An impulse response function approach for predicting ground and structure vibrations

Quelques concepts de la fonction de reponse d'impulsion pour predire desvibrations de sol et de structure

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ABSTRACT: This paper presents the application of the impulse response function concept to solve the geotechnical problem of prediction of ground and structures vibrations before installation of a vibration source. Such an approach employs experimental impulse response functions for the considered dynamic system. These functions reflect real behavior of soil and structures without investigation of soil and structure properties. Duhamel's integral and impulse response functions are used to compute predicted ground and structure vibrations.

RÉSUMÉ: Ce mémoire présente l'application du concept de la fonction de réponse d'impulsion pour résoudre le problème de prédire des vibrations de sol et de structures avant l'installation d'une source de vibration. Un tel procédé emploie des fonctions de réponse d'impulsion expérimentales pour le système dynamique considéré. Ces fonctions réfléchissent les véritables réactions de sol et de structures sans l'investigation des propriétés du sol et des structures. On utilise les fonctions de réponse d'impulsion de Duhamel pour calculer les vibrations de sol et de structure prédites.

1 INTRODUCTION

Construction and industrial dynamic sources, such as dynamic compaction, pile driving and foundations for impact machines, generate elastic waves in soil which may harmfully effect adjacent and remote buildings. Their effects range from serious disturbance of working conditions for sensitive devices and people, to visible structural damage.

Empirical equations are used for practical assessment of expected soil vibrations from industrial and construction sources and they usually allow calculation of only a vertical amplitude of the peak part of vibration records and not always with required accuracy, Svinkin (1999).

Analytical methods (for example, Barkan 1962, Richart et al. 1970, Broers and Dieterman 1992, Wolf 1994) give accurate results for certain limited cases, but these methods are applicable only to well defined and simple sites like a half-space or horizontally layered media. Computed results from the simple models contain valuable data about general tendencies of wave propagation at a site, but cannot take into account spatial variations of soil properties and produce accurate and complete soil vibration records at any point of interest.

This paper deals with the application of the impulse response function concept to predict ground and structure vibrations before the beginning of construction activities or installation of machine foundations. This approach employs experimental impulse response functions reflecting real behavior of soil and structures without investigation of soil and structures properties. It also provides an opportunity for proper determination and monitoring of ground, structures and devices vibration levels prior to start of construction and industrial activities.

2 BASIC CONCEPTS

The proposed Impulse Response Function Prediction method (IRFP) is founded on the utilization of the idea of impulse response function technique for predicting complete vibration records on existing soils, buildings and equipment prior to installation of construction and industrial vibration sources (Svinkin 1996b; 1997). The impulse response function (IRF) is an output signal of the system based on a single instantaneous impulse input (Bendat and Piersol 1993).

These functions are applied for studies of complicated linear dynamic systems with unknown internal structures for which mathematical description is very difficult. In the case under consideration, the dynamic system is the soil medium through which waves propagate outward from a vibrating machine foundation. The input to the system is the machine foundation motion and the output is the ground motion at any location of interest situated on the surface or within the soil medium or anywhere in a building subjected to vibrations. Output signals can be obtained, for example, as vibration records of displacements, velocities or accelerations at locations of interest.

Impulse response functions for a specific dynamic system are determined experimentally, Svinkin (1996a; 1996b). This approach (*a*) does not require routine soil boring and sampling at the site, (*b*) eliminates the need to use mathematical models of soil profiles, foundations and structures in practical applications, and (*c*) provides the flexibility of automatically considering the heterogeneity and variety of soil and structural properties. Unlike analytical methods, experimental IRFs reflect real behavior of soil and structures without investigation of the soil and structure properties. Because of that, the proposed method has substantially greater capabilities in comparison with other existing methods.

The following is a general outline of the methods for predicting vibrations at a distance from a source of impact loads. It is assumed that the dynamic loads transmitted onto the soil are known or can be found using existing theories. At the place in the field for installation of the wave source, impacts of known magnitude are applied onto the ground (Figure 1). The impact can be created using a rigid steel sphere or pear-shaped weight falling from a mobile or bridge crane or a hammer blow on the tested pile. The oscillations resulting from the impact on the ground are measured and recorded at the points of interest, for example, at the locations of instruments sensitive to vibration, communication

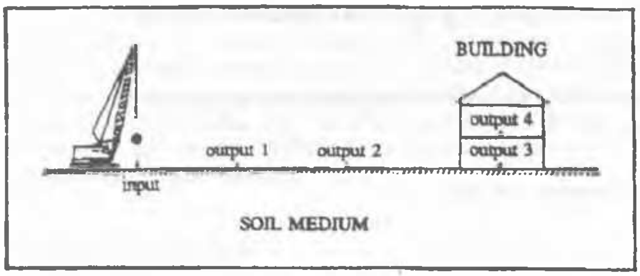

Figure 1. Experimental determination of impulse response functions.

lines and other devices, etc. Recorded oscillations are the impulse response functions of the considered dynamic system which automatically take into account complicated soil conditions. Duhamel's integral (Smith & Downey 1968) is used to compute predicted vibrations.

3 COMPUTATION OF PREDICTED VIBRATIONS

The IRFP method was originated for dynamic sources like machine foundations.

For each single output point, the considered input - soil medium - output system is a one degree of freedom system and predicted displacements can be written as follows

$$Z(t) = \int_0^t F(\tau)\ h_z(t-\tau)\ d\tau \tag{1}$$

where $F(\tau)$ = resultant dynamic force transmitted to the ground; $h_z(t-\tau)$ = impulse response function at the output point under consideration; τ = variable of integration.

Dynamic loads on a machine foundation can be found using existing foundation dynamics theories, for example Barkan (1962), Richart et al. (1970), Arya et al. (1979) and Gazetas (1994). It is known that the equation of vertical damped vibrations of foundations for machines with dynamic loads can be given by

$$M\ddot{z}(t) + c\dot{z}(t) + k_z z(t) = P(t) \tag{2}$$

with initial conditions $z = z_0$ and $\dot{z} = \dot{z}_0$ for $t = 0$. In Equation (2), c = viscous damping coefficient; k_z = spring constant for the vertical mode of foundation vibrations; P(t) = exciting force; M = mass of foundation and machine. Parameters of the foundation-soil system M, c and k_z are considered known in predicting vibrations.

Equation (2) can be converted into another form as

$$\ddot{z}(t) + 2\alpha\dot{z}(t) + f_{nz}^2 z(t) = p(t) \tag{3}$$

with

$$2\alpha = \frac{c}{M};\quad f_{nz}^2 = \frac{k_z}{M};\quad p(t) = \frac{P(t)}{M} \tag{4}$$

where f_{nz} = circular natural frequency of vertical vibrations of foundation; α = damping coefficient.

$$F(t) = M\ [2\alpha\dot{z}(t) + f_{nz}^2 z(t)] \tag{5}$$

An expression derived from Equations (3) and (4) for a dynamic load applied to the soil can be written asThe dynamic force transmitted from the machine foundation to the soil base depends on the foundation and machine mass, the damping coefficient, the circular natural frequency of vertical foundation vibrations and vertical foundation displacements as a function of time.

Equations for computing displacements of target points on soil and in structures were derived for machine foundations with some specific dynamic loads important in practice:

- The instantaneous impulse. Similar loads are transferred to block type foundations from machines that produce impact loads, for example forge and drop hammers.
- The transient state vibration load. Similar dynamic forces are transferred to a foundation under a vibroisolated block for a machine that produce impact loads.

For a source with impact loads, predicted displacements can be computed as

$$Z(t) = \frac{I_F}{f_{nd}} \int_0^t [(f_{nz}^2 - 2\alpha^2)\ e^{-\alpha\tau}\ \sin(f_{nd}\tau) + 2\alpha f_{nd}\ e^{-\alpha\tau}\ \cos(f_{nd}\tau)]\ h_z(t-\tau)\ d\tau \tag{6}$$

where I_F = impulsive loading transmitted from machine to foundation; f_{nd} = circular natural frequency of vertical damped vibrations of foundation; remaining parameters are the same as above.

For transient state vibration loads, the displacements of a point under consideration are derived as a sum of vibrations excited by free and forced foundation vibrations, Svinkin (1997).

In the equations obtained, for example Equation (6), the expected vibrations depend on the impact load applied to a foundation, the damping coefficient of the soil, the circular natural frequencies of vertical foundation oscillations and the impulse response function of the considered dynamic system. The dominant frequency of propagating waves from impact sources ranges mostly between 3 Hz and 60 Hz, Svinkin (1999).

Derived equations can be applied for construction sources of impact loads such as pile driving, dynamic compaction, etc. (Svinkin 1996b).

4 RESULTS OF PREDICTION

Layout of the experimental site and examples of predicted vibrations are shown in Figures 2 and 3.

Measurements and prediction of vertical and horizontal ground surface displacements were made at diverse distances from the foundation under a sizeable drop hammer with a falling weight of 147.2 kN and a maximum drop height of 30.0 m. The soil at the site consisted of about 1.6 m of loose sand followed by about 6.8 m of medium density sand and 1 m of sandy clay underlain by about 10 m of slightly moist sand. The water table was about 6 m below the ground surface. The Rayleigh wave velocity was 270 m/sec.

Predicted and measured vertical and horizontal components of ground surface vibrations at eight locations are shown in Figure 3. It can be seen that good agreement is matched in time domain vibration records, except for horizontal vibrations at two locations close to the foundation. This can be explained by the different wave paths from the foundation under the operating machine and the place for impact on the ground. The distance between these two sources was 18.7 m. Lack of coincidence of the two dynamic sources slightly affected the predicted ground vibrations at a distance from the machine foundation. Agreement of predicted and measured vibration displacements is quite satisfactory. The differences between the peak predicted and measured vibration

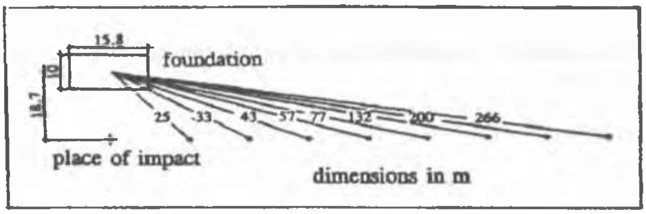

Figure 2. Layout of machine foundation, place of impact loads on ground, and geophones.

amplitudes are less than 30 % at distances larger than 43.0 m from the foundation. For some individual points amplitudes actually coincide.

Spectrum analysis of predicted and measured time histories revealed that both records have similar frequency domain curves with the same dominant frequency. Also, predicted vibration

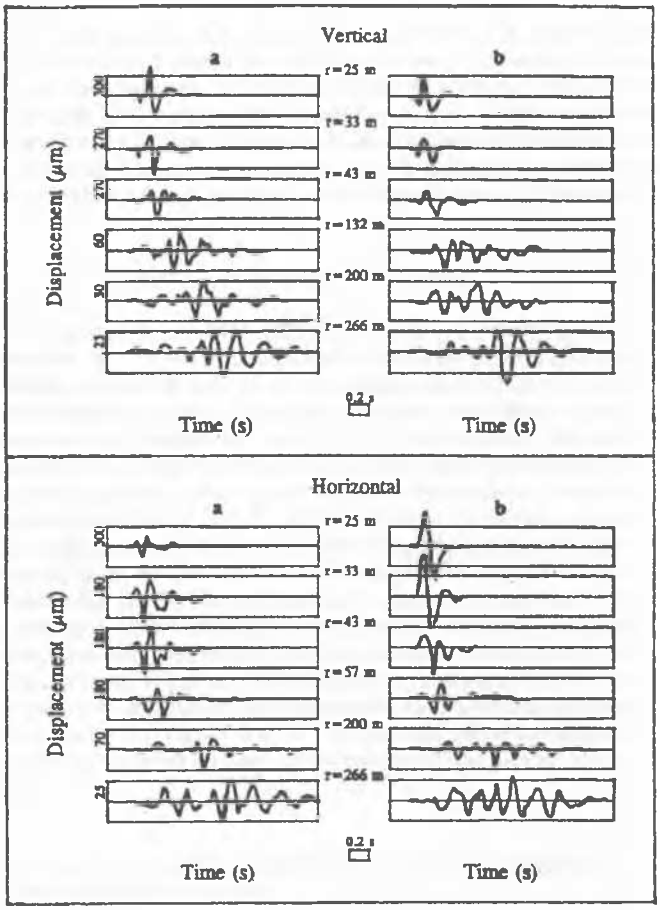

Figure 3. Measured (a) and predicted (b) ground vibration displacements from operating drop hammer.

records were computed at a distance of 266 m from the machine foundation using various values of initial parameters in Equation (5). Spectra of these oscillations showed a stability of frequency composition for even very long duration soil oscillations (Svinkin, 1999).

5 CONCLUSIONS

An impulse response function approach was used for a development of the IRFP method in order to predict complete vibration records of ground and structure vibrations excited by construction and industrial vibration sources. This method is used to solve a geotechnical problem in predicting time domain ground and structure vibrations prior to the beginning of construction activities or installation of machine foundations.

Experimental determination of the impulse response functions of the soil and structures (*1*) does not require characterization of the geologic materials at the site, (*2*) eliminates the need for the use of mathematical models of soil and structures responses, and (*3*) provides the possibility of taking into consideration the heterogeneity and variety of soil and structures properties.

The obtained results have demonstrated the accuracy and efficiency of the method for the predicting soil and structure vibrations prior to installation of foundations under machines with impact loads. In particular, this method is most useful under nonuniform and complicated soil conditions for determination and verification of safe distances from dynamic sources for facilities sensitive to vibrations.

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