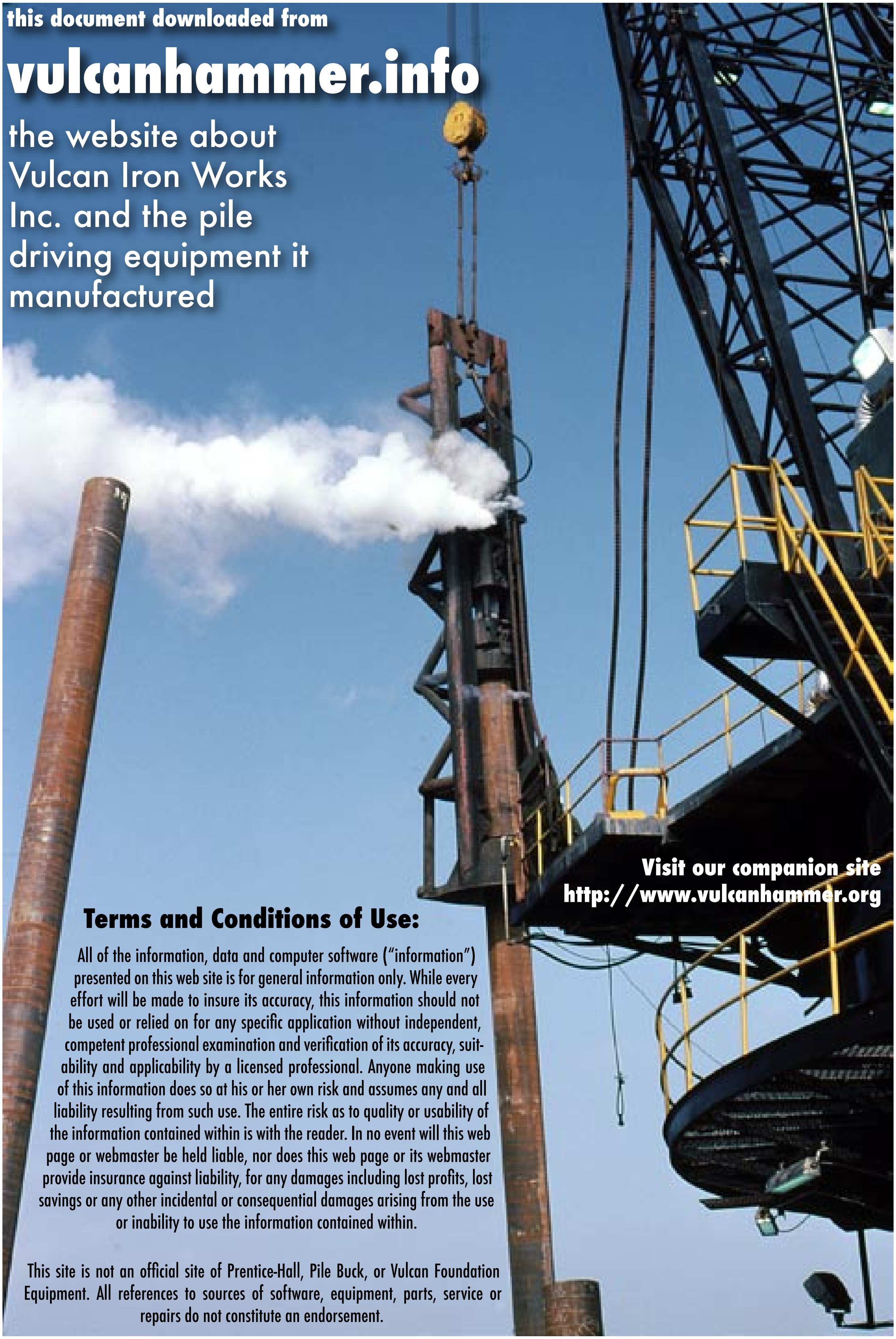

Non-dimension Frequency

DYNAMIC BEHAVIOR OF BATTERED PILES

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W in HBo

INTRODUCTION

There are many different methods for the dynamic analysis of vertical piles. These methods include lumped parameter methods (7), continuum methods (5), and finite element methods (1). However, none of these methods are applicable to the dynamic analysis of battered piles. Poulos (8) discussed several different methods for the static analysis of battered piles. He concluded that the axial and normal displacements of a pile head are nearly independent from the pile batter.

Poulo's results of reference (8) gives rise to the question of whether or not the dynamic behavior of battered piles is similar to that of its static behavior in that its axial and normal dynamic responses are independent from the pile batter. In order to answer this question in an accurate, economical, and simple manner it was decided to generalize the method of dynamic analysis of vertical piles introduced by Novak (5) such that it could handle the battered piles case.

The effects of pile battering on horizontal and vertical compliances are studied for several cases. It is concluded that these effects are more important in the dynamic case than that reported for the static case. These large dynamic effects of pile battering tend to decrease in the higher frequency range.

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THEORETICAL BACKROUND

The formulation of the problem is similar to that of reference (5) in that it is based on evaluating the dynamic soil reactions on the pile using the plane strain assumption of reference (6). The pile is simulated as a set of beam elements. This approach makes it possible to analyze any desired batter angle of the single pile in a simple and economical way.

Dynamic Soil Reactions

It is assumed that the soil medium is linear isotropic with a hysteretic type damping (4). The soil is extended to infinity in the horizontal direction and is supported by either rigid or elastic rock. The dynamic motion is assumed to be harmonic with a forcing frequency Ω.

The dynamic soil reactions on the pile may be easily determined using the method of reference (5) and is based on the assumption that the soil layer is subdivided into several layers and that each sublayer is vibrating in a plane strain fashion. This assumption was investigated in reference (5) for the case of single vertical piles and later in reference (3) for the case of vertical pile groups. Both references concluded that this is an accurate assumption for dimensionless forcing frequencies higher than 0.3. Reference (5) suggested a corrective approach for lower frequencies and, again, reference (3) found later that this corrective approach is fairly accurate for the case of vertical pile groups. Based on these findings, the plane strain assumption will be extended to evaluate the dynamic soil reactions on battered piles. The dynamic soil reactions may be evaluated for cylindrical, plane strain, horizontal soil sublayers, and the resulting expressions for vertical, horizontal, rotational, and torsional soil springs, (K_v, K_h, K_r, K_t, respectively), were obtained using reference (6).

The battered pile is assumed to have a circular cross section, the diameter of which may be varied but is constant along the pile length. The material of the pile is assumed to be linear and isotropic and the pile damping is assumed to be hysteretic. The pile is assumed to be bonded completely to the soil around it and is simulated by a set of finite elements (2). These elements are based on the Engineering Theory of beams and can account for the shear deformations of the pile. The nodal points are located at the same elevations as the interfaces of the soil sublayers. The total dynamic stiffness matrix is assembled first in the local coordinate system of the pile ($\bar{x}_1$, $\bar{x}_2$, $\bar{x}_3$). It is then transformed into the global coordinate system of the soil layer (x_1, x_2, x_3) figure (1). The dynamic soil reactions (springs), (K_v, K_h, K_r, K_t), are then added to the dynamic global stiffness matrix. The pile tip reactions are taken into account using the formulae of the half space soil springs of reference (9). A simple substructuring process may be used to condense all degrees of freedom except those of the pile head, reference (1). The resulting condensed stiffness matrix of the pile head represents the stiffness (impedance) of the pile head in the global coordinate system of figure (1). The pile head flexibility (compliance) will be used in the case studies of this paper and may be obtained by numerically inverting the condensed stiffness matrix of the pile head.

CASE STUDIES

Problem Description

The analytical method described in the previous section will be used to study the behavior of some battered piles. The geometry of the pile in figure (2) will be considered. The pile diameter (d_o) is 2.0 ft. Two pile lengths (L) are studied; 50 ft. and 100 ft. The pile is assumed to be of concrete with a modolus of elasticity (E) of 2.78 x 10^6 psi, mass density of 2.25 x 10^{-4} lb sec^2/in^4, Poisson's ratio (ν) of 0.16, and ratio of critical damping of 0.02. The pile is assumed to be embedded in one soil layer with a shear wave velocity (C_s) of 194.5 ft/sec, dilatational wave velocity (C_p) of 479.3 ft/sec, mass density of 1.8 x 10^{-4} lb sec^2/in^4, and ratio of critical damping of 0.05. The soil layer is resting on rigid rock. The depth of the soil layer depends upon the angle of batter (γ) in order to maintain a constant pile true length. Three angles of batter are considered: 0.0^o, 15.0^o, and

30.0°. The equivalent soil depth (d) is given by:

$$d = L \cos \gamma$$

These pile and soil properties define the pile flexibility factor (K_R) as given by reference (8):

$$K_R = 1.272 \times 10^{-4} \quad \text{for } L = 50.0 \text{ ft., and}$$

$$K_R = 7.947 \times 10^{-6} \quad \text{for } L = 100.0 \text{ ft.}$$

<u>Results</u>

Three directions of motion of the pile head are of interest, namely the axial pile compliance (V), the normal pile compliance in the direction of batter (H_B), figure (2), and the normal pile compliance in the direction normal to the batter plane (H_N). The coupling compliance (C_{VH}) between the axial and normal compliances is also of interest. There is no coupling between the axial and normal compliances in the plane normal to the batter plane.

The four compliances of interest: V, H_B, H_N, and C_{VH} will further be nondimensionalized. The new dimensionless compliances may be defined as:

$$\bar{V} = \frac{V}{V_o}$$

$$\bar{H}_B = \frac{H_B}{H_{Bo}}$$

$$\bar{H}_N = \frac{H_N}{H_{No}}$$

$$\bar{C}_{VH} = \frac{C_{VH}}{V_o}$$

where V_o, H_{Bo}, and H_{No} are the vertical and horizontal compliances of the pile head with $\gamma = 0.0°$. In a similar manner, a dimensionless frequency (a_o) will be used in the study, where:

$$a_o = \frac{\Omega d}{2C_s}$$

Figures (3a - d) show the dimensionless compliances $\overline{V}$, $\overline{H}_B$, $\overline{H}_N$ and $\overline{C}_{VH}$ for $\gamma = 15.0^o$ and 30.0^o as a function of the dimensionless frequency (a_o), for the case $K_R = 1.272 \times 10^{-4}$ and $L/d_o = 25.0$. The battering of the pile has a large effect on the axial compliance ($\overline{V}$). The effects of battering are smaller on the normal compliance ($\overline{H}_B$). Both dimensionless compliances increase with the increase of the angle of batter (γ), which is in agreement with the results of reference (8). The effects of pile battering were calculated to be insignificant in that reference; it was shown that the maximum difference in the static compliance between the vertical and the battered pile was 4%. The results depicted in figure (3), however, show that this difference may be as high as 70% for $\overline{H}_B$ and 14% for $\overline{V}$. The dimensionless compliances are also frequency dependent as they tend to increase slightly with an increase of frequency until the maximum battering effects are reached at a dimensionless frequency (a_o) of approximately 0.15. The battering effects decrease rapidly for higher frequencies. The effect of battering increases, as expected, with an increase of the battering angle (γ). Figure (3c) shows the dimensionless compliance $\overline{H}_N$ as a function of dimensionless frequency. The battering effects for this case are different from the cases of $\overline{V}$ and $\overline{H}_B$ as the dimensionless compliance $\overline{H}_N$ actually increases at higher dimensionless frequencies. Figure (3d) depicts the coupled compliance ($\overline{C}_{VH}$) and shows that the coupled compliance changes rapidly with a change in frequency. Figures (4a - d) depict similar dimensionless compliances for the case of $K_R = 7.947 \times 10^{-6}$ and $L/d_o = 50.0$. The general behavior of the compliances are similar to that of the $L/d_o = 25.0$ case. The battering effects, however, are somewhat smaller.

CONCLUSIONS AND RECOMMENDATIONS

A simple and economical method is presented to analyze single, battered piles which are subjected to harmonic motions. It is found that the battering effects are somewhat higher in the battering plane than those reported in other references concerning static cases. These effects, however, decrease at higher frequencies. It is found that the battering effects increase the pile stiffness (lower compliance) in the plane normal to the battering plane. These observations seem to be independent of the ratio L/d_o. The frequency dependence of the pile compliances seem to be of importance in all cases studied.

Based on the above, it is recommended that additional case studies be performed in order to gain more understanding of the dynamic effects of pile battering. It is also recommended that a proper dynamic analysis using either the method described herein or another method be performed when the piles are subjected to dynamic loads, since the importance of the frequency dependence of the pile battering effects were established.

ACKNOWLEDGEMENTS

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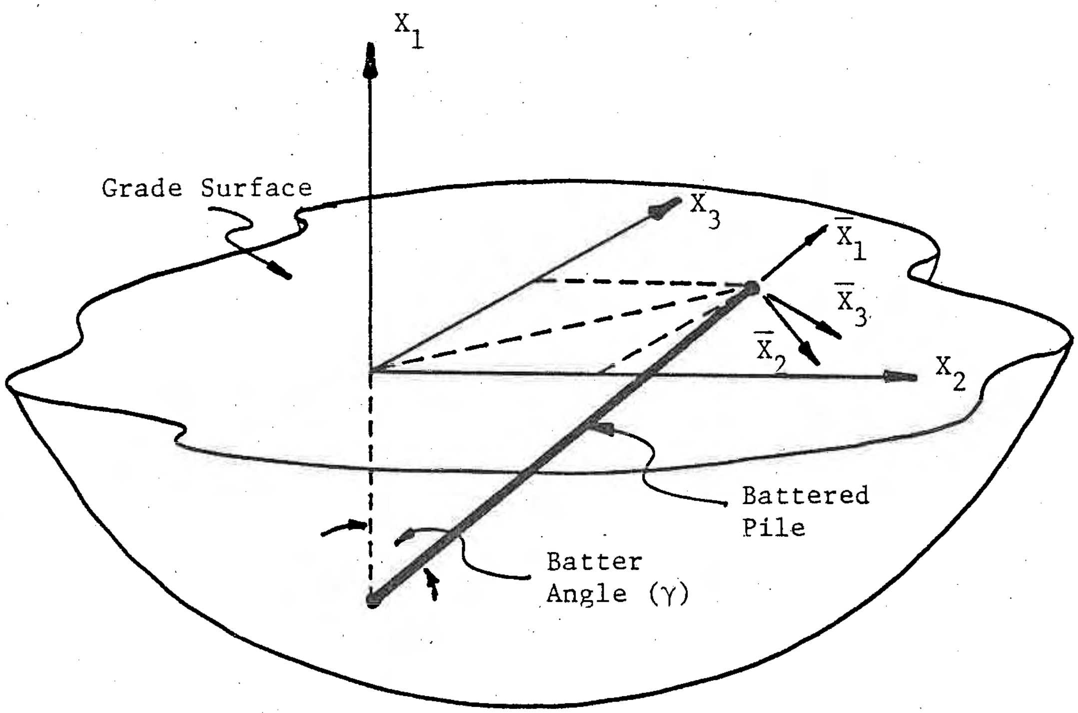

Figure 1 - Coordinate System

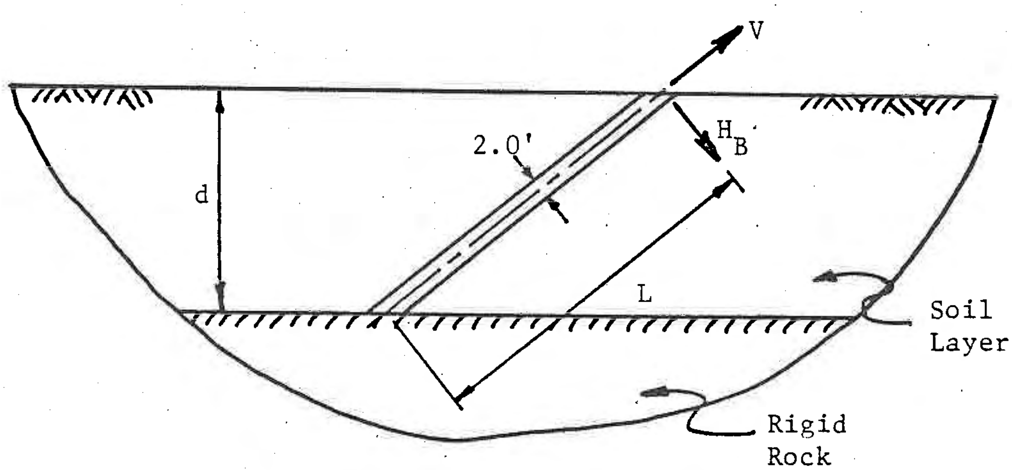

Figure 2 - Case Study

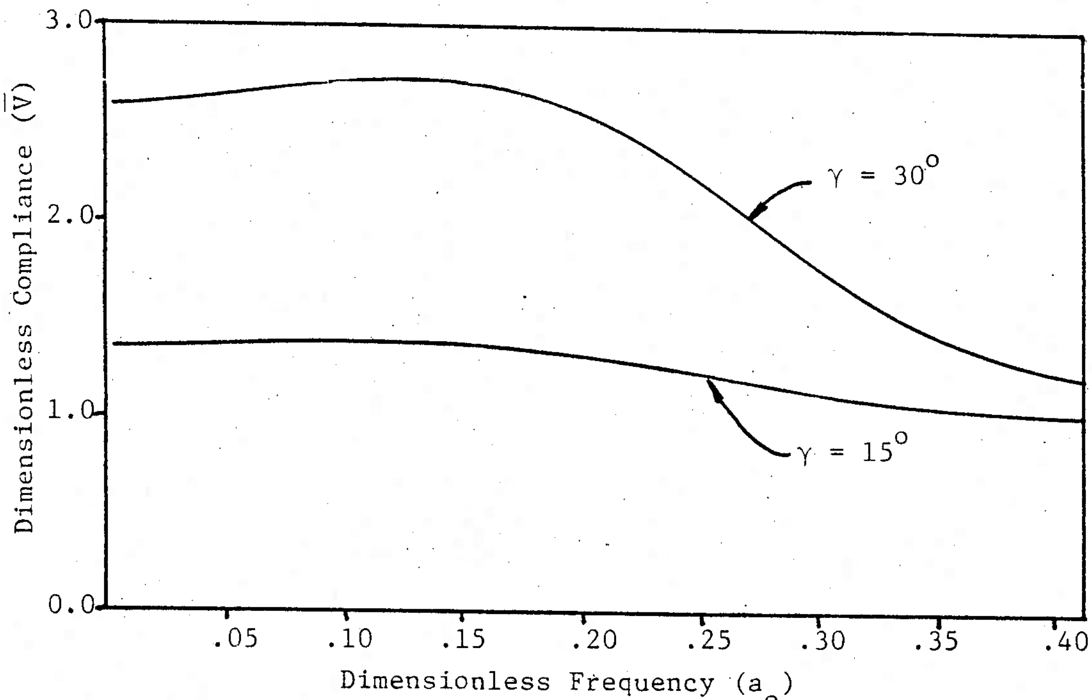

Figure 3a - Compliance Function $\bar{V}$; $\frac{L}{d_o}$ = 25.0

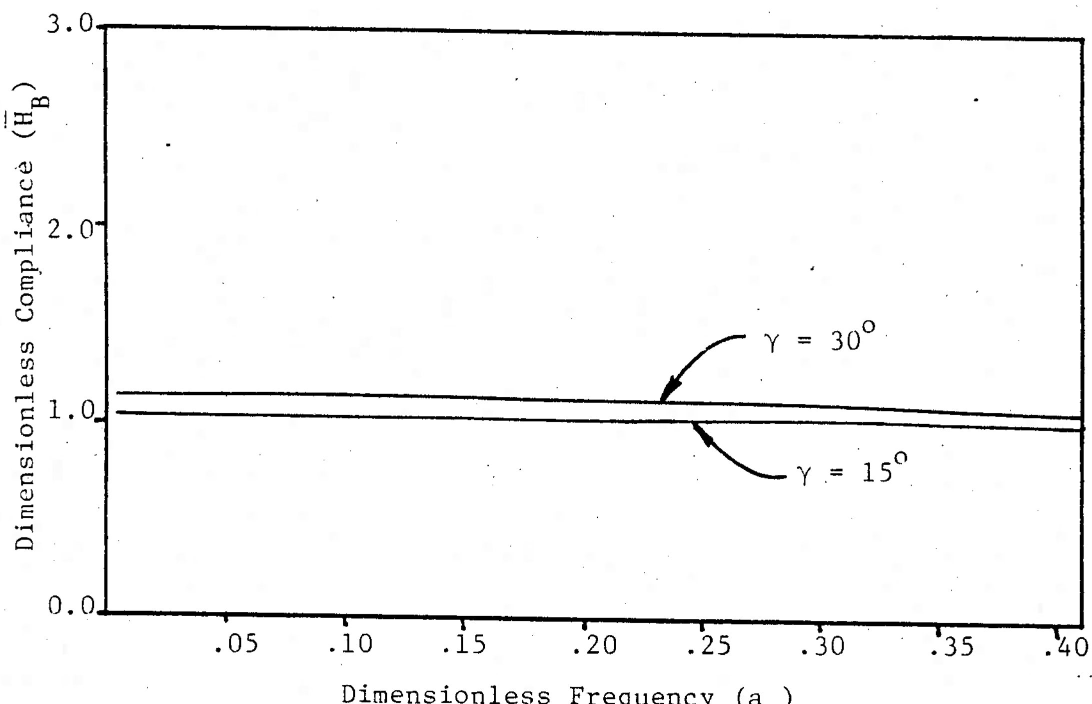

Figure 3b - Compliance Function $\bar{H}_B$; $\frac{L}{d_o}$ = 25.0

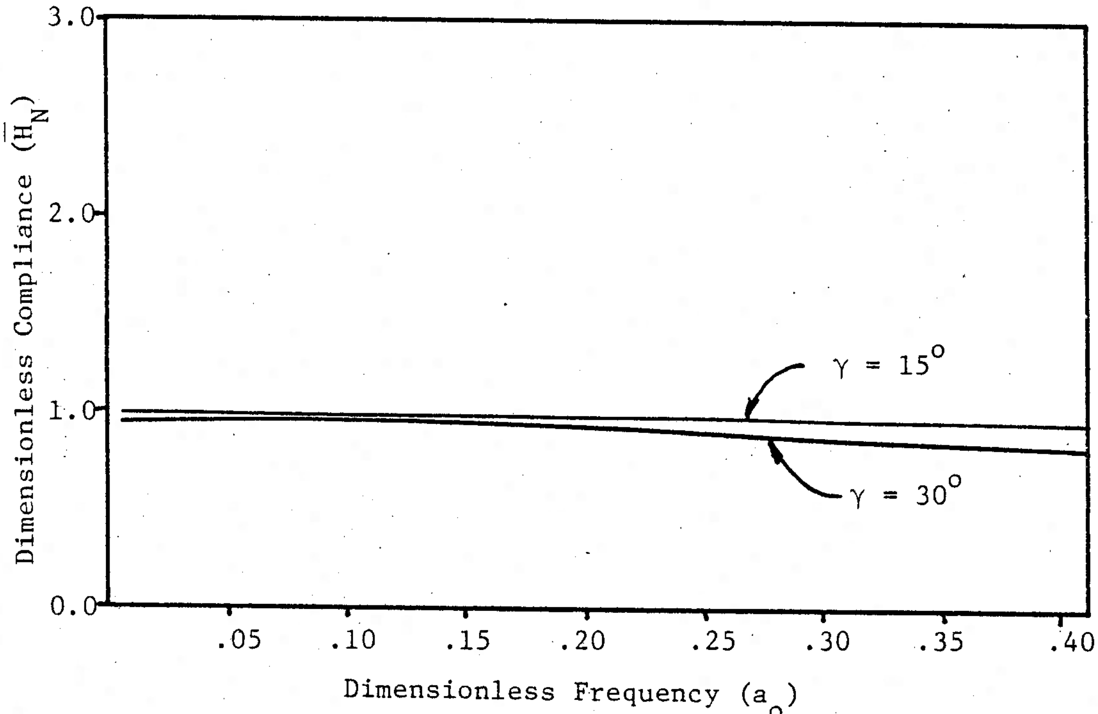

Figure 3c - Compliance Function $\overline{H}_N$; $\frac{L}{d_o}$ = 25.0

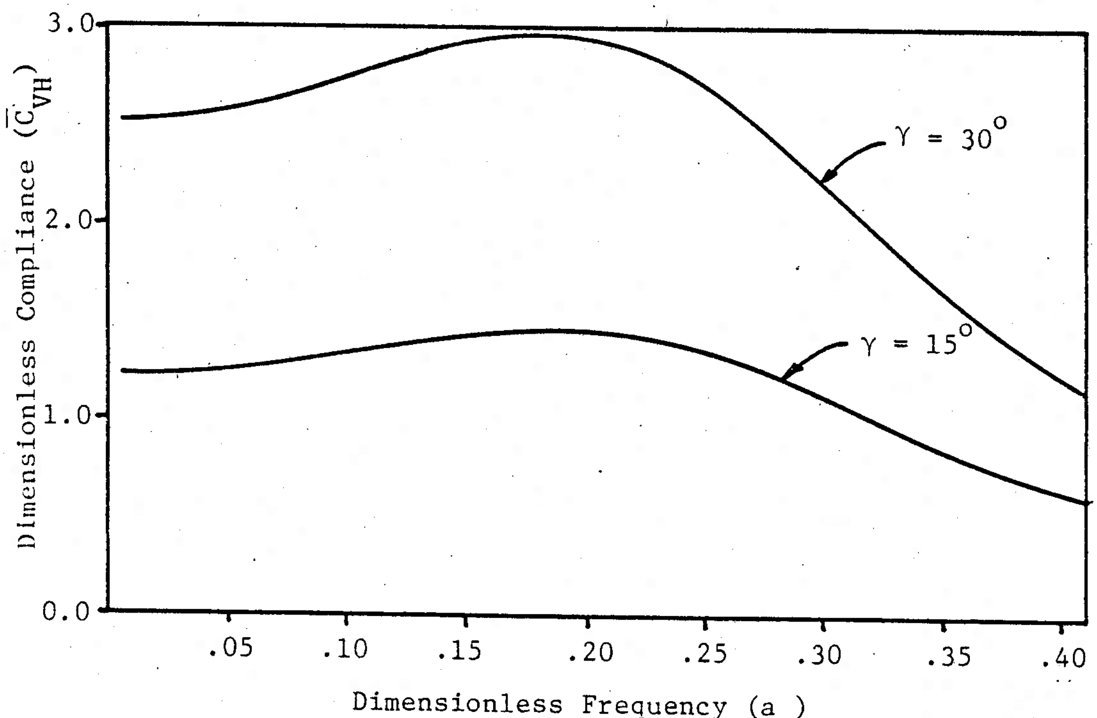

Figure 3d - Compliance Function $\overline{C}_{VH}$; $\frac{L}{d_o}$ = 25.0

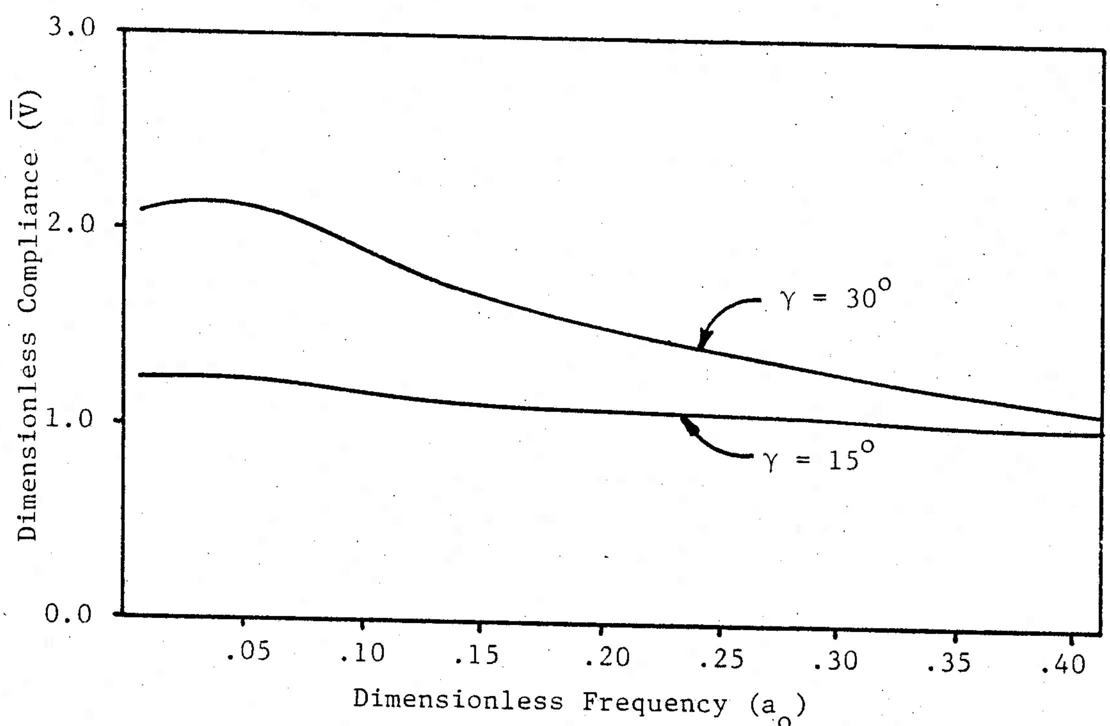

Figure 4a - Compliance Function $\bar{V}$; $\frac{L}{d_o}$ = 50.0

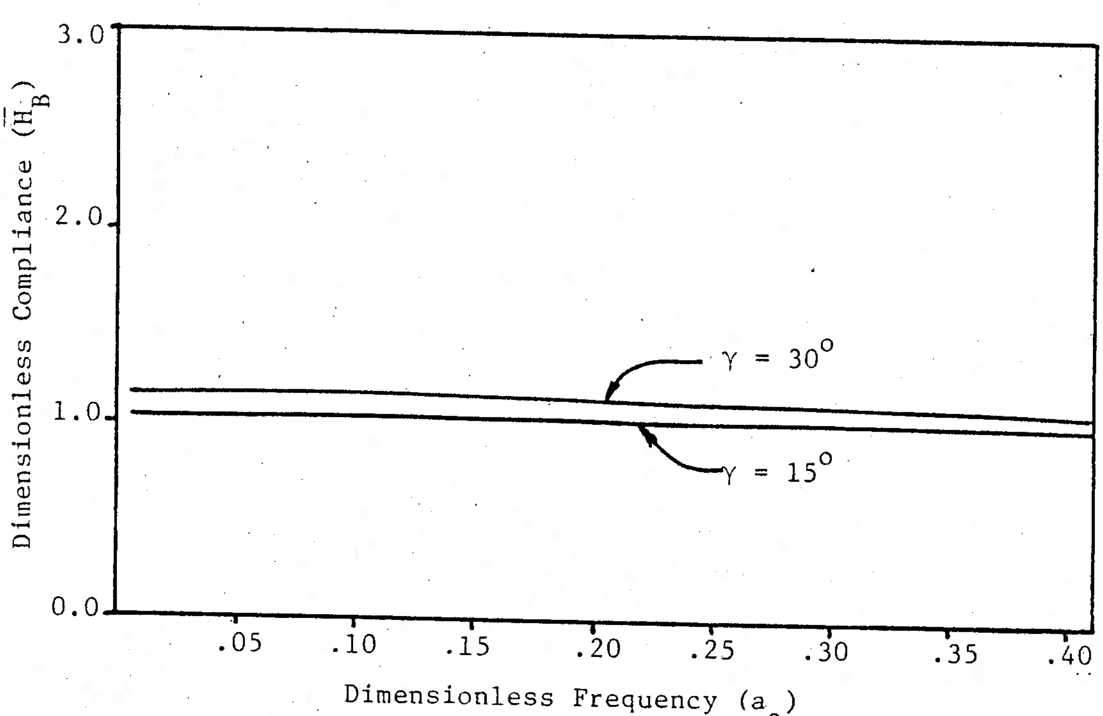

Figure 4b - Compliance Function $\bar{H}_B$; $\frac{L}{d_o}$ = 50.0

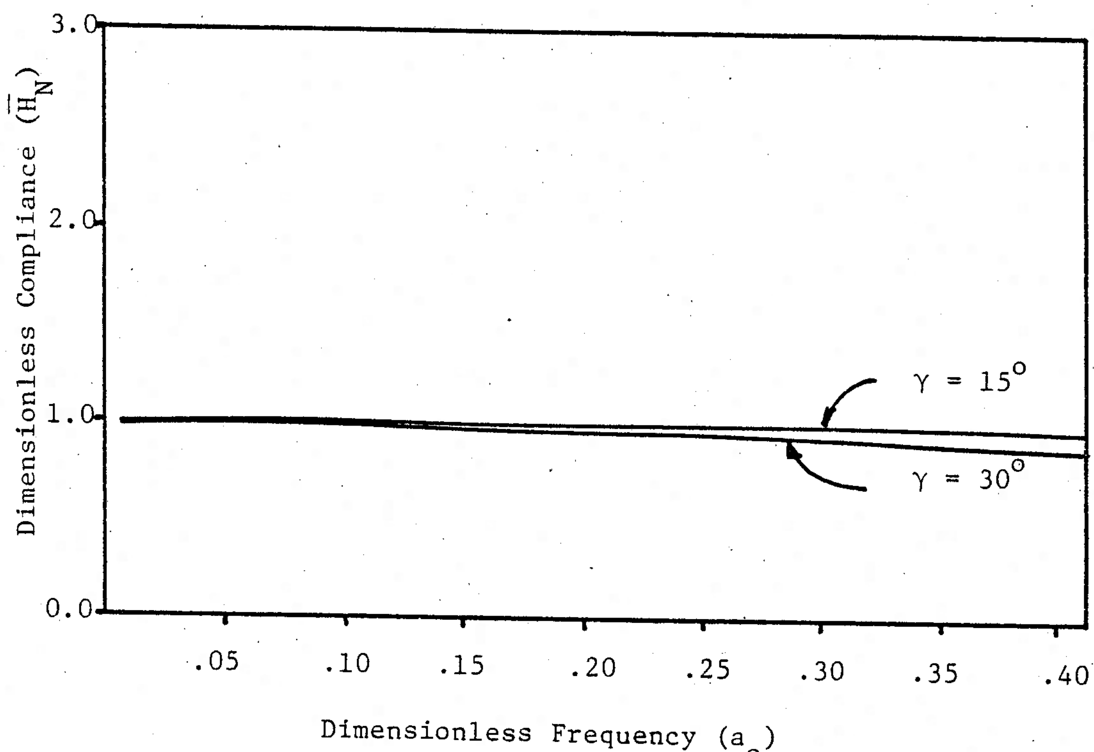

Figure 4c - Compliance Function $\bar{H}_N$; $\frac{L}{d_o} = 50.0$

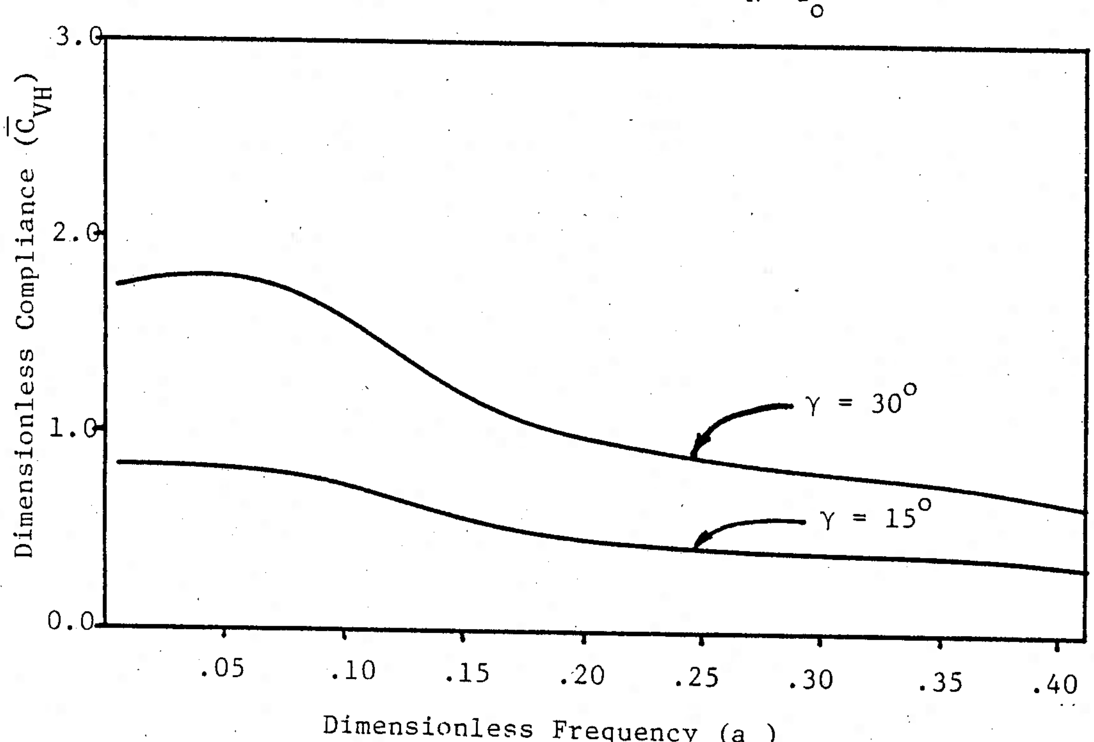

Figure 4d - Compliance Function $\bar{C}_{VH}$; $\frac{L}{d_o} = 50.0$