13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3405

EVALUATION OF SOIL-STRUCTURE INTERACTION EFFECTS OF EMBEDDED STRUCTURE BY SIMPLE METHOD

Suraj PARKASH[1]

SUMMARY

The rigorous solution of soil-structure interaction (SSI) problems under seismic excitation have been studied in the past. In this paper, the simple cone model is used for structures embedded in the rigid foundation and calculated the transfer function amplitude of interstory drift of a multiple degree of freedom (MDOF) super-structure with varying depth of embedment under various soil conditions. The main objective of this study is to evaluate the SSI effects of embedded structures by simple method appropriate for civil engineering practice. In cone model, the force transmitting mechanism of a foundation on the ground subjected to ground disturbances, can be represented by a cone chopped by the foundation. The foundation is assumed as rigid cylinder and only vertically incident shear wave is taken into account. The dynamic stiffness and effective input motion of a foundation on the ground are evaluated by cone model. The MDOF super structure story stiffness and story damping coefficient are combined with cylindrical rigid foundation embedded in half space ground. The equations of motion in the frequency domain of the SDOF super-structure supported by embedded rigid foundation and subjected to the effective input motion are solved for calculation of the transfer function amplitude of the interstory drift of MDOF super structure for various depths of embedment and for different shear wave velocities of soil. It is found that the characteristics of SSI effects due to embedment of foundation can be well captured with reasonably accuracy by the cone model. The reduction in response is observed for smaller ground shear wave velocities compared to the fixed base model, which support the well known fact that response reduction is remarkable in soft soil. The transfer function amplitude at the top of the super-structure is generally reduced with the increase of embedment depth. It is concluded that a simple and fast evaluation of SSI effects of partially embedded structure can be developed by using the cone model.

INTRODUCTION

In the past, sophisticated numerical techniques have been developed for the rigorous solution of boundary-value problems in elastodynamics. These boundary value methods having theoretical background and require extensive computation; they belong more to the discipline of applied mechanics than to civil engineering. As an alternative to the boundary-element approach, the soil may be idealized by one-dimensional truncated cone instead of an elastic half space. The original cone models for translation [Ehlers, 1] and rotation [Meek, 2] represent the behavior of surface mounted disk shaped slabs. The

[1] Scientist, Council of Scientific and Industrial Research, New Delhi, India, E:suraj110565@hotmail.com

accuracy is sufficient for use in actual design work; simple method of analysis appropriate for civil engineering practice [Meek, 3 & 4]. The concepts of cone models are extended to embedded cylindrical foundations by Meek [5] in which double cone models are introduced to represent the disk within an elastic fullspace; their displacement fields define approximate Green's functions in both the frequency and time domains for use in an uncomplicated version of the boundary-element method. The methodology points towards a general strength-of-materials approach to foundation dynamics, based on approximate Green's functions. The cone models neglect large portions of the half space and can't represent Rayleigh surface waves; these potential objectives are investigated by Meek [6] and turns out that cone models indeed incorporate and provide valuable insight into all the salient features of rigorous solutions; the aspects omitted by cones are revealed to be of minor physical importance.

Wolf [7] calculated the dynamic stiffness of a foundation embedded in a multiple layered, postulating one-dimensional wave propagation in cone segments. The sectional property of the cone segments increases in the direction of wave propagation downwards as well as upwards. The method based on one-dimensional wave propagation in cone segments with reflections and refractions at layer interfaces achieves engineering accuracy (deviation of $\pm$20%) for the dynamic stiffness with a vast variation of parameters. The accuracy is, in general, better, in particular no negative damping coefficients in the low frequency range occur, compared to that of the procedure based on cone frustum, which can be regarded as outdated. Author concluded that the method based on wave propagation in cone segments is well suited for everyday practical foundation-vibration analysis, as sufficient generality exists, good accuracy results and the procedure is easy to use.

In the above mentioned studies, impedance and effective foundation input motions have been obtained numerically for various embedded foundations while the effects of embedment on super-structure response have not been clarified in detail even with rather simple methods. Takewaki [8] computed the transfer function amplitude of the interstory drift of a single-degree-of-freedom super-structure for various cases such as no SSI, SSI without embedment and with shallow and deep embedment. The present study is in continuation of this one and studied the various problems by considering multiple degree of freedom super-structure but presented the results for top of the super-structure to confirm the above study as the results of multiple degree of freedom super-structure will be presented in other research paper of Takewaki [8]. It is concluded from the present study that transfer function of the amplitude of the degree of freedom of super-structure can be evaluated by simple method which the site engineer can easily incorporate in the design of a building with various soil conditions of the site.

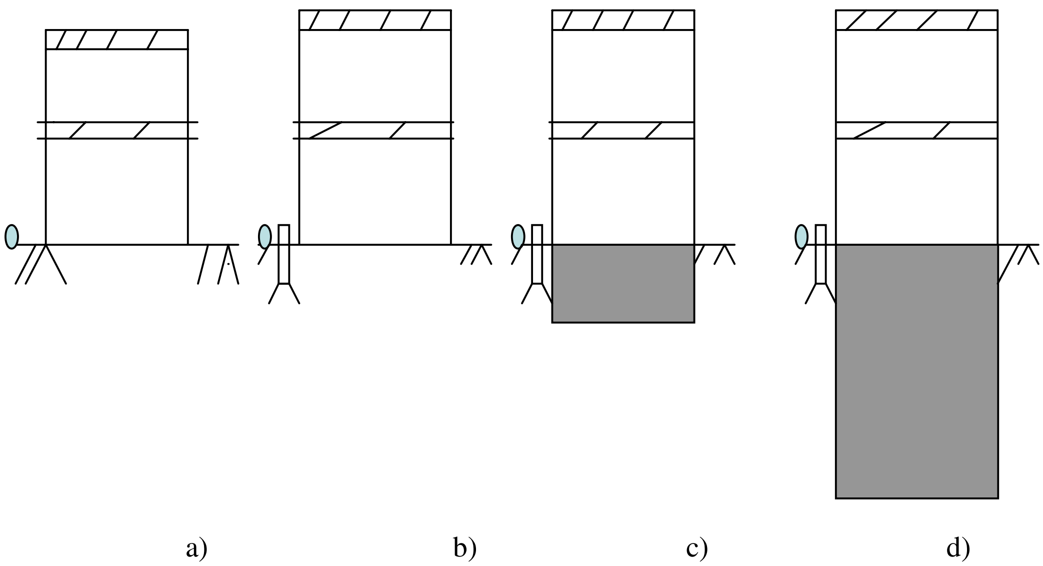
FORMULATION OF CONE MODEL

The transfer function amplitude of two-degree of freedom of super-structure is computed for different cases (Fig. 1), as a) no soil-structure interaction, b) SSI without embedment, c) SSI with shallow embedment and d) SSI with deep embedment.

As the cone model has been proposed by Meek [5] and Wolf [9] for determining the dynamic stiffness and effective input motion of a foundation on the ground. This cone model is used in this paper and foundation is assumed as a rigid cylinder. A set of charts and tables of the impedance functions and the effective input motions is prepared for various depths of embedment and soil properties simply by the cone model. The flexibility of the foundation is not considered.

A two-degree-of-freedom super structure of story stiffness k_1 & k_2 , damping coefficient c_1 & c_2 , is considered, as shown in Fig. 2. This super-structure rests over cylindrical rigid foundation embedded in the half space ground. Let r_0 & e are the radius and depth of the foundation, respectively. Let m_1 & I_1 ; m_2

& I_2 : are the mass and mass moment of inertia of 2-degree of super structure, as shown in Fig. 2. The mass and mass moment of inertia of the embedded foundation around its top central node are denoted by m_0 & I_0 . The height of two nodes of super structures are H_1 & H_2 .



a) No interaction b) Interaction without embedment c) Interaction with Shallow embedment d) Interaction with Deep embedment

Fig. 1 Different Cases of Soil-Structure Interaction Analysis

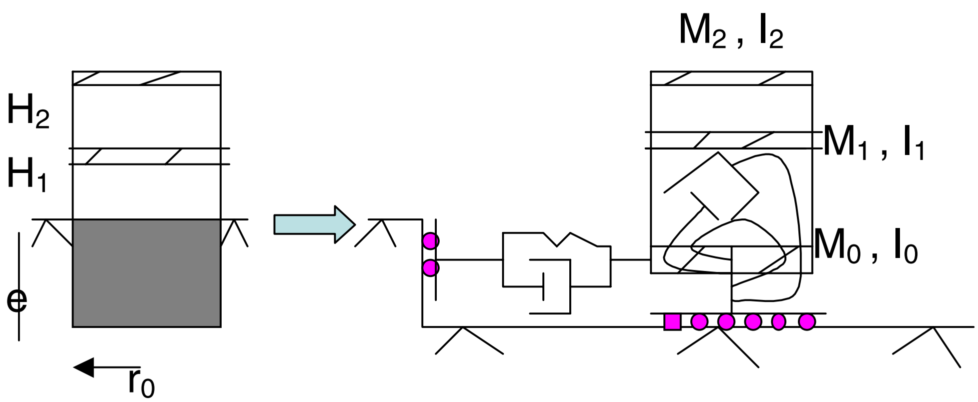


Fig. 2 Two Degree-of-freedom structure with embedded foundation and its modeling

The set of displacement and rotation components of soil-structure system is denoted as, $U = \{ U_1 , U_2 , U_T , \theta_T \}$. The Fourier transforms of the force and moment corresponding to U_T , θ_T are expressed by P_T , M_T , as shown in Fig. 3. Let $\ddot{U}_G$ denote the Fourier transform of the free field horizontal ground-surface acceleration. The equation of motion in the frequency domain of super-structure supported by the embedded rigid foundation and subjected to the effective input motions may be written as :

$$\{-\Omega^2 M + I\Omega[C_S+C_F(\Omega)]+[[K_S+K_F(\Omega)]]\}U(\Omega) = -M\{R_1 S_{HT}(\Omega)+R_2 S_{RT}(\Omega)\}\ddot{U}_G(\Omega) \quad \text{....(1)}$$

where the symbol i and $\mathbf{\Omega}$ indicate the imaginary unit and the excitation frequency.
M = Combined mass matrix of super structure & foundation
K_s = Stiffness matrix of super-structure
K_f = Stiffness matrix of foundation
C_s = Damping matrix of super-structure
C_f = Damping matrix of foundation
$R_1 = \{0\ 0\ 1\ 0\}^T$ and $R_2 = \{0\ 0\ 0\ 1\}^T$

S_{HT} and S_{RT} in Eq.(1) are the ratios of the effective input motions in the frequency domain for horizontal and rotational components respectively, at the top of the foundation to the Fourier transform U_G of the free field horizontal ground-surface displacement. Let us assume only a vertically incident shear wave is considered. These stiffness ratio S_{HT} and S_{RT} at top of the foundation are expressed in terms of the ratios, S_{HB} and S_{RB} at bottom of foundation [5,8,9], as shown in Fig. 3. The Fourier transforms of the force and moment corresponding to U_B, θ_B are expressed by P_B, M_B, as shown in Fig. 3. The foundation impedances at the bottom of the foundation may be expressed as :

$$\{P_B, M_B\}^T = (K + i\,\Omega C)\{U_B, \theta_B\}^T \quad \text{......(2)}$$

where K and C are given by Refs. [5,8]. The solution of Eq.(1) leads to the following expression:

$$U(\Omega)/\ddot{U}_G(\Omega) = -M\{-\Omega^2 M + I\Omega[C_S+C_F(\Omega)]+[[K_S+K_F(\Omega)]]\}^{-1}\{R_1 S_{HT}(\Omega)+R_2 S_{RT}(\Omega)\} \quad \text{.....(3)}$$

The absolute value of the first component in Eq.(3) is a function of the excitation frequency and is called the transfer function amplitude of the interstory drift of top story.

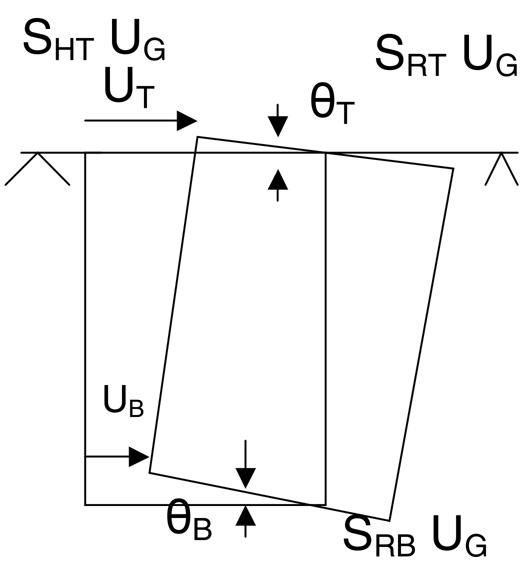


Fig. 3 Horizontal Displacement and angle of rotation of the bottom and top of the foundation

PROCEDURE FOR EVALUATION OF TRANSFER FUNCTION AMPLITUDE OF INTER STORY DRIFT

The procedure for simple and systematic use of the proposed method may be stated as below :

Step 1
Computation of the effective input motions S_{HB} and S_{RB} at the bottom of the foundation by the cone model [5,9]. Once these quantities are derived for various depths of embedment and soil properties, they can be used repeatedly for various super-structures.
Step 2
Transformation of S_{HB} and S_{RB} into the effective input motions S_{HT} and S_{RT} at top of the foundation.
Step 3
Computation of the impedance functions K+i $\mathbf{\Omega}$C at the bottom of the foundation by the cone model[5,9].
Step 4
Transformation of the impedance functions K+i $\mathbf{\Omega}$C into the impedance functions at the top of the foundation.
Step 5
Computation of transfer function of the interstory drift by Eq. (3).

ANALYSIS OF A EXAMPLE PROBLEM

The problem as shown in Fig. 2 is analyzed with the following parameters :
Radius of foundation = r_0 = 5m
$m_1 = 5.0\text{x}10^4$ kg, $m_2 = 7.0\text{x}10^4$ kg
$H_1 = H_2 = 2.5$m

The fundamental natural period of the fixed base superstructure is T_1= 0.35s. So, the damping and stiffness of two degrees of super-structure are calculated. The mass and moment of inertia of the foundation varies as the depth of embedment is changed. The effective input motion for the horizontal and rotational components for various depth of embedment at various frequencies are calculated from the Refs.[5,9]. Thus, the transfer function amplitude at top node of super-structure are computed for various depth of embedment and for various soils from Eq.(3).

RESULTS OF ANALYSIS

The transfer function amplitude of the interstory drift for the top story with respect to nondimensional frequency, A_0 (=$\mathbf{\Omega}$ r_0/Vs) for various depths of embedment are shown in Fig. 4(a) to Fig. 4(d). For each depth of embedment, four types of shear wave velocity of ground are considered. It is observed that for a shallow depth of embedment, the peak of the transfer function amplitude of the interstory drift becomes smaller as decrease in shear wave velocity while reverse is observed for deeper depth of embedment.

Fig. 5(a) to Fig. 5(d) demonstrates the transfer function amplitude of interstory drift with respect to nondimensional frequency, A_0 (=$\mathbf{\Omega}$ r_0/Vs) at top of the super-structure for various ground shear wave velocities. For each shear wave velocity (200m/s), the peak of the transfer function amplitude of the interstory drift becomes smaller as the depth of embedment becomes larger while this property does not exit for shear wave velocity less than or equal to 100 m/s.

The present investigation shows that there is no further error in the computation except that due to the cone model. It is clarify that the combination of foundation with super structure can be achieved in case of rigid foundations, from the bottom of the foundation to the top of the foundation.

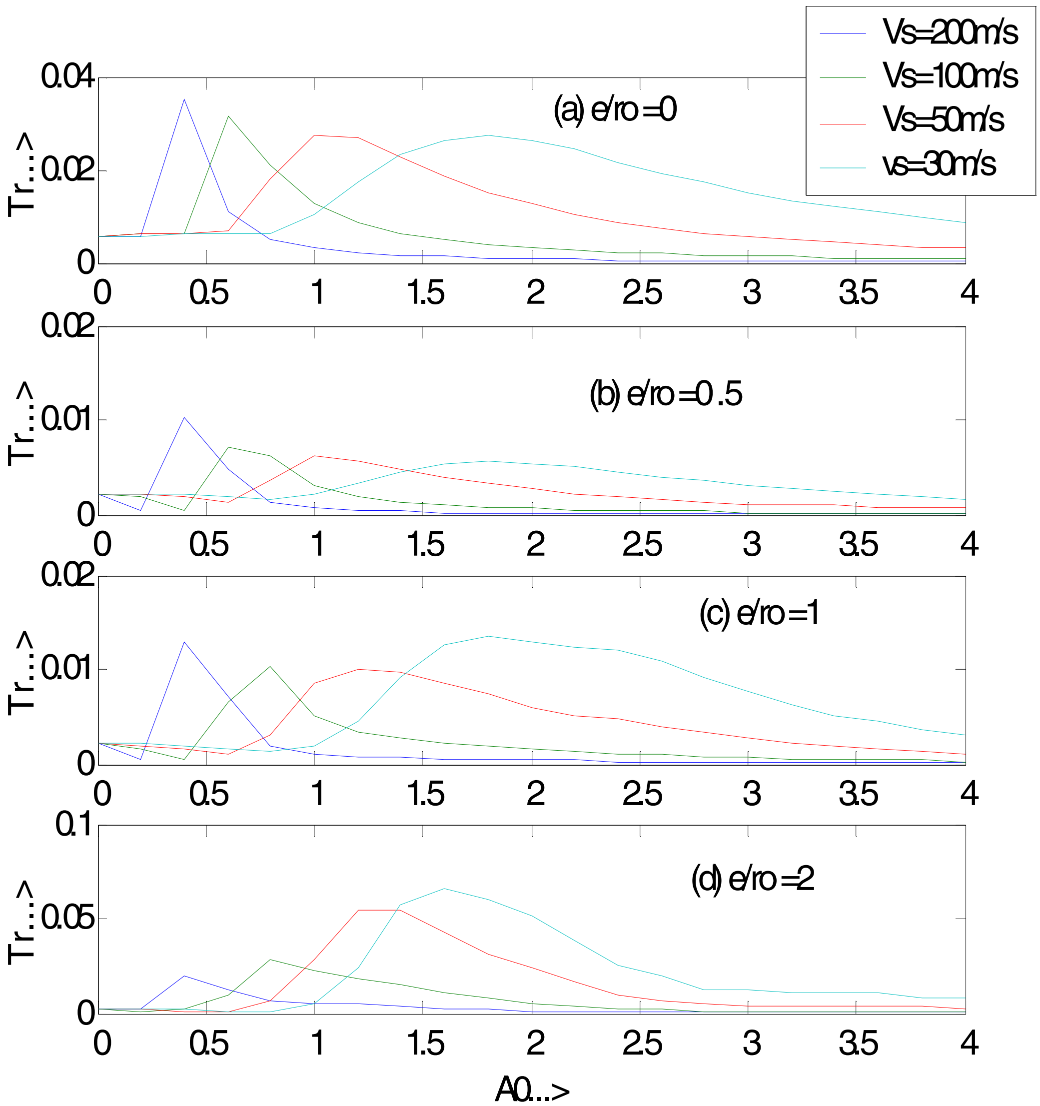


Fig. 4 Transfer function amplitude at top of super-structure in for various shear wave velocities of soil for different depths of embedment, (a) to (d)

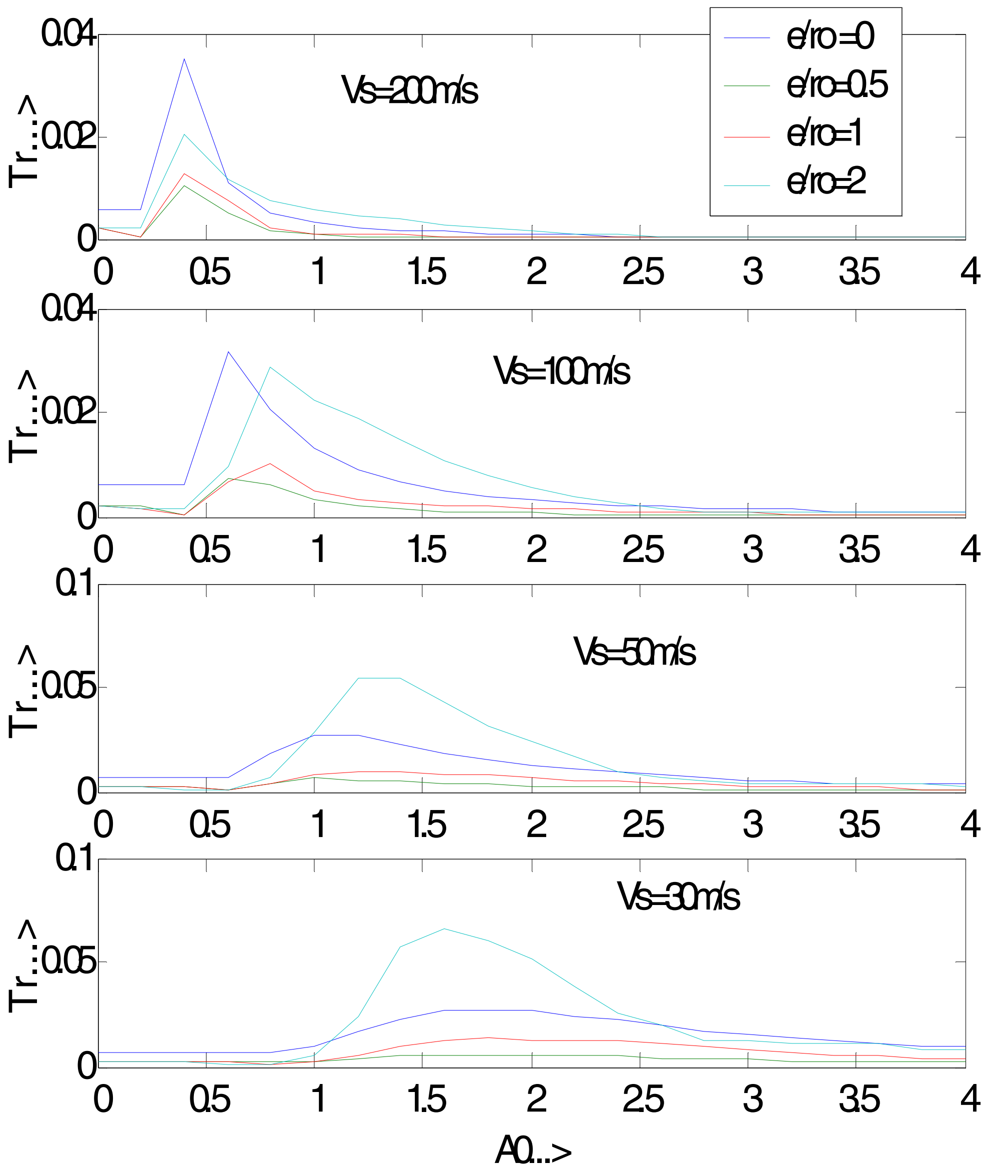


Fig. 5 Transfer function amplitude at top of super-structure in for different depths of embedment for various shear wave velocities of soil, (a) to (d)

CONCLUSIONS AND DISCUSSIONS

It is concluded from the above study that transfer function amplitude of interstory drift is not much affected with the depth of embedment for ground shear wave velocity greater than 100m/s. The characteristics of the transfer function amplitudes for very small shear wave velocity and deeper depth of embedment are not shown any regular pattern. The foundation of the embedded foundation impedance and effective input motion at top of foundation is appropriate for combining the embedded foundation with the multi degree of freedom super structure.

REFERENCES

1. Ehlers G. ”The effect of soil flexibility on vibration systems”, Beton und Eisen, 1942, 41(21/22), 197-203(in German).
2. Meek JW, Veletsos AS. “Simple models for foundation in lateral and rocking motion”, Proc. 5th World Conf. on Earthquake Engineering, Int. Assoc. of Earthquake Engineers., Rome, Italy, 1974, 2, 2610-2613.
3. Meek JW, Wolf JP. “Cone models for homogeneous soil. I ”, J. of Geotechnical Engineering., ASCE,1992 118(5), 667-685.
4. Meek JW, Wolf JP. “Cone models for soil layer on rigid rock. II ”, J. of Geotechnical Engineering, ASCE, 1992,118(5), 686-703.
5. Meek JW. “Cone model for embedded foundation”, J. of Geotechnical Engineering., ASCE,1994 120(1), 60-81.
6. Meek JW, Wolf JP. “Why Cone models can represent the elastic half-space ”, Earthquake Engineering and Structural Dynamics, 1993 22, 759-771.
7. Wolf JP, Preisig M. “Dynamic stiffness of foundation embedded in layered half-space based on wave propagation in cones ”, Earthquake Engineering and Structural Dynamics, 2003, vol.32, 1075-1098.
8. Takewaki I, *et al.* “Fast practical evaluation of soil-structure interaction of embedded structures”, Soil Dynamics and Earthquake Engineering, 2003, vol.23, 195-202.
9. Wolf JP. “Foundation vibration analysis using simple physical models ”, Englewood Cliffs, NJ: Prentice-Hall; 1994.