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Dynamic characteristics of irregularly embedded foundation

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ABSTRACT: A simplified estimation procedure is proposed to obtain the complex soil spring for irregularly embedded foundation. This procedure is based on combining bottom and side soil spring. The bottom soil spring can be easily obtained using the three dimensional wave propagation theory or bondary element method. It is, however, difficult to calculate rigorous solution as for the effect of irregular embedment and composite medium even if the recent computer power becomes strongly. Considerable results using a present method is provided on soil springs for various type of embedded foundations, and it is concluded that this method can be applicable for practical design purpose.

1 INTRODUCTION

In order to make the conventional seismic design of embedded structure, it is well used that the bottom and side soil spring are evaluated separately for a soil structure interaction problem of embedded foundations because of its simplicity of calculation. The elastic wave theory and plane-strain model of Novak et al. are usually used to determine the bottom spring and side spring respectively. However, Novak's method can only be assumed for the fully uniform embedment while some actual seismic design may have to consider an irregular embedment of foundation. A finite element method or a boundary element method is effective to calculate such a complicated foundation, a simplified method to evaluate an irregular embedment is required for the design purpose. This paper proposes a simplified procedure for evaluating in terms of dynamic soil spring of irregularly embedded foundation and verifies its validity comparing with the results by three dimensional boundary element method.

2 ANALYSIS METHOD

A model foundation whose half width is B as shown in Figure 1 is lyiing on a half space layered media and one dimensional wave propagation toward z direction is assumed. The region within the angle θ is only considered the wave propagation. The equilibrium equation to obtain the shearing soil spring in x direction is,

$$\frac{d^2u}{dz^2} + \frac{1du}{zdz} + \frac{\omega^2}{V^2} = 0 \qquad (1)$$

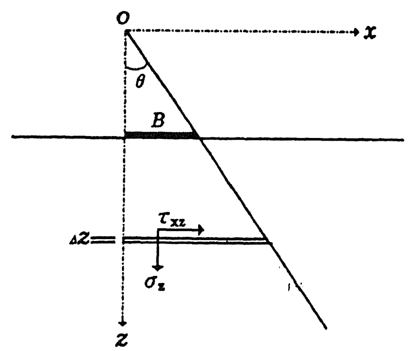


Figure 1 Truncated Pyramid Model

where u is displacement, ω is circular frequency and V is shear wave velocity. The solution of equation (1) is given as:

$$u = a_1 H_0^{(1)}\left(\frac{\omega}{V} z \tan\theta\right) + a_2 H_0^{(2)}\left(\frac{\omega}{V} z \tan\theta\right) \qquad (2)$$

where a_1, a_2 are integral constants. $H_n^{(1)}$, $H_n^{(2)}$ are the first and second kind, n-th order of Hankel function, respectively.

The next assumption is that the soil is composite medium which consists of two different material properties. The displacements decay with distance and stresses at the interface between layers are continuous. The relationship between the reaction force and displacement beneath the foundation leads to the soil spring k'_s in shearing x direction,

$$k'_S = \omega z_1 \rho_1 V_1 \tan\theta \frac{\beta H_1^{(1)}\left(\frac{\omega}{V_1} z_1 \tan\theta\right) + H_1^{(2)}\left(\frac{\omega}{V_1} z_1 \tan\theta\right)}{H_0^{(1)}\left(\frac{\omega}{V_1} z_1 \tan\theta\right) + H_0^{(2)}\left(\frac{\omega}{V_1} z_1 \tan\theta\right)} \qquad (3)$$

$$\beta = \frac{-\alpha H_0^{(2)}(\frac{\omega}{V_1} z_2 \tan\theta)\, H_1^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) + H_0^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) H_1^{(2)}(\frac{\omega}{V_1} z_2 \tan\theta)}{\alpha H_0^{(1)}(\frac{\omega}{V_1} z_2 \tan\theta)\, H_1^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) - H_0^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) H_1^{(1)}(\frac{\omega}{V_1} z_2 \tan\theta)} \tag{4}$$

where V_1, V_2 are shear wave velocity of medium I and II, z_1 is the distance from the origin to the foundation and z_2 is the distance from origin to interface of layers. A parameter $\alpha\,(=\rho_1 V_1/\rho_2 V_2)$ means the impedance ratio. The soil spring k'_L in longitudinal z direction can be expressd the similar form with that in x direction by adopting the longitudinal wave velocity as velocity V in equation (1) because the equilibrium equation is the same form.
Lysmer's analog "wave velocity" defined as :

$$V_L = 3.4 \cdot V_S / \pi\,(1-\nu) \tag{5}$$

is used as the longitudinal wave velocity to avoid that the velocity tend to infinity as Poisson's ratio ν becomes close to zero.
The rotational soil spring around y axis, k'_R, and torsional soil spring around z axis, k'_T, can be obtained by similar formulation as follows,

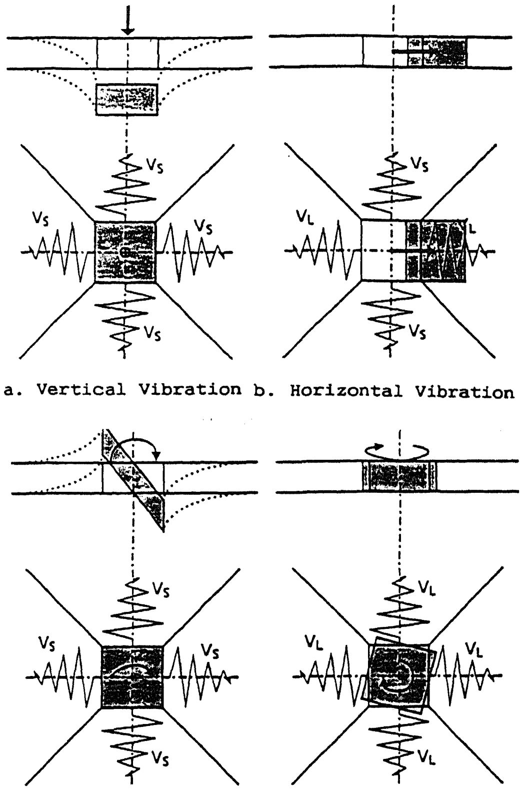
$$k'_{R,T} = \frac{1}{3}\omega z_1^3 \rho_1 V_1 \tan^3\theta \frac{\beta' H_2^{(1)}(\frac{\omega}{V_1} z_1 \tan\theta) + H_2^{(2)}(\frac{\omega}{V_1} z_1 \tan\theta)}{H_1^{(1)}(\frac{\omega}{V_1} z_1 \tan\theta) + H_1^{(2)}(\frac{\omega}{V_1} z_1 \tan\theta)} \tag{6}$$

$$\beta' = \frac{-\alpha H_1^{(2)}(\frac{\omega}{V_1} z_2 \tan\theta)\, H_2^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) + H_1^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) H_2^{(2)}(\frac{\omega}{V_1} z_2 \tan\theta)}{\alpha H_1^{(1)}(\frac{\omega}{V_1} z_2 \tan\theta)\, H_2^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) - H_1^{(2)}(\frac{\omega}{V_2} z_2 \tan\theta) H_2^{(1)}(\frac{\omega}{V_1} z_2 \tan\theta)} \tag{7}$$

3 COMPARISON WITH PRESENT METHOD AND PLANE-STRAIN MODEL

In order to examine the characteristics of present method, the soil spring for embedded foundation was compared with plane-strain model(Novak, Sheta 1980). On condition that the wave propagation from embedded foundation was combined as shown in Figure 2, the vertical, horizontal, rotational and torsional soil spring of fully embedded foundation per unit thickness are,

$$\begin{aligned} k_V &= 8k'_S \\ k_H &= 4k'_S + 4k'_L \\ k_R &= 4B^3 k'_S + 4k'_T \\ k_T &= 8k'_R \end{aligned} \tag{8}$$



a. Vertical Vibration b. Horizontal Vibration

c. Rotational Vibration d. Torsional Vibration

Figure 2 Combination of Vibration Pattern and Radiated Wave

The calculated results are shown in Figure 3 for uniform and homogeneous medium and Figure 4 for composite medium. The soil springs are normalized by shear modulus G and $G \cdot r_0$ in which r_0 is the radius of foundation. Since the present method is basically applicable for rectangular foundation, it is necessary to replace a rectangular to a circle. The equivalent radius of circle which equaled the area or perimeter of foundation were adopted.
The frequency dependency is almost similar with Novak's spring in any components for uniform medium. Especially, the imaginary part of vertical component coincided in case that the perimeter is equivalent to that of circle foundation. The property of real parts show the different tendency, which decline in accordance with frequency while the imaginary parts still show similar results for composite media.

4 VERIFICATION OF SIMPLIFIED PROCEDURE FOR IRREGULARLY EMBEDDED FOUNDATION

Three cases were prepared for verification of simplified procedure. The foundations of

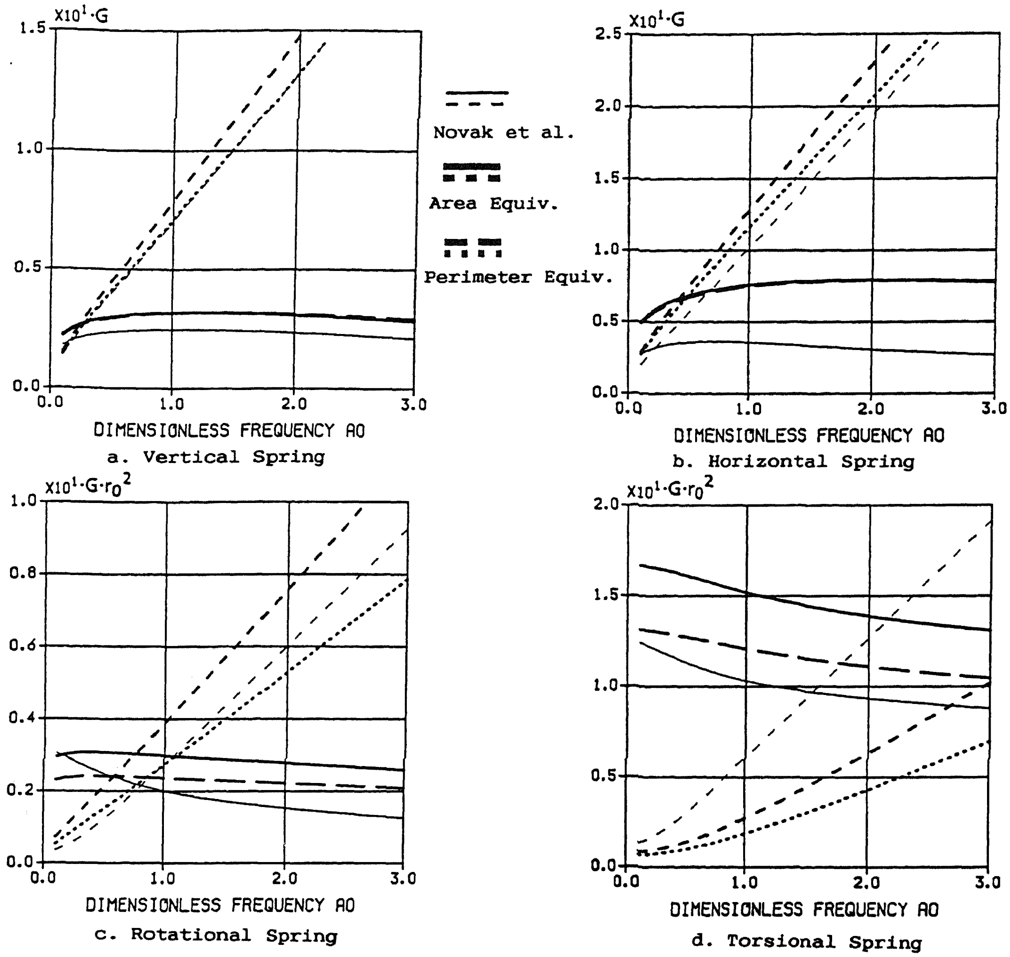


Figure 3 Soil Spring for Uniform Medium

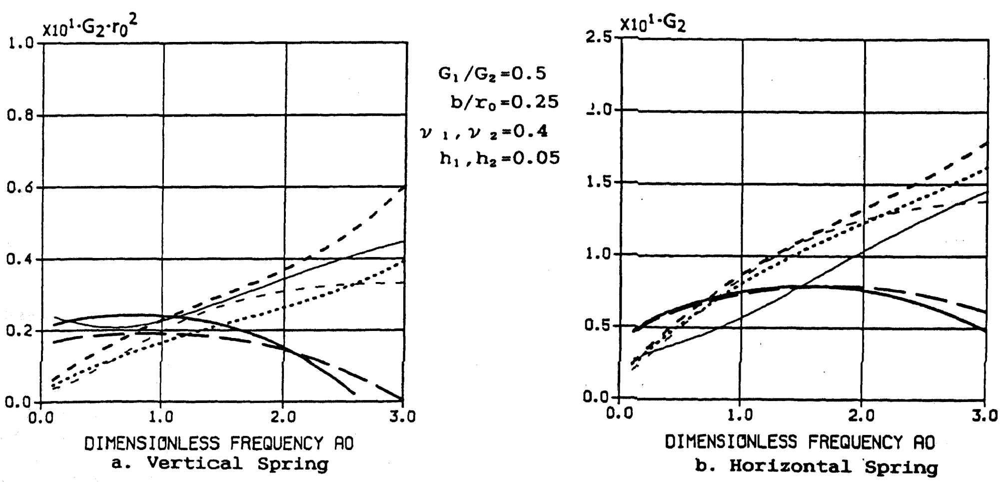
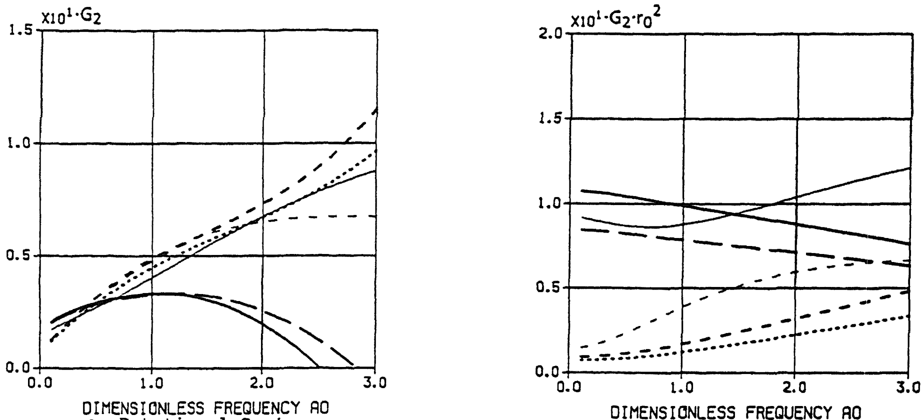


Figure 4 Soil Spring for Composite Medium



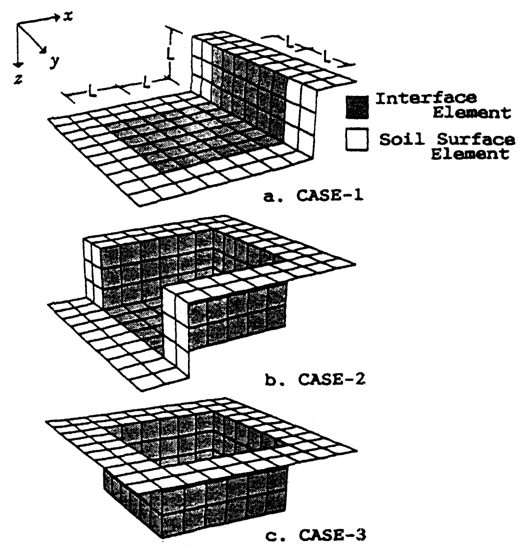
c. Rotational Spring

d. Torsional Spring

Figure 4 Soil Spring for Composite Medium (Continued)

$$\begin{bmatrix} K_x & & & K_{x\theta y} \\ & K_y & K_{y\theta x} & \\ & K_{\theta xy} & K_{\theta x} & \\ K_{\theta yx} & & & K_{\theta y} \end{bmatrix} = \begin{bmatrix} K_{Bx}+K_{Sx} & & & D\cdot K_{Sy} \\ & K_{By}+K_{Sy} & -D\cdot K_{Sx} & \\ & -D\cdot K_{Sx} & K_{B\theta x}+K_{S\theta x}+D^2\cdot K_{Sy}+B^2\cdot K_{Sz} & \\ D\cdot K_{Sy} & & & K_{B\theta y}+K_{S\theta y}+D^2\cdot K_{Sx}+B^2\cdot K_{Sz} \end{bmatrix} \qquad (9)$$

all cases were embedded in the uniform homogeneous medium. The foundation of Case 1 and Case 2 are bonded with soil at one or three directions. A fully embedded foundation is Case 3. Soil springs at the bottom center of square embedded foundation expresses combining the bottom and side soil springs as shown in equiation (9), where D is half of embedded depth, B is length of foundation. The terms of K_{sx}, K_{sy} and K_{sz} are side swaying soil spring in x, y and z direction, respectively. The terms of $K_{s\theta x}$ and $K_{s\theta y}$ are side rotational soil spring around x axis and y axis, respectively. The three dimensional boundary element method (3D-BEM) was adopted to evaluate the bottom soil springs K_{Bx}, K_{By}, $K_{B\theta x}$ and $K_{B\theta y}$ which could be obtained as the soil spring for surface foundation. This boundary element method employs the dynamic Kelvin's solution as the fundamental solution, therefore, it can analyze the irregularly embedment of foundation in the homogeneous media whereas modelling of surface ground isnecessary. Then, the verification was performed comparing with 3D-BEM. The assumedconstants of soil and foundation are shown in Figure 5. The element mesh for 3D-BEM is also shown in the figure.



Shear Wave Velocity:1000m/s
Poisson's Ratio:0.4

Figure 5 Irregular Embedded Foundation and Element Mesh for BEM

The analysis results are shown in Figure 6 through Figure 8 in which the horizontal and rotational soil springs in x direction and y direction are compared. The vertical axes of each figures are normalized by GL and GL^3(G is shear modulus, L is half length of foundation). Horizontal axes are dimensionless frequency a_0 defined by ω L/V_s.

In case that one face of foundation contacts with soil(CASE-1), a simplified procedure agree well with 3D-BEM on horizontal and rotational soil spring in both x and y direction except for real part of spring in low frequency range. It is remarkable that the soil spring in y direction coincides with 3D-BEM and supposed that the contribution of side soil to resist against the shear might be caused by one dimensional wave propagation. On the other hand, the cases whose contact faces increase show the different tendency and frequency dependency characterized as real part decrease in higher frequency region could not be expressed by simplified procedure reflecting the property of side soil spring.

It is satisfied that the imaginary parts give the comparable results with 3D-BEM in spite of the calculation method is simple even though the real part may not be adaptive.

5 CONCLUSIONS

Despite a proposed method based on very simple assumptions, the analysis results were reasonable for practical use.

As the proposed method can deal the more complicated model such as the soil structure consists of composite media and the embedment is irregular, its applicability is wide, flexible and effective for various type of embedded foundations.

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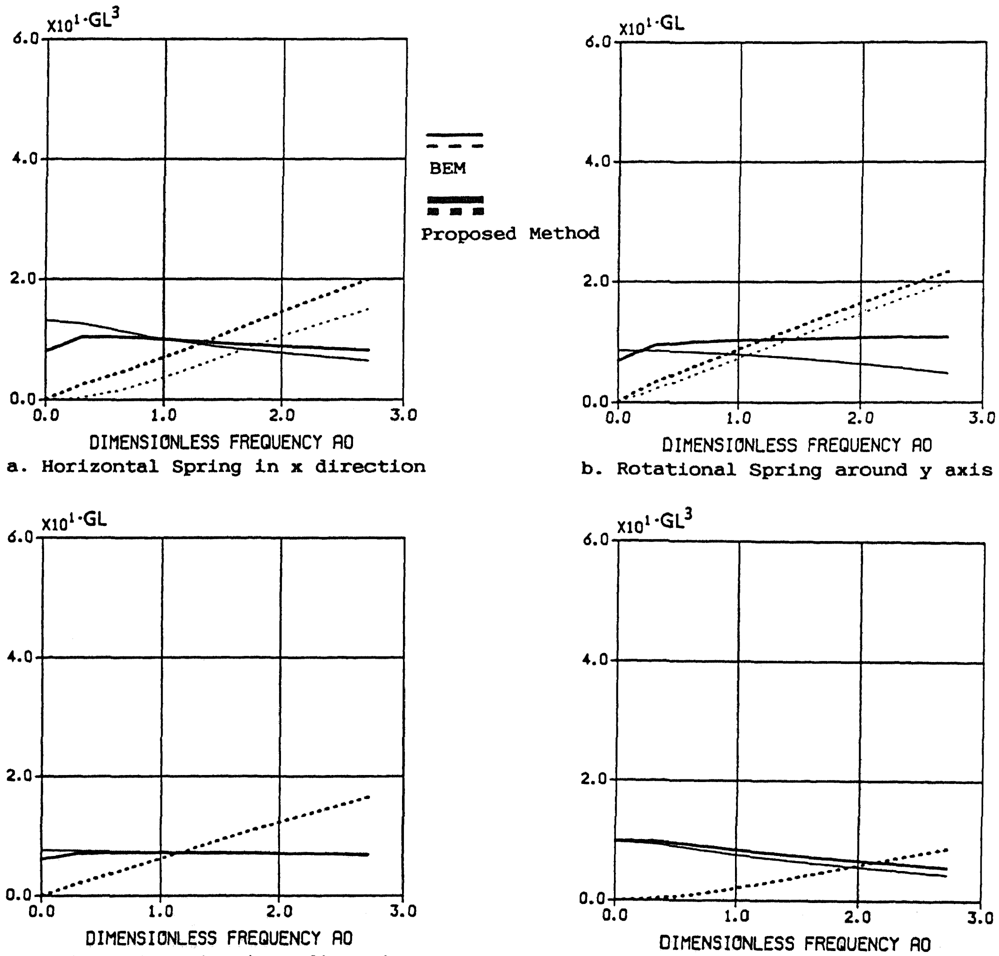


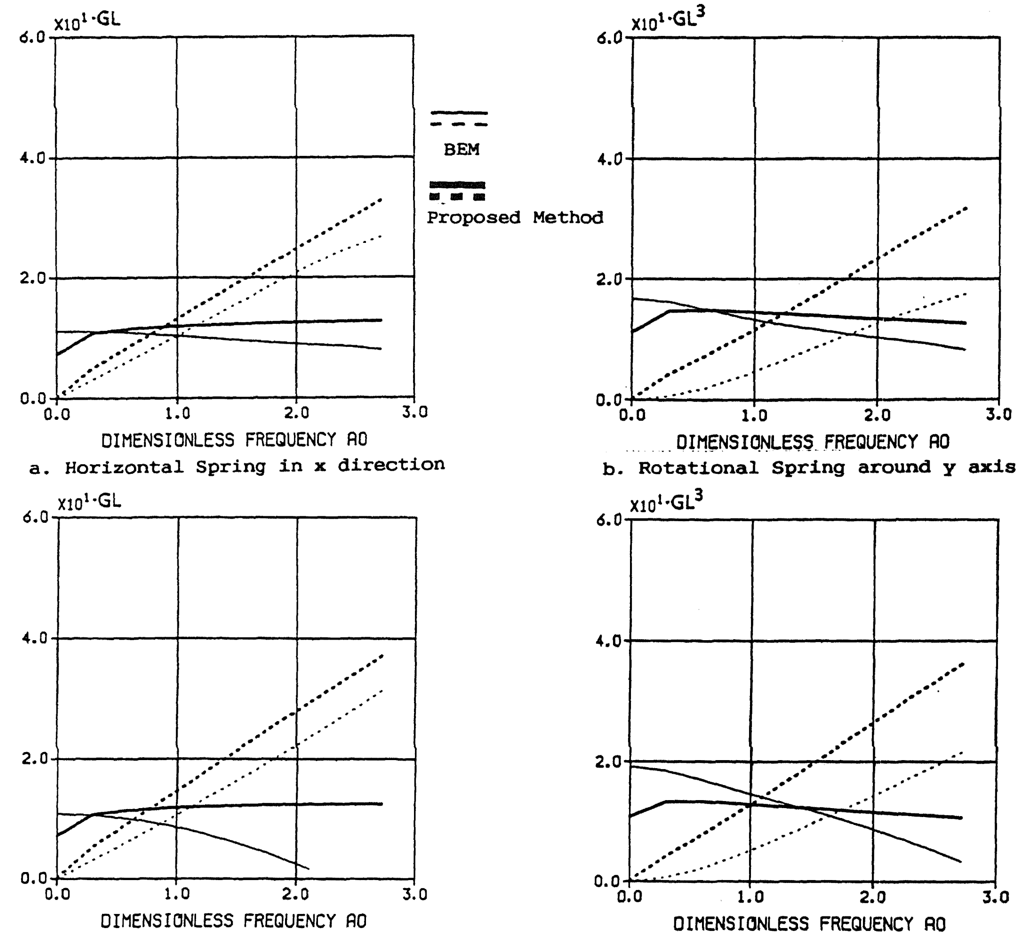
a. Horizontal Spring in x direction

b. Rotational Spring around y axis

c. Horizontal Spring in y direction

d. Rotational Spring around x axis

Figure 6 Concentrated Soil Spring at Bottom of Foundation (CASE-1)



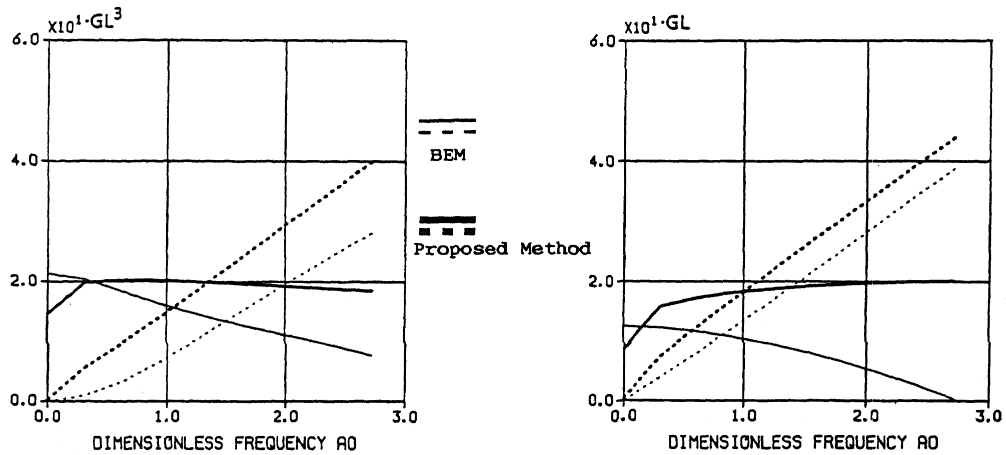
a. Horizontal Spring in x direction

b. Rotational Spring around y axis

c. Horizontal Spring in y direction

d. Rotational Spring around x axis

Figure 7 Concentrated Soil Spring at Bottom of Foundation (CASE-2)



a. Horizontal Spring in x direction

b. Rotational Spring around y axis

Figure 8 Concentrated Soil Spring at Bottom of Foundation (CASE-3)