Estimate of dynamic stiffness and damping by forced excitation test of foundation on bedrock (Part 2)

K.Hirata & T.Matsuda
Central Research Institute of Electric Power Industry, Abiko-shi, Japan
S.Setogawa
Kansai Electric Power Company, Osaka-shi, Japan
O.Ochi
Hokuriku Electric Power Company, Toyama-shi, Japan
Y.Masuda
Chugoku Electric Power Company, Hiroshima-shi, Japan
S.Iwabu
Shikoku Electric Power Company, Takamatsu-shi, Japan
M.Shiota
Kyusyu Electric Power Company, Fukuoka-shi, Japan
M.Inoue
The Federation of Electric Power Companies, Tokyo, Japan

ABSTRACT

Based on the results of forced excitation tests of foundations on bedrock, dynamic complex stiffness (dynamic stiffness and damping) were obtained at many nuclear power plant sites. In this present study experimental results were investigated by three-dimensional wave propagation theory considering layered stratum of bedrock. It is shown dynamic stiffness can be estimated with sufficient accuracy by considering layered stratum of bedrock. Also it is shown that by two-layered ground model estimate of damping characteristics is possible for foundations on multi-layered bedrock.

1 INTRODUCTION

Based on forced excitation test of foundations, dynamic soil-structure interaction characteristics have been investigated in recent years. Using wave propagation theory for uniform media, experimental results could be explained quantitatively in case bedrock is uniform. However, for sites where bedrock has layered structure discrepancy between experimental and theoretical results proved to be difficult to neglect (see Part 1). Herein to improve estimation of soil-structure interaction characteristics in such a case, especially damping characteristics, experimental results were investigated with wave propagation theory for multi-layered media.

2 EFFECTS OF LAYERED-STRATUM ON THE STIFFNESS OF GROUND

It sometimes emerges as a problem to what extent we can estimate ground-stiffness accurately on bedrock with material properties obtained from seismic prospecting (such as PS logging or refraction method). Because sometimes bedrock is cracky and has local irregularity which influences ground-stiffness directly. To estimate the accuracy, ground-stiffness estimated by forced excitation test and three-dimensional elastic half-space theory with material properties obtained by seismic prospecting were compared. Estimate was made in the following way.

First, from the resonance frequency of foundation in the forced excitation test, equiv-

alent shear wave velocity of the ground (denoted by $(Vseq)_E$) was determined so that resonant frequency of the foundation calculated by uniform half-space theory with $(Vseq)_E$ may agree with experimental result. Second, from the material properties of ground obtained by seismic prospecting, elastic stiffness of the foundation considering layered structure of ground was calculated, and in this case also equivalent shear wave velocity of ground (denoted by $(Vseq)_T$) was calculated so that elastic spring by uniform half-space theory with this $(Vseq)_T$ agree with that mentioned above. Estimate was made by comparing these $(Vseq)_E$ and $(Vseq)_T$.

In Fig. 1, comparison between $(Vseq)_E$ and $(Vseq)_T$ is shown in which ground structure at site B, E can be regarded uniform, whereas that of other sites is layered. Although some difference is perceived, both value can be regarded to agree fairly well. From Fig. 2 we can read the ratio $(Vseq)_E/(Vseq)_T$, and average value and standard deviation are 0.97, 0.15 respectively. And about this ratio there seems no tendency as to whether or not the ground is layered, for the value of shear wave velocity. From these results it was shown from soft to hard rock (Vs ranges from 500m/s or less to 1500m/s or more), and whether ground is uniform or layered, we can estimate ground stiffness from material properties obtained by seismic prospecting with sufficient accuracy.

3 EFFECTS OF LAYERED STRATUM ON DAMPING CHARACTERISTICS OF FOUNDATION

Bedding structure of the ground on which experiments were carried out are classified to uniform and multi-layered. For uniform ground it was made clear that using shear wave velocity of ground obtained by seismic prospecting (which is nearly equal to $(Vseq)_E$), damping constant of foundation which mainly results from radiation damping for bedrock site estimated by half-space theory agreed fairly well with experimental results. On the other hand for layered bedrock damping estimated by theoretical solution with $(Vseq)_E$ showed larger value than that by experiment. Obviously it is because of reflection of propagating waves at the boundary of layers which disturbes energy radiation in comparison to the case of uniform ground, and here we analysed experimental results of damping constant for multi-layered ground with the aid of three-dimensional wave propagation theory for multi-layered ground. Herein theoretical solutions were calculated based on Dynamical Ground Compliance (DGC) theory[1], and contact pressure distribution was assumed uniform (for horizontal translation), and triangular (for rotational motion) according to measurement of contact pressure (except for site-G where rigid-base distribution was assumed). And as material damping of bedrock 0.05% is adopted (non-viscous, ie., damping is constant irrespective of frequency). In the estimate of damping some models other than "original ground model" were proposed as shown in Table 1 which are classified as follows.

(1) Original multi-layered ground model; Layered structures were determined by seismic prospecting (denoted by LAYERED).

(2) Modified multi-layered model; Material properties of the first layer was equalized to the second layer in the original multi-layered ground model (denoted by LAYERED (II)).

(3) Two-layered model; Consists of first and second layer of LAYERED model (denoted by 2-LAYERED).

(4) Modified two-layered model; Consists of first and second layer of LAYERED (II) model (denoted by 2-LAYERED (II)).

Result of comparison between experimental and calculated value is shown in Fig. 3~7. Herein dimensionless frequency $2\pi f\sqrt{A}/Vs$ is obtained using Vs from static spring constant for each ground model by theoretical solution and experiment. As for horizontal damping at sites A, C, F theoretical value with uniform ground model tend to overestimate experimental one. But theoretical value with original ground model underestimated experimental value conversely. It is mainly because contrast of impedance between first and second layer was emphasized, and secondly, assuming just under the

foundation, disturbance or relaxation was recovered by overburden load by the foundation, estimate was made with ground model LAYERED-II. In this case both results agreed fairly well. In smaller than those by experiment. With 2- LAYERED(II) model results were similar to those by LAYERED-(II) model and agreed well with experiment. For three-layered ground (site-A) LAYERED(II) coincides with 2-LAYERED(II) model, and for two-layered ground (site-D) LAYERED (II) results in uniform ground.

As for rotational damping, experimental results are larger than theoretical ones with uniform ground model and considering layered structure of the ground does not reduce discrepancy between both results. It should be noted with model LAYERED(II) and 2-LAYERED(II) theoretical results were nearly equal.

As to site G where bedrock is soft in comparison with other sites (see Table 1) theoretical solution with LAYERED model with assumption of contact pressure distribution "rigid base" agreed well with experimental result. This assumption is based on measurement and generally soft bedrock consists of mudstone as this site is not cracky and local disturbance is rare to occur. Therefore it is possible without modifying material properties of surface layer to estimate damping characteristics.

4 ESTIMATE WITH THE RESULT OF PARAMETER SURVEY ON TWO-LAYERED MODEL

In preceding section, it was shown that damping characteristics for multi-layered ground could be estimated with modified ground model (LAYERED(II)), and also with 2-LAYERED(II) model. And herein parameter survey with tow-layered model was carried out to investigate effect on damping characteristics.

In Fig. 8 an example is shown in which dimensionless frequency a_0 ($=2\pi f\sqrt{A}/Vs$) and impedance ratio between two layers Vs_1/Vs_2 are taken as parameters. In this example relations between ratio of damping constant for two-layered ground (h_H (LAYERED)) to that for uniform ground (h_H (UNIFORM)) and ratio of thickness of first layer to the size of foundation are shown.

From this figure followings can be perceived. With decrease of impedance ratio and increase of thickness of first layer, damping decreases as far as thickness is small and in case layer depth is small damping is independent of dimensionless frequency, but for deeper stratum tendencies mentioned above are affected by dimensionless frequency sensitively.

In Fig. 9 comparison was made between results of experiment and parameter survey with two-layered model. As impedance ratio, 3/4 was taken which is nearly equal to that of 2-LAYERED(II) model in each site (see Table-1) and as layer thickness to foundation size ratio, 1/5 (for site C), 1/3 (for site A), 1/2 (for site F) are taken. From this figure it was shown that for multi-layered ground, damping constant (for horizontal motion) can be estimated with two-layered ground model. For which it takes less computation time and results of parameter survey are available.

5 CONCLUSIONS

Results of forced excitation test of foundations on bedrock were analyzed based on three-dimensional wave propagation theory. As to the stiffness of ground we could estimate by elastic half-space theory with material properties obtained from seismic prospecting with sufficient accuracy. As to the damping of foundation-ground system estimate by the theory with original multi-layered model underestimated experimental value. And through modification of ground model common to all sites, fairly good agreement was obtained between experimental and theoretical value. This modification was made for surface thin layer, and for large foundation such as of reactor building effect of such layer can be neglected. As to the damping for rotational motion experimental value exceeded theoretical one for uniform ground and by multi-layered model its estimate was difficult. According to the result of parameter survey

for two-layered ground model, experimental result for multi-layered ground proved to possible to estimate with two-layered model.

REFERENCES

1) T. Kobori, R. Minai, T. Suzuki, Dynamic Characteristics of a Layered Sub-Soil Ground. Annuals of Disaster Prevention Research Inst., Kyoto Univ. No. 19B, pp.167-217, 1976

Table 1 Ground Model Used for Theoretical Calculation

MODEL / SITE	DEPTH(m)	LAYERED Vs(m/s)	LAYERED II Vs(m/s)	2-LAYERED Vs(m/s)	2-LAYERED II Vs(m/s)	Vs_1/Vs_2	$H/\sqrt{A}$
A	0.0~2.0	700		700			
	2.0~5.0	1400	1400	1400	1400	0.70	0.36
	5.0~	2000	2000		2000		
C	0.0~1.0	500		500			
	1.0~2.5	1350	1350	1350	1350	0.66	0.17
	2.5~5.0	2050	2050		2050		
	5.0~	2400	2400				
D	0.0~2.0	1350		1350		—	—
	2.0~	1700	1700	1700	1700		
F	0.0~1.5	600		600			
	1.5~8.0	1550	1550	1550	1550		
	8.0~14.0	2000	2000		2000	0.78	0.53
	14.0~18.0	1600	1600				
	18.0~24.0	2000	2000				
	24.0~	1600	1600				
G	0.0~1.5	300		300			
	1.5~4.5	490	490	490	490	—	—
	4.5~10.5	610	610		610		
	10.5~13.0	370	370				
	13.0~	550	550				

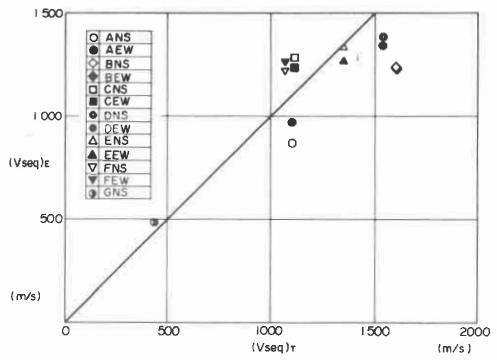


Fig. 1 $(Vseq)_E$ vs $(Vseq)_T$

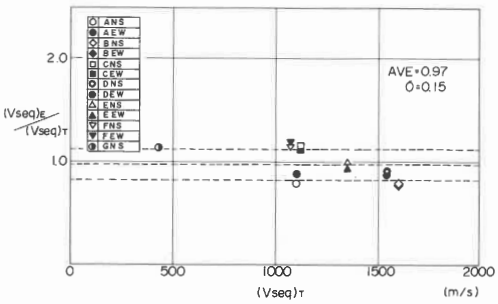
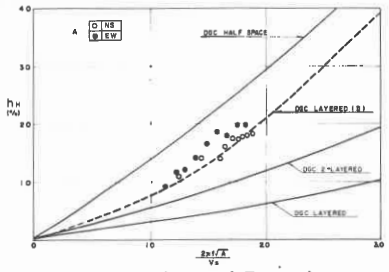
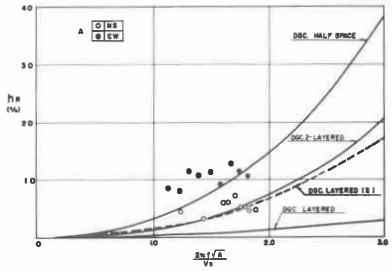


Fig. 2 Ratio of $(Vseq)_E$ to $(Vseq)_T$

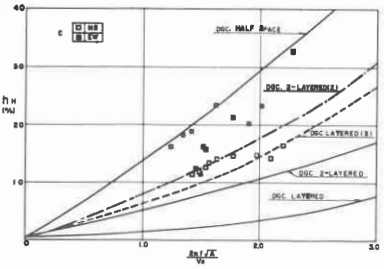


(a) Horizontal Damping

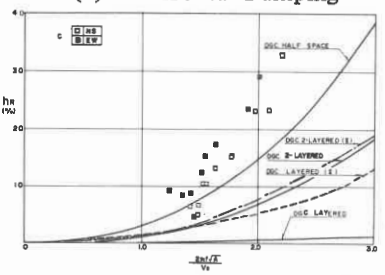


(b) Rotational Damping

Fig. 3 Damping Const. vs. Dimensionless Freq. (Site A)

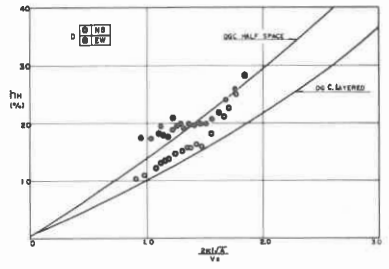


(a) Horizontal Damping

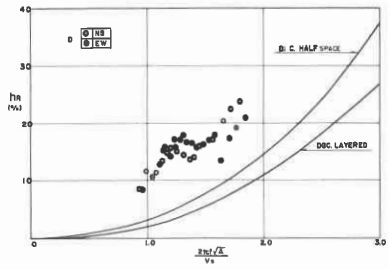


(b) Rotational Damping

Fig. 4 Damping Const. vs Dimensionless Freq. (Site C)

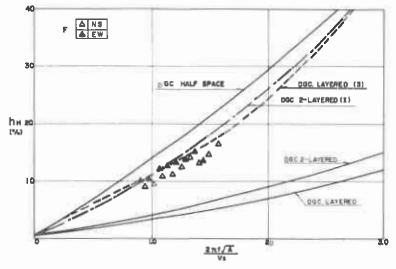


(a) Horizontal Damping

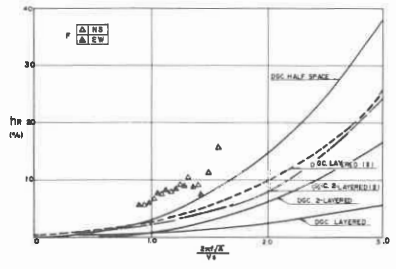


(b) Rotational Damping

Fig. 5 Damping Const. vs Dimensionless Freq. (Site D)

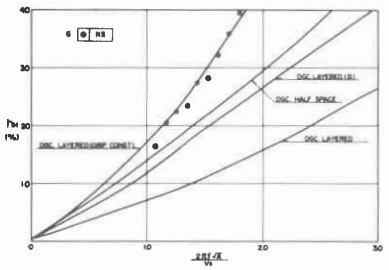


(a) Horizontal Damping

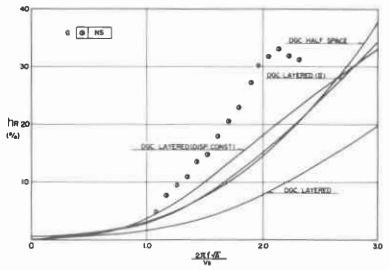


(b) Rotational Damping

Fig. 6 Damping Const. vs Dimensionless Freq. (Site F)



(a) Horizontal Damping



(b) Rotational Damping

Fig. 7 Damping Const. vs Dimensionless Freq. (Site G)

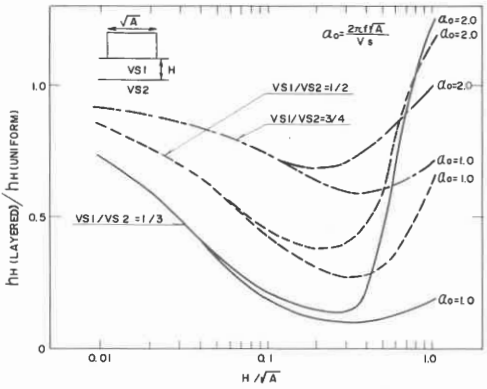


Fig. 8 Comparison of Damping Const. for Two-layered and Uniform Ground

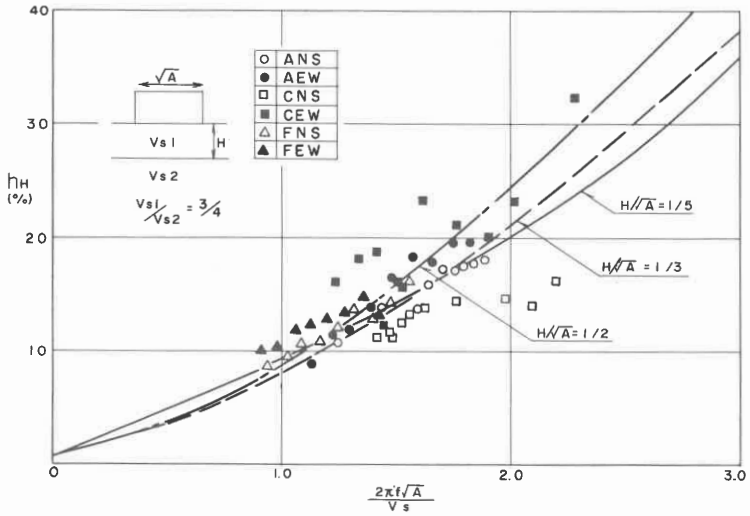


Fig. 9 Comparison of Damping Const. by Experiment and Parameter Survey