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Validity of New Methods in Soil and Structural Dynamics

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Abstract *New inventive methods in Soil and Structural Dynamics typically include acceptance of certain assumptions, a new or modified theoretical approach and development of hardware with software which are necessary for contemporary analysis of the soil-structure dynamic systems. However, hardware and software cannot themselves solve engineering vibration problems without engineering analysis and judgment. For validity of new methods, it is necessary to apply the engineering basis to prove the assumptions used in method derivations, determine accuracy of computed results and find the areas of applications and restrictions of the methods. This approach has been shown on the basis of a new method made for prediction of soil and structural vibrations from impact machine foundations before their construction.*
Keywords: *new methods, soil dynamics, structural dynamics, validity, engineering basis.*

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I. Introduction

It is common that new methods in soil and structural dynamics use computer simulations and require applications of existing or new hardware and software. In the medium of geotechnical and structural engineers involved in dynamic testing, computation and analysis, there is a belief that hardware and software themselves can resolve engineering vibration problems. Indeed, hardware and software are great tools but only tools, and the application of hardware and software cannot replace engineering judgement. Computer misuse comes in many form, and formal implementation of vibration measurements and computing not always may resolve problems with high structural vibrations. The following are two examples. First, there are reliable methods for assessment of stresses in structures from dynamic loads, but if these loads triggered dynamic settlement, other approaches should be used for assessment of vibration effects on structures. Second, resonance pile driving is successfully used for pile installation, but this procedure completely ignores possible resonant vibrations in the hammer-pile-soil system and their effects on structures. The writer has used the impulse response function prediction (IRFP) method as a pattern to demonstrate the necessity of the engineering analysis performed for proving the validity of this method. The IRFP method is the numerical method with experimental soil and structure responses for predicting vibrations from dynamic sources. This method was developed for predicting the complete time-domain vibration records of soil, structures, and equipment prior to installation of construction and industrial vibration sources, for example foundations under machines with impact loads. The method is founded on the utilization of the impact response functions technique that does not require soil boring, sampling, or testing at the site, eliminate the need to use mathematical models of soil profiles, foundations, and structures in practical application, and provides the flexibility of implicitly considering the heterogeneity and variety of soil and structure properties. There are no assumptions about soil conditions and structural properties, Svinkin [1-4].

For the properly worked out engineering methods, it is necessary to substantiate the assumptions used in the method, perform engineering analysis of obtained results, determine areas of applications (applied dynamic loads, soil conditions and structures) and ascertain restrictions of the method. For the IRFP method, different assumptions were verified experimentally or analytically: linearity of the soil-soil and soil-structure systems, application of impact load directly to the soil, soil impulse response functions, influence of a foundation contact area on soil vibrations, effect of eccentricity of impulse loading on a machine foundation, effects of parameters of the machine foundation-soil system on ground vibrations, accuracy of vibration records and an example for implementation of IRFP method's technique for soil and structural vibrations. Also, certain restrictions are shown for the application of the IRFP method.

Equations derived for the IRFP method are presented in Svinkin [3, 4] and they are not shown in this paper in order to emphasize the importance of the method assumptions and outcomes. Practical applications of the IRFP method are demonstrated by Svinkin [2, 6], Svinkin et al. [5], and Baranov et al. [7].

II. Verification of the Method Assumptions

The assumptions of the IRFP method include: 1. Application of a linear approach for the considered dynamic systems. 2. Impacts directly on the soil can be used for determination of impulse response functions. 3. Dimensions of a foundation contact area and foundation vibration parameters do not affect soil vibrations beyond a limited area around the foundation.

The validity of the assumptions in the IRFP method was established mostly experimentally. The experimental study has covered special sites including test foundations and operating shops with foundations under forge and drop hammers. The experimental study at different sites contained foundations with areas ranging from 1 to 158 m^2 and a depth of foundation embedment into the ground between 0 and 5 m. Falling weights were between 1 and 147.2 kN, Svinkin [4].

2.1 Linearity of considered dynamic systems

In comparison with building structures, varieties of soil properties have a much wide range because of soil heterogeneity and uncertainty. However, industrial and construction dynamic sources, for example foundations under forge hammers, produce impact loads in a relatively narrow range for each type of dynamic source. Besides, wave propagation due to machine foundation vibrations and operating construction equipment generates low strains, therefore, the soil is usually assumed to be a linear elastic medium in spite of soil heterogeneity and uncertainty. This approach permits application of the theory of elasticity and the derivation of a number of theoretical solutions which are successfully used in seismology, geophysics, soil dynamics, and structural dynamics. A number of authors have studied soil dynamics problems and they have concluded that the linear elastic model is adequate, for example, Rausch [9], Barkan [10], Lysmer and Richart [11], Sliwa [12], Svinkin [8] and others.

2.2 Impulse Response Functions

One of the basic assumptions of the IRFP method is that impacts directly on the soil can be used for estimating the impulse response functions. The impulse response function (IRF) is an output signal of the system to a delta-function input, Bendat and Piersol [13]. These functions are applied for studies of complicated linear dynamic systems with unknown internal structures for which a mathematical description is difficult. In the IRFP method, the dynamic system is the soil medium through which waves propagate outward from industrial or construction vibration sources. The input to the system is the ground motion under the dynamic source and the output are the ground motions at any location of interest situated on the ground surface or within the soil medium and structural motions anywhere in buildings subjected to vibrations. Output signals can be obtained, for example, as vibration records of displacements, velocities, or accelerations at locations of interest, Svinkin [4].

It is necessary to point out that various impacts can be applied on the ground and they trigger diverse ground vibrations. In a comparison with small impacts, large ones applied to the ground involve deeper soil layers and bigger soil mass in vibrations. Consequently, different impacts excite vibrations of different dynamic systems which cannot be considered as parts of one nonlinear dynamic system. For practical goals and the accuracy of obtained results, it is necessary to perform dynamic testing in the frame of one linear dynamic system. Therefore, the dynamic system should be excited by dynamic loads comparable with the impact load range of the source and impacts on the ground should be not less than 1/10 of the maximum machine dynamic load for obtaining good prediction results, Svinkin [4]. It is possible to apply smaller impacts on the ground, but such a choice should be verified at a site.

In a reality, we have to assess the application of impacts directly on the ground to receive IRFs of considered dynamic systems because it is necessary to keep in mind that impacts applied onto the ground are not the same as the theoretical delta-function. For reliable vibration prediction, it is important to study how shapes and amplitudes of IRFs depend on the conditions at the place of impact and assess the influence of application of impacts directly on the ground for determining IRFs.

Special experiments were performed to investigate the effect of plastic soil deformations at the point of impact under a steel rigid weight on ground surface oscillations. The soil at the site consisted of about 8 m of medium stiff yellow and brown clayey sand. The water table was not encountered in the top 8 m. The falling weight of 1 kN had a cylindrical shape with a 20 cm diameter. A drop height was 2 m.

Impacts were generated by a falling weight at a fixed location on the soil for different conditions at the contact area between the soil and the weight. Impacts were made on the ground surface and the bottom of an excavation with dimensions 0,7 m x 0,7 m in plan and 0.3 m deep. Also, impacts were applied on a steel plate (0.5 m x 0.5 m) with spikes pressed into the soil and on sand or gravel which refilled the excavation. Accelerations of the falling weight and displacements of the ground surface at some distances from the contact area were measured in the experiments, Svinkin [14].

It was found that durations of impulses depends on the conditions in the contact area. The duration of measured impulses ranged from 0.025 to 0.035 s and increased to 0.06 s when impact was done on loose sand. It is important that an increase of the duration of impulse at the source did not change the shape of soil vibration records at distance from the source but decreased slightly their amplitudes at the locations in the proximity of the place of impact. However, these changes decreased with distance from the contact area and for different conditions at the contact area, the shapes and amplitudes of soil vibrations were almost identical at a given distance from the source.

The effect of significant plastic soil deformations at the contact area under a falling weight on ground vibrations at distance was studied with a falling weight of 142.2 kN dropped from a height of 8.6 m. Many impacts were performed at the same spot and consequently significant plastic soil deformations occurred at the point of impact. Comparison was made for records obtained for two equal impacts with different degrees of plastic soil deformations at the contact area, Fig. 1. In particular, vibrations were measured at distance of 43 m for the first and ninth impacts, and at a distance of 57 m for the first and seventeenth impacts. For the first impact, the falling mass dropped on a flat ground surface, but for the seventeenth impact, it dropped into a pit deeper than 1 m. In spite of considerable soil deformations at the contact area, each pair of ground surface vibrations is actually the same at locations of measurements. The results demonstrate that at any location of measurements on the ground from 25 to 266 m from the center of the impact area on the ground, soil vibration displacements caused by an impact on the ground have well-defined shapes and are independent of the magnitude of soil deformations at the contact area. These results agree with a dynamic version of Saint Venant's principle, Timoshenko and Goodier [17], Karp and Durban [18]. The differences between maximum displacements measured during various impacts are in limits of 10%. Based on the experiments it was shown that impacts made directly on the soil can be used for receiving impulse response functions of the considered dynamic systems.

Fig. 1. Comparison of two different displacement records of ground vibrations in sandy soils for identical impacts on ground by falling weight of 142.2 kN (data from Svinkin [4], with permission from ASCE)

2.3 Effects of Machine Foundations on Ground Vibrations

2.3.1 Foundation Contact Area

The effect of the contact area of a machine foundation on ground surface displacements was studied by Svinkin [15] on the basis of experimental data of soil vibrations from various size foundations, natural frequencies of foundation vibrations, distances from foundations, soil conditions with values of wave propagation velocities and Barkan [10] theoretical solutions. Investigation of the effect of the contact area of machine foundations on ground vibrations have shown that foundation dimensions have a negligible influence on the amplitudes of ground vibrations at distances more than 10-25 m from the center of the vibration sources for frequencies less than 200 rad/s (32 Hz). These conditions prevail for soils with Rayleigh wave velocities greater than 100 m/s, which include most soils.

2.3.2 Eccentricity of Impact Loads

The vertical impact loads may be applied to a machine foundation with some eccentricity. The effect of eccentric impulsive loads on soil vibrations was experimentally studied at the site. The dynamic source was a foundation with contact area of 158 m^2 for a powerful drop hammer. The falling weight of 147.2 kN was dropped from the same height of 30.0 m. Four anvils were mounted on a rectangular hammer foundation. The weight could be dropped on any anvil. Soil vibrations were measured at the distances from 25 to 266 m from the center of the foundation in a diagonal direction of the foundation contact area. Experimental investigation revealed that rocking foundation oscillations do not affect soil vibration shapes and minimally influence their amplitudes with distance from the wave source. For example, measured records of foundation and soil vibrations at distance of 43 m from a center of the machine foundation are presented in Fig. 2. Spectra of foundation vibrations have two frequency maxima at 20 and 135 rad/s. These frequencies correspond to vertical (20 rad/s) and rocking (135 rad/s) natural foundation vibrations. At the same time, records of soil vibrations and their spectra reasonably agree regardless of diverse foundation vibrations, Svinkin [4].

Fig. 2. Identical vertical impact loads with different eccentricity induced diverse foundation vibrations and similar soil vibrations at a distance of 43 m from foundation for drop hammer (data from Svinkin [4], with permission from ASCE)

2.3.3 Vibration Parameters of Machine Foundation – Soil Systems

The parameters for a machine foundation-soil system can be determined using existing theories, for example Rausch [9], Barkan [10], Lysmer and Richart [11] and others.

The reason for agreement of predicted results with the use of all of these theories is that ground vibration responses are negligibly dependent on the parameters of the foundation-soil system. For instance, measured and predicted records of soil vibrations at a distance of 266 m from the foundation of a sizeable drop hammer are depicted in Fig. 3. The foundation contact area was 158 m^2. A falling weight of 147.2 kN dropped from a height of 30 m. Predicted vibration curves were computed with various values of initial parameters (Table 1). In spite of the change of the computed natural foundation frequency in the range of 23.8-63.5 rad/s and the damping constant from 8.5 to 60.5 rad/s, the shapes of measured and predicted records are almost the same and their spectra show the same dominant vibration frequency. An increase of the computed natural frequency of foundation vibration with respect to the measured vibration leads to an increase of the largest amplitude by 10-30 % for both vertical and horizontal predicted soil oscillations. Spectra of these oscillations show a stability of frequency composition for even exceptionally long duration soil oscillations. Thus, variations of predicted soil oscillations reasonably agree even with 2.7 times increase in the computed natural frequency of the foundation.

TABLE 1. Parameters of Foundation - Soil System (data from Svinkin [4], with permission)

Record No.	k_z' (kN/m^3)	α (rad/s)	Φ (s/rad)	f_{nz} (rad/s)	M t
2	Experimental time-domain foundation displacement				
3	34433	8.5	0.03	23.8	9614
4	67885	60.5	0.03	63.5	2650
5	39240	35.0	0.03	48.3	2650

Parameters in Table 1: k_z' = coefficient of vertical subgrade reaction, kN/m^3; α = damping coefficient, rad/s; Φ = modulus of damping, s/rad; f_{nz} = circular natural frequency of vertical vibrations of foundation, rad/s; M = mass of foundation and machine, t.

Fig. 3. Records and spectra of vertical and horizontal soil vibrations at 266 m from foundation for drop hammer; measured vibrations: 1, predicted vibrations for various initial parameters defined in Table 1: 2 - 5 (data from Svinkin [4], with permission from ASCE)

2.4 Accuracy of Computed Vibrations

For accuracy assessment of the predicted vibrations, it is necessary to evaluate the accuracy of the digital computer calculation of convolution or Duhamel's integral and Fourier transform. The accuracy of these computations depends on the number of data points collected at the time period of records. The standard 1000 samples per second were used. The damped sinusoid obtained on an analog computer was used as the pattern. The computed spectrum of the damped sinusoid was compared with the analytical spectrum of the same curve. It was found to have a margin of error less than 5- 10 % for Fourier transforms and 0.01 % for Duhamel's (convolution) integrals.

III. Results of Predicting Vibrations

The following is a general outline of the IRFP method for the prediction of complete vibration records of soil and structures prior to installation of a dynamic source: (1) at the place chosen for impact dynamic source, impulse loads of known magnitude should be applied on the ground; (2) at the moment of impact on the ground, vibrations are recorded at the points of interest (for example, at the locations of instruments and devices sensitive to vibrations), and these oscillations are the IRFs of the considered dynamic systems, which automatically take into account complicated soil conditions and structural properties; and (3) a convolution integral of IRF and dynamic loads transferred onto the ground is calculated to obtain the complete records of soil and structure vibrations.

As it was mentioned above, all equations for computation of predicting vibrations from a block-type foundation and a vibration-isolated foundation under machines with impact loads are presented in Svinkin [4].

In the experiments, vertical vibrations of machine foundations and the resulting vertical and horizontal soil vibrations at target locations were recorded. The measured data were compared with predicted responses. In the calculations of predicted soil vibrations from designed foundations for machinery with impulsive loads, the machine foundation motion was assigned as a damped sinusoid. Different equations were used for vibration prediction from a vibration-isolated foundation under the forge hammer, Svinkin [4].

Prediction and measurements of vertical and horizontal ground surface displacements were made at diverse distances from the foundation for a sizeable drop hammer. The foundation contact area was 158 m^2. A falling weight of 147.2 kN dropped from a height of 30.0 m. A layout of the machine foundation, the place of impulsive loads on the ground, and geophones and also the predicting and measured vibration records at various distances from the source are shown in Svinkin [4]. Examples of predicted ground vibrations generated by a wave source-block type foundation at distance of 266 m from the foundation are shown in Fig. 4. The predicted soil vibrations demonstrate a close fit to the measured data.

Other example demonstrates the application of the IRFP method for predicting ground surface oscillations excited by vibrations of the foundation under a vibration-isolated block for the large forge hammer with a weight of falling parts of 157.0 kN. The foundation contact area was 116.4 m. Measured and predicted soil vibrations at a distance of 28.8 m from the hammer foundation are shown in Fig. 5. The predicted soil vibrations demonstrate a close fit to the measured data, Svinkin [4].

Fig. 4. Vertical and horizontal ground vibration displacements at a distance of 266 m from drop hammer foundation: impulse response functions, predicted and measured records (data from Svinkin [4], with permission from ASCE)

Fig. 5. Vertical soil vibrations excited by sizable forge hammer with falling weight of 157 kN installed on vibration- isolated block; predicted vibrations 1 – 3, from forced foundation oscillations 1, from free foundation oscillations 2, summary 3, and measured vibrations 4 (data from Svinkin [4], with permission from ASCE)

The IRFP method for prediction of grounds vibrations on the basis of field experiments was included in the Manual on Design of Foundations under Machines with Dynamic Loads [2].

This method was applied for the prediction of dynamic stresses in steel structures and also the expected accelerations of footings under steel columns from new nine molding machines. Accelerations were predicted for assessment of differential settlements of column footings, Svinkin et al. [5] and Svinkin [6]. In other publication, Baranov et al. [7] utilized this method for predicting vibrations of an administrative building located at 250 m from the place for installation of a designed drop hammer. Besides, the IRFP method can be used for prediction of ground and structural vibrations from construction sources such as impact pile driving and dynamic compaction, Svinkin [8].

IV. Conclusions

New methods in soil and structural dynamics generally use computer simulations and require applications of existing or new hardware and software which are necessary for contemporary analysis of the soil medium and soil- structure dynamic systems. However, hardware and software are only great tools and they cannot themselves resolve structural vibration problems without engineering analysis and judgment. For validity of new methods, it is necessary to apply the engineering basis to prove the assumptions used in method derivations and find the areas of applications and restrictions of the methods. The writer has used the impulse response function prediction (IRFP) method as a pattern to demonstrate the necessity of the engineering analysis performed for proving the validity of this method.

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