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SYNOPSIS: This paper presents a new method that predicts the vibrational effects on existing soil, building and equipment from a designed machine foundation when it will be installed at a specific site. The method requires development of certain experimental data at an industrial site and subsequent computerized data reduction. The results are complete vibro-records at the locations of interest.

The basic prerequisite of the suggested method is an experimental determining of impulse responses of soil and structures. The use of this responses give to an engineer a chance to consider heterogeneity and multiformity of soil properties. The accepted assumptions have been experimentally based. The general set-up of the way of predicting and the examples of predicting soil vibration have been described.

The application of the suggested method gives the possibility of a determination of safe distances from machine foundations to sensitive units.

INTRODUCTION

Technical progress of industry is characterized by the increase in the amount of machinery and its capacities. The pace of development in recent years makes it necessary to install heavy and complex machinery at many factories and plants. The capacities of the widely applicable machinery such as forge hammers, drop hammers, presses, gangsaw, etc.,have increased considerably. New kinds of the machinery, like impact and vibration testing stands, units for explosive punching, etc., are used on a large scale. Simultaneously, industrial enterprises are supplied with precise machines, tools, sets, high technology lines and other objects that are sensitive to vibrations.

Oscillations of machine foundations induce elastic waves in soil. These waves may have a harmful effect on structures, sensitive devices and processes, and people. Often technological processes can be rendered inoperable, sensitive devices and precision equipment can be damaged, and work conditions can become unhealthy. Therefore, evaluation parameters of elastic waves from designed machine foundations are becoming increasingly important.

A strong tendency toward saturation of factories and plants by vibration sources, along with the sensitivity to vibration by factory equipment raises demands for trustworthiness of determining the expecting soil and building vibrations. Still, the demands of an engineering practice to volume and the accuracy of information about expecting soil vibrations often exceed the possibilities of existing calculation methods.

BASIC CONCEPTS AND ASSUMPTIONS

This paper describes a new method for predicting complete vibro-records on existing soil, buildings and equipment from designed machine foundations (new sources of vibrations) before their erection. This method has been developed for foundations under machinery with vertical dynamic loads.

The suggested method of predicting vibrations of soil is founded on utilization of the idea of an impulse response. These functions are applied at the Systems Theory for analyses of complicated linear dynamic systems with unknown internal structures which mathematical description is very difficult. The impulse response describes an output signal in the time of the action of the single instantaneous impulse on an input of the system. Here, the dynamic system is soil at which waves propagate from vibrations of the machine foundation. An input of the system is a base under the foundation foot, an output is a location of interest placed on a surface or inside soil, or any point at the building - a receiver of oscillations. Output can be obtained, for example, as vibro-records of displacements at locations of interest.

Impulse responses of treated dynamic system are determined by setting up an experiment. Such an approach enables the mathematical models of soil bases to not be used for practical applications and gives a chance to take into consideration heterogeneity and multiformity of soil properties.

Basic assumption of the suggested method:
1. A machine foundation and soil are linear systems.

2. Oscillations of machine foundations are excited by vertical dynamic forces, the resultant of which crosses the center of gravity of the foundation. The distribution of stresses is uniform on the contact surface. The interaction between lateral foundation surface and soil is not taken into account.
3. Impacts directly on the soil can be used for determining the impulse responses.
4. Impulse responses for an investigated point of soil at some distance from the foundation can be considered equal when impacts are executed on any part of the place for mounting of the designed machine foundation. The time the waves take to travel within the limits of the load field is neglected. The dimensions of a foundation area are considered not to affect soil oscillations excepting a highly limited zone around the foundation.

The following is a general set-up of the way of predicting the offset of ocsillations:
Dynamic loads from the designed machine foundation are regarded as noted. These loads can be derived in certain ways.
Impacts on the soil with definite magnitude is made on the supposed place of installation of machine foundation - the wave source. For this purpose it is possible to use a steel pig or ram and a bridge or mobile crane. At the time of execution of the impact on soil, oscillations are measured at the points where predicting should be done, for example, at the locations with sensitive to vibrations equipment, technology lines and devices, etc. These oscillations are the impulse responses of the treated system which experimental determining enables to take into account singularities of a geological structure of the site.
Further expected vibrations are computed by using Duhamel's or Fourier integrals.

The similar method can be executed for predicting vibrations of existing buildings from the designed machine foundation.

ANALYTICAL APPROACH

The following algorithm was developed for the realization of predicting vibration of soil.

Let us assume that the origin of coordinates put at the center of gravity of the foundation area. Vertical displacements of soil may be written as follows:

$$Z(x,y,t)=\int_0^t\iint_A \psi(\xi,\eta,\tau)h_z(x-\xi,y-\eta,t-\tau)\,d\xi\, d\eta\, d\tau$$

where
A = Area of foundation
$dA = d\xi\, d\eta$ = Elementary area
$\psi(\xi,\eta,\tau)$ = Contact stresses at elementary areas
x, y = Coordinates of the point under consideration
$h_z(x,y,\tau)$ = Vertical impulse response at the point under consideration

Horizontal displacements of soil are presented in a similar expression.

For some distance from the machine foundation the reckoned conceptions and assumptions permit that uniform dynamic load from the foundation to the base can be replaced by the resultant F(t) at each moment of time and impulse responses of soil for any point under consideration can be accepted as equal ones which are obtained from the action a single instantaneous impulse on any area (dA) at the place of the designed foundation. Then the equation may be approximately rewritten as:

$$Z(x,y,t)=\int_0^t F(\tau)h_z(x,y,t-\tau)\,d\tau \qquad (2)$$

Function $F(\tau)$ is determined by the calculation, supposing a motion of a foundation is described by linear differential equation according to the Pauliuk-Raush Theory. The general solution for determining dynamic displacements of soil was obtained when dynamic load on the machine foundation changed with time:

$$Z(x,y,t)=\int_0^t \left(2c\frac{d}{d\tau}+f_{nz}^2\right)\Big[Ae^{-c\tau}\sin(f_{nd}\tau+\varphi) + \frac{1}{Mf_{nd}}\int_0^\tau P(t_1)\,e^{-c(\tau-t_1)}\sin(f_{nd}(\tau-t_1))\,dt_1\Big] * h_z(x,y,t-\tau)\,d\tau \qquad (3)$$

Where:
M = Mass of foundation
f_{nd} = Natural frequency of vertical vibrations of foundation
f_{nd} = Natural frequency of vertical damped vibrations of foundation
c = Damping constant

Also formulas were obtained for computing displacements of soil from action on the machine foundation at some particular place in practice dynamic loads:
1. The instantaneous impulse. Similar loads are excited by operated machines producing impact loads, for example, large hammers and presses.
2. The dynamic force from an isolated foundation under machines producing impact loads.
3. The harmonic exciting force. Similar loads are excited by different kinds of operated machines, for example, compressors and gangsaws.

In the considered cases the displacements of soils depend on the acting dynamic load to a foundation, damping constant and the natural frequency of vertical oscillations of the foundation.
Investigations of the effect of a field created by applying the dynamic load from the foundation to the base have shown that dimensions of real foundation areas under forge hammers, presses, molding machines, compressors, etc., affect negligibly on the amplitudes of oscillations of soil at distances more than 10-20 meters from the foundation center of gravity for surface wave

speeds exceeding 100-110 m/s. These conditions include practically all kinds of soils.

ACCURACY OF VIBRO-RECORDS

The accuracy of records of soil oscillations depends on the kind of transducers and the manner of the transducer mounting.

Soil oscillations were measured by using seismographs VAGIK and a seismic oscillograph with GB galvanometers.

Distortions of soils oscillations caused by resonance properties of the seismograph-soil system were investigated in the vertical and horizontal directions. The effect of soil conditions, degree of a cohesion of the transducer with soil, increasing the area and the mass of the transducer have been learned through experiments. It was found that records of vertical soil vibrations did not depend on the manner of a seismograph mounting because the frequency of vertical natural oscillation of the seismograph-soil system was higher in two and more times than visible frequency of registered waves.

Records of horizontal vibrations were changed by natural oscillations of the system which frequency was near one of propagated waves in soil. To remove these distortions the seismograph area was increased for account of mounting seismographs on the special steel plates. Sometimes the cohesion of those plates with soil was raised by welding short pintles to the plates.

The accuracy of calculations of Duhamel's and Fourier integrals was estimated for predicting vibro-records. These integrals were computed by a digital computer. Duhamel's integral was calculated with an error margin less than 0.01%. Spectrums of vibro-records were calculated with the accuracy in limits 5-10%.

EXPERIMENTAL INVESTIGATIONS

The assumptions underlying the suggested method of predicting vibrations of soil were grounded experimentally. The study has covered the special sites with testing foundation and the operating shops with foundations under forge hammers, drop hammers, presses, etc., in all 13 sites.

Linearity of oscillations of foundations for machines producing impact loads were estimated by direct verification of requirements which are produced to the linear system: superposition of oscillations and proportionality of amplitudes of system oscillations to operating forces at the system. First of all, a dependance was determined of the largest amplitudes of displacements from values of the operating impulses. Then a comparison was made of some records of foundation displacements in proportional scales corresponding the operating impulses. The same procedure was used for experimental records of vertical and horizontal soil oscillations. The results of investigations showed that views of vibro-records of foundations with large area and soil don't almost depend on the values of impulses and the amplitudes of the displacements were practically proportional to the values of the operating impulses.

The effect of the nonlinear interaction between a foundation and a base in soil oscillations was investigated at the concrete foundation area of 1 m^2. Nonlinear vibrations of this foundation induced nonlinear soil oscillations on close distances from the source. The effect of nonlinear oscillations of the wave source decreases with an increase of distance from the source.

It was found experimentally that machine foundations with areas exceeding 10 m^2 can be considered as linear systems for the legitimate range of amplitudes of vibration displacements. Nonlinear soil oscillations should be allowed for distances smaller than ten equivalent raduises of foundations with areas less than 10 m^2.

Special experiments were made for investigations of the effect of plastic deformations of the base under a steel pig on soil oscillations when the steel pig fell down on the base. The steel pig had a cylindrical shape with a 20 cm diameter and 100 kg mass. Dropping heights were 2 m and 0.5 m.

Impacts were carried out by dropping the steel pig on the same spot on the base for different conditions of contact. First impacts were done on natural soil. Then a hole was dug with dimensions 0.7 m x 0.6 m in a plane and 0.3 m depth, and filled in with sand or gravel. Impacts were carried out on the bottom of the excavation, the sand, the gravel and the steel plate with dipped in soil pintles. Accelerations of the pig and displacements of the soil surface at some distance from the contact place were measured in the experiments.

It was found that the duration of impulses depends on conditions at the contact place. Increasing the duration of an impulse did not change the shape of soil vibro-records and decreased slightly its amplitudes. However, for different contact conditions the amplitudes of soil vibrations were practically identical with moving off from the contact place. The duration of above described impulses was at the limits 0.025-0.06 seconds. To estimate the minimum possible impulse duration the data of Stavnizer's experiments (Stavnizer, 1969) was used, in accordance with which the impulse duration is 0.0019-0.0032 seconds for impossibility of lateral expansion. Spectrums of impulse loads keep their shapes at the range of natural angular frequency from 0 to 80-40 rad/sec for changing of a time impulse duration from 0.025 to 0.06 seconds. When decreased, the range of the time indicated above extends to 800 rad/sec.

It was shown that oscillation of soil base, which were measured at the time of impact on soil by the ram with the mass of 15.0 T, were stable and did not depend on the kind of soil deformations under the ram.

In virtue of executed experiments it was proved that impacts directly on the soil can be used for deriving impulse responses for the dynamic system: the base under the machine foundation - soil some distance from the foundation.

Also it was shown through experimentation, that in order to predict soil vibrations on distances more than 6-8 times of the equivalent raduis of the machine foundation, it is enough to determine one impulse response. That function can be obtained for impacts on any place in the limits of the foundation area.

The experimets described above have given a very substantial confirmation of the basic assumptions of the suggested method.

RESULTS OF PREDICTING

The Predicting of soil oscillations was determined for machine foundations of different foundation areas and depths. Areas of those foundations were in limits from 1 m^2 to 158 m^2.

Basic attention was given to predicting soil oscillation that were excited by vibrating foundations for machines producing impact loads. In the experiments vertical oscillations of machine foundations were derived and excited by them vertical and horizontal soil oscillations were obtained. Data of measurements were compared with the predicting results.

In the calculations of predicting soil vibrations from designed foundations under machinery with impact loads natural vertical oscillations of foundation-wave sources were set function, which changed in time as a damping sinusoid.

The best fit of the records of real and predicting soil oscillations occurred when the parameters of damping sinusoids were taken from experiments.

Figure 1 shows complete vibro-records of vertical and horizontal soil oscillations which were excited by vibrations of the foundations under the powerful drop hammer with the foundation area of 158 m^2.

A tendency of the prediction soil oscillation to fit the real ones is clearly seen when moving off the foundation. The differences between the highest calculated and measured amplitudes of oscillations are less than 15-20 % on the distance of 40 m from the foundation. For separate points amplitudes practically are coincided.

Also the good coincidence of comparable vibro-records was obtained for machine foundations area of 1, 5.1, 12.3, and 80 m^2.

The initial calculation parameters of the damping sinusoids, which approximated natural oscillation of machine foundations, are modules of damping Φ and a frequency of natural vertical vibration of the foundation.

In the calculations of predicting soil oscillations modules of damping was acceptec with known recommendations for foundations area less than 10 m^2 and was taken of 0.01 seconds for foundation areas within from 10 m^2 to 130 m^2 and 0.03 seconds for ones more than 130 m^2 on the ground of author investigations.

The designed value of a frequency can perceptibly differ from a corresponding experimental one. Therefore the effect of inexactitudes in the determining of the frequency of natural vertical oscillations of the foundation was investigated on the final results of predicting soil oscillations. The quantities of indicated above frequencies were calculated using values of a coefficient of elastic uniform compression of soil C_z and a foundation mass. The foundation mass was derived according to foundation geometrical dimensions, and the coefficient C_z was computed by Savinov's method (Savinov, 1964).

Increasing or decreasing of a designed value of the frequency causes changing amplitudes of predicting soil oscillations by 5-30%, affecting the slightest degree at general view of oscillations. In particular, increasing the designed value of the frequency of natural oscillations of the foundation under the drop hammer with respect to experimental value one leads to an increase of the largest amplitude by 12-28% for vertical and horizontal predicting soil oscillations. Spectrums of these oscillations show a stability of

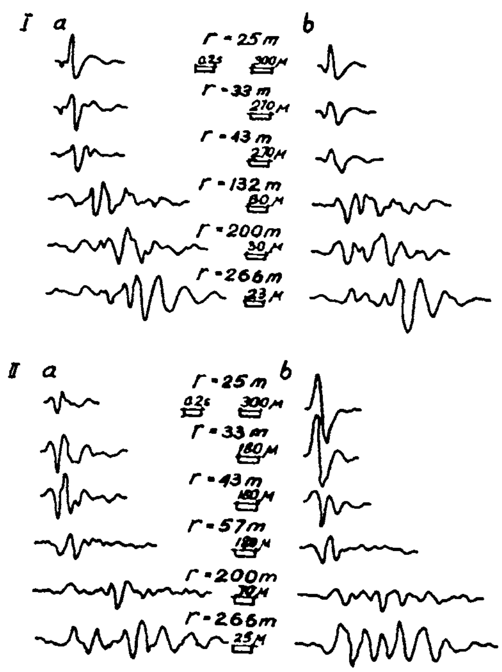

Fig. 1 Vertical-I and horizontal-II soil vibrations during
operating of a drop hammer
a-Real vibrations
b-Predicting vibrations

Parameters f_{nz} = 23.8 rad/sec and c = 9.2 rad/sec were determined by experimentally

frequency composition of even highly long soil oscillations for change of designed values the frequency of natural oscillations of the foundations (Figure 2).

Thus changes of predicting soil oscillations don't exceed measurement errors even for double increasing or decreasing of designed value of frequency.

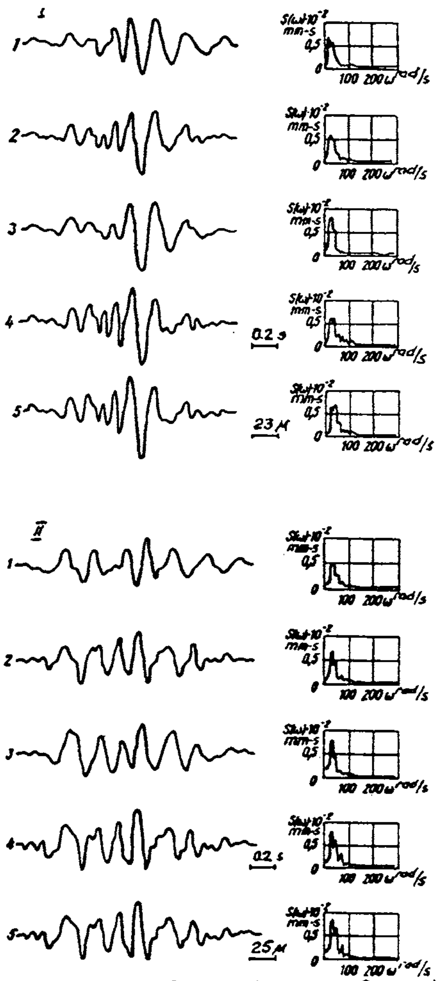

Fig.2 Oscillograms and spectrums of vertical (I) and horizontal (II) soil vibrations during operating a drop hammer
1 - Real vibrations
2-5 - Predicting vibrations were obtained for following conditions:
2 - experimental damping sinusoid
3 - C_z = 3510 T/m, m = 980 T.sec/m, f = 23.8 rad/sec, Φ = 0.032 sec, c = 9.2 rad/sec
4 = C_z = 6920 T/m, m = 270 T.sec/m, f = 63.5 rad/sec, Φ = 0.03 sec, c = 60.7 rad/sec
5 = C_z = 4000 T/m , m = 270 T.sec/m, f^z = 63.5 rad/sec, Φ = 0.03 sec, c = 35.1 rad/sec

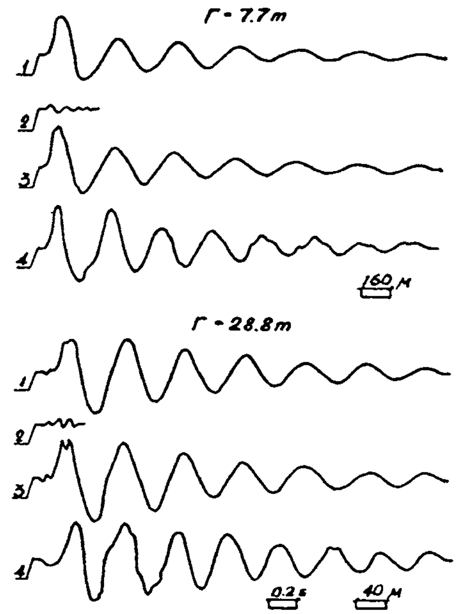

Fig.3 Vertical soil vibrations during operating a large hammer on the isolated foundation
1-3 - Predicting vibrations
1 - From forced outer foundation oscillations
2 - From natural outer foundation oscillations
3 - Summary
4 - Actual vibrations
f_{nz} = 78 rad/sec., c = 30.3 rad/sec.

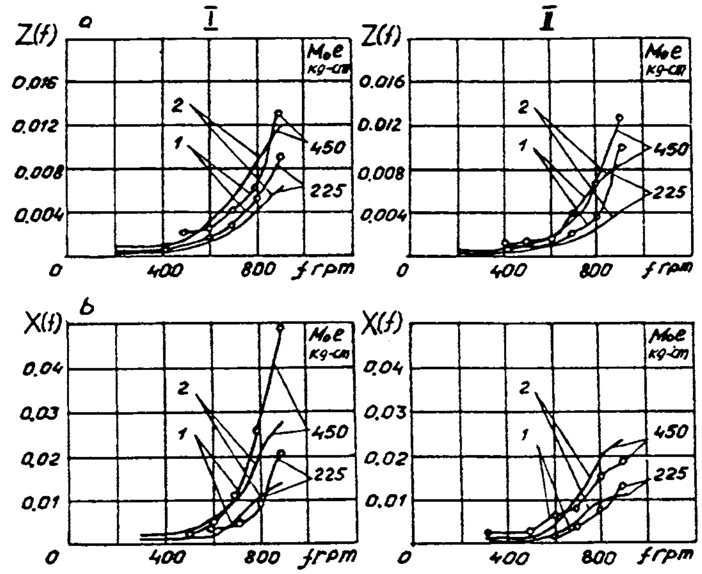

Fig.4 Amplitudes of vertical (a) and horizontal (b) soil vibrations at the distances 16.6 m (I) and 23.3 m (II) from the machine foundation
1 - Actual vibrations
2 - Predicting vibrations

Figure 3 illustrates the possibilities of the suggested method for predicting soil oscillations excited by vibrations of the isolated foundation under the large forge hammer with the mass of falling parts of 16 T. The frequency of natural oscillations of isolated foundation is 15 rad/sec, and the damping constant is 0.88 rad/sec. Outer foundation area is 116 m^2. The predicting soil oscillations are an attractive fit to the actual data.

Figure 4 shows examples of predicting amplitudes for harmonic soil oscillations.

Foundation area is 15.1 m^2. The predicting amplitudes of soil oscillations have matched the real ones at the distance 16.6 m and 23.3 m from the machine foundation in the frequency range 400-800 rpm. The margine of error in determining of amplitudes is 5-20 %.

These examples are powerful arguments for the reasonableness of the suggested method.

CONCLUSION

The described new method was suggested and developed for predicting complete vibro-records of soil and building oscillations excited by dynamically loaded machine foundations.

The basic prerequisite of this method is an experimental determining of impulse responses of soil and structures. This determination enables one to allow the features of the geological structure of an industrial site and deny from the application of mathematical models of soil bases.

Experimental data developed the way of deriving impulse responses of the dynamic system: a base under the machine foundation foot - soil at some distance from the foundation. It was proved that impact directly on the soil can be used for deriving impulse responses for treated dynamic systems. On distances more than 6-8 times of the equivalent radius of the machine foundation foot it is possible to determined one impulse response. That function can be obtained for impact at any place in the limits of the foundation area.

It was confirmed experimentally for the permissible vibration level that machine foundations with an area more than 10 m^2, set at natural base, can be considered linear systems. Nonlinear soil oscillation excited by vibrations of foundations with areas smaller than 10 m^2 can be neglected at distances larger than ten equivalent raduises of the foundation area.

It was established that the dimensions of a field applying the dynamic load from the foundation to the base practically does not affect soil oscillations at distance more than 10-30 meters from the foundation center of gravity.

Ways of accuratly determining measured and computed records of soil oscillations for used devices were also developed.

The suggested method of predicting vibrations is best used for machine foundations with areas bigger than 10 m^2 at distance with more than 5-10 equivalent radius of the foundation foot. For foundations with a smaller area that distance is 20-30 m the equivqlent radius.

The principle of superposition should be applied to cases of shorter distances from the foundation.

The results have proved reliability and efficiency of the suggested method for predicting vibrations of soil and buildings excited by vibrating machine foundations with natural frequencies within 2 Hz to 25 Hz, e.g. practically for whatever foundations under machinery producing impact loads.

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