Soil and Structure Vibrations from Construction and Industrial Sources

Mark R. Svinkin
VIBRACONSULT, Cleveland, Ohio

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Mark R. Svinkin
VIBRACONSULT, Cleveland, Ohio-USA 44118

ABSTRACT

Construction and industrial dynamic sources can produce environmental vibration problems for adjacent and remote structures. High vibrations and unacceptable dynamic settlements could disturb sensitive devices and people and even be the cause of structural damage. The dynamic sources, the geology at a site, and the condition of structures affect ground and structure vibrations. Each construction or industrial site is unique and requires consideration of specific approaches at the site for decreasing vibration effects of construction activities or industrial dynamic sources on surrounding structures. Specifications prepared for a site, calculation and prediction of expected vibrations, and monitoring and control of ground and structural vibrations provide the rational to select measures for prevention or mitigation of vibration problems.

INTRODUCTION

Construction operations involve various sources of vibrations such as blasting, pile driving, dynamic compaction of weak soils, and others. Dynamic effects of these sources may create substantial vibration problems for surrounding buildings influencing structures, sensitive devices, and people. Neglecting vibration problems from construction activities can result in costly litigation and construction delays. Environmental vibration problems in construction of major building projects in urban areas are subjects for important consideration in obtaining the permit from appropriate authorities.

Industrial machines with impact loads, for example forge hammers, punch presses, and others are used for production processes at plants. Ignoring vibration effects of impact machine foundations can create problems for exterior walls of forge shops, people working in the offices at the plants, and residents in neighboring buildings.

The level of structural vibrations caused by construction and industrial sources depends mostly on dynamic loads transmitted on the ground, the medium of soil where wave propagate from the dynamic sources, soil conditions at a site, soil-structure interaction, and susceptibility of structures. Each factor can affect structural vibrations. Only dynamic sources can be modified in certain degree to comply with vibration limits. The rest of the factors cannot be changed. Construction and industrial vibrations differently affect adjacent and remote structures. Knowledge and experience in understanding the causes of vibration effects of construction and industrial sources can be helpful in prevention of harmful ground and structure vibrations.

Each construction or industrial site is different, and vibration mitigation measures should be correctly applied at a site. It is important to set performance criteria relating to vibrations and movement of surrounding buildings. Specifications for the control of construction vibrations should be prepared for major building projects. Harmful soil movements and structural damage from vibrations generated by construction and industrial sources can be prevented in most cases, Dowding (1996), Woods (1997), Svinkin (2004, 2005b).

SOURCES OF CONSTRUCTION AND INDUSTRIAL VIBRATIONS

Dynamic loads of construction sources are in the broad energy and frequency ranges. The maximum rated energy of the most commonly used impact hammers for construction on the land can be up to 300 kJ per blow. Only 30-50 % of this energy is usually transferred to driven piles. Frequencies of natural longitudinal pile oscillations change between 7 and 50 Hz. The maximum pile velocities and displacements measured at the head of steel, concrete and timber piles range from 0.9 to 4.6 m/s and between 12-35 mm, respectively. Vibratory drivers operate with different force amplitude in the frequency range of 10 to 30 Hz. The efficiency of sheet pile driving is below 30 % because of clutch friction between two sheet piles, Svinkin (1999).

For dynamic compaction of loose sands and granular fills, steel and concrete weights of 27 to 400 kN are usually dropped from heights between 1.5 and 45 m. Such dynamic impacts generate surface waves with frequencies between 2 and 20 Hz. The dominant frequency of ground vibrations changes in the limits of 3-12 Hz, Mitchell (1981) and Mayne (1985).

Blasting energy is much bigger than energy of other sources of construction vibrations. Blasting energy is hundreds times greater than energy of other sources of construction vibrations. For example, the energy released by 0.5 kg of TNT is 5400 kJ that is 50-1000 times higher than energy transferred to piles during driving and 15-80 times higher the energy transferred onto the ground during dynamic compaction of weak soils. The dominant frequency of surface waves from quarry and construction blasting ranges mostly between 10 and 60 Hz, Medvedev (1964), Dowding (1996).

Machines with impact loads such as forge and drop hammers are powerful sources of industrial vibrations. The weight of dropping parts can reach up to 157 kN. The frequencies of natural vertical vibrations of machine foundations change between 3-15 Hz. Foundations for impact machines mostly transfer vertical dynamic loads on the ground, Barkan (1962), Prakash and Puri (1988) and Svinkin (1980).

STRUCTURE RESPONSES TO GROUND VIBRATIONS

Construction and industrial vibration sources generate different body and surface waves which travel through the medium of soil deposits and rock. Compression and shear waves are the main types of body waves. The former is similar to acoustic waves, and the latter depends on the rigidity of the soil mass. Compression waves propagate faster than any elastic waves. Reflection and refraction of body waves from boundaries in a layered soil media create various transformation of compression and shear waves.

In addition to body waves, surface waves are generated and transmitted along the ground surface. Rayleigh waves are the primary type of surface waves. In comparison with other wave types observed on oscillation records measured on the ground surface, Rayleigh waves have large displacements, low frequencies, low velocity of wave propagation, and they carry about 2/3 of the total vibration energy. Because Rayleigh waves are potentially the most harmful part of ground vibrations from construction and industrial sources, these waves have the greatest practical interest for structural engineers. Rayleigh waves induce vertical and radial horizontal soil vibrations. In a horizontally layered soil medium, large transverse soil motions could be caused by a second type of surface waves called Love waves; though some authors, for example Tolstoy (1973), do not consider them as boundary waves.

Waves propagate in all directions from construction and industrial sources and induce vertical and horizontal ground vibrations. Longitudinal ground vibrations usually dominate at some distance from the source. Faster attenuation of high frequency components is the basic cause of changes of ground vibrations with distance from the source. Nevertheless, it is common that vibration records can be affected by soil strata heterogeneity and uncertainties. In addition to the peak particle velocity and the dominant frequency, the duration of vibrations is one more important parameter that describes time-domain vibration records. The duration of vibrations increases with moving from the source. This phenomenon is particularly displayed in saturated soils and areas where soil deposit is underlain by rock. For such soil conditions, Siskind and Stagg (2000) obtained interesting results in measurement of ground vibrations at distances 1.6-6.4 km from quarry blasting. They detected vibrations with low attenuation and long duration of about 17 s. These oscillations can be considered as quasi-steady-state vibrations with corresponding consequences.

Elastic waves travel from dynamic sources and induce elastic soil deformations (ground vibrations) which level depends on intensity of propagated waves. The structural responses to ground vibrations depend on soil-structure interaction. Ground vibrations can produce direct vibration effects on structures and trigger resonant structural vibrations of adjacent and remote structures. However, under certain circumstances such as a combination of non-cohesive soil deposits and ground vibrations, elastic waves can be the cause of plastic soil deformations, e.g. liquefaction, densification and soil settlements. Soil-structure interaction will be different for soil failure. The structural response to ground excitation depends on the soil response to waves propagated from the source and soil soil-structure interaction. Thus,

Structural Response = Soil Response + Soil-Structure Interaction

Because elastic and plastic soil deformations cause dissimilar structural responses and damage, diverse thresholds are used for assessment of direct vibration effects, resonant structural vibrations, and dynamic settlements.

Blasting can produce the most extensive ground and structure vibrations, and dynamic effects range from intact structures to considerable structural damage. Siskind (2000) presented the accumulated results of research studies accomplished by the U.S. Bureau of Mines (USBM) and others on vibrations from blasting and their effects on low-rise houses, Fig. 1. Ground vibrations were measured near 1-2 story residential structures from 718 blasts and 233 documented observations were obtained. Non-damaging blasts are not shown although some of them produced relatively high level of ground vibrations even exceeding 51 mm/s. These data indicate different vibration effects on structures depending on the dominant frequency and the peak particle velocity (PPV) of ground vibrations.

Pile installation differently affects structures depending on impact or vibratory pile driving and soil conditions, and dynamic effects of pile driving range from benign to harmful. Harmful results of pile driving occur frequently. In questionnaire responses regarding dynamic effects of pile installations on adjacent structures, 28 State Departments of Transportation and 26 pile driving contractors confirmed their experience with vibration damage from driving bearing, sheet and soldier piles, Woods (1997).

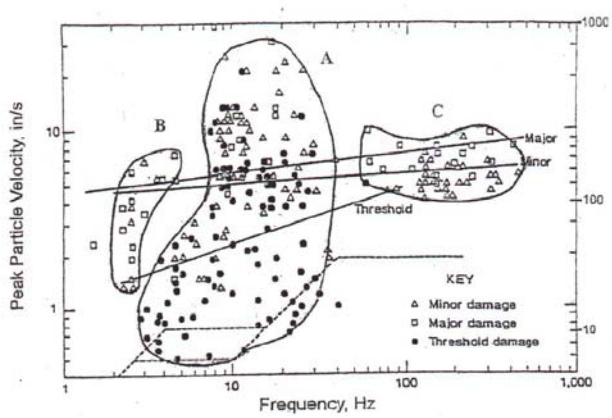

Fig. 1. Ground vibrations from blasting and structure damage summary grouped in three zones. Dashed lines define USBM safe limits. Data were modified from Siskind (2000).

Foundations for machines with impact loads are widespread powerful sources of industrial vibrations that can cause differential settlements and damage to exterior structures of forge shops and adjacent buildings. Also, these vibrations are very disturbing for offices located near forge shops. Barkan (1962) made the comprehensive study of foundations under machines with dynamic loads.

A study of structural damage from construction and industrial dynamic sources is important for prevention of negative vibration effects.

ELASTIC SOIL DEFORMATIONS AND STRUCTURE RESPONSES

In general, elastic soil deformations from construction and industrial sources may affect structures in the following distinct ways.

Direct Vibration Effects on Structures

Ground vibrations may cause direct damage to structures when excitation frequencies do not match natural frequencies of structures. Such vibration effects on sound structures can be considered within a distance equal to the final excavation depth in rock (close-in blasting) or one pile length from a driven pile. These distances can be substantially larger for susceptible structures. Intensity of structural vibrations depends on soil-structure interaction. Direct minor and major structural damage without resonant structural responses were observed in the velocity 33-191 mm/s range for frequencies of 2 to 5 Hz and in the velocity 102-254 mm/s range for frequencies of 60 to 450 Hz (Fig. 1). In practice, actual measured vibrations are often below these velocity values but higher than the USBM vibration limits. Nevertheless, there are a number of case histories that demonstrate no structural damage in the proximity of the dynamic sources with impact loads even if direct damage to structures is possible.

At various distances from the dynamic sources, the direct vibration effects on structures can occur due to interaction of surface waves with different wave length and structures with diverse dimensions and stiffness. A surface wave propagated under the rigid structure foundations forms areas with negative reactions from the elastic soil base that can change the contact condition between the structure and the elastic soil base. As a result the structure-soil system can become unstable. Besides, the effect of surface waves reflection from a structure depends on properties of these waves and structures. The minimum reflection effect corresponds to the rigid structure, and the maximum effect matches to structures with variable stiffness. Surface waves – buildings interactions are very important for analysis of earthquake effects on structures, and these problems have been considered in detail in seismology, for example Housner (1990), Medvedev (1962) and Sinitsin (1967).

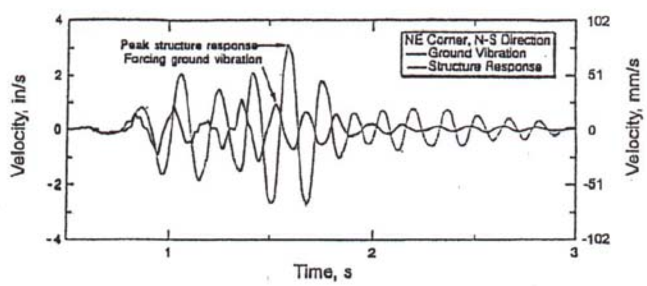

Fig. 2. Ground and structure vibrations with frequency of 5.8 Hz near structure resonance (Siskind 2000). Plot was originally from Crum (1997).

Resonant Structural Vibrations

The proximity of the dominant frequency of ground vibrations to one of building's natural frequency can amplify structural vibrations and even generate the condition of resonance. Records of ground and structure vibrations with close dominant frequencies are shown in Fig. 2. It can be seen that the PPV of structural vibrations increased up to 2.7 times in comparison with that of ground vibrations and structural vibrations began to increase after the first cycle of ground vibrations. If only a few cycles of ground vibrations with the dominant frequency occur, resonant vibrations do not develop. The resonant structural vibrations are independent of the structure stiffness being limited only by damping.

The condition of resonance can be triggered at large distances of a few hundred meters from a pile driving site and even more than one kilometer from a blasting site. Examples of resonance in multistory buildings at distances of about 200 and 500 m from dynamic sources are demonstrated in Svinkin (2004). Resonance of horizontal building vibrations in the frequency range of 2-12 Hz is the major concern. Resonant horizontal wall vibrations and vertical floor vibrations can occur at the frequency range of 12-20 Hz and 8-30 Hz, respectively. Latter vibrations are important when precise and sensitive devices are installed on the floors.

According to Fig. 1, cosmetic cracking and other damage can occur at resonant frequencies between 3 and 35 Hz with velocity values of 12 to 762 mm/s, but transient ground vibrations with short duration cannot trigger resonant structural vibrations at relatively small distances from blasting. To prevent cosmetic cracking from possible resonance, the USBM 51 mm/s limit of ground vibration was decreased in the frequency range below 40 Hz with the minimum tolerable value of 13 mm/s (Siskind et al., 1980).

Nevertheless, it is necessary to point out that vibratory pile installation near structures can trigger resonant floor vibrations. The author experienced an interesting case where vibratory sheet pile driving with the frequency of about 26 Hz generated ground vibrations below 5 mm/s and vertical floor vibrations higher than 51 mm/s in two story house. These vibrations made architectural damage to the house.

Resonance of Soil Layers

Matching the dominant frequency of propagated waves to the frequency of a soil layer can create the condition of resonance and generate large soil vibrations. Such amplification of soil vibrations may happen during vibratory pile driving. Woods (1997) noted that layers between about 1-5 m thick may produce a potential hazard for increasing vibrations when vibrators with operating frequencies between 20-30 Hz install piles in soils with shear wave velocities of 120 to 600 m/s. The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental augmentation of ground vibrations.

Transient soil vibrations can also be affected by resonance of soil layers. Waves from blasting and dynamic sources with impact loads travel through the soil medium in all directions forming a series of quasi-harmonic waves, and they can be amplified as a result of resonant vibrations of soil strata. In most cases, analysis of site responses is focused on the motion at the free ground surface. However, resonant effects may occur at any point within a layered soil profile. It is possible to consider two locations with the same soil within the same site excited by the same dynamic source, and these locations could respond quite differently because of the nature and dimensions of surrounding soil layers, Davis and Berrill (1998).

A bright example of strong ground and structure vibrations due to resonance of a soil layer was reported by Bodare and Erlingsson (1993). At the time of a rock concert held in the Nya Ullevi Stadium in Gothenburg (Sweden), a good half of the audience was in the stands on both sides of the soccer field and more than twenty-five thousand people were standing on the field close to the stage. During the concert, the audience jumped in time to the music. In this way, the audience excited vibrations of a clay layer 25 m thick from the surface. The layer had the same frequency of about 2.4 Hz as the beat of the rock music. Those songs lasted for several minutes and could easily build up a high vibration level. Resonance of the clay deposit amplified ground vibrations and excited violent vibrations of stadium structures. Also, residential buildings 400 m away experienced vibrations.

PLASTIC SOIL DEFORMATIONS AND STRUCTURE RESPONSES

Dynamic forces transmitted from construction or industrial impact and vibratory sources to the medium of soil can be the cause of soil failure that becomes apparent in soil liquefaction, densification and soil settlements beyond the densification zone.

Liquefaction can occur in saturated and dry sand soils. Different criteria are used for assessment of possible liquefaction at construction sites. For consistency with the vibration limits applied for ground vibrations generated by blasting, the PPV values are employed as the blasting vibration threshold for liquefaction in sand soils. Charlie et al. (1992) reported the results of a series of different explosive charges detonated at a depth of 3 m in a dense, saturated, alluvial sand deposit. Liquefaction was induced at the depth of explosives locations for the PPV that exceeded 16 cm/s. In another case history, Sanders (1982) proposed the conservative threshold of 10 cm/s for evaluation of liquefaction hazard to buildings located across a river from proposed blasting to create breaches in a levee system. The report was reviewed by Dr. H.B. Seed who concluded that the threshold was reasonable. Unlike blasting, other sources of construction and industrial vibrations generate considerably smaller ground vibrations which are below the liquefaction threshold.

Blasting, pile driving, and dynamic compaction can densify weak soils. Densification of sands is expected at short distances from blasting and such densification is used for improving loose and saturated sands to receive satisfied soil conditions. Initiation sequences are important for the control of vibration effects on adjacent structures. There is a procedure to calculate a maximum radius of ground surface settlements greater than 1 cm, Dowding (1996). Dynamic loads force piles to vibrate and penetrate into the ground that result in densification and vibrations of soil surrounding a pile. The soil movements may produce heave, settlement and lateral displacement toward the existing nearby foundations and induce vibrations of adjacent structures. Dynamic compaction is used as for densification and improvement of loose sands and granular fills.

Differential ground and foundation dynamic settlements can be triggered by relatively small ground vibrations in sand soils and by soil displacements in clay soils. Such settlements may happen beyond the zone of densification at various distances from construction and industrial dynamic sources. According to Woods (1997), distances as great as 400 m may need to be surveyed to identify settlement damage hazard in sand soils during pile driving.

Dynamic Settlements

Differential soil and structure dynamic settlements are the major cause of structural damage from construction and industrial vibrations.

Blasting. The results of research studies presented in Siskind (2000) did not mention blasting vibration effects on soil deformations, but at least Edwards and Northwood (1960) reported the outcomes of controlled blasting on six buildings and concluded that the damage in the buildings on sand-clay deposits was caused by failure of the soil manifested in settlements under the building rather than by wave energy within the building itself. It can be assumed that differential dynamic settlements could partially be the cause of structural damage in zones A, B, and C (Figure 1).

Impact Machine Foundations. Vertical ground vibrations induced by impact machine foundations in sand soils can cause differential dynamic settlements of column footings in forge shops. Column footings are usually designed for static loads transferred on the ground without taking into account the dynamic loading from ground vibrations which can increase up to 2 times the static pressure on the ground.

Barkan (1962) reported three case histories of detrimental structure footing settlements caused by ground vibrations excited by forge hammer foundations.

In the first case, ground vibrations transmitted from the foundation under a 4.5 tonnes hammer completely destructed a three story auxiliary building attached to a forge shop. There was no manufacturing inside the building. The brick building was located at distance of 6 m from the hammer foundation and erected much later than the forge shop. The building walls were supported by continuous concrete footings. The static pressure on the ground was in the 1.75-2.0 kg/cm^2 range. The soil consisted of fine-graded sands with a higher than medium density. The water table was at a depth of 4.0 m. The maximum displacement of the hammer foundation was about 1.0 mm and the period of ground vibrations was between 0.075 and 0.07 s. The vibration displacements of the building footings at diverse points varied from 0.05 to 0.65 mm. Therefore, the dynamic pressure on the ground was non-uniform and the building footings were undergone considerable differential settlements resulting in the failure of the footings and later the walls.

In the second case, ground vibrations generated by the foundation under a 2.5 tonnes forge hammer were the cause of destroying the forge shop building which brick walls were supported by continuous concrete footings. The static pressure on the ground was in the 2.0-2.5 kg/cm^2 range. The soil consisted of gray and yellow fine-graded sands with a medium density. The water table was at a depth of 8.5 m. During 200 hours of forge hammer operations, shop wall footings were undergone differential settlements and numerous cracks appeared in the brick walls.

The foundation under a 3 tonnes forge hammer was supported by 6 m long timber piles in the third case. The soil consisted of fine-graded uniform sands with a higher than medium density. Two water tables were found at depths of 2.5 and 6.0 m. The static pressure on the ground was in the 1.75-2.0 kg/cm^2 limits. In a short time after the 3 tonnes hammer started to work, differential settlements of the shop columns nearest the hammer foundation were observed. These settlements were the cause of crack formation in the reinforced-concrete frame structures of the shop and in the brick walls.

Pile Driving in Sands. Pile driving in loose to medium uniform saturated sands may cause differential soil and structure settlements. Relative density referring to an in-situ degree of compaction is usually less than 70% for loose and medium compact sands. Also, large settlements have been reported for sites where piles were driven into adverse sands: denser, calcareous, silty, and sand with gravel and rubble. In addition to soil deposit, other factors could be also accountable for dynamic settlement such as the type of piles (displacement or non-displacement), pile spacing, the method of pile installation (impact or vibratory hammer), the sequence of pile driving, and the number of driven piles.

Kaminetzky (1991) reported a case history of serious damage to structures from pile installation by heavy impact hammers at a site with uniform medium dense sands. Street pavements cracked and settled as much as 406 mm after only one-fourth the piles had been driven. Therefore, sheet piles were installed to prevent additional settlement and damage to sewer and water pipelines. After the contractor substituted impact hammers for vibratory drivers, damage became even worse. High-rise neighboring buildings as tall as 19 stories were so severe damaged that eventually all buildings within a radius of 122 m were denounced as unsafe and had to be demolished. A number of case histories with a description of considerable structural damage from subsidence of the existing building foundations induced by pile driving in sand soils are presented in D'Appolonia (1971) and Svinkin (2006a).

Kaminetzky (1991) mentioned an interesting case with building settlement developed at a distance of about 305 m away from a pile driving site. Foundations of the buildings were underpinned on piles down to the tip elevation of the new driven piles to prevent building settlements.

Nevertheless, there are examples of pile driving in sand soils without dynamic settlements. The author experienced a case with concrete piles driven in wet sand soils in the proximity of a five-story brick industrial building. The conclusion about possible safe pile installation nearby the existing building was based on the results of building structural responses to driving a few test piles at a distance of 3 m from the existing building. Measurement of structural vibrations and evaluation of crack behavior in the building structures were made during test pile driving. Special gages were employed for determination of the smallest enlargements of crack widths. Changes in crack lengths were observed as well. An impact hammer induced structural vibrations with the dominant frequency of 7 Hz. A vibratory driver with a low frequency of 420 rpm excited forced structural vibrations with the same frequency of 7 Hz. Additional dynamic stresses computed in the structures were in the allowable limits. Analysis of the crack behavior showed that crack widths and lengths did not enlarge during test pile driving. No signs of damage to the building from pile driving were observed. These results were acceptable for implementation of pile driving in wet sands nearby the existing building. In another example, the author experienced a case where sheet pile vibratory driving into moist poorly graded loose to medium dense slightly silty sand did not trigger settlements of one-two story houses at distances of 9.2-12.2 m from driven sheet piles.

The use of mitigation measures, monitoring and control of soil and structure vibrations can prevent negative effects of pile driving in sand soils. Ashraf et al. (2002) described a case history of driving 356-mm diameter concrete filled steel pipes for a new constructed bridge adjacent to existing abutments and two story houses. The piles were installed in holes preaugered to a depth of 6 m below the ground surface. Besides, the top 2.4 m of the piles was encased in 508 mm diameter steel shells filled with sand to accommodate the pile movement. These measures reduced vibration effects from pile driving and no structural damage occurred during and after driving.

<u>Pile Driving in Clays</u>. There are the different causes of dynamic settlements in sand and clay soils. Ground displacements, not vibrations, are the causes of heave and following settlement in clays. According to D'Appolonia (1971), pile driving in clay soils produces shear disturbance around a pile, increases lateral stresses and pore pressures and results in a heave of the ground surface. After pile installation and excess pore pressure dissipation, the ground surface settles with a net settlement due to increasing soil compressibility. Effects of pile driving in soft to medium clay on the surrounding area should be expected at distances from pile installation equal to about the thickness of the clay layer being penetrated.

The induced pore pressure and movements can be affected by several factors such as the type of piles, the predrilled holes with the proper diameter and depth, the spacing of the piles, and the sequence of pile driving, Svinkin (2006a).

REGULATIONS OF CONSTRUCTION AND INDUSTRIAL VIBRATIONS

There are different criteria for tolerable soil and structure vibrations induced by elastic and plastic soil deformations.

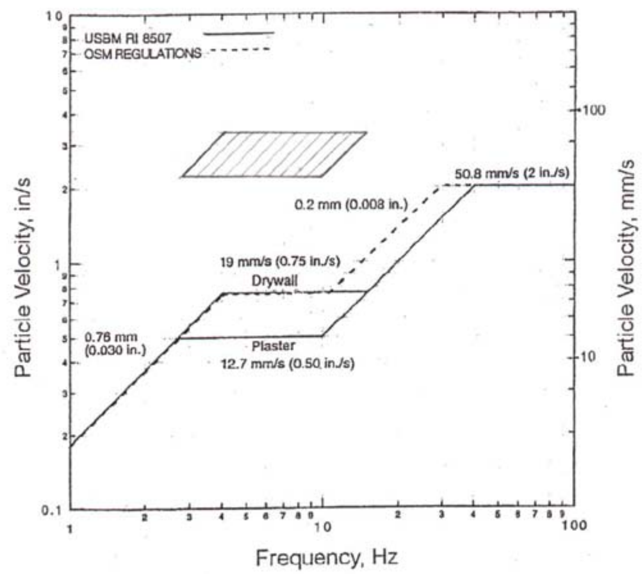

Fig. 3. Safe level blasting criteria from USBM RI 8507 and the derivative version, the Chart Option from OSM surface coal mine regulations. Shaded area shows maximum velocities for amplification of 4.5 at resonance. Data were modified from Siskind (2000).

<u>Vibration Regulations Governing Elastic Soil Deformations</u>

There are no general regulations of construction and industrial vibrations. However, the Explosive Materials Code, NFPA 495 (2001), includes the criteria for the cosmetic cracking threshold developed in the blasting industry for low-rise residential structures. These criteria are the frequency-based safe limits for cosmetic cracking threshold were originated for 1-2 story residential structures by the U.S. Bureau of Mines, Siskind et al. (1980). The limits depicted in Fig. 3 have the following displacement and velocity for the four ranges of the dominant frequency: 0.76 mm (0.03 in.) for 1-4 Hz, 19 mm/s (0.75 in./s) for 4-15 Hz, 0.2 mm (0.008 in.) for 15-40 Hz, and 50.8 mm/s (2.0 in./s) for 40-100 Hz. The limit of 19 mm/s (0.75 in./s) for 4-15 Hz is used for drywall while the limit of 13 mm/s (0.5 in./s) for 2.5-10 Hz is applied for plaster. The derivative version of the USBM safe limits shown in Fig. 3 was included as the Chart Option into the surface coal mine regulations by the Office of Surface Mining, OSM (1983).

All vibration limits mentioned above were built up on the basis of the two decades research studies of a correlation between ground vibrations and observations of cracking damage in low-rise houses which are most typical structures in urban and rural areas. These limits are applied for ground vibrations as the criteria of the possible crack formation in structures. Obviously, these vibration limits can be successfully used for adequate blasting loads, similar structures and ground conditions they were developed for, but different limits should be used for other combination of dynamic loads, soil conditions and structures. Thus, the authors of the USBM limits suggested the limit of 3 mm (0.12 in./s) for a soil stratification with high water table and low wave attenuation in Florida, Siskind and Stagg (2000), Svinkin (2005a). Moreover, the USBM limits do not actually take into account construction blasts with much higher frequency content. Dowding (1996) demonstrated examples where the dominant frequencies of ground vibrations from surface mining and construction blasting would lie between 12 and 18 Hz and 70 and 100 Hz, respectively. It means that the USBM limits cannot be used for construction blasts.

The existing regulations are conservative for assessment of direct blasting vibration effects on structures in the non-resonant frequency zones of structural vibrations when ground vibrations do not trigger plastic soil deformations under structures, but they cannot protect low-rise structures from appearance of cosmetic cracks by amplification of ground vibrations higher than 4.5x and beyond the 4-12 Hz frequency range. Furthermore, the application of these limits to different super and underground structure is incorrect. AASHTO (1996) stated the application of the USBM limits to markedly different types of structures is common and inaccurate.

Therefore, some government, state and local agencies use their own vibration limits of the peak particle velocity. These limits are applied independently of soil conditions and soil-structure interaction. Also, they do not take into account type, age and stress history of structures. If structures receive even cosmetic cracks from blasting or pile driving, the agencies try to decrease the existing vibration limits. It is a wrong policy because such a step cannot prevent new damage without analysis of the causes of cosmetic cracking. Also, this action can negatively affect production blasting, pile driving and other construction operations. What vibration limits can be used for multi-story buildings? Such criteria are not available. This is the reason why some researchers and practitioners measure structural vibrations, Svinkin (2006b).

It is necessary to make direct measurement of structural vibrations accompanied by observation of the results of dynamic effects. For multi-story residential, commercial and industrial buildings, the frequency-independent safe limit of 51 mm/s (2 in./s) can be chosen for the PPV of structural, not ground, vibrations, Svinkin (2004; 2006b). This criterion automatically takes into account soil-structure interaction for the whole building frequency range. The proposed criterion does not exclude higher allowable vibration levels. There are two reasons which confirm truthfulness and expediency of this criterion. First, in the middle of 1940s, the safe vibration limits of 30-50 mm/s (1.18-1.97 in/s) for sound structures were found by the Moscow Institute of Physics of the Earth, Sadovskii (1946). These limits were successfully used for years in former USSR. Second, according to Siskind (2000), the PPV of 51 mm/s (2 in./s) is the highest vibration level generated inside homes by walking, jumping, slamming doors, etc. Without doubts, massive concrete structures have much greater cracking thresholds.

It is easy to demonstrate compatibility of the new simplified safe criterion and the existing vibration limits, Svinkin (2007). To evaluate tolerable structural vibrations, the smallest vibration limits of 13 mm/s (0.5 in./s) and 19 mm/s (0.75 in./s) from the USBM vibration criteria have to be multiplied by 4.5, and their product of 57 mm/s (2.25 in./s) and 85.5 mm/s (3.37 in./s) are higher than the simplified criterion of 51 mm/s (2 in./s). It is important that the limit of 51 mm/s (2 in./s) for structural vibrations can be applied for assessment of vibration effects on 1-2 story houses as well. Furthermore, the simplified criterion is not contradictory to the British Standard because this standard is similar to the USBM vibration limits (Fig. 4). The same conclusions can be drawn regarding the German Standard (Fig. 5).

Vibration Regulations Governing Plastic Soil Deformations

All mentioned above vibration limits have nothing to do at all with structural damage due to plastic soil deformations. There are no federal, state, and local regulations of the critical vibration levels of ground vibrations which may trigger dynamic settlements beyond the densification zone.

Attempts to use the decreased values of the USBM limits for preventing dynamic settlements are unsuccessful. For example, the author experienced a case history of vibration effects on a two story house from vibratory sheet pile driving. The vibration limit of 5 mm/s (0.2 in./s) was used for ground vibrations. This threshold is 2.5 times less than the smallest value from the USBM limits. However, such decreasing the vibration limit did not prevent vibration damage to the house. A settlement crack was found in the brick chimney and a house driveway was destroyed.

There are a couple of published papers with information about the critical vibration levels of ground vibrations, which may trigger dynamic settlements. Lacy and Gould (1985) analyzed 19 cases of settlements from piles driven by mostly impact hammers in narrowly-graded, single-sized clean sands with relative density less than about 50 to 55 %. They found that the peak particle velocity of 2.5 mm/s could be considered as the threshold of possible significant settlements at vulnerable sites. Claugh and Chameau (1980) revealed that acceleration higher than 0.05 g can trigger dynamic settlement in loose sands with rubble and broken rock. This criterion is adequate to the peak particle velocity of 4.3 mm/s for the frequency of 18 Hz of ground vibrations from the vibratory hammer.

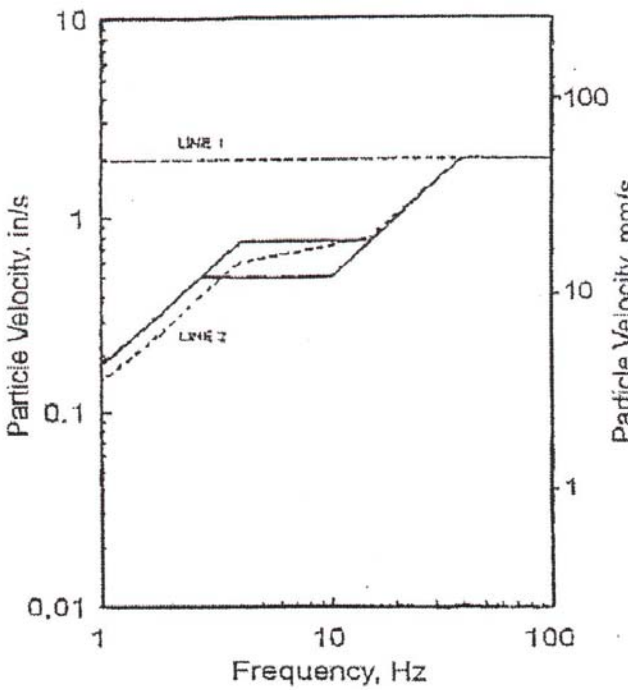

Fig. 4. Vibration guidelines - USBM RI 8507 (solid line) compared to BS 7385 (dashed line). Line 1: reinforced or framed structures, industrial and heavy commercial buildings; line 2: unreinforced or light framed structures, residential or light commercial type buildings. From AASHTO Designation: R 8-96.

Woods (1997) has concluded that simple methods of estimating settlements in loose to medium dense sand during pile driving do not provide practical solutions. He pointed out that the prudent approach is to always proceed with caution when the condition of settlement is known to exist.

The threshold cyclic shear strain for volume change and pore pressure increase has been approximately determined as 0.01 % (Dobry et al., 1981). An estimated shear strain was equal 0.001 % for the first site and 0.002 % for the second site, and these shear strains at both sites were substantially less than the threshold. Perhaps it would be sensible to consider additional effects of static loads (Barkan, 1962) and possible resonance of soil layers (Davis and Berrill, 1998) on the threshold of dynamic settlements at sites with weak soils.

MANAGING VIBRATION PROBLEMS

There are different approaches for managing soil and structure vibrations at the different levels of projects. At the design stage, preparation of specifications for the control of construction vibrations is important to ensure safety and serviceability of adjacent and remote structures, Dowding (1996) and Woods (1997). A preconstruction condition survey should be a part of specifications and has to be conducted with care ensuring documentation of all observable defects. This survey is important for public relations. Calculation, prediction and monitoring of construction vibrations should be made to keep ground and structure vibrations in compliance with the vibration limits. Certain modification of construction dynamic sources can be made for decreasing vibration effects.

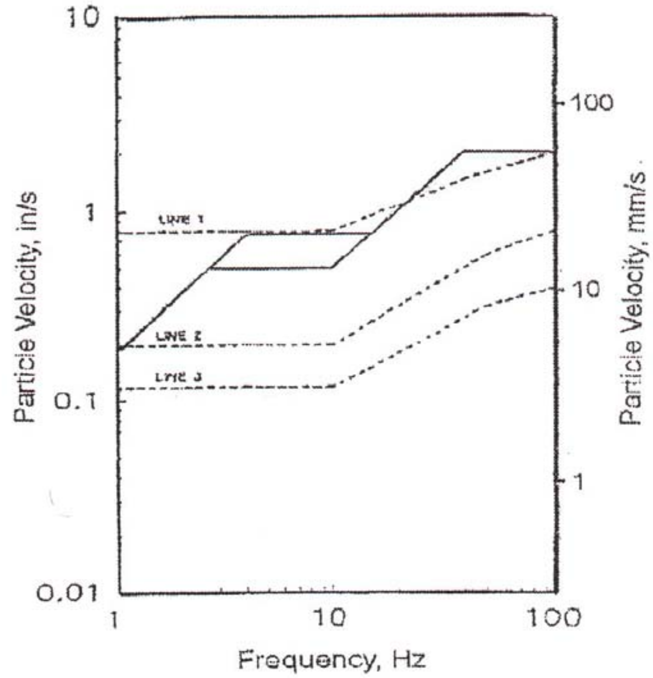

Fig. 5. Vibration guidelines - USBM RI 8507 (solid line) compared to DIN 4150 (dashed line). Line 1: buildings used for commercial purposes, industrial buildings and buildings of similar design; line 2: dwellings and buildings of similar design and/or use; line 3: structures that because of their particular sensitivity to vibration, do not correspond to those listed in lines 1 and 2, and are of great intrinsic values (e.g. building that are under a preservation order). From AASHTO Designation: R 8-96.

Condition Survey of Structures

Construction operations such as excavation of upper soil layers and dewatering accomplished before the beginning of blasting and pile driving can detrimentally affect the existing nearby structures.

Most major building projects include excavating and dewatering. Dowding (1996) has observed that permanent excavation deformations induced in adjacent structures generally exceed those from pile driving. Impact from dewatering can be significant not only for adjacent but for a number of surrounding buildings. D'Appolonia demonstrated several examples of such harmful effects on ground and structures.

It is necessary to separate damage to structures from construction activities and from dynamic sources. Therefore, the pre-driving or pre-blasting condition survey has to be provided when excavating and dewatering have been completed at the site.

Calculation of Ground Vibrations

Ground vibrations can be calculated before the beginning of construction and industrial activities. There are diverse empirical equations used for calculation of ground vibrations.

Golitsin's Equation. For surface waves generated by earthquakes, Golitsin (1912) derived a simple and sensible equation to calculate a reduction of the maximum displacement of ground vibrations between two points at distances r_1 and r_2 from the source as

$$A_2 = A_1 \sqrt{r_1 / r_2}\, e^{-\gamma(r_2 - r_1)} \qquad (1)$$

Where A_1 = peak particle displacement of ground vibrations at a distance r_1 from the source, A_2 = peak particle displacement of ground vibrations at a distance r_2 from the source, γ = attenuation coefficient. The term $(r_1/r_2)^{0.5}$ indicates the radiation or geometric damping and the term $\exp[-\gamma(r_2-r_1)]$ indicates the material or hysteretic damping of wave attenuation between two points.

Equation (2) was originally obtained to estimate attenuation of low frequency Rayleigh waves with large wavelengths for which the coefficient γ depends very slightly on the properties of upper soil layers. For such conditions, the coefficient γ changes reasonably in narrow limits for assessment of wave attenuation in soils, Svinkin (1999).

From 30-ties of the last century, a number of researchers used equation (1) for preliminary computation of ground vibrations from industrial and construction sources. Obviously, some researchers could re-derive the Golitsin's equation, but their derivations must have the name of the first author of the equation.

There are certain problems in the application of the Golitsin's equation for assessment of ground vibrations from construction and industrial sources because waves generated by these sources have higher frequencies and smaller wavelengths in comparison with surface waves from earthquakes and propagate mostly in the upper soil strata close to the ground surface. The coefficient γ is important for accurate calculation of wave attenuation. Collected experimental data indicate that the coefficient γ depends on the energy of vibration sources, the dominant frequency of waves propagated in the medium of soil, the distance from the source and the soil stratification at a site. Experimental data show that for different pairs of widely separated points on the ground surface, values of γ can vary more than an order of magnitude and even change sign. Thus, the coefficient γ acceptable for small distances may be inadequate for long distances. Due to wave reflection and refraction from boundaries of diverse soil layers, an arbitrary arrangement of geophones at a site can yield incoherent results of ground vibration measurements because waveforms measured at arbitrary locations at a site might represent different soil layers, Svinkin (1973; 1999).

Coherent and consistent data for assessment of surface wave attenuation can be obtained on the basis of measurement of ground vibrations reflected from the same soil layer boundaries. Therefore, the best results in the application of the Golitsin's equation can be expected for vibration measurements on half-space soil deposits. At sites with various soil layers, the requirements for appropriate transducer spacing should be similar to spacing used in the application of the spectral analysis of surface waves (SASW) method for evaluation of soil properties.

Scaled-Distance Approach. For assessment of ground vibration attenuation generated by blasting, any distance D from a blast is normalized (scaled) with the explosive energy W. The most popular approach is square-root ($D/W^{1/2}$) scaling. To calculate ground vibrations from blasting, the scale distance (SD) is equated to some number, which may reflect a certain level of ground vibrations. Then this number is verified in the field at the time of blasting.

Wiss (1981) applied the SD approach for construction sources of vibrations and proposed the following scaled-distance equation to calculate the peak particle velocity of ground vibrations

$$v = k[D/\sqrt{W_r}\,]^{-n} \qquad (2)$$

Where W_r = energy of source or rated energy of impact hammer, k = value of velocity at one unit of distance. The value of 'n' yields a slope of amplitude attenuation for all tested soils in the 1-2 narrow range on a log-log chart. Woods (1997) confirmed a soundness of this approach with gathered data from field construction projects and developed a scaled distance chart correlated with ground types. Most of those data correlated with a slope of n=1.5 for soil class II and some of the data presented in that study showed n=1.1 for soil class III.

New Scaled-Distance Equation for Pile Driving. The traditional scaled-distance equation requires the knowledge of a velocity value at some distance from the source for calculating a reduction of ground vibrations. The initial velocity is usually unknown. At the same time, the peak particle velocity of pile vibrations can be calculated prior to pile installation. A new equation uses the scaled-distance relationship between pile and ground velocities as

$$v_g = v_p \frac{\sqrt{Wt}}{D} \qquad (3)$$

Where v_p = PPV of pile vibrations at the pile head, v_g = PPV of ground vibrations, Wt = energy transferred to a pile that can be determined as the product of rated energy and efficiency. The value of n=1 was chosen to obtain the upper limit for the peak particle velocity with the lower value for the attenuation rate.

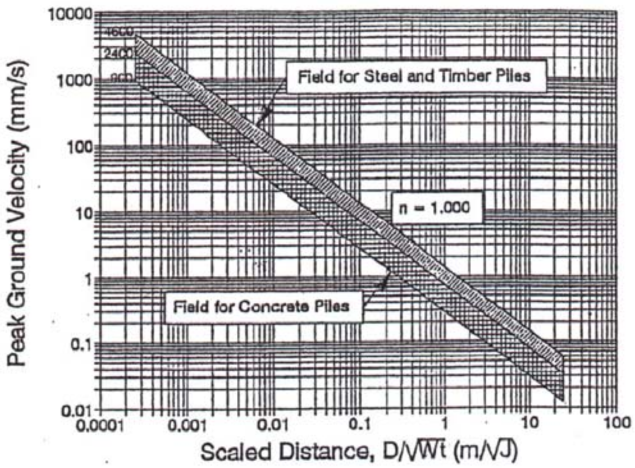

Fig. 6. Peak ground velocity versus scaled distance for pile driving. Figure was modified from Svinkin (1999).

Values of v_p can be determined using the following equation (Svinkin 1996)

$$v_p = \sqrt{2\frac{c}{ZL}W_t} \tag{4}$$

Where c = velocity of wave propagation in pile, Z = ES/c is pile impedance, E = modulus of elasticity of pile material, S = pile cross-sectional area, L = pile length.

Two ways can be used to determine the PPV of vibratory driven piles. First, the maximum energy transferred to a vibratory driven pile per a cycle of driving is the product of the maximum power, the period of pile vibrations and the efficiency. Then the PPV of a vibratory driven pile can be computed using equation (4). Second, the PPV of vibratory driven pile is the product of the maximum pile displacement available in the vibrator specification and the angular frequency of pile vibrations.

Substitution of equation (4) into equation (3) gives

$$v_g = 1.41\frac{W_t}{D}\sqrt{\frac{c}{ZL}} \tag{5}$$

Equation (5) enables one to calculate the PPV of ground vibrations prior to the beginning of pile driving. A graphical presentation of equation (5) with the use of the actual range of energy transferred to piles and the range of measured PPVs at the head of steel, concrete and timber piles are shown in Fig. 6. The reasonable pile velocity ranges for steel, concrete, and timber piles are 4.6 to 2.4, 2.4 to 0.9 and 4.6 to 1.5 m/s, respectively. The latter is actually the same as for steel piles. Values of 4600, 2400 and 900 mm/s have been marked as extreme left values on the slope lines. There are two areas constructed on the diagram: the upper area for steel and timber piles and the lower one for concrete piles with a slope n=1 which determines the upper limit for the peak particle velocity as it was mentioned above. Data presented in Fig. 6 provide an opportunity to construct curves of the expected maximum peak ground velocity for various distances from pile driving sources and different magnitudes of the transferred energy. This development of the scaled-distance approach eliminates the need to know in advance the factor k and increases the accuracy of calculated ground velocity before pile installation.

Prediction of Ground and Structure Vibrations

Ground and structure vibrations can be successfully predicted for certain source of vibrations.

Predicting Natural Frequency of Vertical Foundation Vibrations. Soil conditions predominantly affect machine foundation vibrations. The spectra of ground vibrations caused by impact loads have few maximums which are the natural frequencies of soil layers. The experimental study has revealed that values of these frequencies are practically independent of the condition at the contact area where impacts are made directly on the ground. It has been found that the natural damped frequency of vertical foundation vibrations coincides with the dominant natural frequency of the soil profile, Svinkin (1997a; 2001).

This finding is the basis of the method for predicting the natural frequency of vertical foundation vibrations. Free vibrations of a soil profile are exited by impacts applied on the ground at a place chosen for machine foundation construction. Ground vibrations are also measured at this place but beyond the zone of plastic soil deformations caused by impact forces. The dominant frequency of the spectrum of ground vibrations measured at the place for construction of a machine foundation is the predicted natural frequency of vertical damped vibrations of the foundation for the specified machine with impact loads.

By way of illustration, the results of prediction are shown for the foundation under a press-hammer with the ram mass of 4 tonnes and the foundation base area of 12.3 m^2 installed at the site with mostly a fine sand deposit (Fig. 7). It can be seen a good coincidence of predicted and measured frequencies.

A simple analogy can be used for additional explanation of the presented concept. A small lumped mass installed on a beam cannot change the fundamental beam frequency, but a large lumped mass connected with the beam can considerably affect the fundamental frequency of the new dynamic system where the beam will play a role of an elastic element with a negligible mass. A similar situation is observed for a foundation installed on the ground. Soil stratification under the foundation is a physical body with its own natural frequencies of soil layers. The added foundation mass is relatively small in comparison with the soil mass involved in vibrations and because of that the foundation will vibrate with one of the natural frequencies of the soil profile.

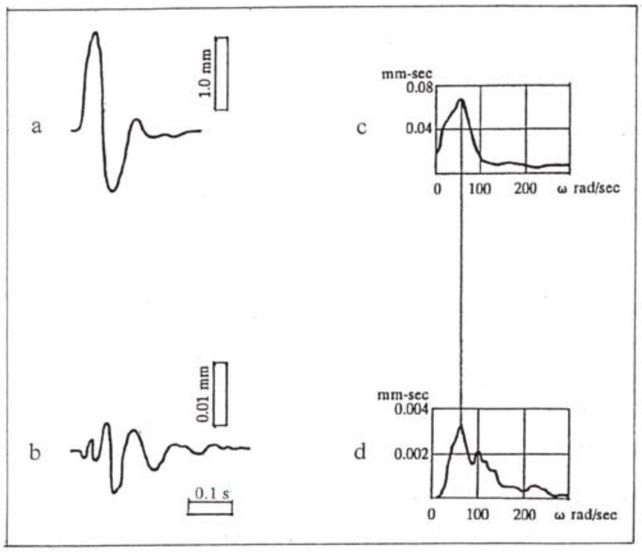

Fig. 6. Peak ground velocity versus scaled distance for pile driving. Figure was modified from Svinkin (1999).

<u>Predicting Ground and Structure Vibrations</u>. An IRFP method can be used to predict complete time-domain records on existing soils, buildings, and equipment prior to installation of construction and industrial vibration sources, Svinkin (1997b; 2002). This method is founded on the utilization of the impulse response function technique that does not require soil boring, sampling, or testing at the site, eliminates 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.

The following example demonstrates the application of the IRFP method for prediction of ground surface oscillations induced by vibrations of the foundation under a sizeable drop hammer with a falling weight of 147.2 kN dropped from a height of 30 m. The foundation contact area was 158 m^2. The soil consisted of mainly sandy soils. The water table was about 6 m below grade. The predicted and measured vertical ground surface vibrations are shown in Fig. 8. It can be seen that good agreement is achieved in time-domain vibration records.

The IRFP method can be also used for predicting vibrations from impact driven piles.

<u>Mitigation of Vibration Effects</u>

There is an experience of managing construction vibrations to eliminate or decrease crack formation and other structural damage. Certain rules can be applied to mitigate vibration effects of structures from construction vibrations, for example, D'Appolonia (1971), Woods (1997), Siskind (2000), and Svinkin (2004; 2006a).

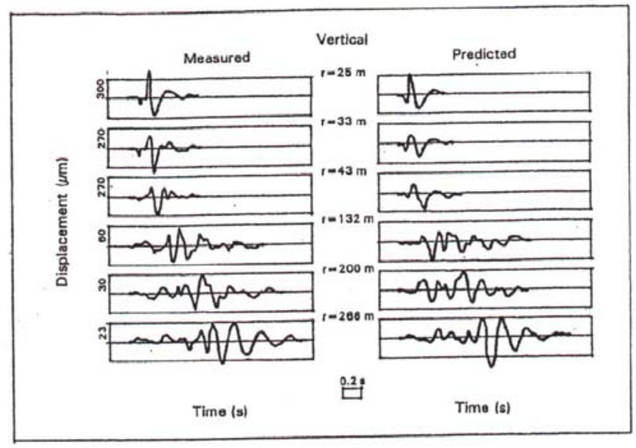

Fig. 8. Measured and predicted ground vibration displacements from operating drop hammer. Figure was modified from Svinkin (2002).

<u>Pile driving</u>. For reduction of vibration effects from driven piles, several preventive measures can be used. *First*, the type of piles is very important; non-displacement piles reduce the volume of soil removed during pile driving and decrease soil and structure vibrations. *Second*, hard pile driving to a depth about 10 m from the ground surface may increase ground vibrations but hard pile driving at a greater penetration depth does not affect ground vibrations. *Third*, predrilling may be helpful for overcoming high penetration resistance in the upper soil layers, but predrilling or jetting in sand should be done with caution; in clay, properly selected the cross section of an auger and the drilled depth can strongly affect the volume of soil movements. *Fourth*, substantial decrease of the hammer energy can be helpful. *Fifth*, vibratory hammers may trigger resonant vibrations of soil layers, but hammers with variable frequency can eliminate these phenomena. *Sixth*, in clay, the spacing of the piles characterized by the average pile density per unit foundation area affects soil movements: the bigger the density the larger the movement. *Seventh*, the sequence of pile driving operations should be directed away from the existing structures.

<u>Blasting</u>. Explosive type and weight, delay-timing variations, size and number of holes and rows, method and direction of blast initiation may affect ground and structure vibrations. Close-in blasting involves drilling, blasting and rock excavation in the proximity of structures at a distance equal to the final excavation depth. The application of controlled blasting techniques for close-in blasting provides structural vibrations without damage, Dowding (1996). The millisecond-delay blasting reduces the PPV of ground vibrations at some distances from blasting. There are two approaches in the use of this technique. On the one hand to avoid the influence of sequential delays too closely spaced, Ambraseys and Hendron (1968) recommend using a delay interval of approximately

one-fourth of the time of wave propagation to the point. On the other hand decreasing millisecond delays provides superposition and strong reduction of ground vibrations.

CONCLUSIONS

Construction operations and industrial machines generate ground vibrations which can detrimentally affect sensitive devices, people, and be the cause of damage to structures. The structural response to ground excitation depends on the soil response to waves propagated from the source and soil soil-structure interaction. Elastic and plastic soil deformations cause dissimilar structural responses and damage. Elastic soil deformations (ground vibrations) may induce direct vibration effects on diverse buildings and trigger structure and soil layer resonant vibrations. Plastic soil deformations may be the cause of differential ground and foundation dynamic settlements triggered by relatively small ground vibrations in sand soils and by soil displacements in clay soils. Such settlements may happen beyond the zone of densification at various distances from construction and industrial dynamic sources.

Diverse thresholds are used for assessment of direct vibration effects, resonant structural vibrations, and dynamic settlements. The USBM limits can be used for similar blasting, soil conditions, and 1-2 story houses they were developed for. These regulations are conservative for assessment of direct blasting vibration effects on structures in the non-resonant frequency zones of structural vibrations when ground vibrations do not trigger plastic soil deformations under structures, but they cannot protect low-rise structures from appearance of cosmetic cracks by amplification of ground vibrations higher than 4.5x and beyond the 4-12 Hz frequency range. Furthermore, the application of these limits to different super and underground structure is incorrect.

For multi-story residential, commercial and industrial buildings, the frequency-independent safe limit of 51 mm/s (2 in/s) can be chosen for the PPV of structural, not ground, vibrations. This criterion automatically takes into account soil-structure interaction for the whole building frequency range. Truthfulness and expediency of this criterion were confirmed in practice. The proposed criterion does not exclude higher allowable vibration levels.

There are no federal, state, and local regulations of the critical vibration levels of ground vibrations which may trigger dynamic settlements beyond the densification zone.

Each construction and industrial site is unique and requires consideration of specific conditions at the site for decreasing vibration effects of ground vibrations on surrounding structures. Specifications for the control of construction vibrations should be prepared for major building projects. A preconstruction condition survey has to be conducted prior to construction activities at a site. There is an experience of managing construction vibrations to eliminate or decrease crack formation and other structural damage. Certain rules can be applied to mitigate vibration effects on structures from construction vibrations. Preventive measures, calculation and prediction together with monitoring and control of ground and structural vibrations provide the basis for prevention or mitigation of vibration problems at construction and industrial sites.

During construction activities such as blasting, pile driving, or deep dynamic compaction in the proximity of the existing sensitive buildings, it is necessary to provide daily inspection of the condition of suspected structures to prevent intolerable vibrations and displacements for protection of sensitive buildings.

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