fig. 5). The 3-D F.E.M. complex dynamic analysis program (TB3D) was developed to execute vibration analysis of foundation and ground of complex shape and structure in a relatively short time. Accordingly, the model of this analysis program limits 3-D modelling to the subject of analysis, representing the circumference and the bottom with axisymmetric co-ordinate model, and setting a transmitting boundary on its circumference (Fig. 6a). In order to reduce distorsion due to discontinuity in element shape occurring in elements near the boundary between the 3-D region and the axisymmetric regular region, Fourier 1st mode deformation only was allowed for the deformation of the boundary elements (Fig. 7). As for the method of ④, a separate report will be presented in the conference by Dr. H. Tajimi.

RESULTS OF EXCITATION EXPERIMENTS [2),3)]

The behavior of the foundation and the surrounding ground was measured during test excitation for checking the performance of the vibration table. Various test excitations were made, and the detailed examination of data was mainly focused on 200 gal sweep excitation for both vertical and horizontal excitations. The behavior of the foundation and that of the ground were examined in terms of phase lag at each measuring point to exciting force, and response curve of the vibration table, etc.

For both horizontal and vertical excitations, the primary resonance frequencies of the foundation were 2 Hz (Figs. 8 and 9), and it was found that the foundation exhibited second-degree sway-rocking vibration in this frequency range since the horizontal component of the acceleration on the foundation during horizontal excitation at 2 Hz was same phase, and the vertical component was the opposite phase at both edges of the foundation (Fig. 10). As for the acceleration distribution during vertical excitation, it was found that at 1 to 2 Hz, the amplitude of the central portion of the foundation was a little larger than that of the edge portions and the phases were the same at the center and the edges. At 8 Hz, however, the phase of the vibration at the center was completely opposite to those at edges of the foundation (Fig. 11), and in the higher frequency ranges, the vertical amplitude was larger than the horizontal one even during a horizontal excitation. From these findings, it was revealed that an apparently very rigid foundation exhibited high frequency mode vibration of elastic plate in higher frequency ranges. This was also indicated by the relationship between dynamic earth pressure distribution and vibration.

RESULTS OF SIMULATIONS OF EXCITATION EXPERIMENTS

The simulations of the horizontal excitations were made by the abovementioned analysis methods ① to ④. The physical properties of the ground used in the analyses using BES-I and TB3D-I were postulated as shown in Table 2, on the basis of a subsurface exploration.

The analytical model using TB3D-I was assumed to be symetrical as shown in Fig. 6b. In this case, the number of nodes of the three dimensional region including the material particle models of the vibration building was 479, and the number of elements was 291. The results of the simulation based on TB3D-I and the conventional vibration theory of rigid plate on open elastic ground demonstrated that the behavior around the first resonant point was able to be simulated satisfactorily. On the other hand, 2-D vibration analysis using BES-I failed to simulate displacement response and phase-lag curve satisfactorily, apparently due to overestimation of damping factor for well embedded foundations (Fig. 8).

RESULTS OF SEISMIC OBSERVATION AND ANALYSIS [5), 6)]

Three earthquakes were observed during a period from December, 1980 to July, 1981. The observed epicenters and magnitudes of these earthquakes were as shown in Fig. 12. Since Fourier spectrual ratios of horizontal components on the foundation (P1) to those of the ground (P10) were almost the same for these three waves, the mean spectral ratio was obtained. On the other hand, the same spectral ratio was obtained by applying the multiple reflection theory to the foundation which was assumed to be an infinite elastic ground. It was confirmed that the simulation was in almost good agreement with the observed values (Fig. 13).

As to Fourier spectral ratios of the foundation to the ground surface (P1/P7), the spectral ratios of both X and Y components were extremely small above 1 Hz, and the low-pass-filter-like aseismic effect of the foundation was confirmed (Fig. 14). On the other hand, as to vertical component of earthquake, no definite aseismic effect was observed. It might be due to small wave impedance ratio for P wave.

Horizontal components of earthquakes were simulated by 2-D F.E.M. BES-I, 3-D F.E.M. TB3D-II and the multiple reflection theory, and spectral ratios (P1

/P7) were obtained from the results as shown in Fig. 15. The analysis of these results also indicated that the above-mentioned methods were able to make good simulation of average spectral ratio (Pl/P7) obtained by seismic observation.

CONCLUSION

On the basis of the results of the research described above, the following conclusions were reached to:

(1) The apparently very rigid reinforced concrete foundation built on sand and gravel ground exhibited sway-rocking vibration in lower frequency ranges, but it exhibited complicated vibration behavior as an elastic plate in higher frequency ranges.

(2) As to the horizontal component, the foundation exhibited low-pass-filter-like aseismic effect during earthquake, but its effect on vertical component was rather small. It was confirmed that the multiple reflection theory was able to predict the aseismic effect of the foundation rather easily.

(3) It was indicated that the behavior was able to be simulated by traditional elastic theory and the 3-D F.E.M. TB3D-I developed by CRIEPI for lower frequency ranges. It was also demonstrated that the developed programs TB3D-II and BES-II were able to simulate the behavior of the foundation on sand and gravel ground during earthquake.

(4) Further efforts are needed to develop and demonstrate methods for analyzing vibration during great earthquakes that produce non-linear phenomena.

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Table 1. Main Performance of the Vibration Table [1]

Item		Performance
1) Max Loading Capacity		1 000 ton
2) Table	Size	$15^m \times 15^m \times 3.5^m$
	Weight	600 ton
3) Excitation Directions		X Horizontal Z Vertical Simultaneously
4) Max Stroke Max Velocity	Horizontal	± 20cm , 75cm/s
	Vertical	± 10cm , 37.5cm/s
5) Max Acceleration	Horizontal	2,970 Gal (500 ton Inertia Load) 1, 800 Gal (1,000 ton Inertia Load)
	Vertical	1,335 Gal (500 ton Inertia Load) 900 Gal (1,000 ton Inertia Load)
6) Excitation	Horizontal	3,000 tonf
	Vertical	3,300 tonf
7) Frequency Range		0— 30Hz

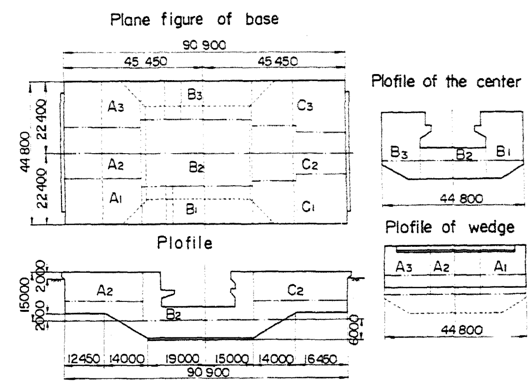

Fig. 1 Notation of the foundation of vibration table.

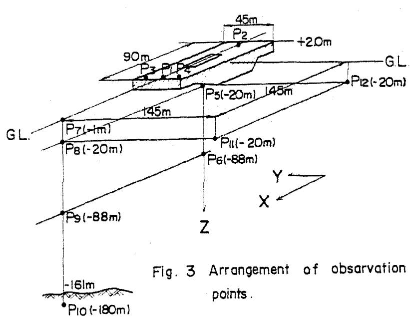

Fig. 3 Arrangement of obsarvation points.

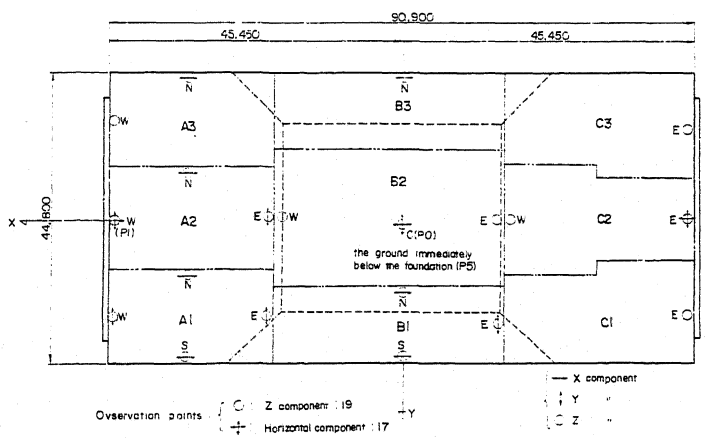

Fig. 4 Arrangment of observation points for the foundation at vibration test.

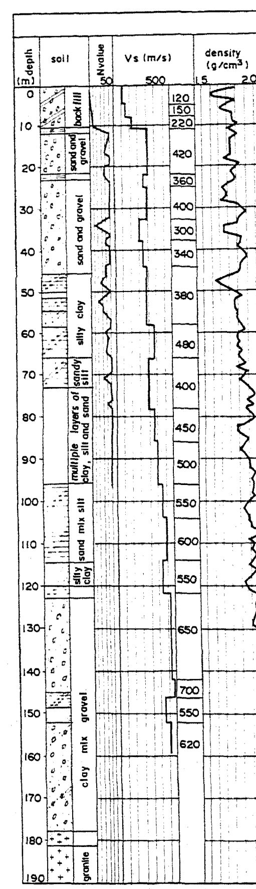

Fig. 2 Main soil profile of the Tadotsu site.

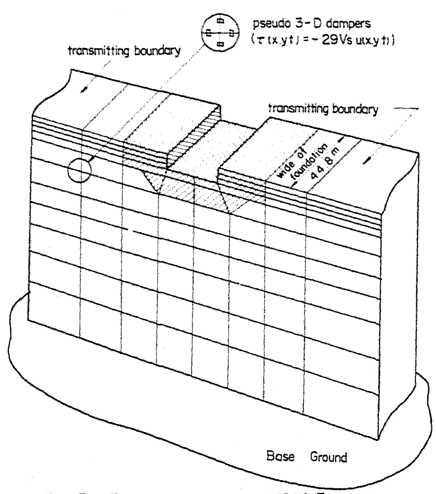

Fig. 5 Two dimensions model (BES II model)

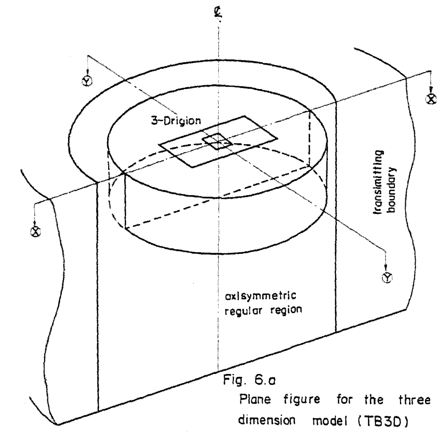

Fig. 6.a
Plane figure for the three dimension model (TB3D)

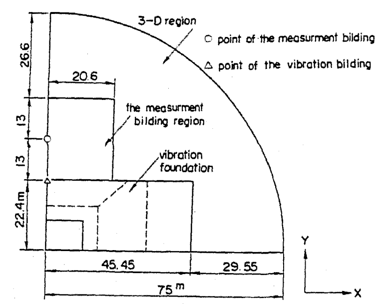

Fig. 6.b Plane figure for the three demension model (TB3D)

Table.2 Physical coefficient of soil layers at the Tadotsu site.

depth (m)	thickness of layer (m)	Vs (m/sec)	G (t/m³)	density		damping ratio	number of division	f max (Hz)
	2	119	2600	1.8	0.484	2.5%	8	13.6
0	12	119	2600	1.8	0.484			
−12	8	402	33000	2.0	0.454		2	20.1
−20	2	321	21000				1	32.1
−22	13	377	29000				3	17.4
−35	24	357	26000				5	14.9
−59	7	480	47020		0.462		1	13.7
−66	12	400	32653		0.476		2	13.3
−78	8	450	41327		0.470		2	22.6
−86	10	500	51020		0.466		2	20.0
−96	8	550	61735		0.463		1	13.8
−104	10	600	73469		0.452		2	24.0
−114	8	550	61735		0.458		1	13.8
−122	20	650	86224		0.450		2	13.0
−142	4	700	100000		0.437		1	35.0
−146	6	550	61735		0.459		1	18.3
−152	8	620	78449		0.447		1	15.5
−160								

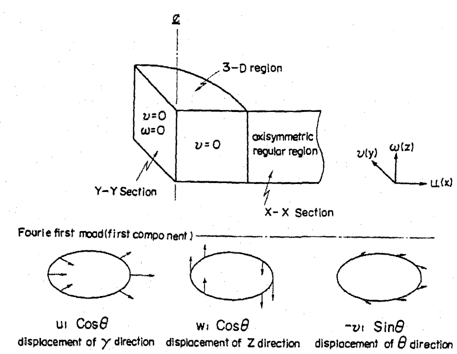

Fig. 7 Boundary condition for TB3D simulation at excitation (X-D rirection.)

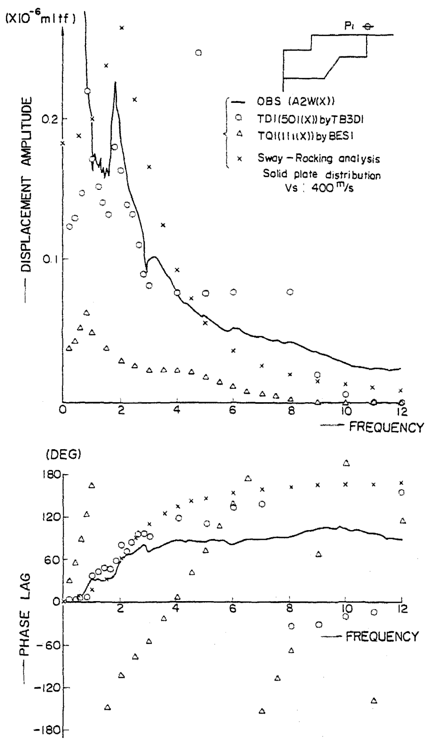

Fig. 8 Resonanse curve and phase lag test of X component of the wedge at horizontal exciting (comparison between the measured value and the caluculated value)

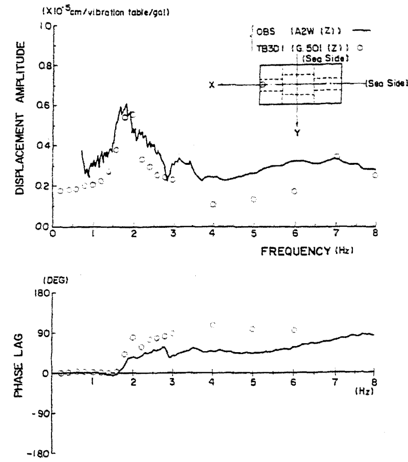

Fig. 9 Resonanse curve and phase lag curve of Z component of the wedge at horizontal exciting test.

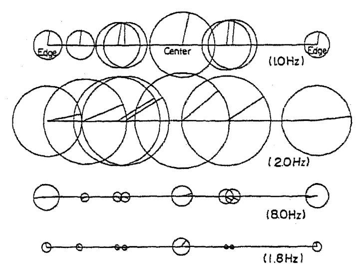

Fig. 11 Vibration distribution on X axis (Z component at vertical excitation)

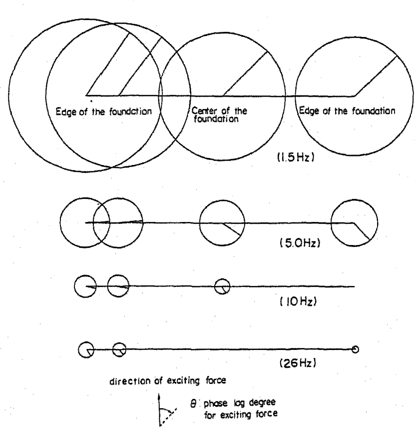

Fig. 10.a Vibration distribution on X axis (X component at horizontal excitation)

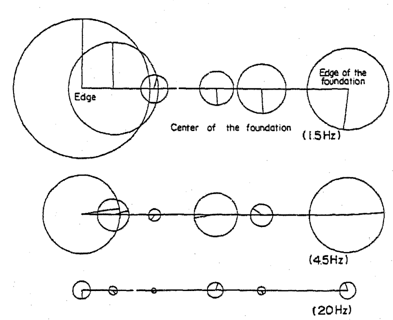

Fig. 10.b Vibration distribution on X axis (Z component at horizontal excitation)

EQ No.	Origin Time Y	M	D	h	m	s	Hypocenter LONG	LAT	H (km)	Hypocentral Distance km	M
1 A B	80	12	12	08	10	02.1	131°55'	32°23'	40	272.0	6.0
2	81	01	22	22	20	20.4	133°55'	34°57'	10	77.5	4.2
3	81	03	06	08	28	22.5	135°23'	33°49'	50	166.2	4.5

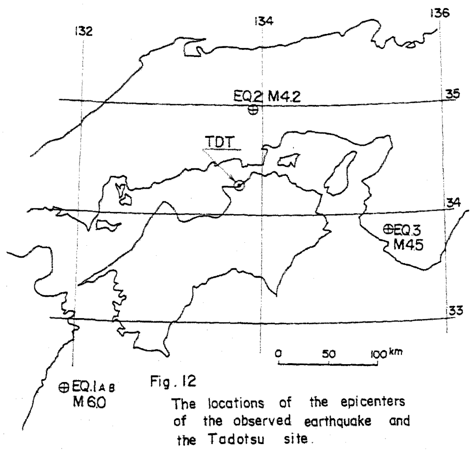

Fig. 12 The locations of the epicenters of the observed earthquake and the Tadotsu site.

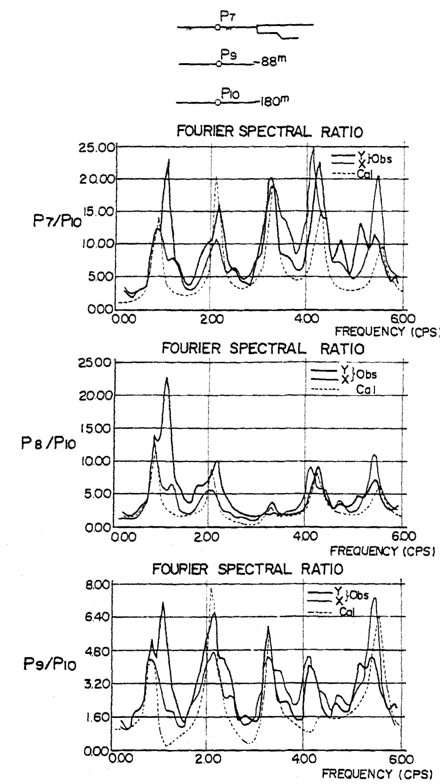

Fig. 13 Comparison of the measured value and the theoretical value (calculated by the multiple reflection theory) of the transfer function between the foundation and each observation point.

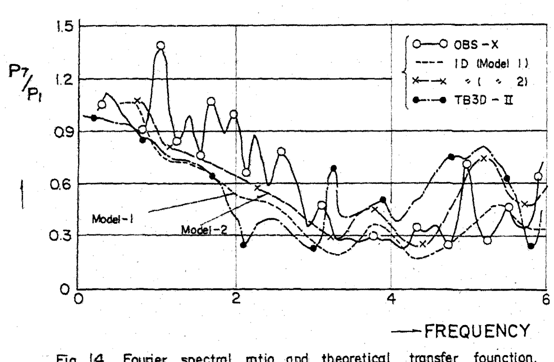

Fig. 14 Fourier spectral ratio and theoretical transfer founction. (Horizontal component between the ground surface and the foundation)