Featured Technical Article

Vibrations Caused by Pile Driving

Part 1 of 2

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INTRODUCTION

Construction activities, such as driving of piles and sheet piles, soil compaction or excavation generate noise and vibrations. In populated areas these can have a negative impact on the environment, disturb inhabitants and, under unfavorable conditions, cause damage to buildings and installations. This condition is aggravated by the growing public awareness of environmental issues and the increasing use of vibration-sensitive electronic equipment and machinery in industry. In many countries, environmental regulations are enforced more stringently and limit or even prohibit the use of impact or vibratory hammers. This development has restricted the use of cost-effective foundation methods, such as driven and vibrated piles and sheet piles.

Vibration problems are gaining importance in many European countries and extensive research has been performed during the past decade, especially with respect to traffic vibrations (Massarsch, 2004). Significant progress has been made owing to the availability of high-quality field measurements and an improved theoretical understanding of how vibrations are generated and transmitted through soil layers. These findings can also be applied to vibration problems associated with construction activities. However, this information is not yet appreciated by the geotechnical profession and even less by the construction industry.

This paper discusses the effects of ground vibrations on the surrounding soil and on buildings, with particular emphasis on the different mechanisms of damage that may occur. Guidance is given on the elements which should be taken into account in an assessment of risks associated with piling projects. A simplified method is proposed for assessing the risk of settlements or strength loss in soil deposits. Limiting vibration levels are presented, based on the Swedish standard, which can be used to assess the risk of damage to buildings. A concept to predict ground vibrations caused by pile driving and the mechanisms which control the propagation of ground vibrations, will be presented the second part of this paper.

RISK ASSESSMENT AND DAMAGE CATEGORIES

Risk Analysis

Before the start of a project, the design engineer or the contractor is often required to present a method statement describing the pile installation process, as well as a risk analysis of the construction process on the environment. However, even specialists often have difficulties assessing in advance how, and to what extent, construction activities will affect surrounding areas and buildings in the vicinity. An important aspect of such a risk analysis is the prediction of ground vibration levels and their effect on soil layers (stability problems or risk of settlement), potential of damage to installations or buildings and disturbance to inhabitants. Little guidance can be found in the literature that can be used by practicing engineers.

Preparing a risk analysis can be a complex task, where the interaction of various factors needs to be considered, (Figure 1). It requires an understanding of the pile installation process, an appreciation of the geotechnical conditions, as well as consideration of the site-specific conditions and of the environmental requirements.

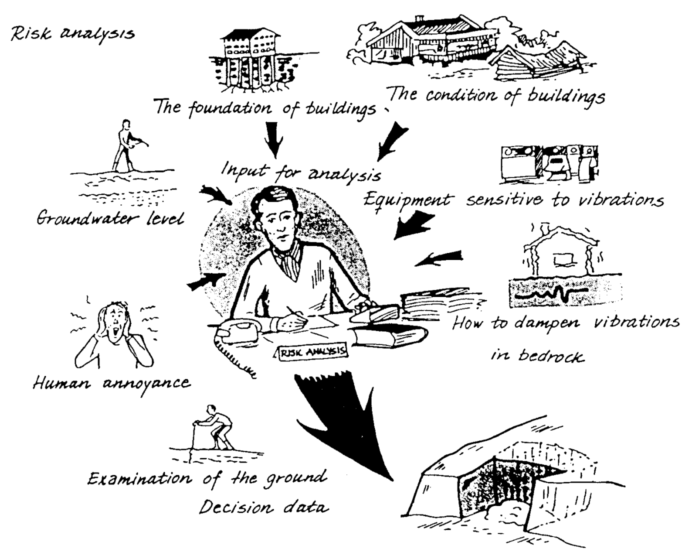

Fig. 1. Factors to be included in a risk analysis, Holmberg et al. (1984).

The risk analysis can have important economic and technical consequences for a project. If unnecessarily conservative assumptions are made, costs will increase. It may also limit the choice of construction methods and delay the project. On the other hand, if important factors are neglected, structures may be damaged or authorities may stop or interrupt construction work. Unexpected damage to structures caused by vibrations, as well as overconservative restrictions concerning vibration threshold levels can have significant economic consequences for society as well. In spite of the fact that damage caused by construction activities is rarely spectacular, the direct and indirect cost can be substantial.

A risk analysis of vibration problems in connection with a piling project should include the following aspects (the risk analysis shall be updated and modified during the project, when field observations and results of vibration measurements become available):

1. Description of the project, including method statement, objectives and responsibilities.
2. Assessment of risks associated with geological and geotechnical conditions, ground water conditions, as well as stability problems and need for settlement observations. If such risks exist, a separate geotechnical investigation shall be carried out.
3. Documentation of buildings and installations in the vicinity and description of their foundation conditions.
4. Inventory of vibration-sensitive equipment and processes in nearby buildings.
5. Documentation of all water mains and installations below ground.
6. Acceptable vibration levels (peak values). These shall be determined taking into account the site-specific conditions and shall consider both damage to buildings and environmental effects on humans.
7. Instructions where vibration measurements should be performed as well as description of other monitoring systems.
8. The document shall also provide information concerning areas of special survey or inspection needs e.g. chimneys, water mains, sewerage lines etc.
9. Specification of project documentation on site.

Damage Mechanisms

In undertaking a risk analysis, the potential mechanisms of damage to buildings must be clearly understood, and assessed individually. Damage in connection with construction work can be caused by different mechanisms. Many of the building damage problems associated with construction are frequently attributed to vibration, but are in fact caused by one of the other mechanisms. Each of the damage categories noted hereafter may, of course, occur simultaneously (Massarsch, 2000).

Category I - Static displacement: such as heave or lateral movements. Soil heave usually occurs in cohesive soils during installation of displacement piles either by static or dynamic installation methods (Massarsch and Broms, 1989). Lateral soil movements and associated stress changes can be due to soil excavation or slope movements. In Category I, structural damage is primarily due to differential settlement; the mechanism is well known and documented in the geotechnical literature. The severity of the problem may be aggravated by ground vibrations but damage is primarily due to static effects.

Category II - Ground distortion: is another "static" problem, although it is the result of wave propagation. This problem category is less well known but has been documented in the geotechnical literature, for instance by Holmberg et al. (1984), Massarsch and Broms (1991), and Massarsch (1993). Horizontally propagating waves result in an undulation of the surface layer to a depth corresponding to approximately one wave length. The propagating waves expose buildings or installations in the ground to repeated "sagging" and "hogging" distortion cycles. The magnitude of the distortion depends on the wave length, the displacement amplitude and the number of cycles of the propagating surface wave. For soil compaction work or pile driving the number of distortion cycles can be very high.

Category III - Cyclic loading: covers permanent settlements and strength loss due to cyclic loading, mainly in loose, granular soils. The main factors associated with this category are the number of loading cycles and the displacement amplitude (Massarsch, 2000). Although indirectly related to wave propagation, this category is also not a dynamic problem.

Category IV - Vibration: is the only category which is directly related to dynamic effects (inertial force). In this category, damage is a direct result of the vibration velocity or acceleration and the vibration frequency.

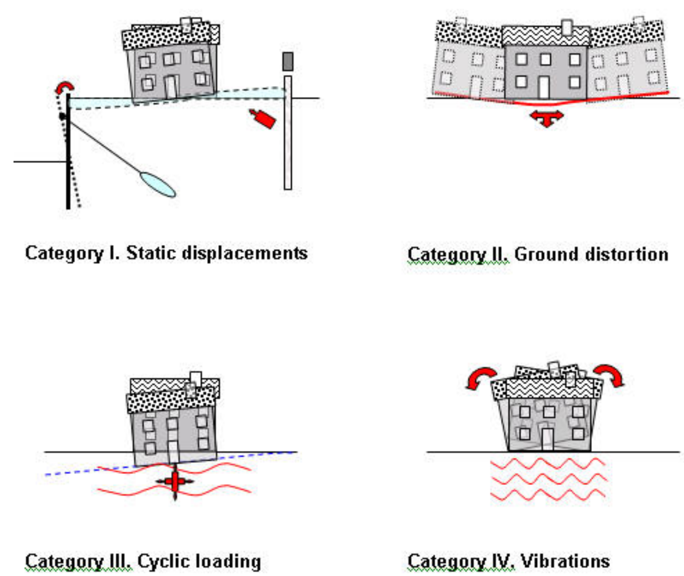

Fig. 2. Energy transfer from pile hammer to surrounding soil and

WAVE PROPOGATION CONSIDERATIONS

Vibration effects are generally poorly understood, and empirical recommendations therefore abound in the literature. These can be very misleading, and it is instructive therefore to consider the basics of wave propagation as a basis for a better risk analysis.

In order to assess the effect of pile driving it is necessary to include the entire energy transfer process, starting with the energy generated at the source (A) by the pile hammer (1), its transmission through the pile cap (2) and pile (3), the interaction of the pile shaft (4) and pile tip (5), the propagation of vibrations through soil layers (B), and the amplification of vibrations in buildings (C), (Fig. 3.). The vibration situation at the source (1 – 5) will be discussed in a separate paper, but the main aspects have been discussed elsewhere (Massarsch, 1992).

Vibrations are generated by the dynamic (loading-rate dependent) component of soil resistance during the penetration of the pile in the ground. There is a maximum level of ground vibrations, which can be transmitted from the shaft and the tip of the pile. In the literature, empirically determined charts have been proposed where the ground vibration velocity is correlated to the driving energy, generated by the hammer. However such predictions do not consider the dynamic properties of the soil through which vibrations propagate. Thus, such empirically developed prediction methods can only apply in cases where the soil conditions are similar to those where the field observations have been made.

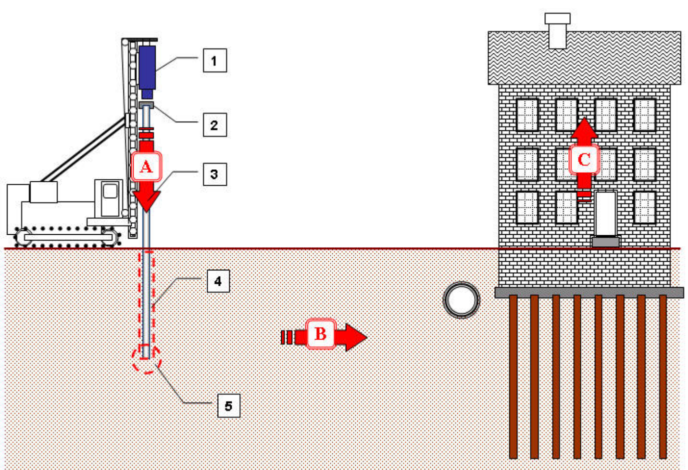

Fig. 3. Energy transfer from pile hammer to surrounding soil and buildings.

Another aspect, which is frequently not appreciated, is the fact that the distance from the vibration source (e.g. the pile tip) changes during driving of piles. Thus it is not correct to establish empirical correlations of the vibration amplitude as a function of the horizontal distance on the ground surface, as is frequently reported in the literature. Many case histories of vibration measurements during pile driving do not even mention which distance has been assumed (horizontal distance or distance to the pile tip or shaft).

When analyzing ground vibrations caused by pile driving it is necessary to distinguish between near-field and far-field conditions. Near-field conditions can be assumed when the distance from the observation point to the vibration source is closer than about 4 times the wave lengths. In the far-field, vibration problems will be caused mainly by surface waves while in the near-field, body and surface waves may occur at the same time. Also, the depth of pile penetration is of importance. During the initial phase of pile installation, the vibration source will be similar to that of a singular point. When the pile penetrates into the ground, several vibration sources can exist at the same time (at the pile tip and along the shaft).

Wave Velocities in Soils

The wave propagation velocity of soil is an important parameter for the prediction of vibration problems. The wave velocity can be determined accurately by measurements in the field or in the laboratory. However, for many practical purposes, it is sufficient to estimate the wave velocity, based on empirical relationships and experience. Typical values of the compression wave velocity (c_p) and of the shear wave velocity (c_s) for different materials are given in Table 1

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Table 1

Soil/Material Type	c_p (m/s)	c_s (m/s)
Ice	3 000 – 3 500	1 500 – 1 600
Water	1480 - 1520	0
Granite	4 500 – 5 500	3 000 – 3 500
Sandstone, Shale	2 300 – 3 800	1 200 – 1 600
Fractured Rock	2 000 – 2 500	800 - 1400
Moraine	1400 - 2000	300 - 600
Saturated Sand/Gravel	1400 - 1800	100 - 300
Dry Sand and Gravel	500 - 800	150 - 350
Clay below GW level	1480 - 1520	40 - 100
Organic soils	1480 - 1520	30 - 50

The surface wave velocity (Rayleigh wave velocity) is only slightly lower than the shear wave velocity and the difference is negligible for practical purposes.

Wave Propagation and Attenuation

Wave attenuation is caused by two main factors: 1) enlargement of the wave front as the distance from the source increases (geometric damping) and 2) internal damping of the wave energy by the soil. The attenuation of ground vibrations is strongly affected by the absorption coefficient α, which depends on the soil damping coefficient *D*, the vibration frequency *f* and the shear wave velocity. For the case of vibration propagation in an elastic medium, the soil damping coefficient is in the order of 3 – 6 %. However, at large strain in the near field of the vibration source, soil damping can increase significantly. Values of the absorption coefficient α, in the literature vary within a wide range and make a rational analysis difficult.

SETTLEMENTS IN SANDS AND SUSCEPTIBILITY TO GROUND VIBRATIONS

Many investigators and practitioners have in the past attempted - and still attempt - to correlate compaction behavior of sands with stress fluctuations and with the values of acceleration and frequency of vibration, associated with the compaction process. The key conclusions are as follows, Massarsch (2000):

- Fundamental concepts and published data show that shear strain is the primary factor causing compaction of granular material.
- Compaction increases with shear strain amplitude.
- The parameter that governs the amount of compression is the steady-state transmitted energy. This is valid for a wide range of frequencies. The residual settlement cannot be correlated to acceleration.
- Compaction is not significantly affected by vertical stress (for strain levels exceeding 0.05 %).
- In the 10 cycles/min to 115 cycles/min (0.17 – 1.9 Hz) range, frequency of straining has no significant effect on compaction behavior.
- Even at static loading conditions, evaluations of settlement are subject to considerable error (+/- 25 – 50 %). For complex conditions associated with cyclic loading, it is unrealistic to expect that evaluations could be made with even this degree of accuracy. However, an approximate evaluation of possible settlement is adequate for many purposes.
- No significant behavioral differences were detected between samples tested dry and similar samples tested in saturated, but completely drained, conditions.

It is possible to determine a range of critical vibration levels, based on the shear strain level generated by ground vibrations. The shear strain level γ can be determined if the vibration amplitude (particle velocity) v and the shear wave velocity c_s are known: i.e. $\gamma = v/ c_s$. For example, if a shear wave velocity (medium dense sand) of 210 m/s, and a particle velocity of 20 mm/s, are assumed, the shear strain level is about 0.01 %. The threshold strain is defined as the value of cyclic shear strain such that the cyclic shear strains less than γ_t will not cause any densification of dry granular soils, or any pore pressure build-up in water-saturated granular soil. Mohamed and Dobry (1987) suggest that for most sands, the threshold strain is $\gamma_t \sim 0.01\%$.

Figure 4 shows the relationship between vibration velocity (particle velocity) and shear wave velocity for two different levels of shear strain. If the shear strain level of 0.001% is not exceeded, the risk of ground settlement or strength loss is very low. However, if the shear strain level caused by ground vibrations exceeds 0.1 % there is significant risk of settlements or loss of shear strength in cohesive soils. It should be noted that Fig. 4 does not consider the effect of the number of load cycles.

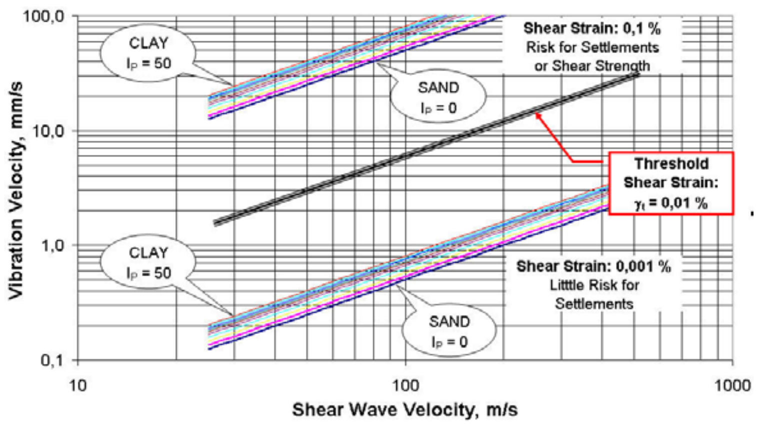

Fig. 4. Settlement risk and strength loss due to vibration velocity.

The second part of this paper will show how the concepts introduced here can be used both to predict ground vibrations and to establish rational vibration limits.

(Part 2 to be published in Fall 2004 issue.)

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Vibrations Caused by Pile Driving

Part 2 of 2 (Continued from Summer 2004 edition)

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SETTLEMENTS IN SANDS

Vibrations, which are caused by the installation of piles in dry or permeable soils can cause settlements. The magnitude of settlements depends on several factors, such as soil type and stratification, ground water conditions (degree of saturation), pile type and method of pile installation (driving energy). A method of settlement prediction due to construction-induced vibrations has been presented by Massarsch (2000). However, in many cases, an engineering assessment must be made at an early stage of a project. The following simplified procedure can be used to estimate settlements in a homogeneous sand deposit adjacent to a single pile, Fig. 5. This approach is based on extensive experience from soil compaction projects.

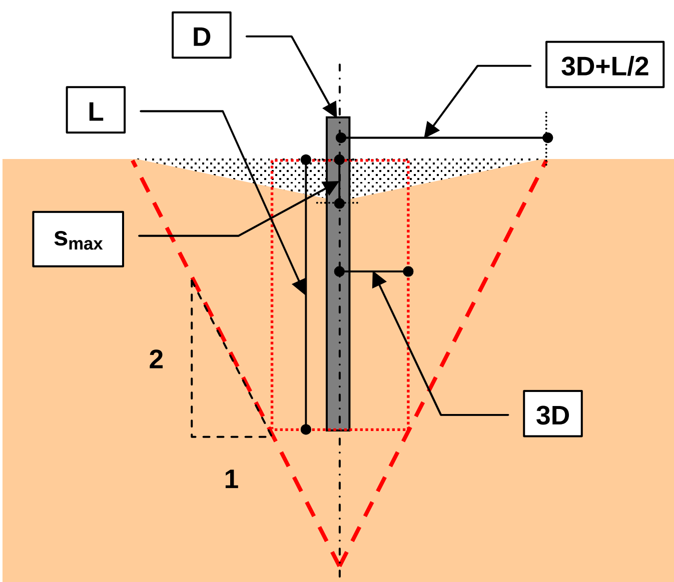

Fig. 5. Simplified method of estimating settlements adjacent to a single pile in homogeneous sand deposit

It is assumed that intense densification due to pile penetration occurs within a zone corresponding to three pile diameters. The volume reduction resulting from the propagating vibrations will cause settlements in a cone with an inclination 2V:1H, with the tip at a depth of 6 pile diameters. Thus the settlement trough will extend a distance of $3D+L/2$ from the centre of the pile, with maximum settlements at the centre of the pile. Maximum settlements, $s_{\max}$ and average settlements, s_{av} can be estimated using the following relationship choosing an appropriate value of the soil compression factor, α Table 2.

$$s_{\max} = \alpha(L+6D); \qquad s_{av} = \frac{\alpha(L+6D)}{3}$$

Table 2. Compression factors for different ground conditions and driving energies

	Compression factor, α		
Driving Energy	**Low**	**Average**	**High**
Very loose	0.02	0.03	0.04
Loose	0.01	0.02	0.03
Medium	0.005	0.01	0.02
Dense	0.00	0.005	0.01
Very dense	0.00	0.00	0.005

The driving energy depends on the method of pile installation, soil stratification and the pile type. The displacement volume of the installed pile has been neglected. The simplified method is applicable for estimating settlements at the perimeter of a pile group. It should be noted that settlements also occur outside the assumed cone, but these are often negligible. The effect of incompressible layers should be taken into account by adjusting the effective pile length.

As an example it is assumed that a concrete pile (D = 0.3 m) with an effective pile length (length in the compressible layer, L = 10 m), is driven into a deposit of medium dense sand. The pile is driven using an impact hammer, and pile penetration is normal (no stiff layers requiring high driving energy). The compression value for medium dense sand and average driving energy according to Table 2 is α = 0.010. The volumetric compression in the settlement cone is 4.3 m^3. The maximum settlement adjacent to the pile, and the average surface settlement of the cone are 11.8 cm and 3.9 cm, respectively. The radius of the settlement cone is estimated to 5.9 m, resulting in an average surface inclination of 1:50 (0.118/5.90).

LIQUEFACTION CAUSED BY PILE DRIVING

In loose, saturated sands or silts, pile driving can generate high pore water pressures, which can reduce the stability of slopes and excavations. Analytical methods developed in earthquake engineering can be used to identify soil deposits which may be susceptible to liquefaction. As a general recommendation, it should be assumed that liquefaction can occur when piles are driven into saturated sands with a cone resistance lower than 3 MPa.

When piles are driven into soft clay, soil displacements will cause a temporary increase of pore water pressure. However, the effect of ground vibrations on the undrained shear strength of homogeneous clays is generally negligible, even in the case of hard driving, as the undrained shear strength of homogeneous clays is not affected by excess pore water pressures. Experience from numerous piling and blasting projects in Scandinavia and elsewhere suggests that even in sensitive clays, vibrations have no noticeable effect on the stability of slopes or excavations.

When piles are driven into clay deposits with layers or seams of permeable material (saturated silt or sand), there is a risk that excess pore water pressures reduce the shear strength of the granular layers. Stability problems and slope failures have been observed in such slopes and excavations. Therefore, it is recommended to check whether permeable layers or seams occur. A suitable investigation method is cone penetration testing with pore water pressure measurement (CPTU).

VIBRATION SOURCE DURING PILE DRIVING

For the prediction and analysis of ground vibrations (vibration attenuation) during pile driving, it is important to take into account that the source of vibrations changes during the penetration of the pile into the soil. Conventional geotechnical investigations (penetration tests) are usually sufficient to identify the likely critical layers for vibration energy emission.

Three common situations of pile installation, which can cause excessive ground vibrations, are shown in Fig. 6. Case A illustrates the driving of a pile into a stiff surface layer. The energy source is at the ground surface and vibrations will propagate mainly in the form of surface waves. This case can be readily analyzed using simple vibration propagation methods (Massarsch, 1993). Case B is typical for displacement piles being driven into medium dense and dense sand deposits. Most of the vibration energy will be dissipated along the shaft of the pile. At a horizontal distance of twice the pile penetration, the vertically polarized shear waves will be gradually transformed into surface waves. In dense sands or in the case of obstructions, vibrations may also be emitted from the pile base, mainly in the form of compression waves. Case C is typical for the driving to refusal of end-bearing piles. Also in this case, vibrations will propagate as body waves (mainly compression waves) towards the ground surface, and there be transformed into surface waves.

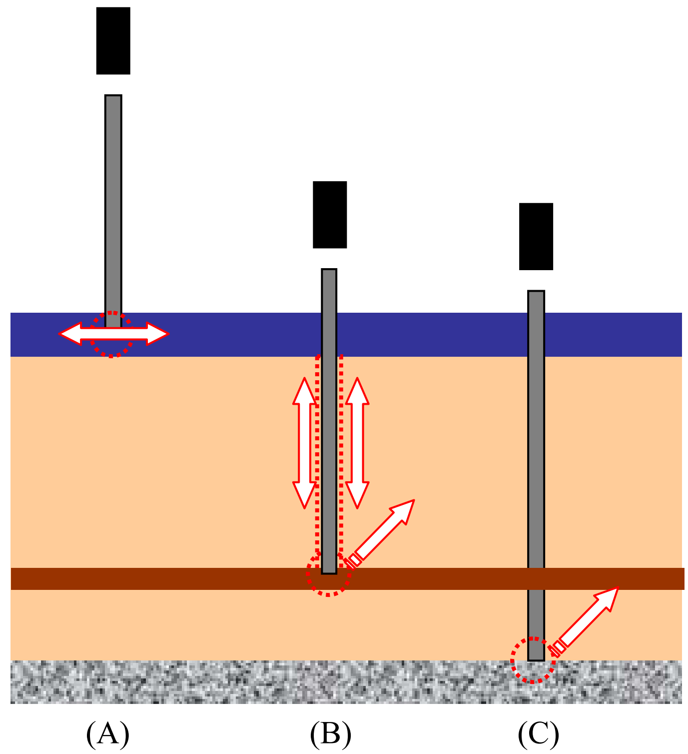

Fig. 6. Typical cases of ground vibrations during pile installation.

RESONANCE EFFECTS

An important, but often neglected effect of pile driving is the resonance effect, which can occur during both impact and vibratory driving. Figure 7 shows vibration measurements during installation of a 10 m long steel pile with a Müller variable frequency vibrator (MS24) into medium-dense sand. Vibrations were measured at 4 m distance from the pile. The vibration frequency was simultaneously recorded.

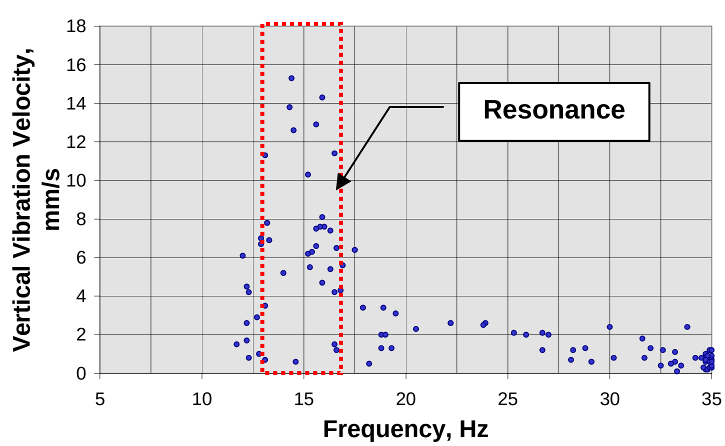

Fig. 7. Ground vibrations as function of vibration frequency.

When the pile was driven at high frequency (>20 Hz), ground vibrations were low (<2.5 mm/s). However, when the vibration frequency was lowered to the resonance frequency of the vibrator-pile-ground system (around 15 Hz), vibrations were amplified (by a factor 10). In such situations, the pile vibrates in phase with the surrounding soil and pile penetration becomes very slow. As a result of these strong ground vibrations, large settlements are created in the vicinity of the pile.

In the case of impact driving, the entire frequency spectrum will be excited and the maximum response of soil deposit will be at its resonant frequency. However, when piles are to be installed/extracted by a vibrator, it is possible to avoid resonance. Piles installed by vibrators should be driven at a frequency of at least 1.5 times the resonance frequency of the soil deposit, which will generate significantly less ground vibrations than impact driving.

RISK OF BUILDING DAMAGE

The risk of damage to buildings and installations in the ground due to pile driving can be assessed by theoretical and empirical methods. As the problem is very complex, theoretical methods can not be applied reliably in practice. However, it is possible to assess the risk of damage to buildings based on statistical observations. This approach is used in standards and is limited to the specific conditions on which the observations are based. Thus, local building standards should be applied with caution in other regions, where pile driving methods, geological conditions and building standards may be different.

In Europe, several standards relating to ground vibrations from traffic and construction activities have been developed (Massarsch & Broms, 1991). The Swedish Standard SS 02 52 11 was established in 1999 and is the most elaborate standard currently available (SIS 1999). It deals with vibrations caused by piling, sheet piling, excavation and soil compaction. Guidance levels of acceptable vibrations, as well as instructions for measurement of vibrations in buildings are given, based on more than 30 years of practical experience in a wide range of soils. Under the Swedish standard, a risk analysis is carried out for most construction projects. The proposed vibration values do not take into consideration psychological effects (noise or comfort) on occupants of buildings. Neither do they consider the effects of vibrations on sensitive machinery or equipment in buildings.

The vibration levels in the standard are based on experience from measured ground vibrations (vertical component of particle velocity) and observed damage to buildings, with comparable foundation conditions. The vibration level V is expressed as the peak value of the vertical vibration velocity. It is measured on bearing elements of the building foundation and is determined from the following relationship

$$V = V_0\ F_b\ F_m\ F_g$$

where: V_0 = vertical component of the uncorrected vibration velocity in mm/s, F_b = building factor, F_m = material factor and F_g = foundation factor. Values for V_0 are given in Table 3 for different ground conditions and construction activities, and are maximum allowable values at the base of the building.

Table 3. Uncorrected vibration velocity, V_0

Foundation Condition	Piling, Sheet piling or Excavation	Soil Compaction
Clay, silt, sand or gravel	9 mm/s	6 mm/s
Moraine (till)	12 mm/s	9 mm/s
Rock	15 mm/s	12 mm/s

Buildings are divided into five classes with respect to their vibration sensitivity (see Table 4). Classes 1 – 4 apply to structures in good condition. If they are in a poor state, a lower building factor should be used.

Table 4. Building Factor, F_b

Class	Type of Structure	Building Factor, F_b
1	Heavy structures such as bridges, quay walls, defense structures etc.	1.70
2	Industrial or office buildings	1.20
3	Normal residential buildings	1.00
4	Especially sensitive buildings and buildings with high value or structural elements with wide spans, e.g. church or museum buildings	0.65
5	Historic buildings in a sensitive state as well as certain sensitive ruins	0.50

The structural material is divided into four classes with respect to their vibration sensitivity (see Table 5). The most sensitive material component of the structure determines the class to be applied. Table 6 defines a foundation factor. Lower factors are applied to buildings on shallow foundations, whereas buildings on piled foundations are accorded higher factors due to their reduced sensitivity to ground vibrations.

The following example illustrates the practical application of the standard. Piles are to be installed in the vicinity of a residential building with brick walls, which are supported by end-bearing piles in clay. If the following factors are chosen according to Tables 3 to 6: V_0 = 9 mm/s, F_b = 1.00, F_m = 1.00, F_g = 1.00, the maximum allowable vertical vibration amplitude measured at the base of the foundation is V = 9 mm/s.

Table 5. Material Factor, F_m

Class	Type of Building Material	Material Factor, F_m
1	Reinforced concrete, steel or timber	1.20
2	Unreinforced concrete, bricks, concrete blocks with voids, light-weight concrete elements	1.00
3	Light concrete blocks and plaster	0.75
4	Limestone, lime-sandstone	0.65

Table 6. Foundation Factor, F_g

Class	Type of Building Material	Material Factor, F_g
1	Slab, raft foundation	0.60
2	Buildings founded on friction piles	0.80
3	Buildings founded on end-bearing piles	1.00

VIBRATION MEASURMENTS AND ANALYSIS

According to the Swedish Standard, vibration sensors must be installed in the part of the building which is closest to the vibration source. Vibration sensors (geophones) are to be rigidly mounted on the building foundation at the ground level. The vibration measurements must be performed during the entire construction period to monitor maximum vibration amplitudes. The measuring instruments must record the peak value in mm/s as well as the date and time of registration. The vibration reporting is to indicate the location of the measuring point and the type of instrument. In cases where damage may be expected, or when a risk analysis suggests that the buildings are vulnerable to vibrations, the number of measuring points should be increased.

When damage is observed in spite of vibration levels being below the guidance level, the extent of vibration measurements must be increased. Such measurements may include detailed vibration monitoring including frequency analyses, measurement of triaxial vibrations, measurements at different floor levels and instrumentation using strain gages.

Background vibration noise must be established on site prior to the start of the vibration measurements. The measuring frequency must cover the range of 5 – 150 Hz, or 2-150Hz if the soil depth exceeds 20 m. Measurements shall be carried out in the range 0.1 – 25 mm/s but not lower than the highest guidance level. The measuring accuracy should be at least 0.1 mm/s.

REFERENCES

Clough, G. W. and Chameau, J. 1980. Measured effects of vibratory sheet pile driving. Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT10, Oct., pp. 1080 - 1099.

Dobry, R. Ladd, R. S., Yokel, F. Y., Chung, R. M. and Powell, D. J. 1982. Prediction of pore pressure buildup and liquefaction of sands during earthquakes by the cyclic strain method. Building Science Series 138, U. S. Nat. Bureau of Standards, Washington, D. C, pp.

Holmberg, R., (Editor), 1982. Vibrationer i samband med trafik, (Vibrations in connection with traffic), Byggforskningen, T-skrift T43, Stockholm.

Massarsch, K. R. and Broms, B. B., 1991. Damage Criteria for Small Amplitude Ground Vibrations, Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, Missouri, March 11 - 15, 1991, Vol. 2, pp 1451 - 1459.

Massarsch, K. R. 1992. Static and Dynamic Soil Displacements Caused by Pile Driving, Keynote Lecture, Proceedings, 4th International Conference on the Application of Stress Wave Theory to Piles, the Hague, pp. 77 - 84.

Massarsch, K. R., 1993. Man-made Vibrations and Solutions, State-of-the-Art Lecture, Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1 - 6, 1993, Vol. II, pp. 1393 - 1405.

Massarsch, K. R., 2000. Settlements and damage caused by construction-induced vibrations. Proceedings, Intern. Workshop Wave 2000, Bochum, Germany 13 - 15 December 2000, pp. 299 - 315.

Massarsch, K. R. 2004. Mitigation of Traffic-induced Ground Vibrations. Keynote Lecture, The 11th International Conference on Soil Dynamics and Earthquake Engineering (ICSDEE) and The Third International Conference on Earthquake Geotechnical Engineering (ICEGE), 7 – 9th January, 2004, Berkeley, California. Proceedings Vol. 1 pp. 22 - 31.

Mohamed, R. and Dobry, R. 1987. Settlements of cohesionless soils due to pile driving. Proceedings, 9th Southeast Asian Geotechnical Conference, Bangkok, Thailand, pp. 7-23 – 7-30.

- Swedish Standard. 1999. Vibration and shock – Guidance levels and measuring of vibrations in buildings originating from piling, sheet piling, excavating and packing to estimate permitted vibration levels. SS 02 52 11. Swedish Institute for Standards, SIS. Stockholm 1999, 7 p.

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