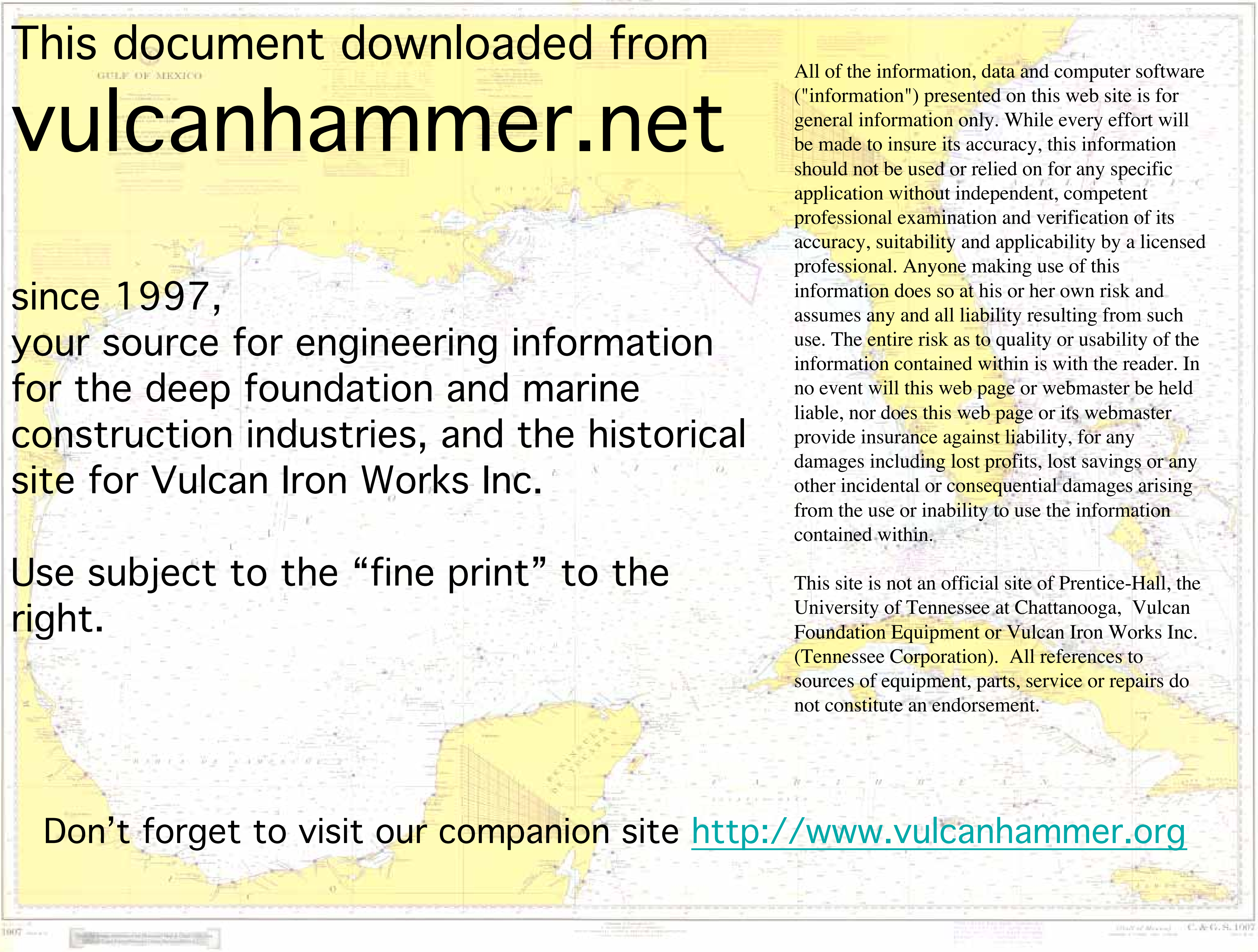

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Environmental vibration problems during construction

Problemes de vibration environnementale pendant la construction

M.R. Svinkin
VibraConsult, Cleveland, USA

ABSTRACT

Construction operations with involvement of impact or vibratory sources produce environmental vibration problems for adjacent and remote structures. High vibrations and unacceptable dynamic settlements could seriously disturb sensitive devices and people and even be the cause of structural damage. Each construction site is unique and requires consideration of specific conditions at the site for decreasing vibration effects of construction activities on surrounding structures. Monitoring and control of ground and structural vibrations provide the rational to select measures for prevention or mitigation of vibration problems.

RÉSUMÉ

Les opérations de construction qui entraînent des sources d'impact ou de vibration produisent des problèmes de vibration environnementale pour des édifices soit adjacents soit éloignés. Des vibrations fortes et des tassements dynamiques inacceptables pourraient perturber sérieusement des appareils et des gens et être même la cause de dégâts structuraux. Chaque site de construction est unique et exige la considération de conditions spécifiques au site pour des effets diminuants de vibration d'activités de construction sur des édifices avoisinants. La surveillance et le contrôle de vibrations de terrain et de structure fournissent le raisonnement pour choisir des moyens de prévention ou d'amoindrissement de problèmes de vibration.

1 INTRODUCTION

Construction activities involve various sources of vibrations such as blasting, pile driving, dynamic compaction of weak soils, and operating heavy machines. 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.

The level of structural vibrations caused by construction work depends mostly on interaction of three major factors: dynamic sources, geology, and structures. Each of them affects structural vibrations. Only dynamic sources can be modified in certain degree to comply with vibration limits. The rest of the two cannot be changed. Construction vibrations differently affect adjacent and remote structures. 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.

2 DYNAMIC EFFECTS ON ADJACENT STRUCTURES

Blasting and pile driving used for foundation construction may damage structures nearby a construction site. However, construction operations such as excavation of upper soil layers and dewatering accomplished before the beginning of blasting and pile driving can also detrimentally affect the existing nearby structures.

2.1 *Soil movement from non-vibration sources*

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. Steding (2001) has described a case history in which dewatering caused structural settlements up to 4.5 cm. These structures were separated from the new construction site by a city street of six lanes wide.

2.2 *Direct vibration effect on structures*

Dynamic loads of construction sources are in the broad energy and frequency ranges. Maximum rated energy of the most commonly used impact hammers varies from 5 to 200 kJ per blow. Frequencies of natural longitudinal pile oscillations change between 7 and 50 Hz. Vibratory hammers operate with different force amplitude in the frequency range of 10 to 30 Hz. Dynamic soil compaction with a large weight between 27 and 400 kN and a dropping height between 15 and 30 m generates surface waves with the dominant frequency of 3 to 12 Hz. Blasting energy is hundreds times greater than energy of other sources of construction vibrations. The dominant frequency of surface waves from quarry and construction blasting ranges mostly between 10 and 60 Hz.

The direct vibration effect on structures can be considered within a distance to existing structures equal to the final excavation depth in rock (close-in blasting) or one pile length from a driven pile. Blasting produces the most extensive ground and structure vibrations. Siskind (2000) has presented the U.S. Bureau of Mines (USBM) accumulated results of structural responses and damage produced by ground vibrations from surface mine blasting. These results were obtained from 718 blasts and 233 documented observations of cracks.

Analysis of these data indicates different vibration effects on structures depending on the dominant frequency and the peak particle velocity (PPV) of ground vibrations, Svinkin (2004, 2005). 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 at relatively small distances from the dynamic sources transient ground vibrations with short duration cannot trigger resonant structural vibrations. Direct minor and major structural damage 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. In practice, actual measured vibrations are often below these velocities but higher than the USBM vibration limits. Nevertheless, there are a number of case histories that demonstrate no structural damage in the proximity of sources with impact loads though direct damage to structures is possible.

2.3 *Soil settlement in sandy soils from vibration sources*

Blasting 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).

Pile driving in loose to medium uniform saturated sands may cause soil and structure settlements due to densification and liquefaction of vulnerable sandy soils. 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.

D'Appolonia (1971) and Woods (1997) has reviewed a number of cases histories with settlements from pile driving in sandy soils and demonstrated substantial structural damage caused by dynamic settlements.

2.4 *Soil heave and settlement in clayey soils from pile driving*

D'Appolonia (1971) has summarized numerous research studies of clay behavior under dynamic loads from pile driving, which 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.

Movements of nearby structures caused by pile driving is shown in Figure 1. A site with soil deposits of soft to medium clay is located in Boston. Pipe piles were driven into predrilled holes. Maximum heave and settlement were about 1.3 and 3.8 cm, respectively (D'Appolonia and Lambe, 1971). Driving of displacement piles without predrilled holes in similar soils at a site in Tokyo (Hokugo, 1967) caused heave and settlement 3-4 times higher than at Boston site.

Displacements in clay soils may be aggravated by the same factors, which affect settlements in sands.

3 DYNAMIC EFFECTS ON REMOTE STRUCTURES

3.1 *Resonant structural vibrations*

Low-frequency ground vibrations with the dominant frequency between 3-12 Hz can trigger resonant horizontal building vibrations. These vibrations may be harmful to structures. To prevent cosmetic cracking at the possibility of resonance, the USBM 51 mm/s (2 in/s) limit of ground vibration was decreased to 13 mm/s (0.5 in/s) in the 2.8-10 Hz frequency range for plaster and to 19 mm/s (0.75 in/s) in the 3.6-12 Hz frequency range for drywall (Siskind et al., 1980).

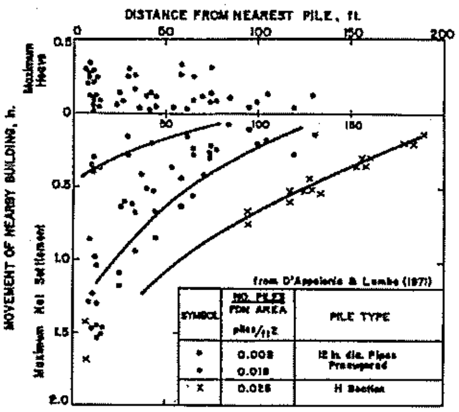

Figure 1. Heave and settlement of nearby structures caused by driving low displacement piles in Boston, after D'Appolonia (1971)

Resonant structural vibrations 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. Resonance of building horizontal vibrations 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.

It is important that structure vibrations start to increase after the first cycle of ground vibrations with the dominant frequency near the natural structure frequency, but if only a few cycles of the dominant frequency occur, resonance does not develop. The resonant structural displacement is independent of the structure stiffness being limited only by damping.

3.2 *Soil settlement caused by vibrations*

Densification of sands is expected at short distances from the dynamic sources, but surface settlements extend beyond the zone of densification. Ground and foundation settlements as a result of relatively small ground vibrations in loose sands may happen at various distances from the source. According to Woods (1997), distances as great as 400 m may need to be surveyed to identify settlement damage hazard.

It is important to determine 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 narrow-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. Clough and Chameau (1980) have 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.

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 the sites.

4 VIBRATION LIMITS

The USBM vibration limits are depicted in Figure 2. These limits were obtained on the basis of correlation between the damage in structures and the peak particle velocity of ground vibrations. The limits indirectly take into account soil-structure interaction to prevent structural damage of one-two story houses with possible amplification of resonant structural vibrations from 2 to 4.3 times in the 2.8-12 Hz frequency range. At the same time, there are case histories with a higher magnifying factor up to 9x at resonance of low-rise houses, Quesne (2001). Furthermore, dynamic responses of other structures than low-raise houses are different.

The U.S. Office of Surface Mining (OSM) uses the upper line in Figure 2 for regulations of blast vibrations. These vibration limits should be used as a guideline. The structure response to the ground vibrations is important for a choice of vibration criteria. The save vibration limits of 30-50 mm/s independently of the vibration frequency has to be used for assessment of structural vibrations (Svinkin, 2004).

5 MANAGING OF VIBRATION PROBLEMS

Specifications for the control of construction vibrations are 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 the Specifications and has to be conducted with care ensuring documentation of all observable defects. This survey is important for public relations. Monitoring of construction vibrations should be made to keep ground and structure vibrations in compliance with vibration limits. Certain modification of construction dynamic sourced can be made for decreasing vibration effects.

5.1 *Calculation of ground vibrations*

Wiss (1981) has suggested his version of the scaled-distance approach to calculate the PPV of ground vibrations at a surface distance, D, from the source normalized with source energy, W_r, as

$$v = k\,[D/\sqrt{W_r}\,]^{-n} \qquad (1)$$

Where k = factor dependent on ground conditions and a type of the dynamic source. The value of 'n' yields a slope in a log-log plot between 1.0 and 2.0

Equation (1) is used to calculate ground vibrations from pile driving. On the basis of the actual range of energy transferred to piles and the PPV measured at the top of steel, concrete and timber piles, equation (1) was applied to construct a diagram for calculating the PPV of ground vibrations versus scaled distance prior to the beginning of pile driving, Svinkin (2004).

To calculate ground vibrations from blasting, the scale distance is equated to some number, which may reflect a certain level of ground vibration. Then this number is verified in the field at the time of blasting (Wiss, 1981).

5.2 *Machine foundations*

Sites assigned for installation of vibrating machine foundations have a set of problems with vibration effects on surrounding structures. A new impulse response function prediction method (IRFP) has been developed for predicting complete time-domain vibration records on existing soils, structures and equipment prior to installation of construction and industrial sources (Svinkin, 2002).

Estimating the natural frequency of damped vertical vibrations of a foundation that will be built for a machine with dynamic loads can be made at any site prior to construction (Svinkin, 2001). The method pertains principally to a relationship between the dominant frequency of vertical vibrations of the foundation-soil system and the natural frequencies of soil profiles at construction sites.

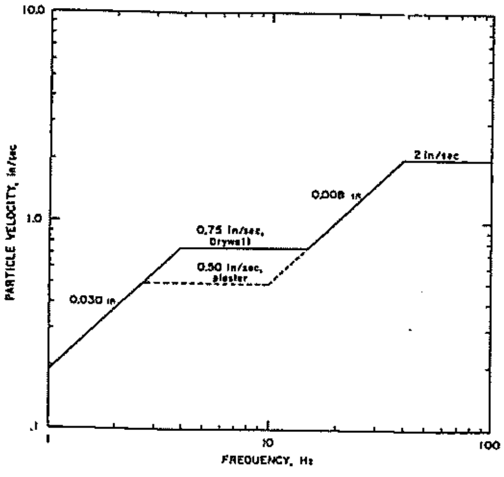

Figure 2. Safe level of blasting vibrations for houses using a combination of velocity and displacement, after Siskind et al. (1980)

5.3 *Pile driving*

5.3.1 *Steady-state and transient vibrations*

A coincidence of the operating frequency of a vibratory hammer with the soil layer frequency may generate large ground vibrations of the soil surrounding a pile. The use of vibratory hammer with variable frequency and force amplitude may minimize damage due to accidental ground vibration amplification.

Hard pile driving in the upper sandy and clayey layers to the depth about 10 m may induce adverse transient ground vibrations but pile penetration to a greater depth does not effect ground vibrations (Svinkin et al., 2000). Pre-auguring or jetting the holes to the depth about 10 m ahead of pile driving will reduce ground and structure vibrations.

Low-frequency transient vibrations appear at some distances from pile driving and may trigger resonant soil layer and structure vibrations. It occurs seldom and there are no readily apparent means for reducing resonant vibrations. However, resonance problem can be detected in advance with the IRFP method (Svinkin, 2002).

5.3.2 *Dynamic settlements.*

There are preventive measures to decrease settlements in some extent. Pre-auguring affects the soil settlement in less degree than soil vibrations. Using the least hammer energy could be helpful. It is not easy to calculate expected settlement from any specified ground vibrations. Woods (1997) has analyzed the existing approaches to determine the amount of settlement, summarized that settlement of loose sand during pile driving is clearly a problem, and concluded that simple methods of estimating the magnitude of settlement are still out of reach. Also, he has pointed out that the prudent approach is to always proceed with caution when the settlement condition is known to exist.

Observations indicate that displacements in clay should be expected at distances from a driven pile up to the thickness of the clay layer being penetrated. To decrease soil displacement caused by pile driving in soft to medium clay, high capacity and low displacement piles should be driven to pre-augured holes in the sequence from the nearby structures (D'Appolonia, 1971).

5.4 *Dynamic compaction*

A smaller dropping weight is more effective to reduce ground vibrations than a smaller dropping height.

5.5 *Blasting*

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.

6 SUMMARY AND CONCLUSIONS

Each construction site is unique and requires consideration of specific conditions at the site for decreasing vibration effects of construction activities 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.

Dynamic sources can be modified in certain degree to comply with vibration limits for ground and structural vibrations. To reduce blasting vibration effects, it is imperative to change an order of operation and blast parameters. To reduce vibration effects from pile driving, it is necessary to pre-drill holes with certain requirements in clays and sands and use the least hammer energy.

Monitoring and control of ground and structural vibrations provide the rational to select measures for prevention or mitigation of vibration problems.

REFERENCES

Ambraseys, N.N. and Hedron, A.J. Jr. 1968. Dynamic behavior of rock masses. Rock Mechanics in Engineering Practice, Stagg and Zeinkiewicz (Eds.), John Wiley & Sons, New York.

Barkan, D.D. 1962. *Dynamics of Bases and Foundations*. McGraw Hill Co., New York, 434p.

Clough, G.W. and Chameau, J-L. 1980. Measured effects of vibratory sheetpile driving. *Journal of the Geotechnical Engineering Division*, ASCE, 106 (GT10), 1081-1099.

D'Appolonia, D.J. 1971. Effects of foundation construction on nearby structures. *Proceedings of the 4th Panamerican Conference on Soil Mechanics and Foundation Engineering*, V. 2, Puerto Rico, 189-235.

D'Appolonia, D.J. and Lambe, T.W. 1971. Performance of four foundations on end bearing piles. *Journal of the Soil Mechanics and Foundation Division*, ASCE, SM1, January.

Davis, R.O. and Berrill, J.B. 1998. Site-specific prediction of liquefaction. *Ceotechnique*, 48(2), 289-293.

Dobry, R., Stokoe, K.H., II, Ladd, R.S., and Youd, T.L. 1981. Liquefaction susceptibility from S-wave velocity. *Preprint 81-544*, ASCE, 29-50.

Dowding, C.H. 1996. *Construction Vibrations*. Prentice Hall, Upper Saddle River, 610p.

Hokugo, H. 1967. Observation of soil movement due to pile driving. *Building Engineering News*, Nippon Telegraph and Telephone Public Corporation (in Japanese).

Lacy,H.S. and Gould, J.P. 1985. Settlement from pile driving in sand. *Proceedings of the Symposium on: Vibration Problems in Geotechnical Engineering*, G. Gazetas and E.T. Selig (Eds.), ASCE, New York, 152-173.

Quesne, J.D. 2001. Blasting vibrations from limestone quarries and their effect on concrete block stucco homes. *Vibration problems*. Geo Discussion Forum. http://www.geoforum.com (May 6, 2002).

Siskind, D.E., Stagg, M.S., Kopp, J.W., and Dowding, C.H. 1980. Structure response and damage produced by ground vibrations from surface blasting. *RI 8507*, U.S. Bureau of Mines, Washington, D.C., 74p.

Siskind, D.E. 2000. *Vibration from Blasting*. ISEE, Cleveland, 120p.

Steding, J. 2001. What? "You can't drive piles because of the vibrations." *Pile Buck, The Pile Driving, Foundation and Marine Contractor's Newspaper*, January, 6A-22A.

Svinkin, M.R., Roth, B.C., and Hannen, W.R. 2000 The effect of pile impedance on energy transfer to pile and ground vibrations. *Proceedings of the Six International Conference. on the Application of Stress-Wave Theory to Piles*, S. Niyama and J. Beim (Eds.), A.A. Balkema, Rotterdam, 503-510.

Svinkin, M.R. 2001. Natural frequency of vertical foundation vibrations evaluated from in-situ impact test. *Proceedings of the Fourth International. Conference on Recent Advances in Geotechnical. Earthquake Engineering and Soil Dynamics*, UMR, paper No. 2.33.

Svinkin, M.R. 2002.Predicting soil and structure vibrations from impact machine. *Journal of the Geotechnical and Geoenvironmental Engineering*, ASCE, 128(7), 602-612.

Svinkin, M.R. 2004. Minimizing construction vibration effects. *Practice Periodical on Structural Design and Construction*, ASCE, 9(2), 108-115.

Svinkin, M.R. 2005. Engineering vibration investigation in geophysical exploration at construction sites. *Proceedings of Geo-Frontiers 2005*, ASCE, Austin, Texas, (to be published).

Wiss, J.F. 1981. Construction vibrations: State-of-the-art. *Journal of Geotechnical Engineering Division*, ASCE, 107 (2), 167-181.

Woods, R.D. 1997. *Dynamic Effects of Pile Installations on Adjacent Structures*. NCHRP Synthesis 253, TRB, National Research Council, Washington, D.C., 86p.