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Results of a parametric study on site response effects

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ABSTRACT

This paper presents a brief overview and some results of a parametric study on site response effects due to strong earthquake ground motions. Influence of the soil type, site thickness as well as frequency content and intensity of the seismic motion are investigated. The results are presented in the form of dynamic foundation factors. Comparisons are made with the proposed foundation factors in the National Building Code of Canada (NBCC) 1990. These show that the computed foundation factors significantly exceed the code values when the predominant period of the earthquake motion is close to the site period.

INTRODUCTION

Seismic waves propagating through near-surface soil layers can amplify and produce free field ground motions much larger and with different characteristics than those at rock. The combined effects of earthquakes and local site conditions are commonly referred to as site response effects. There are many examples when extensive damage has been caused by site response effects. During the 1985 Mexico City earthquake, site amplification caused substantial damage and collapse of many buildings. Similarly, the site response effects during the 1989 Loma Prieta, California earthquake were the major cause of failure for many facilities.

In the seismic provisions of the NBCC 1990 (Associate Committee on the National Building Code 1990), the site effects are represented by foundation factor. The soil conditions are categorized into 4 types, and values are assigned to the foundation factor, depending on soil type and depth. In order to evaluate the code foundation factor, an extensive investigation of site response has been

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conducted at McMaster University (Heidebrecht et al. 1990, Henderson et al. 1990). One phase of this investigation is the parametric study of site response effects (Elhmadi et al. 1990). The parameters include soil type, site thickness, frequency content and intensity of earthquake motion. This paper presents an overview and some results of this parametric study.

METHODOLOGY OF THE PARAMETRIC STUDY

Soil Categories

Four categories of soil deposits are considered in the parametric study. These categories are: (i) normally to lightly overconsolidated clay (NC), (ii) heavily overconsolidated clay (OC), (iii) alluvial sand and silt (AS), and (iv) dense sand (DS). For each category, site thicknesses of 5, 15, 40 and 100 m are considered in the analysis. These types of soil and thicknesses cover a wide range of sites expected to produce site response effects. The soil properties required for the site response analysis are based on measured data from actual sites (Elhmadi et al. 1990). Figure 1 shows the low strain shear modulus, G_o, versus depth for the four soil types. The low strain fundamental periods for each of the sites considered are given in Table 1.

Table 1. Low strain site periods (sec)

Site. Categ.	Thickness (m)			
	5	15	40	100
NC	0.37	0.65	1.10	1.70
OC	0.12	0.32	0.70	1.34
AS	0.18	0.40	0.83	1.65
DS	0.08	0.18	0.39	0.77

Input Motion

It is well recognized that the frequency content of strong seismic ground motion can be characterized by the a/v ratio, in which a is the peak horizontal ground acceleration (g) and v is the peak horizontal ground velocity (m/sec). High a/v ratios are characteristic of earthquake motions with high frequency (low period) content; low a/v ratios are characteristic of motions with low frequency (long period) content. It should be mentioned that the NBCC 1990 uses peak ground velocity, v, to scale the intensity of ground motion and three ranges of a/v ratio to define different force coefficients for structures of low period (i.e., <0.5 sec).

The strong motion database at McMaster was used to select three ensembles of actual time histories, recorded on rock or stiff soil. The three ensembles and their relationships to the zonal combinations in NBCC 1990 ($Z_a>Z_v$, $Z_a=Z_v$ and $Z_a<Z_a$) are defined as follows: H - high a/v ratios, mean a/v ≈ 2 ($Z_a>Z_v$); I - intermediate a/v ratios, mean a/v ≈ 1 ($Z_a=Z_v$); and V - very low a/v ratios, mean a/v ≈ 0.5 ($Z_a<Z_v$), where Z_a and Z_v represent respectively acceleration and velocity related seismic zones. Each ensemble contains 15 different time

histories. A detailed listing of all records is given in Elhmadi et al. (1990). Figure 2 shows the mean acceleration response spectra for each of the three ensembles of records, scaled to peak ground velocity of 1 m/sec. The relations between the a/v ratios and the frequency content of the ensembles are evident from this figure. The predominant periods for H, I and V ensembles are in the neighbourhood of 0.15, 0.3 and 1.0 sec respectively.

For the purposes of the parametric study, all the time histories are scaled to four levels of peak ground velocity, v. These levels correspond to v=0.05, 0.1, 0.2 and 0.4 m/sec. It should be noted that this range of v covers the full range of zonal velocities defined in the seismic zoning maps used with NBCC 1990.

Response Analysis

In the parametric study, the soil deposits are modelled as one-dimensional layered systems with propagation of shear waves only in the vertical direction. The computer program SIREN developed by J.W. Pappin at Ove Arup & Partners (Henderson et al. 1989) is used for the response analysis. The soil is represented as a series of lumped masses connected by nonlinear springs. The soil behaviour is modelled by a hysteretic stress/strain relationship satisfying the Massing principles (Pyke 1979).

For each site and value of v (0.05, 0.1, 0.2 and 0.4 m/sec), surface acceleration time histories were computed using each time history in each ensemble as input motion at the base of the soil profile (rock level). The response characteristics of the motions at both the rock and surface level were also computed and then analyzed statistically for each ensemble. The following response characteristics were computed and analyzed in the parametric study (all are for 5% damping): (i) elastic base shear coefficients for wall- and frame-type structures, (ii) base shear coefficient ratios (surface to rock), and (iii) dynamic foundation factors. Detailed discussion for all of these characteristics is given in Elhmadi et al. (1990). This paper presents some of the results for foundation factors.

FOUNDATION FACTORS

For structures of normal importance, the elastic base shear, V_e, in the NBCC 1990 is defined as

$$V_e = F(vSW) \tag{1}$$

in which F is the foundation factor, having a value of 1 for rock or stiff soil sites and a value of 1.3 to 2 for other site conditions (see NBCC 1990 for detailed description of soil categories); v is the zonal horizontal velocity coefficient, as specified in the seismic zoning map, and equivalent to peak velocity in m/sec; S is the seismic response factor or unit velocity base shear coefficient; and W is the dead load. Note that in terms of F, NBCC 1990 provides for low period "caps" on base shear by specifying upper limit on the product FS, namely: FS need not be greater than 4.2 when $Z_a > Z_v$, and FS need not be greater than 3.0 when $Z_a = Z_v$ or $Z_a < Z_v$.

In order to evaluate the NBCC 1990 foundation factor F, it is necessary to compare the code base shear (Eq. 1) with the surface base shear implied by the response analysis. The implied base shear at the surface level is designated by V_s and can be expressed in the following form:

$$V_s = C_{rs} vW \quad (2)$$

The coefficient C_{rs} is the dynamic unit velocity elastic base shear coefficient for input motion at the rock level and structures located at the surface. In this equation, v represents peak velocity of the rock motion and it is identical to the code velocity coefficient in Eq. 1. For easier comparison, Eq. 2 can be rewritten as follows:

$$V_s = (C_{rs}/S) vSW = F^*(vSW) \quad (3)$$

The quantity F^* is a "dynamic" foundation factor which can be compared with F in Eq. 1, including the NBCC 1990 provision that specifies an upper limit on the product FS, as described above.

In the parametric study, the base shear coefficients C_{rs} were computed for each of the surface level time histories for two types of structures, i.e. uniform frame and (shear) wall structures. Simple continuum models of frame and wall structures were used (Heidebrecht and Stafford Smith 1973). The computation was performed using five modes and 5% modal damping. Only frame structures results were analyzed since they exceeded those for wall structures in the low and intermediate period regions. For each site and each set of input motion (H, I and V ensemble; v=0.05, 0.1, 0.2 and 0.4 m/sec), the mean plus one standard deviation dynamic foundation factor spectra, F^*, versus fundamental structural period, T, were computed. Recognizing that the site period, T_s, is one of the most important factors in site response effects, the F^* spectra are converted into normalized spectra (i.e., F^* versus T/T_s).

This paper presents only results for two soil categories (normally to lightly overconsolidated clay, NC, and dense sand, DS) and two site thicknesses (5 m and 100 m). These represent limits in terms of the soil categories and thicknesses considered in the parametric study. The results for the other two soil categories and thicknesses follow the same trends and they are within the range of the results from these limit cases. In order to compare the dynamic foundation factors with the provisions of the NBCC 1990, the code foundation factor, F, for the sites whose results are presented here, is prescribed as follows: F=1 for NC - thickness of 5 m, and for DS - thickness of 5 m and 100 m; F=2 for NC - thickness of 100 m. Figure 3 shows the code foundation factor F=2 versus fundamental structural period, for the three zonal combinations; note that the effective value is reduced at low periods because of the limitation of the product FS as proposed in NBCC 1990. The code foundation factor F=1 has a value of 1.0 for all periods and zonal combinations.

Figures 4 to 7 show the dynamic foundation factors for the soil categories NC and DS, for the thicknesses of 5 m and 100 m. As can be seen, the peak values of F^* are between 1.0 and 6.5. These peak values occur in the range of T/T_s from 0.5 to 1.5. Among the parameters studied, the intensity level, v, is the most influential. The values of F^* are a decreasing function of v. This is due to the lower energy absorbtion and damping at relatively low strain levels. The influence of v, however, is less pronounced for the dense sand deposit. In terms of the influence of the soil category, the peak values of F^* for the soft soil deposit, NC, are in general larger than those for the stiff soil deposit, DS. An exception to this is the 5 m thick soil deposit subjected to H ensemble, which shows larger F^* values for DS site than those for NC site, for v=0.2 and 0.4 m/sec. Concerning the influence of site thickness and frequency content of the input motion, the results follow expected trend for DS site but not for NC site. As is shown in Fig. 6, the largest values for the 5 m DS site are associated with H ensemble (F^*_{max}≈3.5), while the effect of V ensemble is very small (F^*_{max}≈1). However, the V ensemble produces significant peak values at the 100 m DS site (F^*_{max}≈2). In terms of NC site (Figs. 4 and 5), the effect of the frequency content on the peak values cannot be recognized when one compare the results for 5 m with those for 100 m soil deposit. For example, the 5 m and 100 m NC sites show similar peak values, when subjected to H ensemble. This is also true for I and V ensemble. An explanation for this is associated with the effect of the top layers. Based on the results presented in Figs. 4 and 5 and those for thicknesses of 15 m and 40 m given in Elhmadi et al. (1990), it seems that the response of the NC site is characterized by that of the top 5 to 10 m soil deposit.

Comparing the dynamic foundation factors, F^*, with the corresponding NBCC 1990 foundation factors, F (i.e., a value of 1.0 for all periods, for F=1; Fig.3 for F=2), one can see that the F^* values in the neighbourhood of the site period exceed the code values in almost all cases. The difference is especially large for low intensity levels of the input motion. The same conclusion is true for the results corresponding to thicknesses of 15 m and 40 m (Elhmadi et al. 1990).

CONCLUSIONS

Results of a parametric study on site response effects due to strong earthquake ground motion are summarized in this paper. The parameters include the soil type, site thickness, frequency content and intensity level of the seismic motion. The results are presented in terms of dynamic foundation factors, F^*, versus the ratio of the fundamental structural period to the site period, T/T_s. The main conclusions are:

- Among the parameters studied, the intensity level, v, is the most influential parameter. Values of F^* are a decreasing function of v. The influence of v is less pronounced for denser deposits.
- The site period, T_s, which is a function of almost all parameters (i.e. intensity level, soil type, site thickness, shear modulus and damping ratio), is a very important factor in studying site response effects.
- In the neighbourhood of the site period, the dynamic foundation factors exceed the NBCC 1990 foundation factors, in almost all cases.

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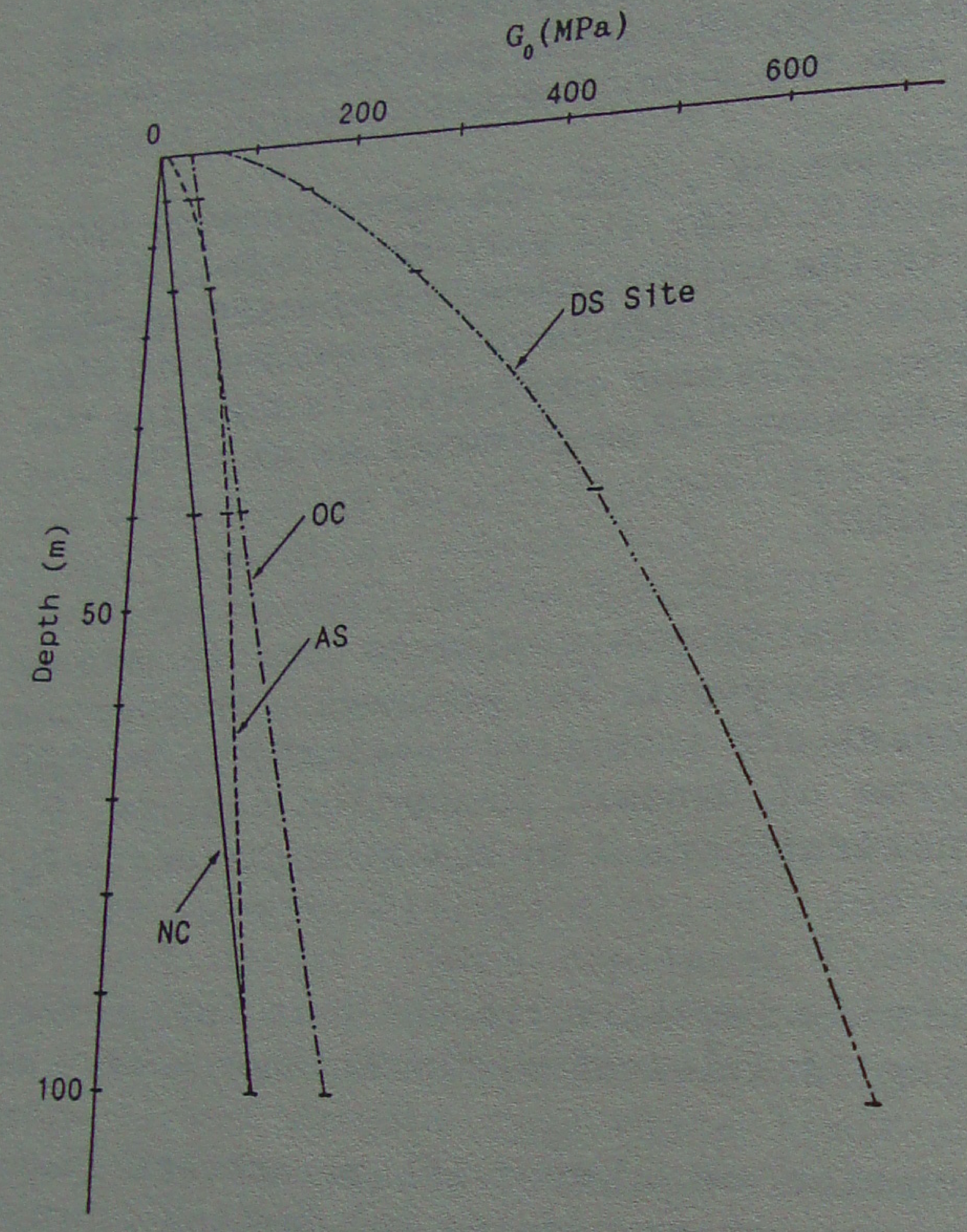

Figure 1. Low strain shear moduli profiles for all four soil categories

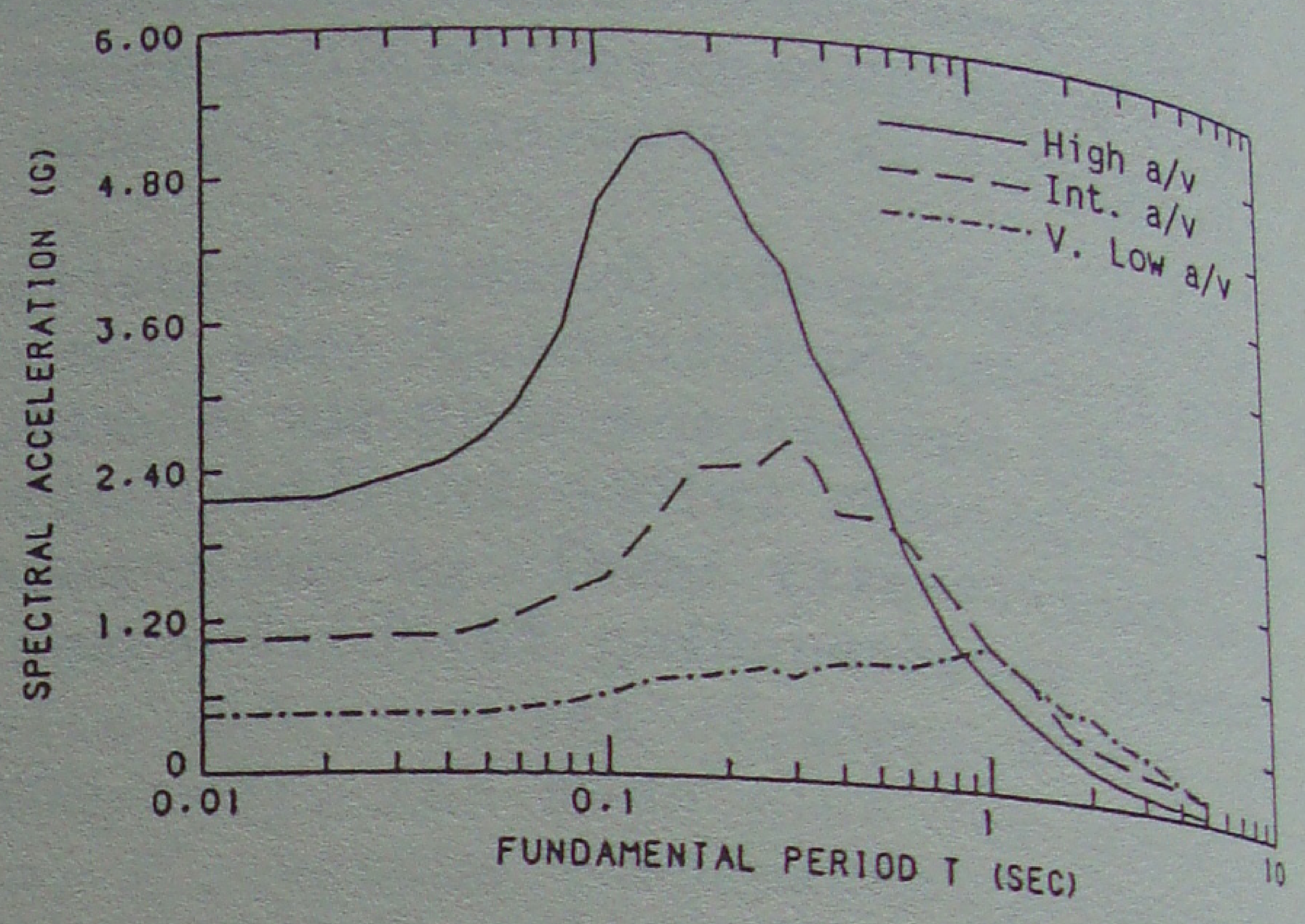

Figure 2. Mean acceleration response spectra for the three ensembles of input motions; 5% damping, v=1 m/sec

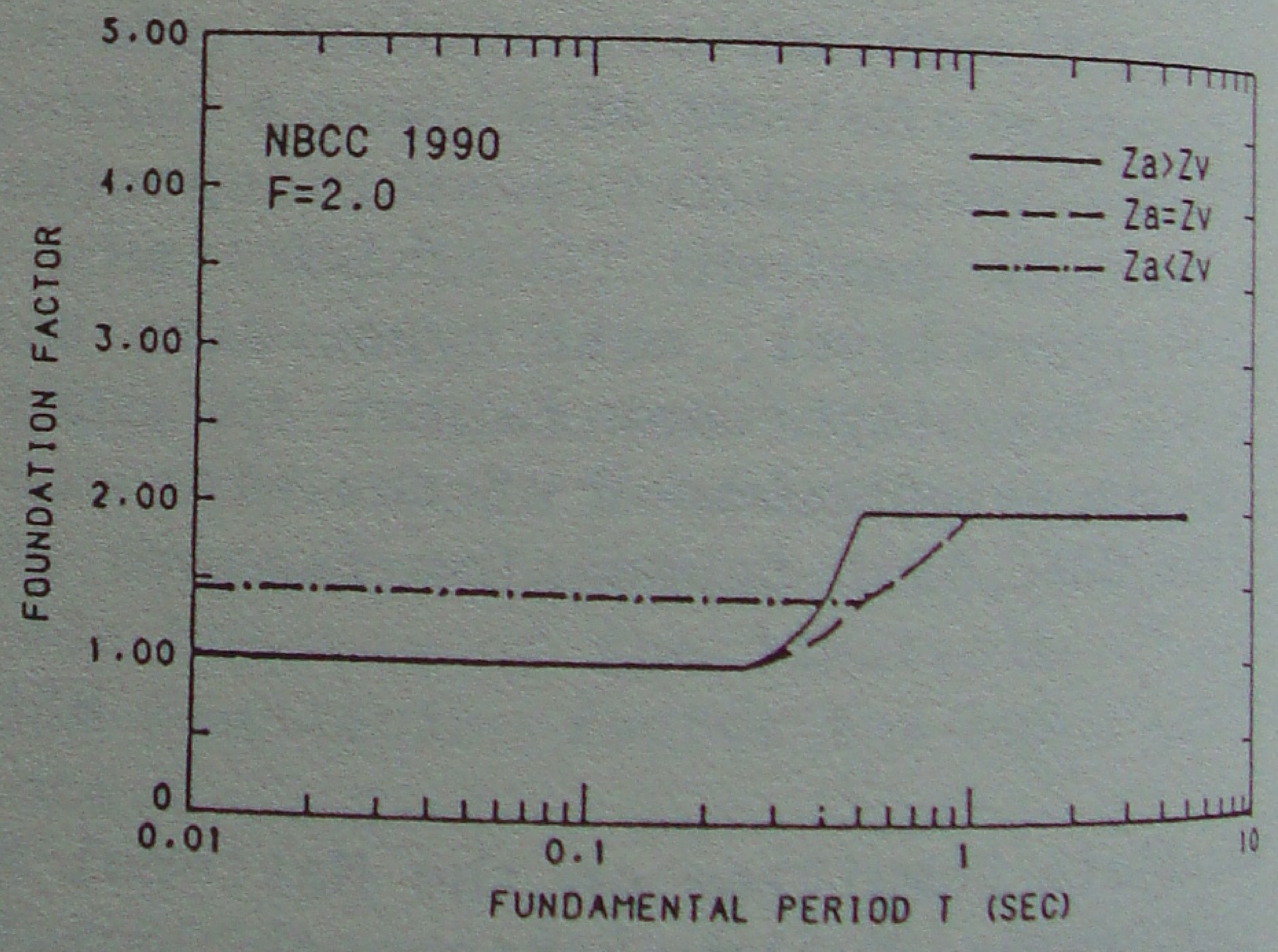

Figure 3. NBCC 1990 foundation factor F=2

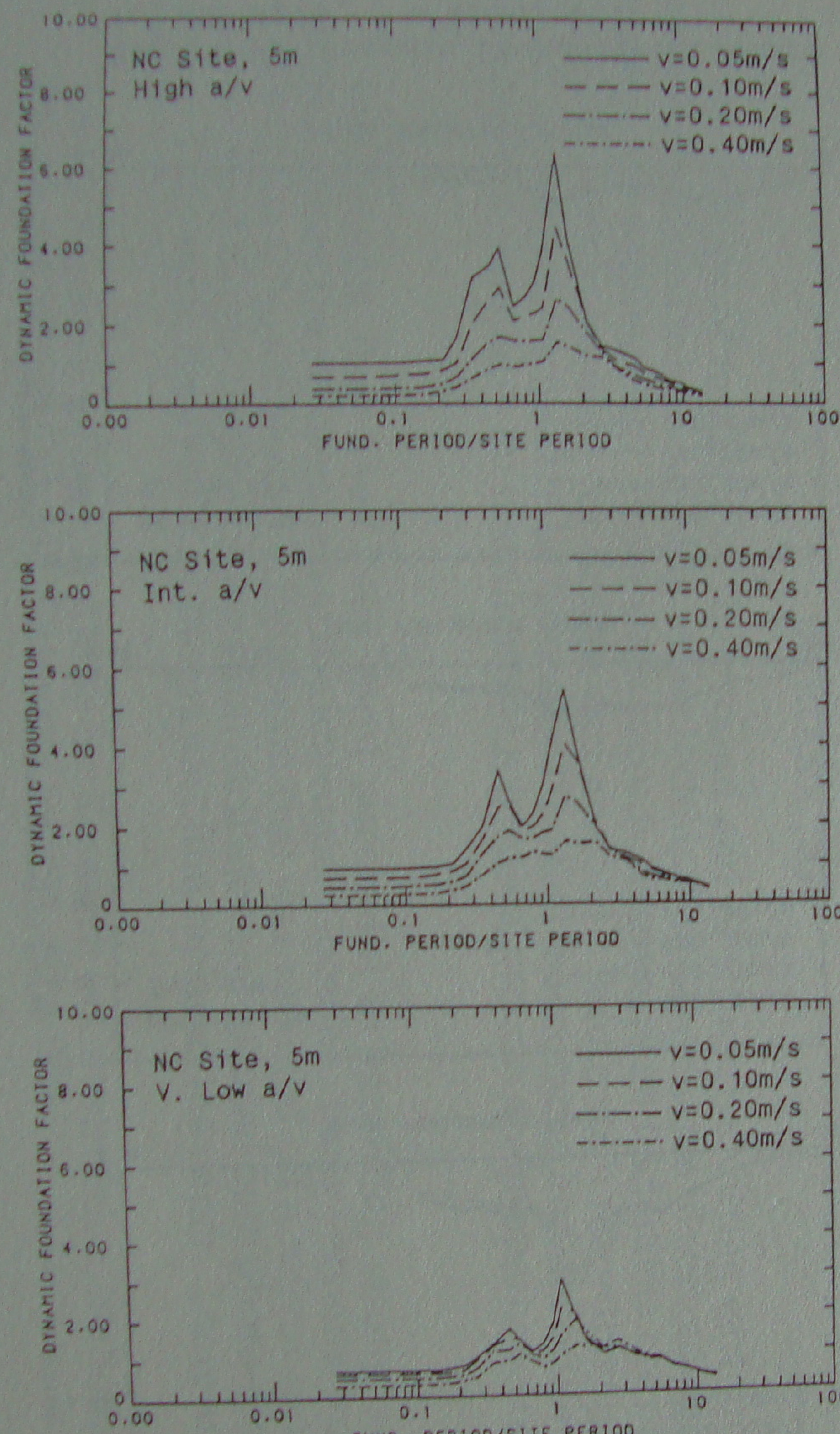

Figure 4. Dynamic foundation factors for NC site, 5 m thickness

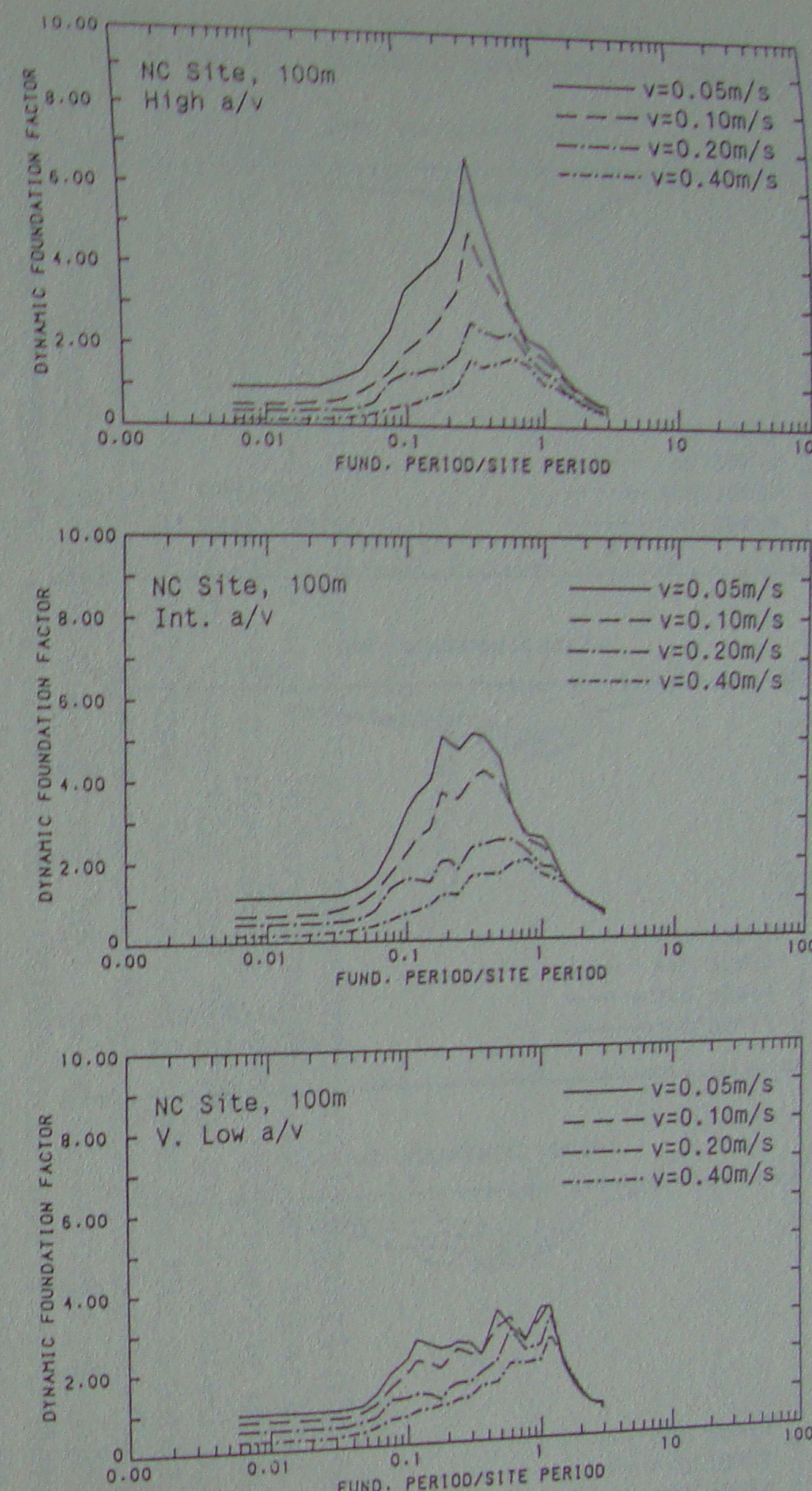

Figure 5. Dynamic foundation factors for NC site, 100 m thickness

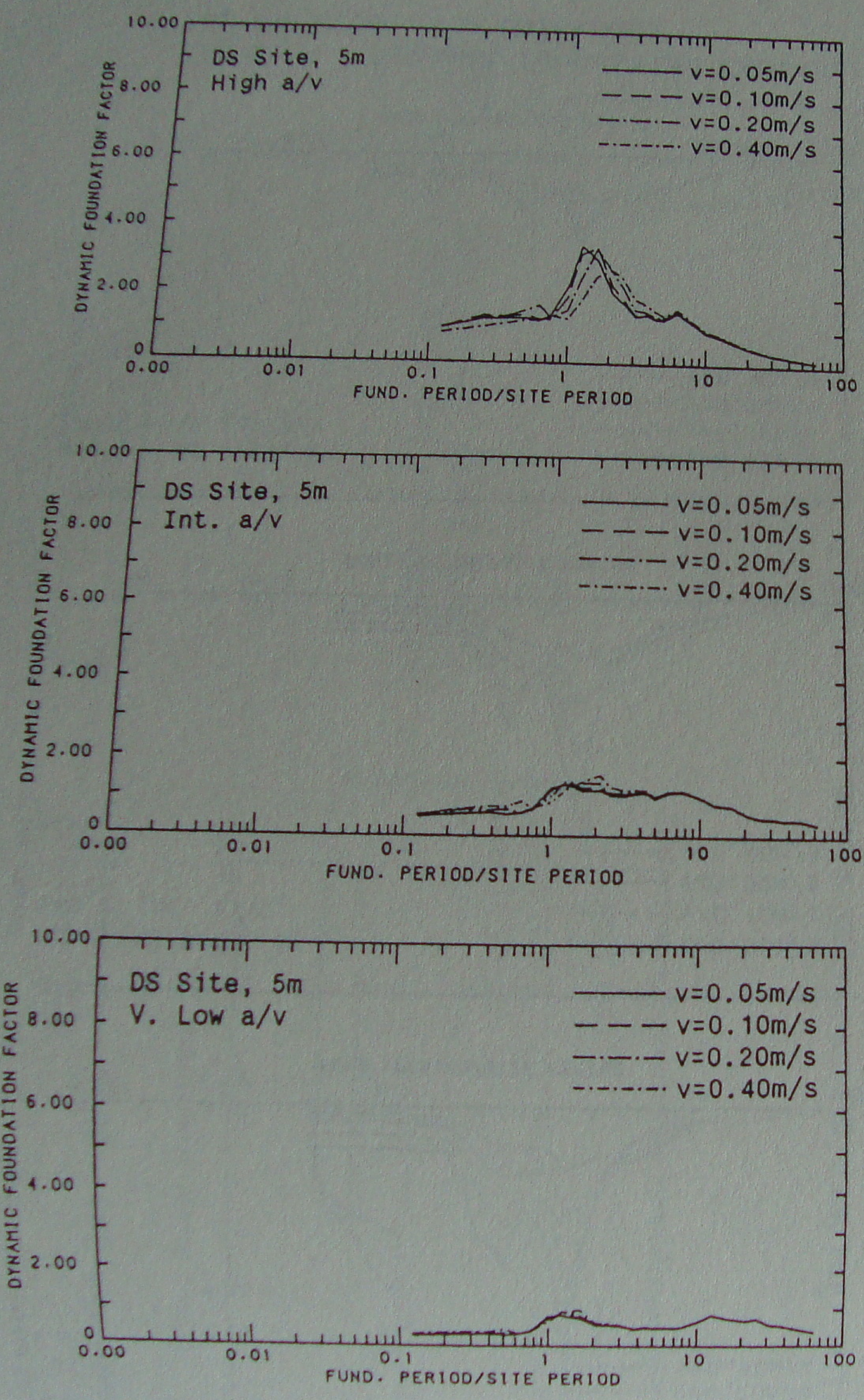

Figure 6. Dynamic foundation factors for DS site, 5 m thickness

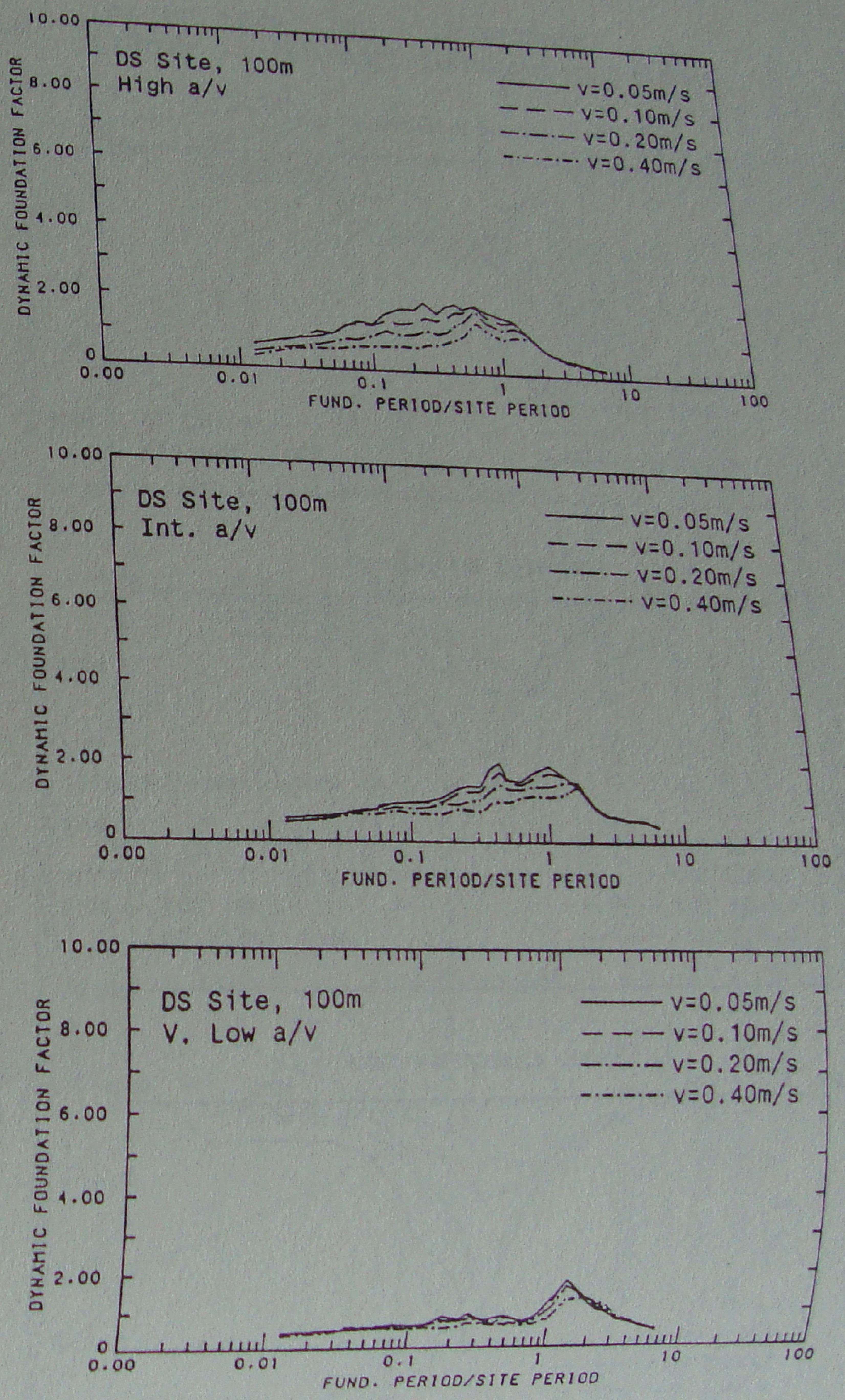

Figure 7. Dynamic foundation factors for DS site, 100 m thickness