Controversial and Contradictory Evaluations in Analyses of Ground Vibrations from Pile Driving

Évaluations controversées et contradictoires dans l'analyse des vibrations de terre par suite de l'enfoncement de pieux

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ABSTRACT: Pile driving operations are powerful and wide-spread sources of construction vibrations which may detrimentally affect adjacent and remote structures, make obstacles for operating sensitive processes and devices, and disturb people. A number of factors can affect ground vibration from pile installation. Wave propagation from pile driving is a complicated problem, and different approaches are utilized to analyze this phenomenon. A paper presents several controversial and contradictory issues in assessment of ground vibrations generated by pile driving such as connections between wave propagation in piles and ground vibrations, the relationship between pile impedance and intensity of ground vibrations, effects of the hammer energy on ground vibrations and a possible correlation between pile capacity and ground vibrations. Also, it is important to show the inadequate roles of condition surveys of structures and monitoring of ground vibrations and the necessity to properly assess crack changes in condition surveys. Analysis and clarification of various approaches are important for practical applications.

RÉSUMÉ: Les opérations d'enfoncement de pieux sont des sources puissantes et très répandues de vibrations de construction qui pourraient affecter de façon nuisible des structures adjacentes et éloignées, faire obstacle à l'utilisation de procédés et d'appareils sensibles, et perturber des gens. De nombreux facteurs peuvent affecter la vibration du sol par suite de l'installation de pieux. La propagation d'ondes causée par l'enfoncement de pieux est un problème compliqué, et diverses méthodes sont utilisées pour analyser ce phénomène. Cet article présente plusieurs points controversés et contradictoires dans l'évaluation des vibrations de sol générées par l'enfoncement de pieux, telles que des connections entre la propagation des ondes dans les pieux et les vibrations de sol ; les rapports entre l'impédance des pieux et l'intensité des vibrations de terre ; des effets de l'énergie percutante sur des vibrations de sol, et une corrélation possible entre la capacité des pieux et les vibrations de sol. De plus, il est important de montrer le rôle inadapté des conditions de surveillance des structures, du contrôle des vibrations de sol et la nécessité d'évaluer les modifications des fissures par les opérations de contrôle. L'analyse et la clarification de diverses méthodes sont importantes pour des applications pratiques.

KEYWORDS: pile driving, ground vibrations, stress wave theory, impedance, energy, survey

1. INTRODUCTION

Installation of driven piles creates soil vibrations and displacements which may affect adjacent and remote structures, people and sensitive equipment. Therefore, various approaches are used for evaluation of vibration effects of pile driving.

There is a trend to connect stress-wave propagation in piles during pile driving with prediction or calculation of the peak particle velocity (PPV) of ground vibrations from pile installation. However, there are ambiguous problems in using of this approach for assessment of ground vibrations.

Pile impedance affects force and velocity at the pile head in opposite ways at the same time. Therefore, the pile impedance effect on the intensity of ground vibrations is not obvious.

Pile driving generates ground vibrations due to the hammer energy applied to a pile, but some case histories demonstrate no correlations between the hammer energy and the maximum velocity of ground vibrations. Other factors such as the depth of pile penetration into the ground and soil resistance to pile driving should be taken into account.

The relationship between pile capacity and ground vibrations is not clear. Moreover, pile capacity and ground vibrations are outcomes of pile driving and only an accidental correlation between them is possible. For sure, both variables are dependent on the hammer energy.

On the one hand approximate calculation of expected ground vibrations and even vibration monitoring yield relative information on vibration effects on structures, and these results could be inconclusive. On the other hand condition surveys of structures before, during, and after pile driving provide complete information on structural responses to vibration excitations and this information can be much beneficial than vibration assessment and measurements.

Clarifications of different ways used for analyses of pile driving as the source of construction vibrations, ground vibrations generated by pile driving and various effects of these ground vibrations on structures, people and sensitive devices are important to understand the problem and prevent harmful consequences of pile driving operations.

2. STRESS-WAVES PROPAGATION IN PILES AND GROUND VIBRATIONS

For about forty years, the stress-wave theory is successfully used for driveability analysis of driven piles and also for determination of pile capacity at the time of testing, for example Proceedings of IS-Kanazawa 2012 (2012). In recent years, there is a trend to connect stress-wave propagation in piles during pile installation with prediction or calculation of PPV of ground vibrations generated by pile driving, Robertson (2006) and Massarsch & Fellenius (2008).

The first such an attempt was made by Svinkin (1996) in favor of the Impulse Response Function Prediction (IRFP) method for prediction of ground and structure vibrations from pile driving; the method was developed toward prediction of complete time-domain vibration records on existing soils, buildings, and equipment prior to installation of impact machine foundations, Svinkin (2002). In the application of this method to pile driving, wave equation analysis was used to assign a movement of the pile top, but it's necessary to underline that the top pile movement can be assigned arbitrarily, for example as a damped sinusoid, because ground vibrations at some distance from a dynamic source depend only on the dynamic force transmitted on the machine support and soil properties, Svinkin (2002).

It is necessary to point out that a connection of the stress-wave theory with ground vibrations from pile driving has few problems. First, there are several different programs for signal matching techniques which produce diverse results for the same piles and their outcomes depend on variety of soil conditions and pile types, Svinkin (2012). It is not clear what software should be used. Second, stress waves in piles obviously generate internal forces in driven piles. Third, according to Saint Venant's principle, wave propagation in piles does not affect dynamic field at some distance from a driven pile.

It is known that impact hammers for pile driving and forge hammers released comparable amounts of the energy and they generate similar vibration records of ground vibrations (Steffens 1974). Therefore, it is reasonable to compare both dynamic sources and their effects on ground vibrations.

A forge hammer foundation is considered as a rigid body which transfers impacts loads from a hammer onto the ground. Dynamic forces in the machine foundation itself are internal forces generated by stress-waves propagated in the machine foundation under forge hammer impact. The duration of internal forces is substantially smaller than the duration of dynamic forces transferred from a machine foundation onto the ground, and these two kinds of dynamic forces work in different time frames. Consequently, internal dynamic forces in hammer foundations are not taken into account in determination of dynamic loads transferred from a hammer foundation on the ground and consideration of ground vibrations generated by oscillations of forge hammer foundations (Barkan 1962 and Richart et al. 1970).

In prediction of ground vibrations from operating forge hammers, ground vibrations depend on the impulse dynamic load applied to a hammer foundation, the damping coefficient and the natural frequency of vertical foundation oscillations, and also the impulse response functions of the considered dynamic systems. The latter represent the soil medium where wave propagate from the hammer foundations to destination locations. The experimental studies showed that at some distances from the source, ground vibrations become dependent only on the impulse load transmitted to a hammer foundation and the soil medium where waves disseminate from the source (Svinkin 2002). These results are in agreement with a dynamic version of Saint Venant's principle (Timoshenko & Goodier 1951and Karp & Durban 1997).

A similar picture of a dynamic load transfer from a forge hammer on its foundation and the ground can be represented for pile installation. Piles also can be considered as rigid bodies in which stress-waves propagate from hammer ram impacts and generate internal forced in piles which are the causes of pile movement and vibrations. Besides, a pile-soil load transfer is released by means of both concentrated loads from the pile toe and distributed loads generated along pile shaft. Similarly to hammer foundations, at some distances from a pile, as the dynamic source, ground vibrations become dependent only on the dynamic load applied to a pile and the soil medium where waves propagate from the source. It is known that velocities of wave propagation in piles are about 4000 m/s in concrete piles and about 5100 m/s in steel ones (PDA 1991). Velocities of shear wave propagation in the ground are shown in Table 1. Velocities of surface waves are equal about 0.92-0.96 of the velocities of shear waves, Barkan (1962).

Table 1. Velocity of shear waves in soils, Savinov (1979)

Soil	Velocity m/s
Sand	120 – 150
Sand with gravel	150 – 250
Loess with natural moisture	130 – 160
Plastic clay	150 - 400

It can be seen that that wave propagation in piles under impact load is much faster process in comparison to wave propagation in the ground. Therefore, dynamic loads transferred from driven piles onto the ground for practical purposes can be considered as the point impulse load at some distance from the source, Svinkin (2000).

It can be expected that this conception is correct at distance derived from an assumption that the time of surface wave propagation with velocity, c_s, in the ground at distance, D, from a driven pile is 5-10 times larger than the time of stress wave propagation with velocity, c, in the pile with length, L (Svinkin 2000).

$$D = (5-10)Lc_s / c \tag{1}$$

Minimum distances from a driven concrete pile as the point vibration source are shown in Table 2 (coefficient 10 was used).

Table 2. Minimum distance from pile as point vibration source

Pile Length	c_s/c			
	150/4000		300/4000	
m	Lc_s/c m	$10Lc_s/c$ m	Lc_s/c m	$10Lc_s/c$ m
10	0.375	3.75	0.75	7.5
15	0.5625	5.63	1.125	11.25
20	0.8438	8.44	1.5	15.0
30	1.125	11.25	2.25	22.5
40	1.6875	16.88	3.0	30.0

It can be expected at distances determined by equation (1), that only dynamic forces transferred to piles during pile driving and soil medium where waves propagate from driven piles will affect ground vibrations generated by pile driving.

It is important to point out that calculation of expected ground vibrations during the time of pile installation is irrelevant. For example, Massarsch & Fellenius (2008) tried to connect stress-wave propagation in piles under the hammer ram impact with ground vibrations, but they eventually suggested the old empirical equation to calculate attenuation of PPV of ground vibrations generated by surface waves, which contain more than 2/3 of the total vibration energy, from pile installation without any connection with the stress-wave theory. Ground vibrations have to be measured during pile driving operations.

3. PILE IMPEDANCE

During pile installation, an impulse load from the hammer ram is applied to the pile top, and dynamic longitudinal force in the pile is transferred to the surrounding soil. According to Peck et al. (1974) and Woods (1997), pile impedance affects the force transmitted down the pile. Pile impedance characterizes the pile ability to overcome the soil resistance to pile penetration and develop required capacity.

One of pile impedance, Z, definition can be presented as

$$Z = EA / c \tag{2}$$

where E is modulus of elasticity of pile material; A is pile cross-section area; and c is longitudinal stress wave velocity. It can be seen that impedance depends only on the pile material and dimensions.

Recognizing the importance of pile impedance for assessment of to the ground vibration, Heckman and Hagerty (1978) proposed the equation for the peak particle velocity of ground vibrations from pile driving as a function of the rated hammer energy, W_r, and the distance, D, from a driven pile with the coefficient, k, which is dependent on pile impedance.

$$v = k\sqrt{\frac{W_r}{D}} \tag{3}$$

The coefficient, k, is inversely proportional to pile impedance. It means that driven piles with higher impedance generates lower PPV of ground vibrations and vice versa.

Svinkin (2000) derived equations for PPV of pile vibrations, V, and the maximum force, F, measured at the pile head as

$$V = \sqrt{\frac{2cW_t}{ZL}} \tag{4}$$

and

$$F = \sqrt{\frac{2cZW_t}{L}} \tag{5}$$

where W_t is the energy transferred to a pile.

Similarly to equation (3), equation (4) shows that the velocity triggered by the hammer ram impact is an inversely proportional function of pile impedance. However, equation (5) displays that the force is proportional to the root square of pile impedance. It means that pile impedance affects force and velocity at the pile head in opposite ways.

Case histories presented in a number of publications, for example Svinkin (2000), demonstrate higher ground vibrations triggered by installation of high soil displacement piles (concrete piles and steel pipes with closed ends) in comparison with low soil displacement piles (H-piles and steel pipes with open ends). A practical experience is the evidence that pile impedance affects ground vibrations in the proximity of driven piles, but this pile property does not affect the dynamic field at some distance from driven piles in accordance with Saint Venant's principle.

4. HAMMER ENERGY

Pile installation generates ground vibrations due to the hammer energy applied to a pile. Obviously, PPV of ground vibrations have to be a function of the hammer energy transferred on a pile. However, some case histories demonstrate no correlations between the hammer energy and PPV of ground vibrations, Hope and Hiller (2000). It happens due to the effects of soil conditions, the pile penetration depth, and the soil resistance to pile penetration into the ground. Nevertheless, the hammer energy is the major cause of ground vibrations because without the hammer energy there are no pile penetration into the ground and ground vibrations.

5. PILE CAPACITY AND GROUND VIBRATIONS

Some authors, for example Robinson (2006), found enormous scatter of PPV of ground vibrations as a function of the hammer energy. For example, PPV of ground vibrations changed between about 0.4-21.6 mm/s at the rated energy of 135 kJ and between about 0.9-17.8 mm/s at the transferred energy of 40 kJ. It happened because other factors mentioned above affected ground vibrations and in consequence that data measured at various construction sites with different soil conditions, pile types and pile driving implementations were considered together. However, Robinson (2006) suggested a correlation between ground vibrations and pile capacity determined during pile driving. He believes that pile-soil interaction, not energy, is the major influence in the generation of ground vibrations from driven piles. Obtained conclusions are not accurate because ground vibrations and pile capacity are outcomes of the same pile driving process and only an accidental correlation between them is possible.

It is necessary to say that ground vibrations and pile capacity for sure depend on the hammer energy because pile capacity cannot be mobilized without the sufficient hammer energy. Moreover, during pile driving, the static pile capacity is determined by signal matching software on the basis of force and velocity measurements at the pile head. Unfortunately, different software produces different results. It means that PPV of ground vibrations are dependant on signal matching technique used for analysis of testing data. Besides, during pile installation, ground vibrations should be measured not calculated because of possible detrimental effects of pile driving operations and also measured ground vibrations are more reliable than calculated ones.

6. CONDITION SURVEYS AND VIBRATION MEASUREMENTS

Approximate calculation of expected ground vibrations and even vibration monitoring yield relative information on vibration effects on structures, and these results could be inconclusive. Moreover, there is uncertainty in application of the existing vibration limits for assessment of pile driving effects on soils and structures. Therefore, it is imperative to perform condition surveys of structures before, during and after pile installation which provide complete information on structural responses to vibration excitations. Obtained information can be much beneficial for analysis of causes of damage to structures than vibration assessment and measurements. Dowding (1996) pointed out the necessity of professional performance of a preconstruction survey.

Condition surveys during pile installation and after the completion of pile driving are significant for analysis of possible causes of damage to structures. Each construction site is unique and even similarity of soil deposits does not mean the same condition of the dynamic settlement development. Physical evidences of damage to structures from dynamic sources are very important. Therefore, much attention is provided for measurement of crack width at condition surveys of structures during pile driving.

Changes of crack dimensions are the major evidences of vibration effects on structures. Micrometers are used to determine changes of crack widths. It is necessary to keep in mind that each structure has its own "breathing" because of microseisms in the earth and human activities inside and outside structures. Hence, it is typical that crack widths may vary in time. If crack widths increase without increasing of crack lengths, it is a safe situation. However, if variations of crack widths trigger increasing of crack length, it becomes dangerous for structures. Thus, changes of crack widths alone are not the indicators of damage to structures from pile driving. Therefore, it is necessary to measure crack widths together with assessment of crack length enlargements.

7. CONCLUSIONS

Ground vibrations from pile driving may harmfully affect structures, people and sensitive devices, and these effects should be evaluated before and during pile driving operations.

The paper presents several controversial and contradictory issues in assessment of ground vibrations generated by pile driving. Analyses of various approaches are important for practical applications.

A connection of the stress-wave theory with ground vibrations from pile driving has few problems. There is no unique solution of stress-wave propagation in the pile because different signal-matching software provides different outcomes. Internal forces in piles may somewhat affect ground vibrations in the proximity of the pile. However, according to Saint Venant's principle, wave propagation in piles does not affect dynamic field at some distance from a driven pile.

Pile impedance affects ground vibrations in the proximity of driven piles, but this pile property does not affect the dynamic field at some distance from driven piles in accordance with Saint Venant's principle.

Pile installation generates ground vibrations due to the hammer energy applied to a pile. Missing correlation between PPV of ground vibrations and the hammer energy in some case histories occurred on account of the effects of soil conditions, the pile penetration depth, and the soil resistance to pile penetration into the ground. Nevertheless, the hammer energy is the major cause of ground vibrations because without the hammer energy there are no pile penetration into the ground and ground vibrations.

Pile capacity and ground vibrations are outcomes of the same pile installation and only an accidental correlation between them is possible.

Condition surveys should be performed before, during and after pile driving. Assessment of crack length enlargements has to accompany measurements of crack widths because changes of crack widths alone are not the indicators of damage to structures from pile driving.

Clarification of different views on the problems would be helpful in practice for assessment of pile driving effects on surrounding structures.

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