EARTHQUAKE RESPONSE OF EMBEDDED CYLINDRICAL FOUNDATIONS TO SH AND SV WAVES

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SUMMARY

A study of the frequency and earthquake responses of a rigid cylindrical foundation embedded in a homogeneous elastic half-space and subjected to SH and SV waves excitation with different angles of incidence is presented. Particular emphasis is given to the study of effects of the embedment depth and angle of incidence on the seismic responses. The results indicate that the horizontal component of responses reduces remarkably with increase of the embedment depth due to filtering effect on the side of the embedment. On the other hand, the rocking component tends to increase as the embedment depth increases.

INTRODUCTION

In the analysis of the earthquake response of structure, it has been assumed that the seismic waves impinge vertically on the foundation. However, it has been reported that the analysis based on the assumption of vertical incidence cannot explain the results of seismic motion observed in the structures (Ref. 1, 2). The effect of nonvertically incident waves on the response of flat foundation has been discussed and studied in recent years.

While the response of embedded foundations to obliquely incident seismic waves has also become of major interest and studied extensively, most of the studies are restricted to the analyses of the two-dimensional embedments and very few have been addressed to the three-dimensional embedded foundations (Ref. 3-9). Day (Ref. 3) and Iguchi (Ref. 4-6) have considered the harmonic response of a cylindrical foundation embedded in a homogeneous elastic half-space and subjected to nonvertically incident SH and Rayleigh waves. Dominguez (Ref. 7) has considered the harmonic response of a rectangular foundation embedded in a homogeneous elastic soil and subjected to nonvertically incident SH, SV and P waves. Torsional response of a hemispherical foundation subjected to obliquely incident SH waves has been analyzed by Luco (Ref. 8), while Lee and Trifunac (Ref. 9) have studied the other components for a hemispherical foundation excited by obliquely incident SH, SV and P waves. All these studies, however, have been addressed to the analyses of harmonic response and limited to the qualitative investigations. Under these conditions, it is required to study the response of embedded foundations to more general seismic excitation to draw definite conclusions.

This paper studies the frequency and time-domain responses of a cylindrical foundation embedded in a homogeneous elastic soil and subjected to nonvertically incident SH and SV waves. The analysis is based on an approximate procedure proposed by Iguchi (Ref. 4). In numerical evaluation, the effects of the embedment depth and incident angle on the seismic response are studied. The emphasis is also given to the study of seismic forces and moments that the soil exerts on the foundation during earthquakes.

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ANALYSIS OF FOUNDATION RESPONSE

The model considered in this study is illustrated in Fig. 1, and it consists of a rigid cylindrical foundation of radius a and embedment depth h bonded to and embedded in a homogeneous elastic half-space. The seismic excitation is represented by obliquely incident SH and SV waves impinging on the foundation with vertical angle Θ and particle motions in the vertical plane parallel to the y-axis for both incident waves as shown in Fig. 1.

The first basic problem that needs to be considered corresponds to the evaluation of the impedance functions for the foundation. The results of the impedance functions for the embedded cylinder have been presented by Day for some embedment depths and for a Poisson's ratio $\nu = 0.25$ (Ref. 3) and will not be discussed here. The second basic problem is associated with the evaluation of the harmonic response of the rigid massless embedded foundation subjected to incident harmonic waves. The resulting response of the foundation, referred to here as foundation input motion, may be represented by the six generalized coordinates

$$\{U^*\} = (\Delta_x^*, \Delta_y^*, \Delta_z^*, \Phi_x^*, \Phi_y^*, \Phi_z^*)^T \tag{1}$$

consisting of three translational and three rotational components as shown in Fig. 1. The time factor $\exp(i\omega t)$, with circular frequency ω, is omitted in Eq. (1). The translational components Δ_x^*, Δ_y^* and Δ_z^* are defined at the center of the top of the foundation. The evaluation of the foundation input motion $\{U^*\}$ entails the solution of a mixed boundary value problem in elastodynamics. An approximate method of the solution has been presented by Iguchi and is made use of in the present analysis. By use of the procedure, the foundation input motion may be obtained by a simple algebraic calculation. The detail of the method may be found elsewhere (Ref. 4) and will not be repeated here.

Once the impedance functions and foundation input motion for massless embedment have been solved, the effect of mass of foundation may be incorporated by a standard procedure. The additional harmonic response caused by the inertia forces of the foundation may be represented by a six-component vector $\{U\} = (\Delta_x, \Delta_y, \Delta_z, \Phi_x, \Phi_y, \Phi_z)^T$ and can be evaluated by

$$\{U\} = ([I] - \omega^2[K]^{-1}[M_f])^{-1}\{U^*\} \tag{2}$$

where $[I]$ and $[M_f]$ represent the 6x6 identity and mass matrices, respectively, for the rigid foundation and $[K]$ is the 6x6 impedance matrix which consists of the horizontal, vertical, rocking, torsional and coupling impedance functions. These functions have been presented by Day (Ref. 3) and are made use of in the present analysis. If $\{F^s\} = (F_x^s, F_y^s, F_z^s, M_x^s, M_y^s, M_z^s)^T$ represent the resultant inertia forces and moments about the point of reference in the foundation, the generalized forces $\{F^s\}$ may be calculated by

$$\{F^s\} = \omega^2[\overline{M}_o]\{U\} \tag{3}$$

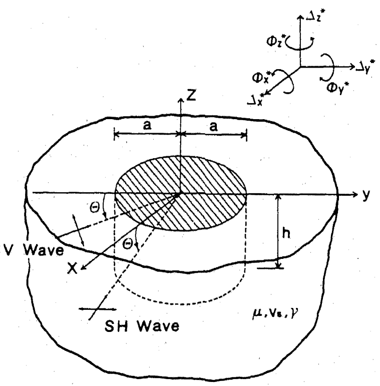


Fig. 1
Description of the model.

in which $[\overline{M}_0]$ is the 6x6 mass matrix and depends on the distribution of mass of the rigid foundation.

FOUNDATION INPUT MOTION

Two types of harmonic excitation (SH and SV waves) are considered in this study. The response of a massless cylindrical foundation to the obliquely incident SH waves with particle motion in the y-direction consists of a horizontal Δ_y^*, rocking Φ_x^* and torsional Φ_z^* components. The result of the torsional component has been shown in Ref. 4 and will not be discussed here. The normalized amplitudes $|\Delta_y^*/u_0|$ and $|a\Phi_x^*/u_0|$ (where u_0 is the horizontal amplitude of free-field motion on the soil surface) versus the dimensionless frequency $a_0 = \omega a/V_s$ (where V_s is shear wave velocity of soil) are shown in Fig. 2 for five incident angles Θ, four embedment ratios $\delta = h/a$ and a Poisson's ratio $\nu = 0.25$. The results shown in Fig. 2 indicate that the reduction of horizontal component is remarkable at high frequencies for obliquely incident SH waves and this fact is valid for both flat and embedded foundations. It is also seen that the horizontal component decreases with increase of embedment ratio for incident angles greater than 45°. This result may be interpreted as a filtering effect on the side of the embedment. On the other hand, a large rocking component is obtained for embedded foundation at intermediate and high frequencies. In addition, the rocking component tends to increase with increase of δ in the frequency range $a_0 < 2$. For a flat foundation, the rocking component becomes zero in the present analysis.

The response of a massless cylindrical foundation to obliquely incident SV waves propagating along the y-direction consists of a horizontal Δ_y^*, vertical Δ_z^* and rocking Φ_x^* components. The normalized amplitudes $|\Delta_y^*/u_0|$, $|\Delta_z^*/w_0|$ and $|a\Phi_x^*/u_0|$ (where w_0 is the vertical amplitude of free-field motion on the soil surface) are shown in Fig. 3 versus the dimensionless frequency a_0. The results shown in Fig. 3 reveal that the reduction of the horizontal and vertical components are remarkable at intermediate and high frequencies for nonvertical incidence. It is also seen from the results that the horizontal and vertical components decrease with increase of the embedment ratio δ in the frequency range $a_0 < 2$. On the other hand, pronounced rocking component is obtained for a flat foundation $\delta = 0$, but tends to decrease with increase of the embedment ratio. Comparing the response for incidence of SV waves with that for SH waves shown in Fig. 2, it is noticed that the rocking component

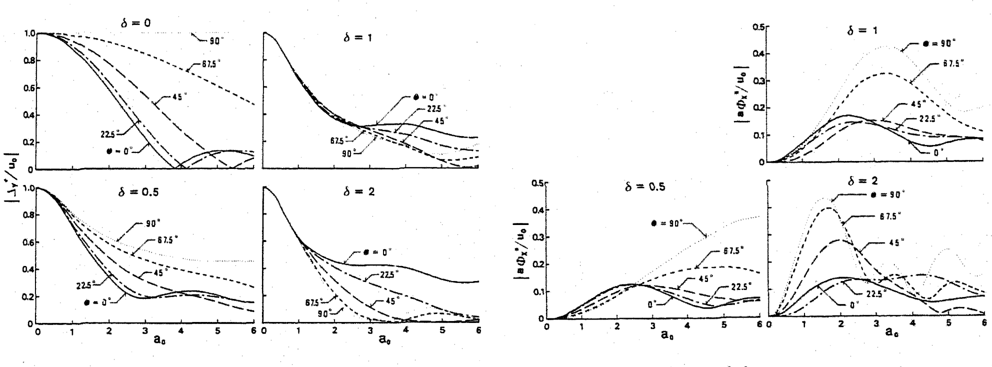


Fig. 2 Normalized amplitudes of the horizontal and rocking components of the foundation input motion for SH wave excitation.

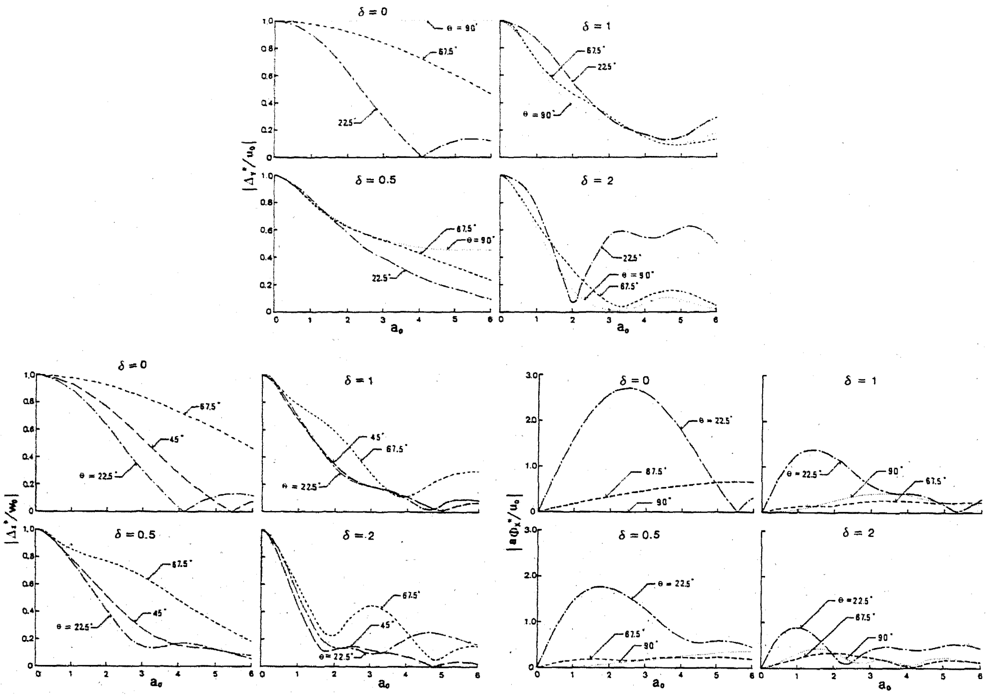


Fig. 3 Normalized amplitudes of the horizontal, vertical and rocking components of the foundation input motion for SV wave excitation.

for SV waves is greater than the result for SH waves excitation especially in the case of shallow angles of incidence; e.g. Θ = 22.5°.

SEISMIC RESPONSE TO SH AND SV WAVES

The seismic response of the massless embedded foundation subjected to two types of seismic excitation (SH and SV waves) is calculated on the condition that the acceleration time history for the NS component of the El Centro(1940) record be the motion in the y-direction on the free-surface ($\ddot{u}_0$) for both SH and SV waves. In the calculation, the Fast Fourier transform algorithm is made use of and the frequencies more than 10Hz contained in the El Centro record are cut off and neglected for computational reasons. The original and filtered acceleration time histories are shown in Fig. 4. The maximums of these two accelerograms change from 341.7gals to 356.6gals.

The translational and rotational seismic responses of the cylindrical embedment may be characterized by the embedment ratio, value of a/V_S, angle of incidence, type of excitation and a Poisson's ratio of soil. The maximum acceleration responses of the horizontal components at the top and bottom of the foundation is shown in Figs. 5(a) and (b) versus the embedment ratio δ for three values of a/V_S, two incident angles Θ, two types of excitation and a Poisson's ratio ν = 0.25. The results presented in Fig. 5(a) show that the reduction of the horizontal response with increase of δ is slight for a/V_S = 0.025sec but pronounced for a/V_S = 0.075sec. It is important to notice that the reduction of the horizontal response for Θ = 67.5° is less remarkable,

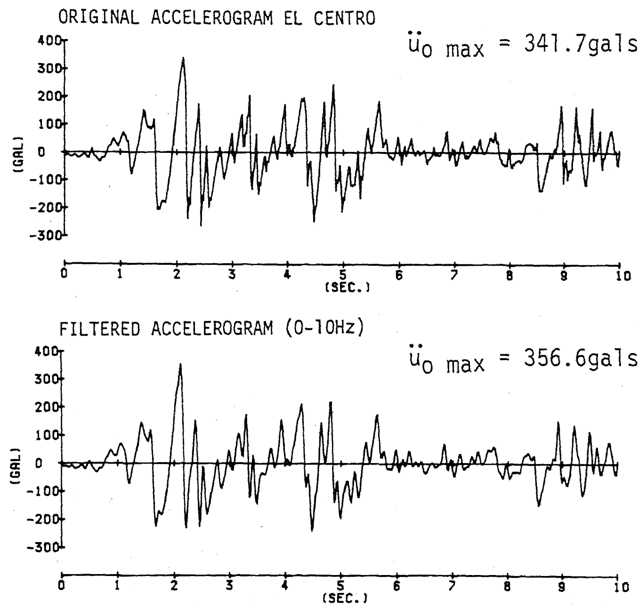
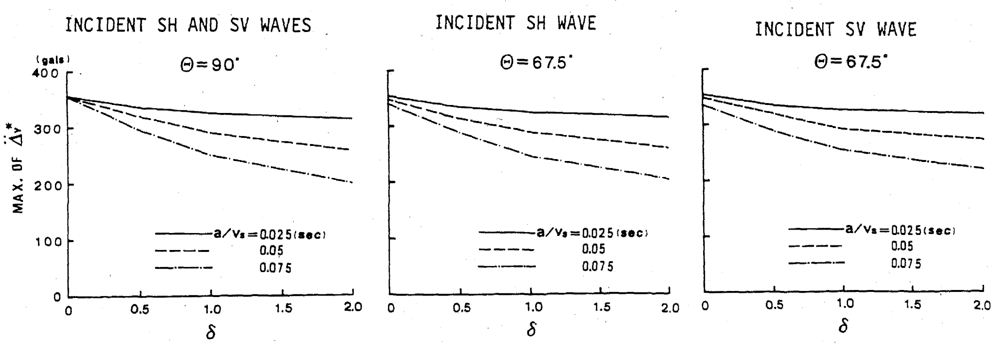
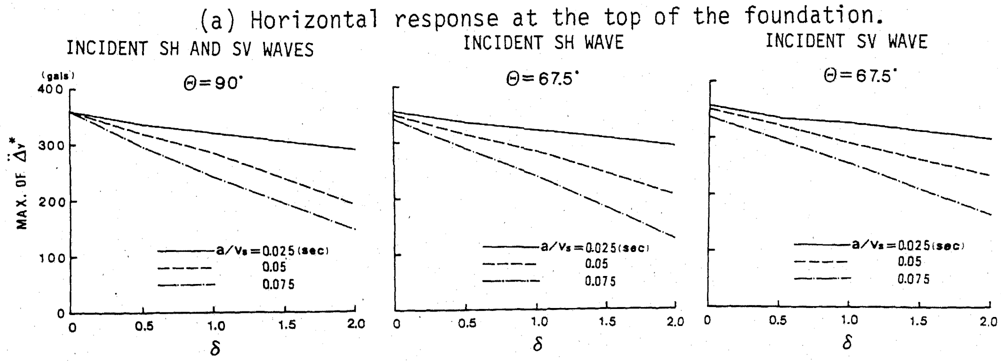


Fig. 4 Original and filtered acceleration time histories.



(a) Horizontal response at the top of the foundation.



(b) Horizontal response at the bottom of the foundation.

Fig. 5 Max. of horizontal acceleration responses for massless embedment.

especially for SV wave incidence, than that for the vertical incidence $\Theta = 90°$. The results shown in Fig. 5(b) indicate that the horizontal response at the bottom of the embedment tends to decrease with increase of δ more remarkably than the response at the top.

The maximum acceleration response of the vertical component $\ddot{\Delta}_z{*}$ versus the embedment ratio δ is shown in Fig. 6 for SV wave excitation and an incident angle $\Theta = 67.5°$. The results presented in Fig. 6 reveal that the vertical component decreases slightly with increasing the embedment ratio δ.

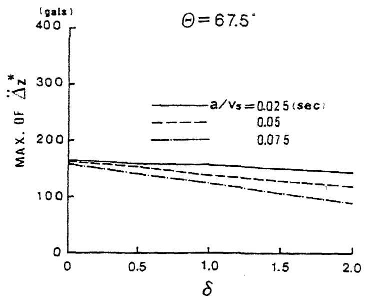


Fig. 6
Max. of vertical acceleration response for massless embedment excited by SV waves ($\ddot{u}_{0\,max}$ = 356.6gals).

The maximum acceleration response of the rocking component about the x-axis $a\ddot{\Phi}_x{*}$ is shown in Fig. 7 for two incident angles Θ, three values of a/V_s and two types of excitation. The results shown in Fig. 7 indicate that the rocking response tends to increase about linearly with increase of δ for SH wave incidence. The different tendency may be observed for the SV wave incidence with angle of incidence $\Theta = 67.5°$. The rocking response for this specific case becomes minimum at $\delta = 1.0$. The result of the rocking response $a\ddot{\Phi}_x{*}$ may be interpreted as the vertical response at the edges of the foundation. Comparing the rocking response to SV wave impinging with an angle $\Theta = 67.5°$ with the vertical response shown in Fig. 6, it may be seen that the vertical response associated with the rocking motion is considerably smaller than the translational component ($\ddot{\Delta}_z{*}$) for a/V_s = 0.025sec, while is comparable for a/V_s = 0.075sec and for $\delta = 2$.

HORIZONTAL AND ROTATIONAL SEISMIC FORCES

One of the most interesting responses of the rigid embedded foundation is the seismic forces and moments acting on the embedment during earthquakes. The resultant inertia forces and moments evaluated by Eq. (3) may be interpreted as the seismic forces and moments that the soil exerts on the foundation.

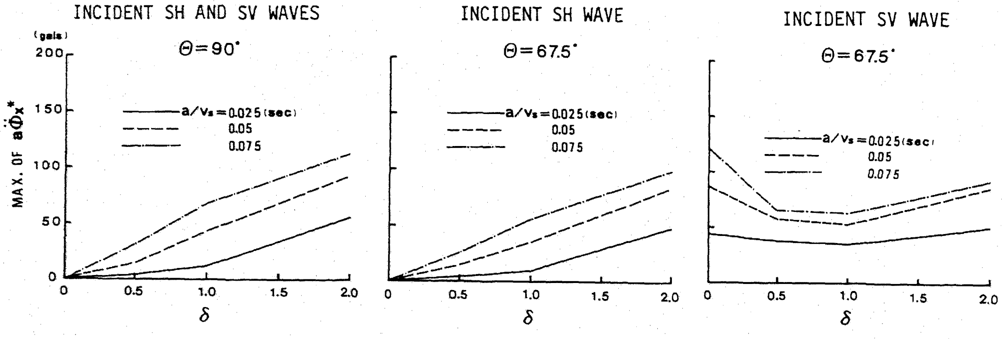


Fig. 7 Max. of rocking acceleration responses for massless embedment excited by SH and SV waves. ($\ddot{u}_{0\,max}$ = 356.6gals)

The maximum earthquake response of the horizontal seismic forces in the y-direction $F_y{}^S$ normalized by the total weight of the foundation $M_0 g$ (where g is the acceleration of gravity) is shown in Fig. 8 versus the embedment ratio δ for two types of seismic excitation, two incident angles, three values of a/V_S and a mass ratio M_0/M_S (where M_S is the mass of soil of the same volume as the embedment). Thus normalized value corresponds to horizontal seismic coefficient $k_H = F_y{}^S/M_0 g$. In the calculation, the mass of the foundation is assumed to be uniformly distributed. The results shown in Fig. 8 indicate that the horizontal seismic coefficient decreases about linearly with increase of embedment depth. The increase of a/V_S also reduces the seismic coefficient significantly. Similarly, the maximum response of the seismic moment at the center of the embedment $M_x{}^S$ normalized by $aM_0 g$ is illustrated in Fig. 9. The normalized result may be interpreted as rocking seismic coefficient $k_\Phi = M_x{}^S/aM_0 g$. The results shown in Fig. 9 indicate that for SH wave excitation the rocking seismic coefficient increases remarkably with increase of δ and a/V_S. Also, the difference of the incident wave may have a significant effect on the result for $\Theta = 67.5°$ and for small values of δ.

Observing the results shown in Figs. 8 and 9, it may be also seen that the calculation based on the usual assumption of vertical incidence results in overestimation in the horizontal seismic forces for $\delta < 0.5$ and underestimation for $\delta = 2.0$. As for the rocking seismic moments, on the other hand, the assumption leads to overestimation for the embedded foundations and for SH wave incidence, but underestimation for $\delta < 1.0$ and for SV wave incidence.

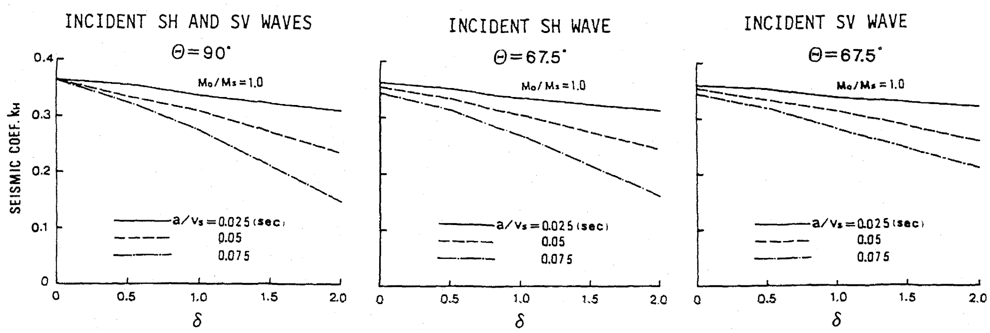


Fig. 8 Horizontal seismic coefficients for $M_0/M_S = 1.0$ ($\ddot{u}_0$ max = 356.6gals).

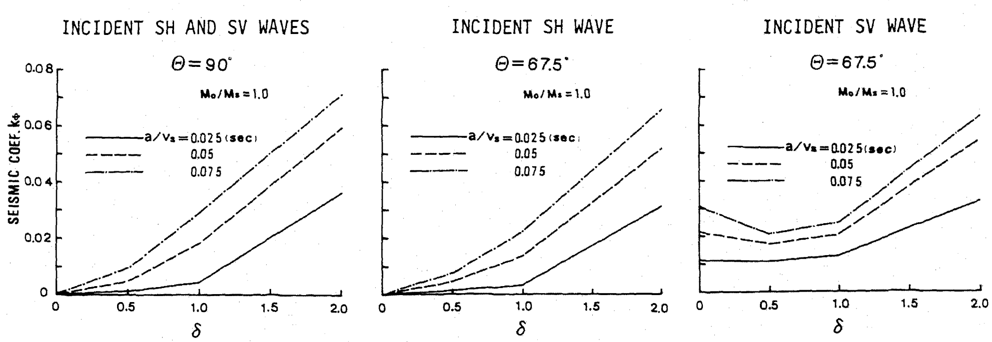


Fig. 9 Rocking seismic coefficients for $M_0/M_S = 1.0$ ($\ddot{u}_0$ max = 356.6gals).

CONCLUSIONS

The harmonic and seismic responses of a cylindrical foundation embedded in a homogeneous elastic soil and subjected to two types of nonvertically incident waves (SH and SV waves) have been obtained. For both types of the excitation, it has been found that the horizontal response decreases remarkably with increase of the embedment ratio δ and decrease of the shear wave velocity of soil. On the contrary, for SH wave excitation the rocking response tends to increase with increasing the embedment ratio and decreasing the shear wave velocity of soil. In addition, the horizontal and rocking seismic coefficients for the rigid embedded cylinder have been studied. The results obtained indicate that the horizontal seismic coefficient decreases about linearly with increase of the embedment depth, while for SH wave incidence the rocking seismic coefficient increases notably with increasing the embedment ratio. These seismic coefficients have been found to be affected remarkably by the value of a/V_S.

It may be also concluded from the results obtained in this study that the calculation based on the usual assumption of the vertically incident seismic excitation does not yield the conservative side results not only for the flat foundation but for the embedded foundation.

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