Forced vibration tests of a model foundation on rock ground

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1 INTRODUCTION

The effect of the dynamic soil-structure interaction was investigated experimentally by forced vibration tests of a model foundation resting on rock surface. The experiment was carried out in 1985 at Tomari nuclear power plant site, Hokkaido Japan. The model foundation was made of reinforced concrete of 14m*14m in plan and 5m thick and the total weight was 2352 ton. The ground was made of two layers whose interface was inclined by certain degree from north-west to south-east. The forced vibration tests were carried out mainly by an exciter of maximum 4 ton force. Micro-tremor and micro-earthquake were also observed. In this experiment such special attention was paid for obtaining good traction data beneath the foundation as accurate calibration of pressure gauges at the site and the use of auxiliary exciter with larger capacity. Simulations are carried out by wave propagation theory and FEM. Simulated results can reasonably explain the experimental results and the dynamic soil-structure interaction effects in various aspects. Resultant forces and moments evaluated by experimentally obtained tractions with approximated polynomial distribution are in good agreement with those evaluated by displacements.

2 EXPERIMENTS

The ground consists of two layers with inclined interface. The shear wave velocities shown in Fig.1 are deduced from PS wave velocity test. The upper layer has the shear wave velocity of 900m/sec and the lower 1400m/sec respectively. The model foundation was made of reinforced concrete of 14m*14m in plan and 5m thick with the total weight of 2352ton. Forced vibration tests were carried out by two kinds of exciters. 4ton exciter was used in X,Y and Z directions up to 50Hz for the purpose of obtaining resonance curves and 50ton exciter was used in X and Y directions up to 8.5Hz for obtaining the distribution of tractions. Displacements were measured of the foundation and also on the ground surface and beneath the foundation in certain levels. Pressure gauges were arranged densely beneath the quarter portion of the foundation, considering the symmetry of the motion. Arrangements of pick-ups are illustrated in Fig.2 for displacements under X direction excitation and in Fig.3 for tractions. At each measuring point of traction, three pressure gauges were combined to measure X and Z components of traction as seen in Fig.4. Prior to the construction of the foundation and after removing the foundation, pressure gauges were calibrated by water pressure bags of various radii loaded with concrete blocks. The calibration scheme is also shown in Fig.4 and the relation of calibration factor and the radius of water pressure bag is shown in Fig.5 indicating that the calibration factor is approaching to cerain value asymptotically with increase of the radius of water pressure bag.

In Table 1 the experimental results are summarized with regard to eigen frequencies and damping factors deduced from displacement resonance curves at the foundation top. In this table, eigen frequencies are different in X and Y directions by about 3Hz which indicates certain unisotropy in macroscopic sense. Damping factors are almost the same in two horizontal directions and larger damping is observed in Z direction. In Table 2 the contribution of sway and rocking motion to the horizontal displacement of the foundation top at resonance are summarized, which indicates the principal motion of the foundation at resonance was swaying. Displacement resonance curves under both of horizontal excitations are shown in Fig.6, indicating that the soil stiffness in Y direction is larger than that in X direction. Vibration mode at resonance under the excitation in X direction is shown in Fig.7, which indicates that the axis of rocking does not coincide with the axis of symmetry located at the bottom.

The traction resonance curves were also obtained, whose peaks are at the same frequencies of displacement resonance curves indicating the quality of acquired traction data.

3 ESTIMATION OF THE RESULTS

The simulation of the experimentally obtained data was carried out by wave propagation theory with lumped mass modeling in regard to the impedance functions and the displacement at the top. In that theory the impedance functions are obtained replacing the foundation by uniform distribution of horizontal traction for swaying and triangular distribution of vertical traction for rocking. These impedance functions are shown in Fig.9, in which the functions evaluated experimentally with lumped mass modeling (shown in Fig.8) are compared with those evaluated analytically by elastic half-space varying its shear wave velocity from 600m/sec to 900m/sec. The horizontal displacements are compared in Fig.6 at the top of the foundation. The shear wave velocities of the equivalent half-space are 660m/sec for X direction and 780m/sec for Y direction, which are estimated as optimum velocities to give the same eigen frequencies of the experiments. From these results the real part of the analytical impedance functions do not exhibit sharp decrement with increase of frequency as is seen in experimental ones. But the analytical displacement at the top has reasonable peak value since the proper damping factor is estimated at eigen frequency.

Quasi-3 dimensional FEM is also utilized to simulate the displacements, especially studying about the unisotropic phenomena obtained by experiments in macroscopic sense. The soil models used for quasi-3 dimensional FEM shown in Fig.10 are made by referring to the geotechnical survey of the site. As shown in Fig.11, eigen frequency in X direction of the displacement resonance curve is lower than that in Y direction, which is in agreement with the tendency of the experimental result. So the unisotropy in macroscopic sense observed in experiments is qualitatively explained by FEM modeling.

The tractions were obtained under the excitation in X and Y directions. In X direction, horizontal and vertical components were obtained and in Y direction only vertical component was measured. The distribution of tractions are shown in Fig.12 at 8.5Hz under X direction excitation. With regard to vertical component, the axis of zero traction does not pass through the centroid of foundation as well as the axis of rocking shown in vibration mode. The distribution of horizontal traction indicates the intermediate of uniform and Boussinesq distribution and the vertical component concerned with rocking motion is the intermediate of triangular and asymmetric Boussinesq distribution. Since the tractions are obtained only at 13 measuring points under the foundation, it is hard to evaluate the resultant forces and moments without making approximation on the distribution of tractions. The polynomial approximation is used to expand the traction field beyond the instrumented area. Comparison of approximated distribution with experimentally obtained one is also shown in Fig.12, in which polynomials are selected considering the fundmental symmetry and asymmetry. Experimentally obtained tractions seem to be properly expanded to uninstrumented region. The resultant forces and moments evaluated by approximated tractions are compared with those evaluated by displacements. The resultant forces are in the ratio 0.95:1 and the resultant moments 1.33:1 showing good agreement and suggesting the high quality of the data.

4 CONCLUSION

The displacement and tractions are experimentally obtained by forced vibration tests of a model foundation to investigate the effects of the dynamic soil-structure interaction. Impedance functions and displacements are well simulated by wave propagation theory and quasi-3 dimensional FEM including unisotropy in macroscopic sense. Tractions are also obtained with high quality so that the integrated values such as resultant forces and moments are in good agreement with those evaluated by experimentally obtained displacements.

Table 1. Summary of experimental results

	Eigen Frequency[Hz]	Damping Factor
X	15.9	0.198
Y	19.1	0.171
Z	19.5	0.391

Table 2. Contributions to the horizontal displacement at the top

	Swaying Ratio	Rocking Ratio	Deformation Ratio
X	0.67	0.29	0.04
Y	0.57	0.37	0.06

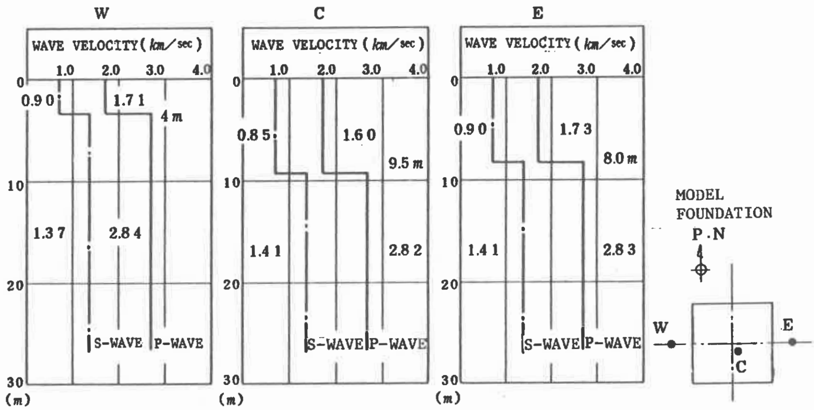


Fig.1 Body wave velocities around the model foundation

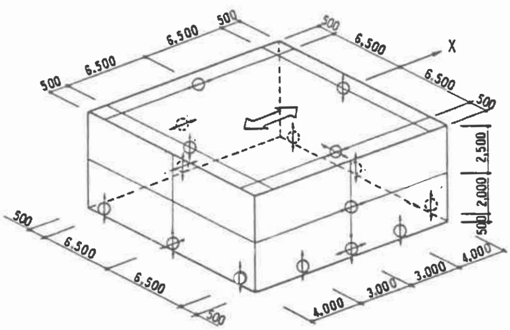


Fig.2 Arrangement of pick-ups for measuring displacements

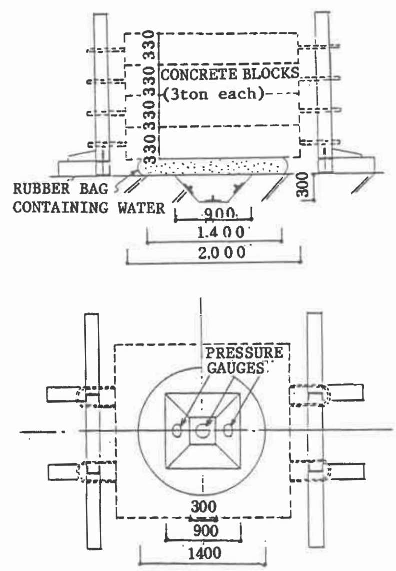


Fig.4 Calibration of pressure gauges with water pressure bag

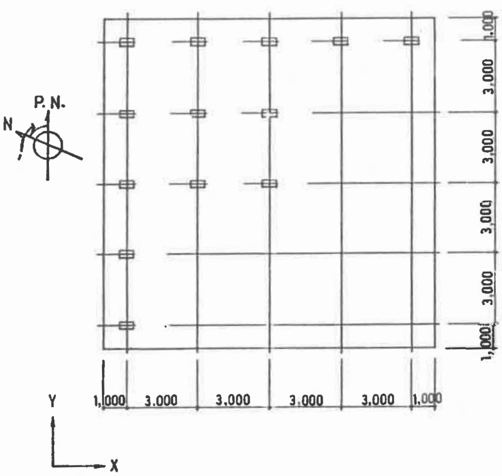


Fig.3 Arrangement of pressure gauges under the foundation

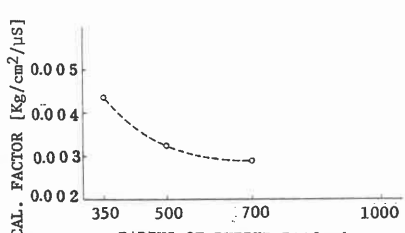


Fig.5 Typical calibration factor of a pressure gauge

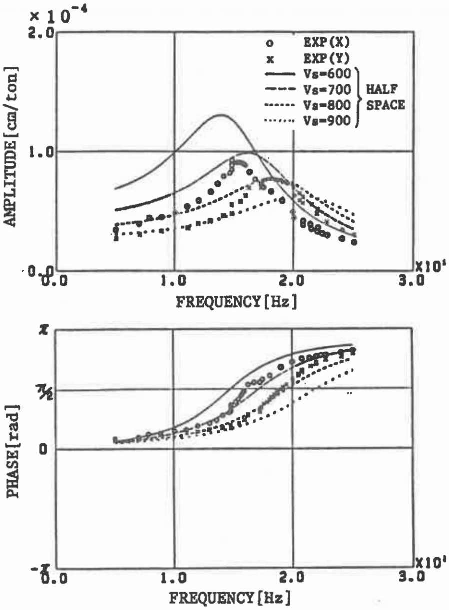


Fig.6 Displacement at foundation top estimated by wave propagation theory

(HALF SPACE: ν=0.35, γ=2.0g/cm^3
h=2%, Vs=600∿900m/sec)

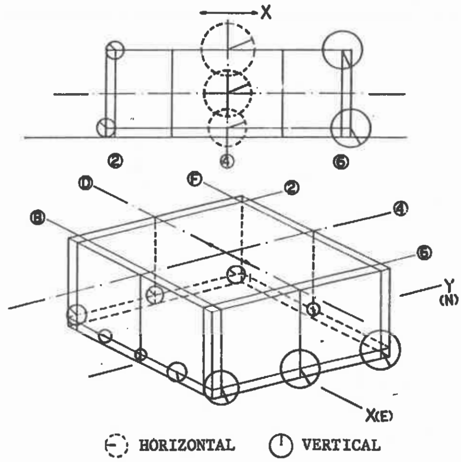


Fig.7 Vibration mode
(X-excitation)

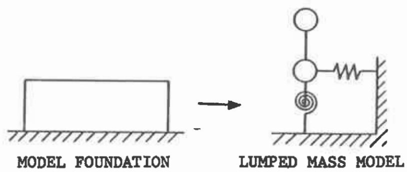
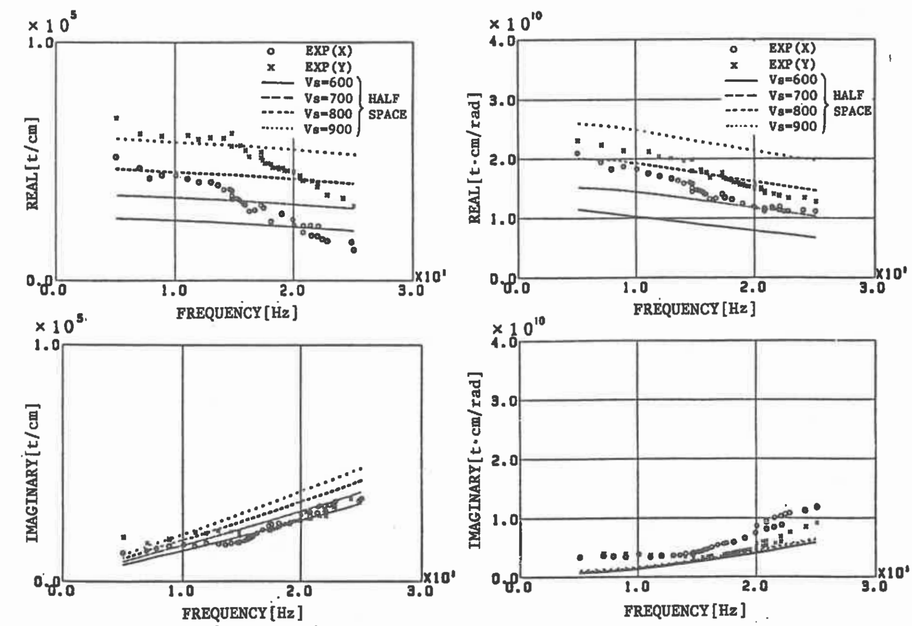


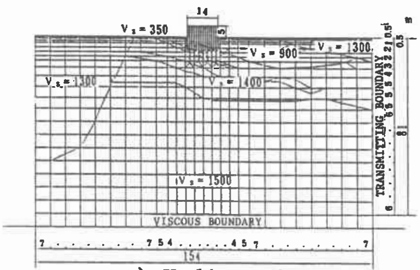
Fig.8 Lumped mass model



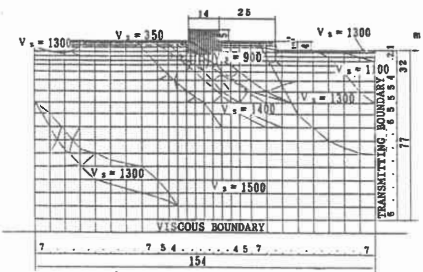
a) Horizontal component

b) Rocking component

Fig.9 Impedance functions estimated by wave propagation theory
(HALF SPACE: ν=0.35, γ=2.0g/cm^3, h=2%, Vs=600∿900m/sec)

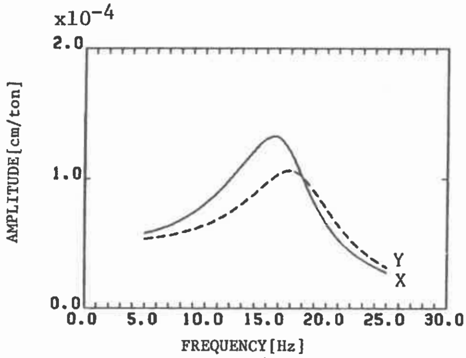


a) X direction



b) Y direction

Fig.10 FEM model



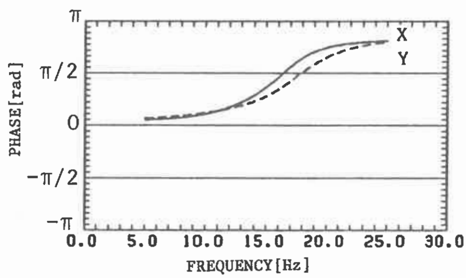
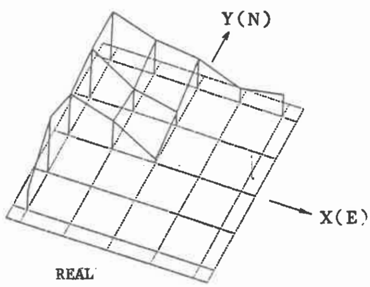
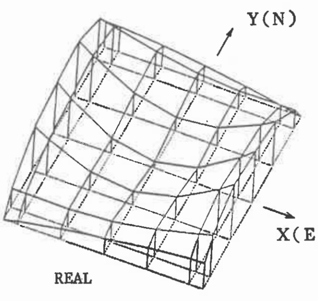


Fig.11 Displacement at foundation top estimated by FEM



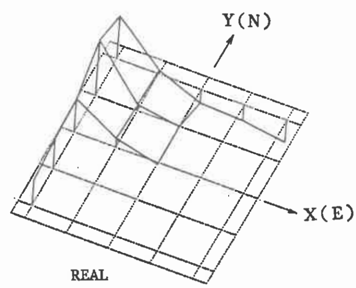
EXPERIMENTAL RESULTS



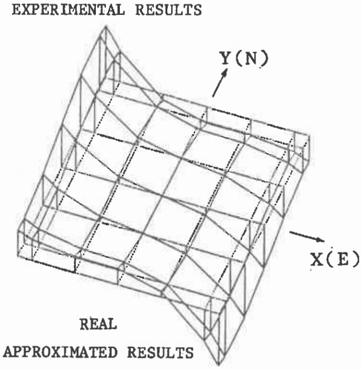
APPROXIMATED RESULTS

$f = a_0+a_1X^2+a_2XY+a_3Y^2+a_4X^4+a_5X^2Y^2+a_6Y^4$

a) Horizontal component (X-excitation)



EXPERIMENTAL RESULTS



APPROXIMATED RESULTS

$f = a_0+a_1X+a_2Y+a_3X^3+a_4X^2Y+a_5XY^2+a_6Y^5$

b) Vertical component (X-excitation)

Fig. 12 Polynomial approximation of tractions under the foundation