SCREENING OF INCIDENT PLANE WAVES BY A CYLINDRICAL FOUNDATION

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ABSTRACT

The importance of seismic observation for evaluation of soil-structure interaction has been emphasized. To fully understand the meaning of recordings on and around the building foundation, however, we must first explore the nature of the ground surface motion near the foundation.

In this paper the boundary element method is used to analyse the ground surface motion around a cylindrical foundation subjected to incident body and Rayleigh waves. The study shows that, a shadow zone is formed behind the foundation on the opposite side of the incident waves, in which the ground surface motion is smaller than that of the free field motion in high frequency range. When the non-dimensional frequency \(a_0 \geq 2\) (or the ratio of the foundation's radius to the wavelength of incident waves \(a/\lambda \geq 0.3\)), there will be a remarkable reduction of amplitudes. For incident body waves, when incident angle and the embedment ratio of the foundation become larger, the corresponding reduction effect becomes greater. For incident Rayleigh waves, the reduction of amplitudes is very pronounced and the bound of the reduction extends widely, regardless of the embedment ratio. The plane distribution of the reduction range and the effect of the flexibility of the foundation on the reduction have also been analysed.

Afore-mentioned phenomenon can be interpreted in terms of screening of incident waves by the foundation. The experimental studies on the isolation effect of a screen aiming to decrease vibration of structure backed up these analytical conclusions.

Key words: boundary element method, dynamic interaction, earthquake, wave propagation, screen (IGC : B 4/E 8)

INTRODUCTION

The importance of seismic observation for the verification of soil-structure interaction analyses has been emphasized recently (Tajimi, 1988). Observation studies of the soil-structure interaction are based on the simultaneous measurement of the free field ground motion and the response of the building foundation (Duke et al., 1970). By comparing these simultaneous motions, some information can be derived about the nature and

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significance of the interaction.

For example, the response of a foundation subjected to incident waves may be reduced in high frequency range. This has been verified by strong motions recorded in and outside the basement of the Hollywood Storage building (Duke et al., 1970). However recordings in the Imperial Valley, California, suggest that the opposite behavior is possible as well (Lee et al., 1982). Jiang and Kuribayashi (1988) have studied the dynamic responses of flexible foundation subjected to incident waves and pointed out that, the flexibility of actual foundation may diminish the reduction of translational responses and increase the rotational responses of the foundation in high frequency range.

On the other hand, the so called free field motion is generally recorded on ground surface close to the building foundation, such that the “free field” may include the effect of waves scattered from the foundation. To fully understand the meaning of seismic observation for evaluation of soil-structure interaction, we must explore the nature of the ground motion near the foundation.

There has been few studies on ground surface motion around a foundation subjected to incident waves. Trifunac (1972) studied the model, which consists of an infinitely-long elastic shear wall erected on a rigid semi-cylindrical foundation, and investigated the nature of the ground surface motion near the foundation subjected to incident SH waves. Trifunac showed that waves scattered from a rigid foundation contribute significantly to the ground surface motion near the foundation and at distances at least one order of magnitude greater than the characteristic length of the foundation. The Fourier displacement amplitude ratio of the foundation to the surrounding ground is showed for several incident angles and different positions, both in front of and behind the foundation. Results indicated that, when the incident angle approaches $\pi/2$, the shadow zone behind the foundation significantly changes the Fourier spectral ratio. Thus, waves scattered by the foundation must not be neglected, when the Fourier amplitude ratios of accelerograms recorded in and around the foundation are used to study the soil-structure interaction.

This paper presents studies on the ground surface motion surrounding a rigid cylindrical foundation subjected to incident body waves, namely P, SV and SH waves, and Rayleigh surface waves. The boundary element method is used to investigate the nature of the ground surface motion near the foundation.

**METHOD OF ANALYSIS**

The model to be analyzed is a rigid cylindrical foundation embedded into an elastic half-space, as showed in Fig.1. The foundation has height $H$, radius $a$, and embedment depth $h$. The incoming waves are obliquely incident body waves and Rayleigh surface waves. By using boundary element method the dynamic responses of the foundation subjected to incident waves can be referred to Eq. (25) in reference 4) (Jiang and Kuribayashi, 1988), as in the following equation,

$$\{\tilde{V}\} = \left[ [I] \right] - \frac{\pi a^2}{\gamma} \rho F \sqrt{K} [M]^{-1} \{V\}$$

(1)

where $\delta = h/a$ is the embedment ratio, $[I]$ is a unit matrix, $\rho F$ and $\rho$ are the mass.
density of the foundation and soil respectively, $a_0=\omega a/v_s$ is the non-dimensional frequency, $[K]$ is the dynamic impedance function matrix, which can be calculated by Eq. (16) in reference 4), $\{V^*\}$ is the effective input motion, which can be calculated by Eq. (24) in reference 4), and $[M]$ is a non-dimensional mass matrix defined as,

$$
[M] = \begin{bmatrix}
1 & 0 \\
1 & 1/4+1/3\Delta^2+\delta^2-\Delta\delta \\
0 & 1/4+1/3\Delta^2+\delta^2-\Delta\delta \\
0 & 1/2
\end{bmatrix}
$$

(2)

where $\Delta=H/a$.

After obtaining the responses of the foundation, the displacement of elements located on the interface between the foundation and soil can be written as,

$$
\{u\}_t = [\tilde{A}][\tilde{V}]
$$

(3)

where $[\tilde{A}]$ defined as Eq. (11) in reference 4).

Corresponding to Eq. (22) in reference 4) the traction of elements located on the interface can be obtained as,

$$
\{t\}_t = [\tilde{U}]_{tt}^{-1}[\tilde{T}]_{tt} [\tilde{A}][\tilde{V}]-[\tilde{U}]_{tt}^{-1}\{\tilde{u}_f\}_t
$$

(4)

where matrices $[\tilde{U}]_{tt}$ and $[\tilde{T}]_{tt}$ and vector $\{\tilde{u}_f\}_t$ can be referred to Eqs. (7) and (8), and Eq. (21) in reference 4).

Having obtained $\{u\}_t$ and $\{t\}_t$, the displacement of elements located on the ground surface around the foundation can be solved from Eq. (20) in reference 4).

$$
\{u\}_n = [T]_{nn}^{-1}[U]_{nt}\{t\}_t - [T]_{nt}\{u\}_t + \{\bar{u}_f\}_n
$$

(5)

where $\{\bar{u}_f\}_n$ is defined as Eq. (23) in reference 4).

For an axisymmetric foundation the problem can be solved by considering the cyclic symmetry of coefficient matrices, and by introducing a transformation, hence the computer can be used with high efficiency. The reader may refer to reference 6) (Jiang and Kuribayashi, 1988) for details.

**NUMERICAL ANALYSIS**

The calculation has been performed to study the effects of the frequency of the incident waves, the embedment of the foundation, the oblique incidence of body waves, and the incidence of Rayleigh waves on the surface ground motion near the foundation. The parameters are selected as follows, the mass density ratio is $\rho/\rho_s=0.9$, the Poisson ratio of soil is $1/3$, $\Delta=H/a=1.0$, and the non-dimensional frequency is $a_0=1.0$ to 6.0 (Assuming $a=10$ m and $V_s=400$ m/s, $a_0=0$ to 6 corresponds to frequency range $f=\omega/(2\pi)=0$ to $38.2$ Hz).

Fig. 2 shows ground surface displacement amplitudes around a foundation with embedment ratio $\delta=0$ subjected to incident SH waves with incident angles $\theta=30^\circ$, $45^\circ$, $60^\circ$ and $75^\circ$ for non-dimensional frequency $a_0=1$ to 6. In this figure the left notation with negative $x/a$ specifies the motion in front of the foundation, the right notation with positive $x/a$ specifies the motion behind the foundation, and the $b-b'$ notation represented by broken line specifies the motion on the axis $b-b'$. From this figure, the ground surface motion in front of the foundation and that on the axis $b-b'$ approaches the free field motion, when the values of $x/a$ become larger. However a shadow zone is formed behind the foundation, in which the ground surface motion is smaller than that of the free field motion in high frequency range $a_0\geq 2$. When the incident angle becomes larger, the bound of the shadow zone increases, and when $\theta=75^\circ$ the bound is larger than the value of $x/a=5$.

Fig. 3 shows the effect of the embedment ratio on the shadow zone in the same condition as in Fig. 2, except that the embedment ratio is now $\delta=1$. In comparison with Fig. 2 the bound of the shadow zone extends and the reduction of the ground motion becomes more pronounced for this larger embedment ratio.

Fig. 4 shows ground surface vertical displacement amplitudes around a foundation with embedment ratios $\delta=0$ and 1 subjected
Fig. 2. Ground surface displacement amplitudes for incident SH wave ($\delta=0$)
Fig. 3. Ground surface displacement amplitudes for incident SH wave ($\theta = 1$)
to oblique incidence of SV wave with an incident angle $\theta = 45^\circ$ for $a_0 = 1 \sim 6$. Fig. 5 shows ground surface horizontal displacement amplitudes around a foundation with embedded ratios $\delta = 0$ and 1 subjected to oblique incidence of P wave with an incident
Fig. 6. Ground surface displacement amplitudes for incident Rayleigh wave ($|u_x|$)

Fig. 7. Ground surface displacement amplitudes for incident Rayleigh wave ($|u_z|$)
angle $\theta = 60^\circ$ for $a_0 = 1 \sim 6$. Both of these two figures show that the same phenomenon of the shadow zone can be found for incident SV and P waves.

Fig. 6 and Fig. 7 show ground surface vertical and horizontal displacement amplitudes around a foundation with embedment ratios $\delta = 0$ and 1 subjected to incident Rayleigh waves for $a_0 = 1 \sim 6$. In high frequency range $a_0 \geq 2$, considerable reduction of the

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**Fig. 8.** Displacement spectral ratio for incident SH wave

**Fig. 9.** Displacement spectral ratio for incident Rayleigh wave
Fig. 10. Displacement ratio distribution behind the foundation for incident SH waves ($\beta=1, \theta=45^\circ$ and $75^\circ$)

Fig. 11. Displacement ratio distribution behind the foundation for incident Rayleigh waves ($\beta=1$)
ground motion behind the foundation is found for both vertical and horizontal displacement amplitudes, and the bound of the shadow zone is larger than $x/a=5$. The characteristics different from the incidence of body waves is that, the embedment ratio does not give remarkably effect on the extent of the reduction and on the bound of the shadow zone.

Fig. 8 and Fig. 9 show the displacement spectral ratio of the ground surface motion to the free field motion for certain positions at $x/a=1.51, 2.11$ and $3.10$. The embedment ratios are $\delta=0$ and 1, the incident waves are SH waves for Fig. 8 and Rayleigh waves for Fig. 9. Both of these two figures show that, the spectral ratios in front of the foundation (left) and on the axis $b-b'$ rise and fall around 1.0, but the curves of the spectral ratio behind the foundation (right) go down remarkably in high frequency range $a_0 \geq 2$. The reduction of the spectral ratio depends on the embedment ratio, the type of incident waves and incident angle, and diminishes when the position is far away from the foundation.

Fig. 10 and Fig. 11 have been produced to study the plane distribution of the reduction range. They show the displacement ratios of the ground surface motion to the free field motion for incident SH waves with $\theta=45^\circ$ and $75^\circ$ as shown in Fig. 10, and similarly for incident Rayleigh waves as shown in Fig. 11. The results are only shown for the upper side behind the foundation (the lower side is symmetric with the upper side). The embedment ratio is $\delta=1$, and the non-dimensional frequency is $a_0=2-6$. The displacement ratios are plotted along five representative circles with radii of $x/a=1.51, 2.11, 3.10, 4.09$ and $5.21$.

From Fig. 10 one finds that, for incident angle $\theta=45^\circ$ the reduction range is within a radius of $x/a=3.10$, however for $\theta=75^\circ$ the reduction range is outside a radius of $x/a=5.21$. Fig. 11 shows that the reduction range is outside a radius of $x/a=5.21$ both for vertical and for horizontal components. Both of these two figures show that, for smaller radius the plane distribution of the reduction range extends widely, and for larger radius the plane distribution of the reduction range is restricted to a narrow bound in the vicinity of the foundation axis.

The effect of flexibility of the foundation on the reduction of the spectral ratio behind the foundation has been analysed for incident Rayleigh waves. The analysis is performed for flexible foundation with $\nu_s/\nu_{SP}=0.4$, the shear speed ratio between soil and foundation, and with Poisson ratio $\nu_F=1/6$. Fig. 12 shows the displacement spectral ratio of the ground surface motion to the free field motion for positions at $x/a=1.51, 2.11$ and $3.10$ behind the flexible foundation. To make a comparison the results of the rigid foundation ($\nu_s/\nu_{SP}=0$) are shown in the same figure. From Fig. 12 one finds that the amplitude reduction behind the flexible foundation in high frequency range $a_0 \geq 2$ is also

![Fig. 12. Displacement spectral ratio behind rigid and flexible foundations ($\delta=1$) subjected to incident Rayleigh wave](image-url)
very remarkable, but the reduction diminishes in some extent in comparison with that of the rigid foundation.

SCREENING EFFECT

In former days Barkan (1962) performed experimental studies on the isolation effect of trenches and sheet piles constructed in order to decrease vibration of structures. According to the experiment results, Barkan pointed out that, if waves meet a screen placed parallel to the wave front, then a screened zone is formed behind the screen. The amplitude of soil vibration behind the screen depends mainly on the relationship between the screen dimensions and the length of the propagation waves. Barkan concluded that, when the ratio between the depth \(h\) and the length \(\lambda\) of the propagation waves is \(h/\lambda \geq 0.3\), there will be a screening effect. Namely, not all frequencies will be screened, but mainly the high frequency, and it is impossible to screen waves propagating with low frequency.

These conclusions present an experimental background for our analytical studies. Even though the purpose of this paper and Barkan’s studies is different, but the phenomenon of the screening of propagation waves by a screen is the same. According to this analysis the screening effect depends mainly on the non-dimensional frequency \(a_0 = a/\lambda\), and if \(a_0 \geq 2\) there is a considerable screening effect. On the other hand, \(a_0\) can be represented as \(a_0 = 2 \pi a/\lambda\), where \(\lambda\) is the wavelength. In correspondence with the condition \(a_0 \geq 2\), under which the screening effect is remarkable, the ratio is then \(a/\lambda \geq 0.32\), which is consistent with Barkan’s conclusion. In addition, this analysis investigates that the screening effect depends also on another dimension of the foundation, that is the embedment ratio \(\delta\), as well as on the type of the incident waves, in categories of incident body waves with several incident angles, and incident Rayleigh waves.

CONCLUSIONS

In this paper the ground surface motion surrounding a rigid cylindrical foundation subjected to incident plane waves has been studied. This analysis shows that the ground surface motion behind the foundation decreases remarkably in high frequency range. This phenomenon can be interpreted in terms of screening of incident waves by the foundation. The characteristics of the screening effect can be concluded as follows.

1) The screening effect depends on the ratio of the characteristic dimension of the foundation to the wavelength of the incident waves. When the ratio is \(a/\lambda \geq 0.3\) (or the non-dimensional frequency \(a_0 \geq 2\)), there will be a remarkable screening effect. For incident body waves the screening effect depends also on the embedment ratio \(\delta\) of the foundation. When \(\delta\) becomes larger the screening effect is more pronounced. For incident Rayleigh waves, conversely, the screening effect is independent of the embedment ratio.

2) The screening effect also depends on the type of the incident waves, in the cases of body waves with several incident angles and Rayleigh waves. For example, when \(\delta = 1\) the influence range of the screening effect for incident SH wave with \(\theta = 45^\circ\) is about \(x/a = 3.0\), while for the same wave with \(\theta = 75^\circ\) the influence range becomes in excess to \(x/a = 5.0\) And for incident Rayleigh waves the influence range of the screening effect is larger than the foundation radius in about one order of magnitude, regardless of the embedment ratio. The nature of the plane distribution of the screening effect is that, at smaller distance behind the foundation the influence range extends widely, and at larger distance the influence range is restricted to a narrow bound.

In consequence of the fact that the incident waves are screened by the foundation in high frequency range, high frequency components of the ground surface motion behind the foundation may be reduced. As a result the Fourier spectral of recordings on ground
surface behind the foundation may be different significantly from that of the free field motion in high frequency range. When we evaluate the soil-structure interaction from the seismic observation on measuring accelerograms on and around the building foundation, it is necessary to study the recording positions of the “free field”, especially when the observation station is located behind the foundation. To avoid the screening effect of the incident waves by the foundation the observation station should not be established behind the foundation in the opposite side of the incident waves.

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