Vibration Tests of a Rectangular Concrete Foundation and its Analyses

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Abstract

Vibration test of a rectangular concrete foundation (15m x 15m x 12.5m) was carried out on the hardrock in order to elucidate the characteristics of soil-structure interaction (S.S.I.). The stiffness and the damping of S.S.I. were explained well by using the two-layered structure model arranged from the geotechnical investigations. The result of the simulation analyses based on the three-dimensional wave propagation theory showed good agreement with the vibration test results in the resonant frequencies, amplitudes and vibration mode shapes. Therefore it was proved that the analytical model and the analytical coefficients of rock and concrete were reasonable and that the three-dimensional wave propagation theory was valid.

1. Introduction

Soil-structure interaction is considered to be one of the major factors influencing the seismic response of rigid structures such as reactor buildings. Recently analytical researches in this field have been developing rapidly. In accordance with this trend, more and more effort has been put into experimental researches in order to investigate the validity of the theory.

Experiments on soil-structure interaction have been performed mostly on comparatively soft ground, with only a few cases on hard ground. Since reator buildings in Japan are constructed on hard ground, it is necessary to elucidate the characteristics of soil-structure interaction on hard ground and to investigate the validity of the theory.

With such a viewpoint, vibration tests on a rectangular concrete model of the structure was performed at a projected construction site for a reactor building and an analyses of the results were undertaken.

2. Test Conditions

2.1 Description of Test Model

The tests were performed on the hard rock near the projected construction site for the reactor building (BWR-Mark I). An excavation bottom with an area of 30m x 30m was provided, excavated to approximately 10m so that the top soil and weathered rock could be removed. On this a concrete foundation of 15m x 15m and height 12.5m was set diretly, as shown in Fig. 1. The dimensions and size of the foundation were such as to allow for limitations of the test method as determined by preliminary discussion of the experiment. In addition, the tests and the accompanying analysis have indicated that there was no infuence of the side slopes to experiments.

Three kinds of test on the concrete material were undertaken: test pieces sampled during construction of the concrete foundation; core samples of the concrete taken after the tests; and the P-S log of the concrete block. The elastic moduli obtained from these tests are shown in Table I.

2.2 Description of Ground

The site exploration covered geological survey, P-S log, seismic prospecting, and core tests. For the geological survey, an observation of the geological feature of the surface ground at the excavated part and the surrounding area was made, and boring at three places was undertaken. For P-S log, P-S-wave velocity,* the damping factor and vertical distribution were investigated. As for seismic prospecting, the main object of investigation was the horizontal distribution of S-wave velocity near the surface ground. The density of the soil was obtained through core tests, and dynamic and static tests were conducted to compare the results with those of other in-situ tests.

Geologically the test site and its vicinity was composed of mainly massive tuff and tuff breccia, with a general strike and dip of N70° - 80°W/30° - 45°N and with a velocity distribution of horizontal layered structure. The rock immediately below the concrete foundation comprised two distinct parts: a loose stratum resulting from the excavation, and hard rock. The loose stratum was 1 - 2.5m thick with an average of approximately 1.2 m; the damping factor of the hard rock was 3%.

The results of the site exploration are shown in Table I, while the three-dimensional structure of the loose zone is shown in Fig. 2.

2.3 Test Method

Vibration tests were performed for three directions: N-S excitation, almost at right angles to the rock strike; E-W excitation lateral to this; and vertical excitation. Three different exctation forces were applied for comparison: constant 10t, constant 20t, and constant eccentric moment (i.e. $F \propto \omega^2$). The report on the vertical excitation has been ommitted as space is limited.

Displacement was measured at a total of 60 points covering the foundation, ground surface and underground; the earth pressure gauges, which were modified to allow for the high regidity and workability of the rock, were buried in the concrete in order to measure the pressure at bottom of the foundation. The number of measuring points was 21 for vertical earth pressure and 5 (10 components) for horizontal.

3. Test Results

3.1 Displacement Measurement Results

The peak resonant frequency and damping factors during the horizontal-excitation tests are listed in Table II, while the horizontal displacement resonance curves and phase-lag curves of the concrete top are shown in Fig. 3. Response amplitude was converted to unit excitation force (μ/t), and the phase-lag curve shows the lag to the excitation force (degrees).

It was found that the peak resonant frequency varied slightly with the magnitude of the exciting force and that the E-W peak resonant frequency was a little higher than the N-S. As an example of vibration-mode shapes of the foundation, the results of the N-S direction at a constant excitation of 10t are shown in Fig. 4. The bottom of the foundation remained as rigid plate, while elastic deformation to displacement at the top was 20%. Other tests showed similar results: in general, sway was 30%, rocking 50%, and elastic deformation 20%. This indicates elastic deformation in concrete foundation on hard ground is not negligible.

3.2 Results of Earth Pressure

The results for vertical and horizontal earth pressure of N-S direction are shown in Fig. 5

as examples of resonance curves and phase-lag curves of earth pressure; earth-pressure distribution at the peak resonant frequency is shown in Fig. 6. In addition, the horizontal earth pressure was calculated as the resultant force of a couple of earth pressure guages set on the facing 45° slope. The amplitude is converted to unit excitation force ($g/cm^2/t$); the phase lag is shown in terms of the lag relative to the excitation force, and corresponds closely with the displacement resonance curve and the phase-lag curve. The distribution characteristics are similar to those in rigid plates, where earth pressure becomes larger nearer the edges. The resultant force calculated using respective measuring points for this particular earth-pressure distribution was about seven-tenths of the overturning moment calculated using displacement measurement and excitation force. Similar results were also obtained in other tests. Considering the error arising from the fact that the points of measurement are 55 cm in from the edges and are concentrated in one-fourth of the foundation, the results are judged to be valid.

4. Analysis According to Three-Dimensional Wave-Propagation Theory

4.1 Comparison of Complex Stiffness of Ground and Three-Dimensional Wave-Propagation Theory

Using measured values of displacement, the complex stiffness (horizontal and rotational) of the ground was deduced, taking into account sway, rocking, and elastic deformation of the foundation. The results are compared with the theoretical value of the three-dimensional wave-propagation theory as follows:

(1) Comparison with the theoretical value as a semi-infinite homogeneous medium (Fig. 7)

Using the results of the site exploration as a reference, the theoretical values were fixed as: density γ=2.39 t/m^3, Poisson's ratio =0.438, shear-wave velocity V_s=600 - 1750 m/s. Vertical deformation of the bottom of foundation was set as rigid plane, considering measured values of earth pressure and displacement as a reference.

The real parts of sway are in the range V_s=1000 - 1300 m/s; and V_s=1000 - 1200 m/s for the range 10 - 20 Hz, which is close to the peak resonance. On the other hand, for the imaginary parts, V_s=600 m/s is generally in good accordance with experimental values. V_s=1000 - 1300 m/s, which is in good acordance in the real parts, is an overvaluation in the imaginary parts.

For the real parts of rocking, similar to sway, the range is V_s=1000 - 1300 m/s, with an average of approximately V_s=1100 m/s. There is no corresponding value in the imaginary parts.

The above results tend to indicate that there is no equivalent shear-wave veloity expressing both real and imaginary parts of sway and rocking when a simi-infinite homogeneous medium is assumed; and it has been suggested that there is an influence by the layered structure.

(2) Comparison with theoretical value with consideration of layered structure

During the site exploration, it was confirmed that there is a loose stratum with an average thickness of approximately 1.2m on top of the hard rock. Therefore, a parameter analysis, shown in Table III, was undertaken. Earth-pressure distribution is assumed to be the same as in (1); ground damping is taken as 0% and 3%, the latter figure being based on the results of site exploration. Since the hard rock consists of two alternate layers, i.e. V_s=1550 - 1600 m/s and V_s=2000 m/s, two values of V_s were adopted: 1500 m/s, considering the upper 6.5m; and 1750 m/s, considering the average of the deeper-part value.

For the real parts of sway, V_{s1}=600 m/s and V_{s2}=1750 m/s correspond closely with experimental values; while V_{s1}=600 m/s and V_{s2}=1500 m/s correspond more closely in the case of rocking.

For the imaginary parts, both the above values correspond roughly with the experimental values when an internal damping of 3%, obtained through P-S log, is estimated.

As a result of the above, it was concluded that the complex stiffness of the ground, which was derived through this test, can explain each of the real and imaginary parts of sway and rocking uniformly when the layered structure is adopted.

4.2 Simulation Analysis Considering Elastic Deformation

As the experimental values indicated that elastic deformation occurred in the concrete foundation, a simulation analysis was performed according to the analysis model shown in Table IV. The measured values listed in Table 1 were used as material constants for the concrete. The results are shown in Fig. 9.

The analytical value generally corresponds closely with the measure value in peak resonant frequency, amplitude and vibration-mode shape. Thus it was concluded that the analytical model and the analytical coefficients of material, e.g. the results of site exploration etc., are in general valid. Furthermore, as the measured value of the damping factor for the loose stratum of the surface ground was not provided, 3% -- the measured value for hard rock -- and its doubled value were adopted. Consequently the value was estimated to be 5%, the middle of these two.

5. Conclusion

This paper reports a comparison between features of soil-structure interaction obtained by means of excitation tests on a concrete foundation set on hard ground and the result derived by means of theoretical analysis. It indicates that the results of site exploration, the experimental values and the three-dimensional wave-propagation theory are all in good accordance and they can be expressed uniformly. It also proves the validity of the three-dimensional wave-propagation theory. The characteristics of dynamic interaction dealt with in the experiment are as follows:

i) In this experiment, in order to develop a theoretical discussion, it is necessary to apply a method which takes account of the layered structure, because the loose stratum resulting from excavation greatly affects the vibration characteristics of the concrete foundation.

ii) Complex stiffness arising from soil-structure interaction varies with frequency. Moreover, in the low-frequency range of sway and rocking, which has only slight radiation damping, the effect of the internal damping of the ground is relatively large; and this should be taken into consideration when explaining actualities.

iii) The distribution of earth pressure shows similar features to those of the distribution in rigid plates, where the amplitude increases closer to the structure's edge. Moreover, the resultant of measured earth pressure is almost equal to the overturning moment occurring at the bottom of the structure, which is calculated from displacement measurement; thus the earth-pressure measurement is considered to be valid.

iv) For tests on hard rock, it is possible that elastic deformation occurs in a concrete foundation, and this should be taken into account in complex stiffness discussion and simulation analysis.

6. Acknowledgments

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Table I Elastic Moduli of Rock and Concrete

		D (m)	Vp (km/s)	Vs (km/s)	r (t/m³)	ν
ROCK	PS LOGGING	0- 1.5	1.8	0.6	2.39	0.438
		1.5- 8.0	3.5	1.55	2.50	0.378
		8.0- 14.0	4.0	2.0	2.50	0.333
		14.0- 18.0	4.0	1.6	2.50	0.405
		18.0- 24.0	4.2	2.0	2.50	0.353
		24.0- 30.0	3.6	1.6	2.50	0.377
	*1	LOOSE	1.5	0.7	2.40	0.361
		HARD ROCK	3.5	1.5	2.50	0.388
CONCRETE			4.2	2.1	2.30	0.333

*1:SEISMIC PROSPECTING

Table II Resonant Frequency and Damping Factor

	EXCITING FORCE		FREQUENCY(Hz)	DAMPING h(%)
NS	CONSTANT FORCE	10t	14.8	6.4
		20t	14.6	6.5
	CONSTANT ECCENTRIC MOMENT	Max.=130t	14.0	6.4
		Max.= 7t	14.8	6.5
		Max.= 1t	15.0	6.0
EW	CONSTANT FORCE	10t	15.4	7.1
	CONSTANT ECCENTRIC MOMENT	Max.=110t	15.2	7.3-7.5
		Max.= 7t	15.9	6.7

Table III Analytical Model for Layered Structure

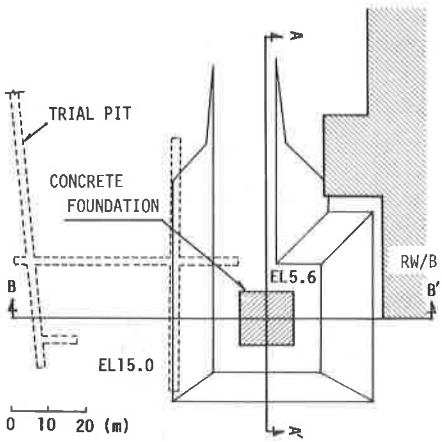
MODEL	NO	H (m)	Vs (m/s)	r (t/m³)	ν	h (%)
1st	1	1.2	600	2.39	0.438	3.0
2nd	2	∞	{1500, 1750}	2.50	0.369	3.0

Table IV Analytical Model for Concrete Foundation

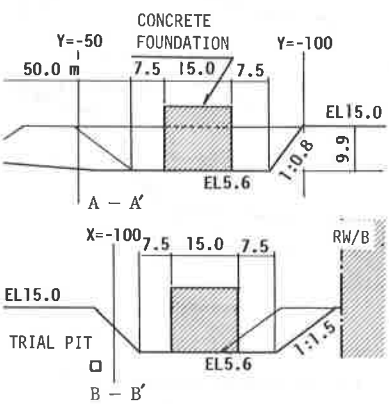
NO	H (m)	W (t)	Ig (t·m²)	J (m⁴)	A (m²)
1	14.125	27.1	26.5	∞	∞
2	12.89	526.5	9926	4218.8	225
3	10.89	1053.0	20115	4218.8	225
4	8.89	1118.8	21420	4218.8	225
5	6.64	1355.7	26196	4218.8	225
6	3.74	1534.7	29893	4218.8	225
7	0.81	992.5	18922	∞	∞
8	0.00	0	0		

Note;

H:Height , W:Weight , A:Area , h:Damping Factor
Vs:Shear Wave Velocity , r:Density , ν:Poisson Ratio
Ig:Rotatory Inertia , J:Geometrical Moment of Inertia
No.1:Vibration Generator , No.8:Foundation Bottom



(1) Plan



(2) Section

Fig. 1 Outline of Test Model

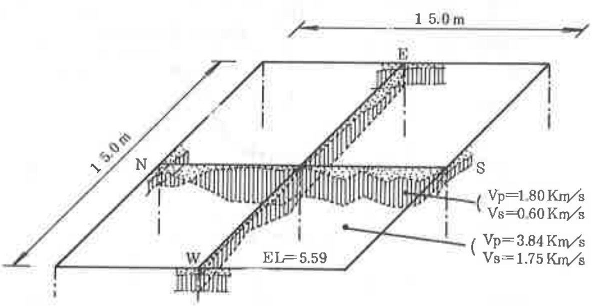
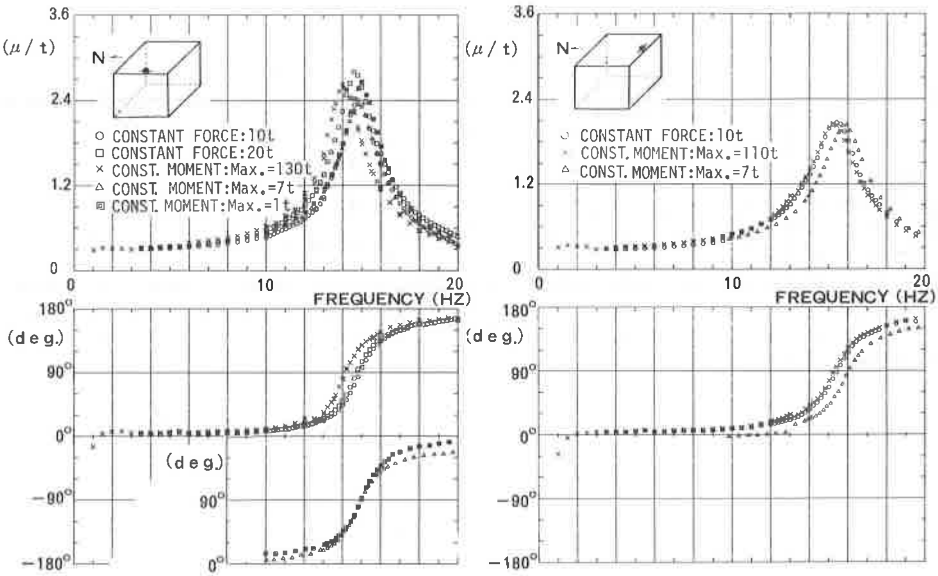
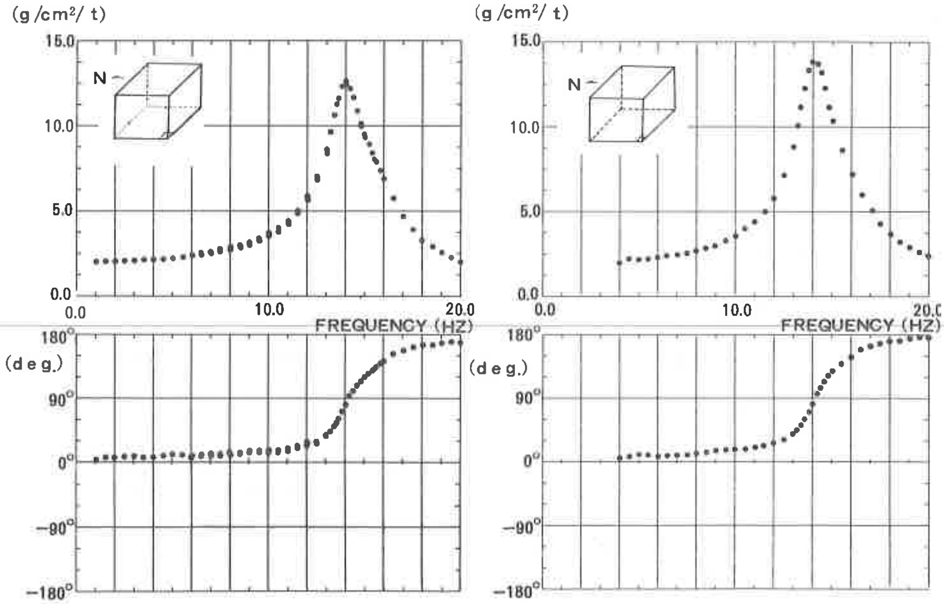


Fig. 2 Distribution of Loose Rock Resulting from Excavation



(1) N-S Direction (2) E-W Direction

Fig. 3 Resonance Curve and Phase-Lag Curve of Displacement



(1) Vertical Earth Pressure (2) Horizontal Earth Pressure

Fig. 5 Resonance Curve and Phase-Lag Curve of Earth Pressure

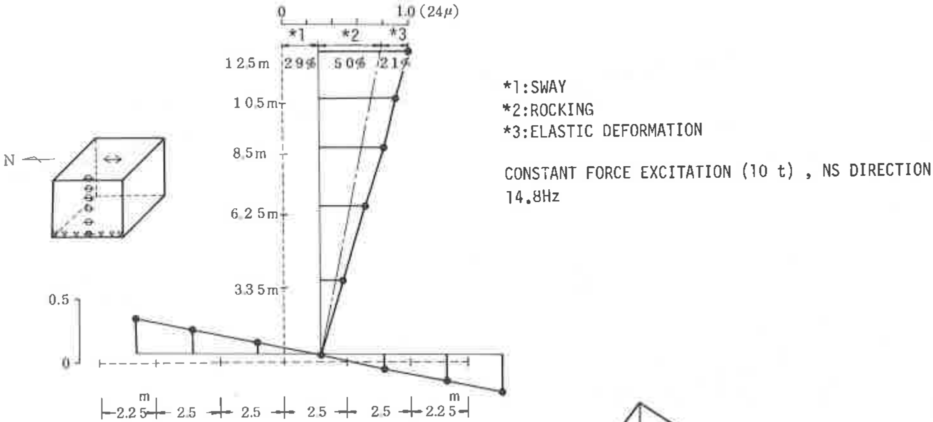


Fig. 4 Mode Shape at Resonant Frequency

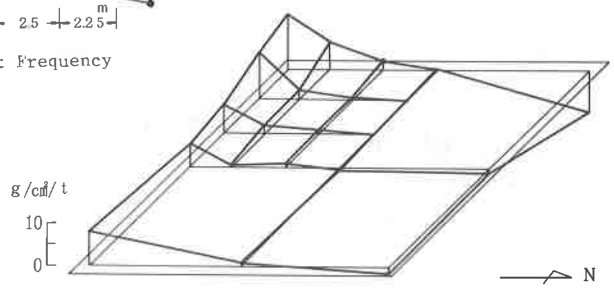
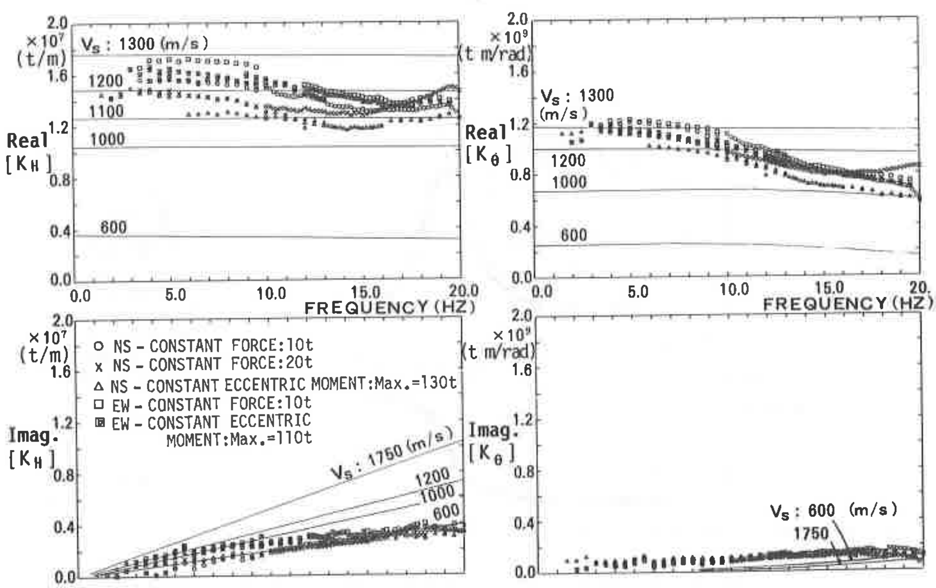


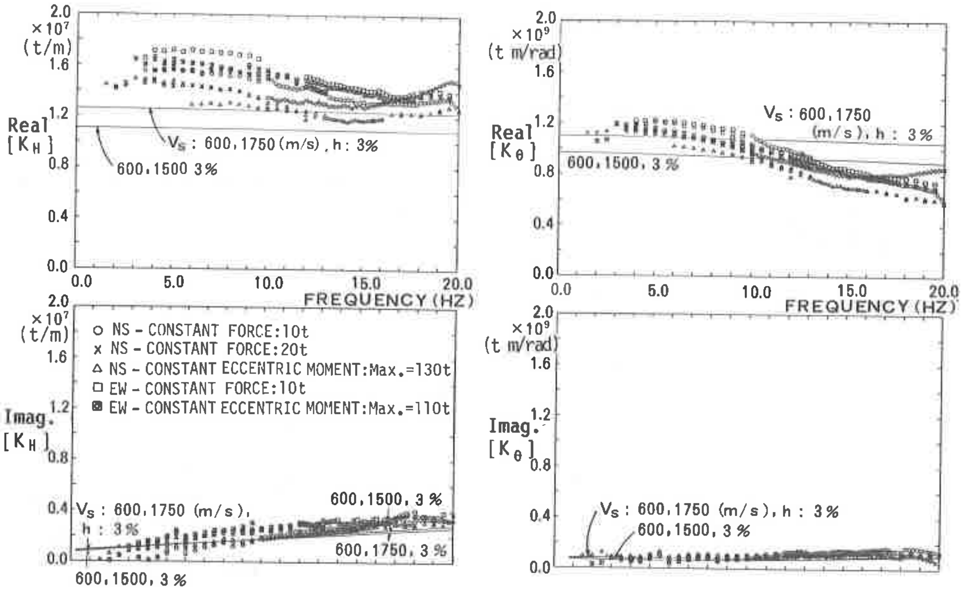
Fig. 6 Distribution of Vertical Earth Pressure at Resonant Frequency



(1) Complex Stiffness of Sway

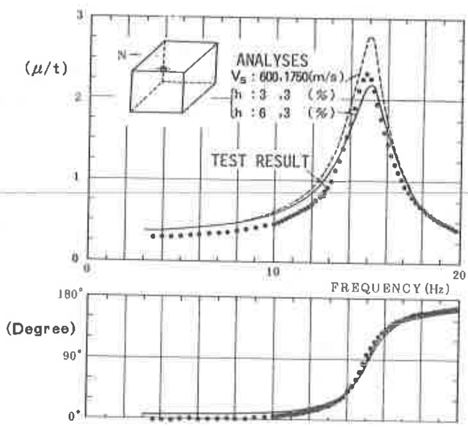
(2) Complex Stiffness of Rocking

Fig. 7 Comparison of Theoretical Values and Experimental Values of Semi-Infinite Homogeneous Medium

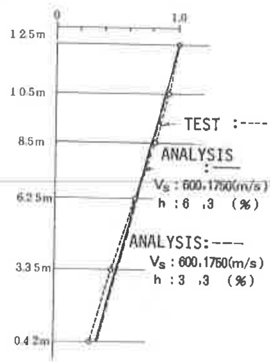


(1) Complex Stiffness of Sway (2) Complex Stiffness of Rocking

Fig. 8 Comparison of Theoretical Values and Experimental Values of Layered Structure



(1) Resonance Curve and Phase-Lag Curve of Displacement



(2) Mode Shape at Resonant Frequency

Fig. 9 Simulation Analysis using Layered Structure Model