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Vibrations of Impact Machine Foundations and Footing Settlements

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SYNOPSIS Foundations under machinery that produce impact loads, such as in forge shops, are major industrial sources of wave propagation in soil. The resulting vertical soil vibrations may cause dynamic settlements of column footings. Analyzing of a number of case histories shows that dynamic settlements of footings under columns and connected with them exterior walls at forge shops occur relatively slowly when the soil conditions are different from saturated sands. There are other causes of extensive damage of shop exterior walls. For predicting the dynamic settlements from new machine foundations, it is necessary to know expected footing vibrations. These vibrations can be determined using the method for prediction of soil and building vibrations before installation the foundation under machine producing impact loads.

INTRODUCTION

Vibrating foundations under machines with impact loads, mainly forge hammer foundations, are the most widespread industrial vibration sources. Oscillations of machine foundations induce elastic waves in soil. These waves may have a harmful influence on structures, precision instruments, and various technological processes. In particular, waves from hammer foundations often cause nonuniform settlements of columns and walls of forge shops that leads to skewing of bridge crane tracks, damage of walls, and weakening of connections between structural elements. Therefore, the question regarding the action of vibration waves from foundations for impact machines is of substantial practical importance. Considerable theoretical and experimental studies of residual dynamic settlements of foundations undergoing shock or vibrations were performed by Barcan (1962).

The vibration effect depends on soil conditions, parameters of propagated waves, and types of structures like footings, walls and connections between walls and columns. Obviously, vibrations affect on footing settlements strongly in cases where footings are erected on water saturated fine grained sands. However, considerable damage in forge shops and adjoined buildings are observed regardless from soil conditions. There are certain concerns about the causes of those damage. This paper presents results of experimental investigations made for exterior walls of numerous forge shops with various types of hammer equipment. Also, it is shown the influence of vibrations of foundation under powerful drop hammer to break scrap iron on settlements of column footings for crane tracks.

An increase of machine capacity, such as forge or drop hammers, and/or installation new machinery like impact and vibration testing stands, units for explosive punching might be the cause for dynamic foundation settlements of surrounding building structures. The paper attracts attention to a procedure for predicting the vibration effect on existing soil and buildings from the designed machine foundation when it will be installed at a specific site.

MACHINE FOUNDATIONS AS SOURCES OF INDUSTRIAL VIBRATIONS

There are two types of forge hammers. Drop hammers for die stamping commonly apply in forging to receive the required precision of blows. Forge hammers proper are usually perform free forging operations. The latter machines represent greater interest from the point of an influence of forging operations on surrounding structures.

For forge hammers, the nominal mass of dropping parts ranges from 1 to 25 tonnes and substantial dynamic forces can be transmitted to hammer foundations, Svinkin (1980). A shape of the impact force is very close to the wave half of the sinusoid. Rausch (1950) found that a impact duration of dropping parts on an anvil is approximately 0.01 sec. Foundations under forge hammers as sources of vibration waves can be divided into three groups. On the basis of published data (Rausch, 1950; Shcheglov, 1960; Barcan, 1962; Klattso, 1965; Glazyrin and Martyshkin, 1971) and studies performed by writer, vibration parameters and energy transferred onto soil have been obtained for each foundation group (Table 1).

The first and second groups adduce foundations installed on natural bases. For these foundations with the exception of individual foundations under low-powered forge hammers, periods of free vibrations are in limits of 0.16-0.07 sec, corresponding frequencies range from 40 to 90 rad/sec, and, consequently, the impact loads on forge hammer foundations can be considered instantaneous. The impact loads excite free foundation vibrations with duration of one or two periods and shape close to a sinusoid with large damping. Foundation vibrations are transferred onto the soil.

Frequencies of free foundation vibrations changes in a relatively narrow range. However, even in these limits it is possible to observe the tendency how the frequencies of free vibrations of massive machine foundation depend on forge hammer capacities (Figure 1). Foundations under powerful forge hammers have the lowest frequencies. The highest frequencies correspond to foundations under forge hammers with weight of dropping parts from 1 to 3 tonnes.

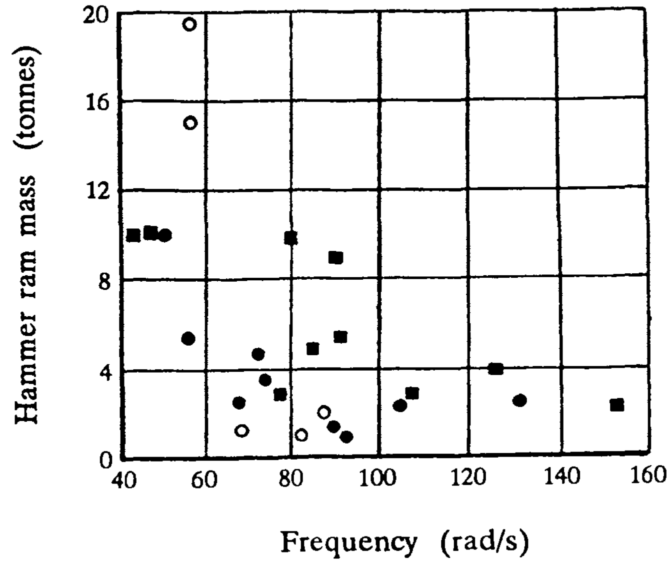

FIG. 1. Relationship between Mass of Dropping Parts and Frequency of Free Foundation Vibrations for Various Soil Conditions: ●- Sandy Soils, ○- Loess Loam, ■- Clayey Soils

TABLE 1. Forge hammer foundations as sources of industrial vibrations

Groups of Foundations	Machine Foundations	Vibration Parameters				Energy Transferred onto soil (kJ)
		Frequency (rad/s)	Displacement (mm)	Velocity (cm/s)	Acceleration (cm/s^2)	
1	Large forge hammers	40-60	0.4-1.0	2.0-6.0	120-420	0.8-5.9
2	Forge hammers with mass of dropping parts less than 5 tonnes	60-90	0.3-1.0	1.9-8.8	120-770	0.06-1.5
3	Vibration isolated forge hammer foundations	19-38	0.1-0.7	0.4-1.6	14-17	0.01-2.8

Third group (Table 1) represents vibration isolated foundations for forge hammers. A concrete block together with a hammer is mounted freely on vibroisolators for which steel springs and rubber dashpots are mostly used. Records of natural block vibrations are similar to low frequency damped sinusoid with small damping. The block oscillations are transmitted to the foundation and induce wave propagation in soil.

The comparison of data from Table 1 shows that maximum values of displacements, velocities and big accelerations are observed for foundations under large forge hammers. Minimum values of vibration parameters are related to vibration isolated hammer foundations. Maximum accelerations up to 0.8 g were obtained from free vibrations of foundations under relatively small forge hammers (group 2). This result is due to comparatively high frequencies of vibrations of these foundation.

Vibrations of hammer foundations induce wave propagation in soil. Typical records and spectrums of foundation and soil vibrations from the operating forge hammer with mass of dropping parts of 7.25 tonnes are shown on Figure 2. Soil vibrations were measured on ground surface at various distances from machine foundation. Soil deposits were loess loams with natural moisture. Analyzing the experimental data reveals that soil vibrations are mostly vertical nearby the wave source.

At certain distance, vertical and horizontal vibrations become similar and, for some locations on ground surface, amplitudes of horizontal vibrations might be greater in 2-3 times than vertical ones. Waves travel in all directions from hammer foundations forming a series of fairly harmonic waves with the predominant frequency of the source. This phenomenon is observed especially well in saturated sands.

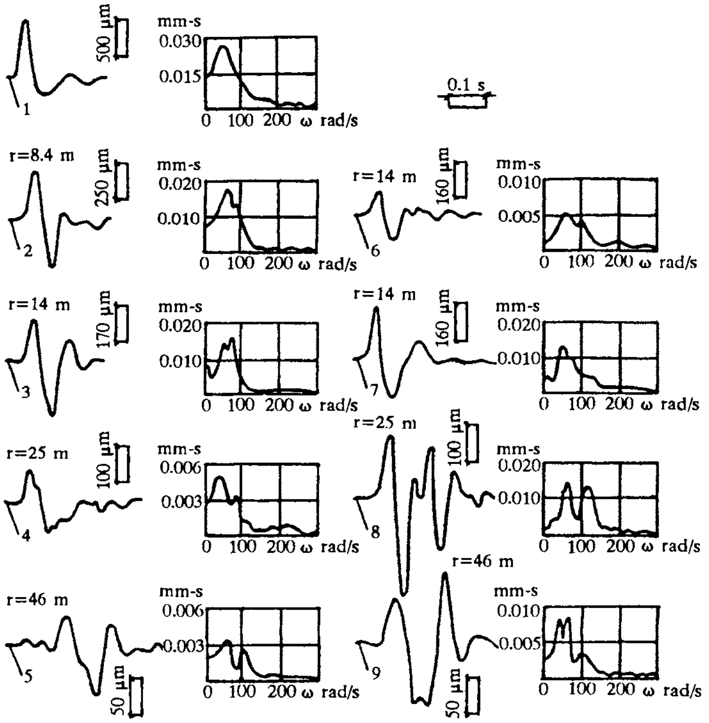

FIG. 2. Records and Spectrums of Hammer Foundation (1) and Soil (2-9) Vibrations: 1-5 - Vertical Component, 6 - Horizontal Tangential Component, 7-9 - Horizontal Radial Component

The proximity of the source frequency to one of natural building oscillations may generate resonance building vibrations. Rausch (1950) reported the case when intolerable vibrations were arisen in an administrative building located 200 m away from the foundation under a hammer with mass of dropping parts of 1.5 tonnes. Similar situation with resonance building vibrations was described by Svinkin (1993), where a five story apartment building was placed at approximately 500 m from the vibration-isolated foundation under a powerful forge hammer with mass of dropping parts of 16 tonnes.

However, within the relatively small space of forge shops, horizontal soil vibrations from hammer foundations installed on natural base have only one-two cycles of oscillations. It is not enough to induce resonance vibrations of forge shops if even the frequency of horizontal building vibrations coincides with the frequency of forced vibrations. Hence, amplitudes of structural horizontal vibrations in forge shops are usually of the same order as the amplitudes of soil vibrations at the locations of the footings under exterior forge shop structures. These vibrations are not dangerous with respect to the strength and stability of the structures.

Besides the horizontal vibrations, footings of shop columns are subjected to vertical soil vibrations with amplitudes dependent on distance from the hammer foundations. Because of that static and dynamic loads are transferred on bases of column footings like on bases of hammer foundations. As mentioned above, accelerations of hammer foundation motion may reach the value of 0.8 g and, therefore, the actual pressure on the base will be in 1.8 times higher than the static pressure. The design of the machine foundations provides for a smaller static pressure on the soil as compared with foundations which support only static loads. Usually, the pressure on bases of the shop column footings is computed without taking into account the dynamic effect that may provoke additional irregular settlements of column footings.

TABLE 2. Accelerations of hammer foundation and soil from Figure 2

Hammer Foundation	Distance from source (m)			
	8.4	14.0	25.0	46.0
0.178 g	0.076 g	0.05 g	0.025 g	0.013 g

The settlements of foundations undergone static loads and vibrations are proportional to accelerations of vertical footing motion (Barkan, 1962). Accelerations decrease very fast with increasing the distance from the source of impact loads. For example, accelerations presented at Table 2 correspond to soil vibrations shown on Figure 2. The vibration amplitude of the hammer foundation was about 0.7 mm and the frequency of source vibrations and the predominant frequency of the waves propagated from source was 50 rad/sec. On the distances 8.4 and 46.0 m from the hammer, acceleration of soil vibrations diminished in 2.3 and 13.7 times respectively.

OBSERVATIONS AND VIBRATION MEASUREMENTS OF FORGE SHOP EXTERIOR STRUCTURES

Experimental studies of a ten forge shops were carried

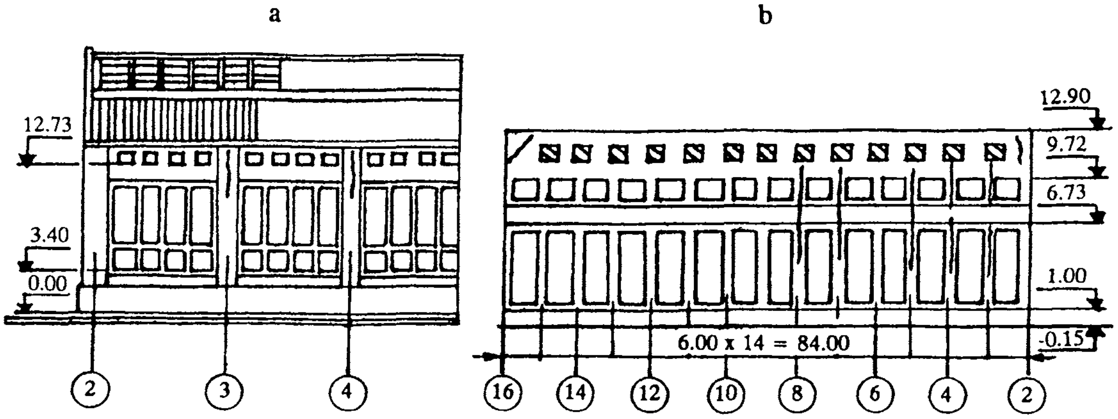

FIG. 3. Elevations of Exterior Walls of Forge Shops containing Hammer Foundations with Mass of Dropping Parts of 15 and 20 tonnes (a), and 1, 2, and 3 tonnes (b)

out due to unsatisfied conditions of shop exterior structures. All projects were performed at industrial enterprises located on the territory of former USSR currently Ukraine. The buildings of forge shops have similar structural set-ups: one story braced steel frame construction and exterior brick walls supported directly on spread footings or column footings with foundation beams. In a certain degree the exterior brick walls are necessarily included to the total rocking resistance of the structures for the expense of affixing the walls to the columns. There were various soil conditions on sites: fine and middle sands with natural moisture, moist and very moist loams, and clays.

Cracks and damage of the exterior brick walls were revealed at the time of visual observations. Examples of investigated brick walls of two forge shops are depicted in different scales in Figure 3. All dimensions are shown in meters. The most characterized cracks were in the walls along steel column axes. A length of cracks ranged from 1 to 7 m and a crack width was between about 2-30 mm; oblique cracks were found at wall corners. Also, cracks were found in brick walls situated next to the hammer foundations. The holes from fallen bricks marked both sides of some parts of the exterior walls. Considerable deformations of the masonry were in the walls of auxiliary buildings abutted to the forge shops.

Vertical and horizontal vibrations were measured on the column footings and brick walls during operation of 24 forge hammers with mass of dropping parts from 1 to 20 tonnes. Moreover, vibrations of structures exited by operating bridge cranes were recorded, particularly from motion and braking by bridge cranes and crab motors. Measurement system comprised seismographs VAGIK or K-001 and oscillograph with GB galvanometers. The frequency range of this system was from 1 to 100 Hz. Vertical vibrations of the column footings located close to the hammer foundations had a shape of motion similar to vibrations of the hammer foundation, but their amplitudes decreased by 2-5 times dependent of the distance from source and soil conditions. Vibrations of the column footings further away attenuated quickly with distance from the hammer foundation.

At time of the investigations, maximum transverse wall vibrations with amplitude of 0.7 mm were observed in shop spans against hammer foundations at upper part at the walls. Frequencies of these vibrations of 50-88 rad/sec coincided with frequencies of free vibrations of hammer foundations. At the rest of the shop spans, free wall vibrations occurred with frequencies of 19-34 rad/sec and considerably smaller amplitudes. Horizontal displacements along the walls were 5-10 times less than maximum transverse amplitudes at the same points. Dynamic loads from bridge cranes induced wall vibrations with frequencies 17-34 rad/sec and maximum wall amplitudes between columns of the same order like ones from operating hammers. Wall transverse vibrations had certain peculiarities at the locations of the wall affixing to the columns. On the wall section located against hammer foundations, vibrations of the brick masonry on the different sides of the columns had the same phase and close amplitudes. Phase changes of these vibrations and an increase of the differences between their amplitudes were found with moving away from a span with the hammer foundation. This phenomenon was pronounced during operations of bridge cranes.

The performed experimental study of ten forge shops allowed to uncover the causes behind crack origination, damage and, in some cases, intolerable brick masonry destructions of the shop exterior walls. It is customary to consider differential column footing settlements induced by the static pressure and vibrations as the basic cause of damage and cracks in the exterior walls. It is quite fair for saturated sand strata and close distance from the hammer foundations. However, in numerous cases the masonry damage of the shop walls are observed when other soils deposits are in the bases of forge shops. Deformations of exterior structures for reason of differential column footing settlements were not visible at the observed forge shops even built on cohesionless soil.

The analysis of the derived results showed that cracks and damage of the brick walls bordered with steel columns had occurred under the effect of wall vibrations relatively to the columns. While one part of the wall on one side of steel column moved, another part on second side stayed immovable because of the vibration phase change. These vibrations were induced mostly by dynamic loads from operating bridge cranes. Evaluated computations showed that tension stresses in the masonry were greater than the allowable ones. Mentioned cracks at the upper part of walls were not dangerous for the qualitatively built masonry. When quality of the masonry was unsatisfactory, permanent vibrations developed cracks which length reached several meters with a width of 2-3 cm. This phenomenon is intolerable because it splits the masonry wall into separate parts. The appearance of extensive damage of the masonry at locations of the shop walls were attached to auxiliary buildings may be explained by insufficient quality of expansion joint between buildings and unequal settlements of the attached buildings.

INFLUENCE OF THE OPERATING POWERFUL DROP HAMMER ON SETTLEMENTS OF COLUMN FOOTINGS UNDER CRANE TRACKS

Free vibrations of the drop hammer foundations are similar to ones of the forge hammer foundations but there are some differences. A frequency of their free vibrations ranges from 3 to 8 Hz. Maximum amplitudes of vertical and rocking foundation motions are 3 mm and 6 mm respectively. Accelerations reaches values of 600 cm/sec^2. These foundations transfer significant amount of energy, up to 35 kJ, to the soil. Probably, the foundations under this type of drop hammers are the most powerful sources of industrial vibrations.

Investigated drop hammer to break scrap iron had a ram mass of 15 tonnes and the height of falling of 25-30 m. Soil on the site was fine sand, weakly moist, weak and middle density. Bridge cranes served drop hammer operations. Open crane tracks were situated in immediate proximity to the drop hammer foundation. The extreme columns were located on distance of 6.5 m from the foundation side under drop hammer. The span of columns was 6 m. Results of vibration measurements are shown at Table 3.

TABLE 3. Vibration parameters of column footings under crane tracks

Column Footing	Maximum Displacement (mm)	Frequency (rad/s)	Maximum Acceleration (cm/s^2)
1	0.360	50.6	92.0
2	0.358	50.6	91.6
3	0.345	50.6	88.0
4	0.298	50.6	76.0
5	0.223	39.3	34.0
6	0.220	37.4	30.8
7	0.170	37.4	23.8

Static pressure under column footings combined with action of waves propagated from the drop hammer foundation led to nonuniform settlements of column footings. As the result, elevation of crane tracks were changed and that caused skewing of crane rails. This is an example of the long term effect of dynamic loads on the footing settlements.

PREDICTION OF EXPECTING VIBRATIONS FOR ASSESSMENT OF FOOTING SETTLEMENTS

For evaluation of anticipated additional settlements of existing footings under superstructures induced by wave propagation from designed machine foundations, it is necessary to determine expected vibrations of these footings.

Prediction of footing vibrations for existing buildings from new hammer foundations prior to their installation can be relatively easy performed using method reported by Svinkin (1991). This method has very distinctive practical application because it allows to take into consideration uncertainties of soil conditions at the site and to predict reliable complete records of soil and building vibrations. The effect of soil properties on expected vibrations is determined with implementation of simple experiments on the site where the machine foundation will be installed. Impacts on the soil with definite magnitude are made on the known place for installation of a new machine foundation. For this purpose, it is possible to use a steel ram and bridge or mobile crane. At the time of executing the impact on soil, vibrations are measured at the locations of interest. Obtained vibration records are the impulse responses of the considered system at those locations, and their experimental determination enables one to take into account properties of soil and building structures. Dynamic loads from the designed machine foundation can be calculated using any known procedure, for example Barcan, 1962. Further expected vibrations are computed by using Duhamel's integral.

An example of predicting soil vibrations is shown on Figure 4. The Svinkin (1991) method was applied for prediction of ground surface vibrations at distances at 8.4 and 14 m from the foundation under the forge hammer with mass of dropping parts of 7.25 tonnes. The dynamic force transmitted from the machine foundation to the soil base depends on foundation and machine mass, the damping constant, the frequency of free vertical foundation vibrations and dynamic vertical foundation displacement as a function of time. It turned out that changes of initial parameters affected weakly on computed records. Expected vibrations were calculated with frequency values derived from various procedures. It can be seen in Figure 4 that actual and predicted records have very close shapes and the difference between maximum amplitudes is 9-25 % and 2-10 % for distances from the hammer foundation at 8.4 and 14 m respectively. There is the tendency for reliable coincidence of actual and predicted vibrations with increasing the distance from the hammer foundation.

The application of the mentioned above method for predicting irregular settlements of the column footings from new nine molding machines have been described by Svinkin (1993).

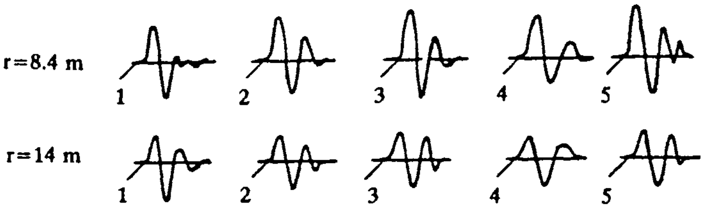

FIG. 4. Records of Vertical Soil Vibrations Induced by Hammer Foundation Vibrations: 1 - Actual, 2-5 - Predicting

CONCLUSIONS

The hammer foundations are powerful vibration sources of wave propagation in soil that may detrimentally affect surrounding structures and sensitive to vibrations devices and equipment. The vibration effect depends on soil conditions, parameters of propagated waves, and types of structures.

Horizontal soil vibrations may induce resonance building oscillations when soil vibrations are transformed in series of quasi-harmonic waves with the predominant frequency equal to the frequency of vertical vibrations of the source.

Vertical vibrations of column footings increase the pressure on their bases. The vibration effect combined with the static pressure may cause dynamic settlements of column footings in the forge shops. The development of this phenomenon depends on soil conditions and a distance from the hammer foundation. In saturated sands, dynamic settlements of column footings located in proximity to the source result in heavy damage of shop exterior structures. Generalization of case histories of ten investigated forge shops with 24 forge hammer foundations shows that in soil conditions different from saturated sands dynamic settlements occur in considerably lesser degree and the other causes, like dynamic loads from operating bridge cranes, produce extensive damage of the exterior shop walls.

One case history demonstrates the influence of vibrations of foundations for powerful drop hammer on nonuniform settlements of column footings that results skewing of crane rails.

For evaluation of footing settlements from new machines with dynamic loads, it is necessary to know expected vibration parameters of structures. The paper has brought attention to the method for predicting the vibrations of soil and existing buildings prior to installation the foundation under machines with impact loads.

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