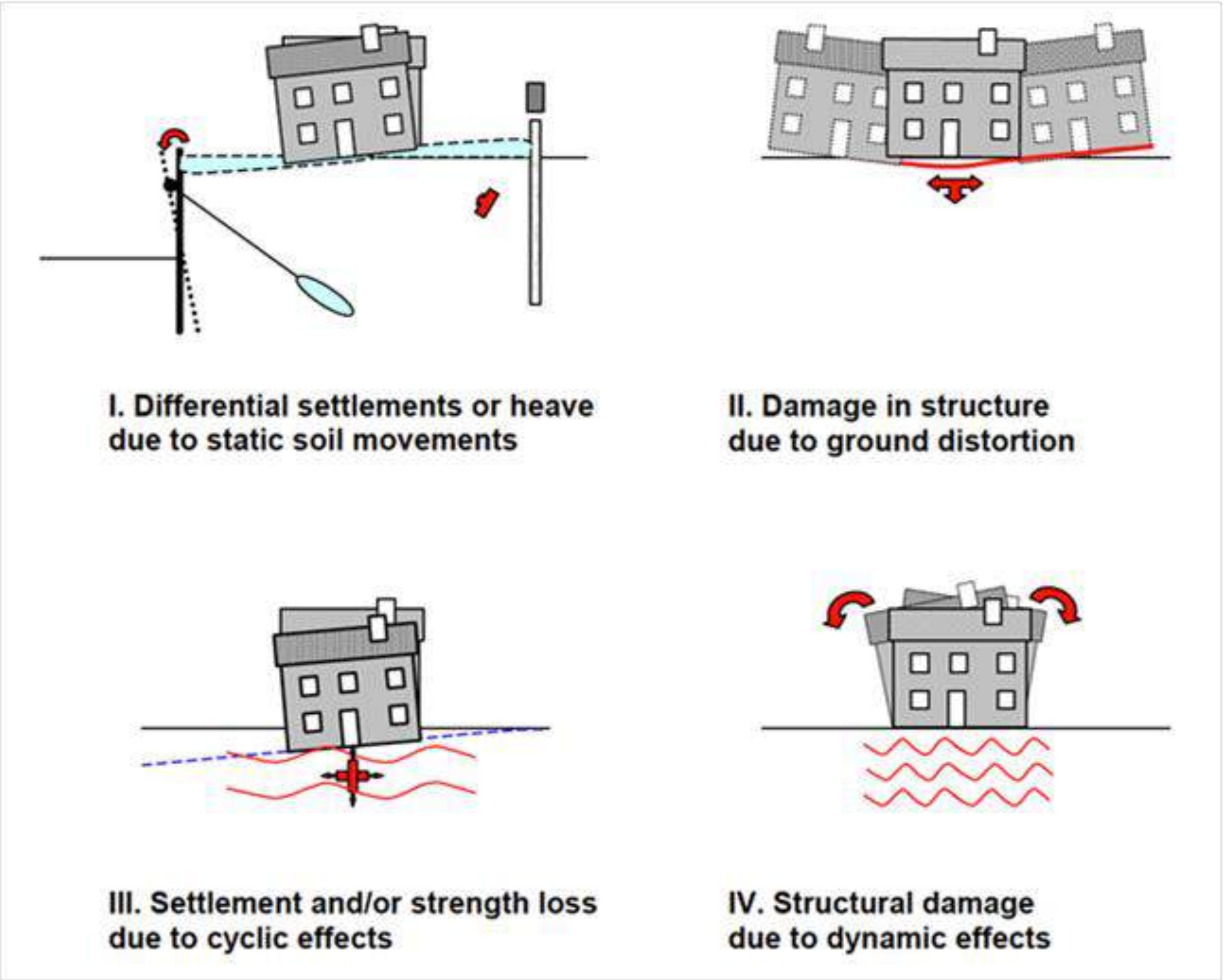

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GROUND VIBRATIONS FROM PILE AND SHEET PILE DRIVING
Part 1 — BUILDING DAMAGE

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Abstract Vibrations generated during the driving of piles or sheet piles can affect buildings or installations in the ground. However, observed building damage is not always caused directly by dynamic effects, but can also be related to foundation conditions. The importance of geotechnical conditions is usually not taken into consideration in most vibration standards. This paper describes how building foundations, and in particular mixed foundation types, are especially sensitive to ground vibrations. A method is presented for assessing the risk of settlement due to vibrations in granular soils. Also, a simple concept is proposed for estimating settlements in the vicinity of driven piles.

1. INTRODUCTION

Under unfavorable conditions, the installation of piles or sheet piles can cause damage to buildings or other structures on the ground. Frequently, such damage is attributed to vibrations of the building itself. In many countries, national or international standards are used to assess the risk of vibration damage to buildings. As such standards are often prepared by engineers with little or no geotechnical knowledge, the effects of ground conditions on vibration propagation and damage to building foundations are generally not recognized, and damage criteria based solely on the dynamic response of buildings neglect the importance of damage mechanisms governed by geotechnical conditions. One potentially important damage mechanism is differential settlement below buildings, especially when these are founded on loose granular soils. When seeking guidance in the literature, little or no information can be found regarding methods to assess permissible levels of ground vibrations with respect to risk for settlement.

This paper focuses on building damage that can be attributed to foundation conditions. In the case of ground vibrations due to pile and sheet pile driving, differential settlements are of particular importance as the ground vibrations attenuate relatively rapidly from the source. Consequently, settlement below part of the building, which is located close to the vibration source, can be significantly larger than at a distance further away.

Piles are often a cost-effective foundation solution for buildings on loose and compressible soil, frequently located in urbanized areas. Sheet piles are commonly used as support for deep excavations. While impact driving is most commonly used to install piles, vibrators are frequently used for driving (and extraction) of sheet piles. It is important to recognize the fundamental differences between impact and vibratory driving. During impact driving, the pile is subjected to stress waves of short duration. The driving process creates vibrations, which radiate from the shaft and/or the toe of the pile into the soil. The larger the intensity of the stress wave, the larger the dynamic force and the intensity of ground vibrations. In addition to the vibration intensity, which often is expressed in terms of particle velocity, also the vibration frequency is important. When the dominant frequencies of the generated vibrations harmonize with the resonance frequency of buildings or building elements, the risk of building damage increases.

In the case of impact pile driving, the frequency content of ground vibrations cannot be controlled by changing the pile driving process. In contrast, during vibratory driving, the pile or sheet pile is rigidly attached to the vibrator, which oscillates vertically at a frequency, which can be chosen and modified by the operator. The operating frequency and amplitude of modern vibrators can be adjusted in order to achieve optimal driving while minimizing environmental impact. However, if a vibrator is operated at or near the resonance frequency of buildings or building elements, strong vibrations can be generated. This effect can be used to increase the efficiency of deep vibratory compaction systems, such as “resonance compaction” (Massarsch and Fellenius, 2005).

When a pile penetrates easily into the ground, the intensity of transmitted vibrations will be low. However, vibrations increase when denser soil layers are encountered and pile penetration speed decreases. Ground vibrations depend thus on the geotechnical conditions which need to be considered in the risk assessment. During the initial phase of pile penetration, the source of vibrations will be located close to the ground surface. However, when the pile penetrates deeper into the ground, the source of vibrations becomes more complex. Vibrations can be emitted from the toe of the pile but also along the pile shaft. Therefore, geotechnical conditions are of great importance when trying to predict the intensity of ground vibrations. It is important that the location is known of stiff soil layers, through which the pile shall be driven and which can give rise to strong ground vibrations. An in-depth discussion of factors influencing ground vibrations due to pile driving was given by Massarsch and Fellenius (2008).

2. RISK OF BUILDING DAMAGE DUE TO VIBRATIONS

In assessing the risk for damage to a building due to pile-driving induced vibrations, it is important to make clear—define—the type of building damage that is considered. Moreover, one must also realize that the damage can occur as a secondary effect of the vibration, that is, it can result from settlement of the soil on which the building is resting.

2.1 Damage Categories

Damage can occur to buildings in connection with construction activities. Although noise and vibrations caused by pile and sheet pile installation can be experienced by humans as annoying or disturbing, these do not necessarily cause damage. Damage to buildings and their foundations can be related to different mechanisms. In Figure 1, four different damage categories are shown. Damage Category (I) comprises static ground movements, which can occur for instance in the vicinity of deep excavations. The installation of displacement piles can also give rise to heave and lateral displacements, which can damage buildings. Another possible source of static soil movement can be from the vibration-triggered movement of adjacent slopes or excavations with low factor of safety. Damage to buildings caused by ground distortion belongs to Damage Category (II). When the waves propagate along the ground surface, foundations of adjacent buildings can be subjected to a large number of upward (hogging) and downward (sagging) movements. The risk of damage is then largest when the length of the building corresponds to approximately half the wave length. Massarsch and Broms (1991) described how damage to buildings or installations can be analyzed when subjected to ground distortion. Damage to buildings due to settlement caused by ground vibrations belong to Damage Category (III). Settlement due to vibrations is largest in loose, granular soils, such as sand and silt. In the case of pile driving, differential settlements are more critical than total settlement. This topic is the main subject of this paper. Damage Category (IV) comprises building damage caused by dynamic effects in the building itself and is the only damage category, which is normally considered in vibration standards.

2.2 Influence of Building Foundation

Ground conditions play an important role when assessing the risk of damage due to pile-driving induce vibrations. Figure 2 illustrates three examples with larger than normal risk for damage to buildings. The first example (a) is a building on loose sand or silt. If the building is founded on uncompacted granular soil and the area has not previously been exposed to strong ground vibrations, the building is more prone to suffer vibration damage. When piles or sheet piles are driven at a distance of approximately less than one pile length, the risk of differential settlement damage can be significant, especially when piles are driven through a stiff surface layer. This is due to the fact that vibrations will be largest close to the source but attenuate quickly, thereby increasing the risk of differential settlement. However, when the vibration source is located at larger depth, vibrations at the ground surface will vary less at the ground surface and the risk of differential settlement is lower.

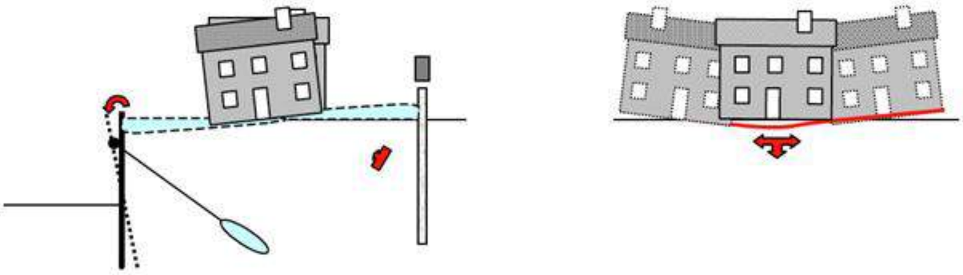

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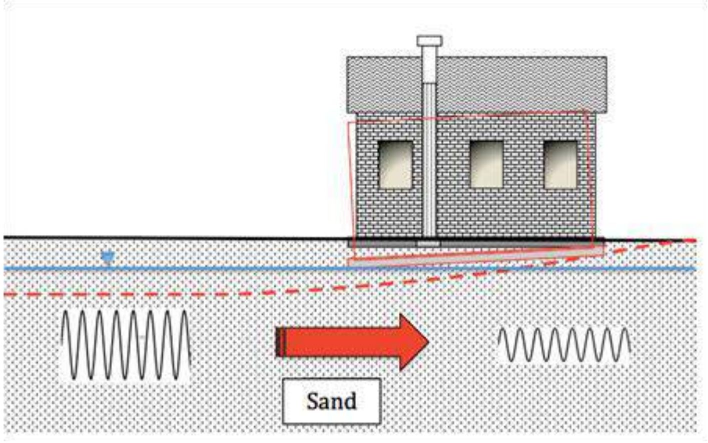
Figure 1 Possible damage mechanisms due to driving of piles or sheet piles, (Massarsch, 2000).

The second case (b) shows a building, which is founded in a slope, where material had been excavated from the slope and placed to create a level foundation. Unless the placed fill is well-compacted, the risk of differential settlement between the fill and the excavated area below the building will be high. The third example (c) shows a building, which is partly founded, on natural or filled soil, and partly on piles. Differences in stiffness of the foundation can lead to differential movements between different parts of the building.

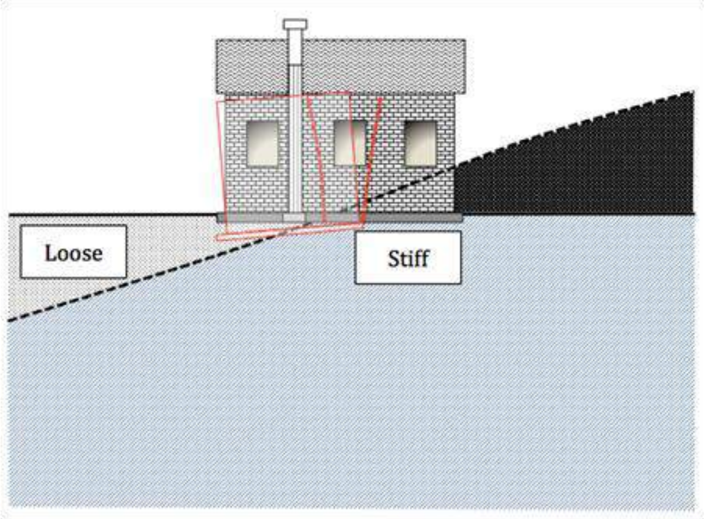
3. SETTLEMENT IN GRANULAR SOIL DUE TO GROUND VIBRATION

While most vibration standards address the effects of ground vibrations on buildings, few recognize the potential risk of building damage that can be caused by settlement in the ground below a building foundation. A major improvement of the understanding of vibration-induced settlement resulted from the knowledge gained within the area of earthquake engineering, e.g., Seed and Silver (1972), Youd (1972), and Seed (1976). Recent work by Stewart et al. (2004) is of particular relevance when assessing the effect of ground vibrations on settlement in sand. This knowledge can—with some modifications—also be applied to other types of vibration problems, such as pile driving.

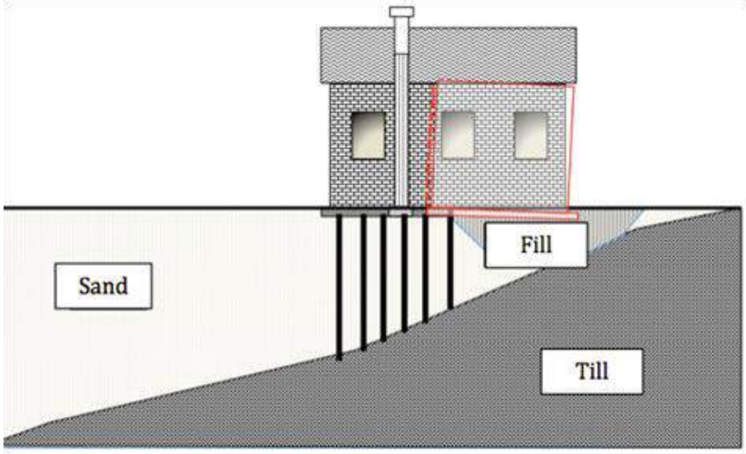
The risk of settlement due to ground vibrations exists primarily in loose sand and silt. In other soils, such as soft clays, vibrations can contribute to but are rarely the main source of settlement. The topic of settlement due to pile-driving induced ground vibrations has been addressed only in a limited number of publications (Brumund and Leonards 1972, Clough and Chameau 1980, Mohamed and Dobry 1987, Massarsch 2000, Massarsch 2002, and Massarsch 2004a). There is a need for guidance documents that can be used by the practicing engineer to assess the risk of settlements.



a) Variation of vibration amplitude with distance from source



b) Variable ground conditions below building



c) Mixed foundation types

Figure 2 Importance of foundation conditions on total and differential settlement caused by ground vibrations.

3.1. Vibration Limits

The first step is to determine vibration limits below which the risk of settlement is negligible. It is possible to determine critical vibration levels, which are based on the shear strain level generated by ground vibrations. When vibrations pass through material, strain is induced. Strain, ε, caused by propagation of a compression wave (P-wave) can be determined from Eq. 1 if the particle velocity, v_P, measured in the direction of wave propagation, and the wave speed, c_P are known (Eq. 1).

$$\varepsilon = \frac{v_p}{c_p} \tag{1}$$

Similarly, as shown in Eq. 2, the shear strain, γ, can be calculated by dividing the particle velocity, v_s, measured perpendicularly to the direction of wave propagation with the shear wave speed, c_S.

$$\gamma = \frac{v_s}{c_s} \tag{2}$$

As will be shown, shear strain is an important parameter when assessing the risk of settlement in granular soils or disturbance of cohesive soils. A threshold strain level, γ_t, exists below which it is unlikely that any rearrangement of soil particles can occur and, therefore, the vibrations will not generate an increase of pore water pressure in water-saturated sands. Drnevich and Massarsch (1979) and Mohamed and Dobry (1987) have shown that soil disturbance will not occur if shear strain are below a threshold value of $\gamma_t \approx 0.001\%$ $(10 \cdot 10^{-6})$. When this level is exceeded, the risk of particle rearrangement and thus settlement increases. At a shear strain level of ≈0.010 % $(100 \cdot 10^{-6})$, vibrations can start to cause settlement and this value should not be exceeded. Significant risk of settlements exists when the shear strain level exceeds ≈0.100 % $(1{,}000 \cdot 10^{-6})$. It is important to note that shear modulus and shear wave speed are affected by shear strain. Massarsch (2004a) has shown that the shear wave speed decreases with increasing shear strain and that this reduction depends on the fines content (plasticity index) of the soil. The reduction of shear wave speed is more pronounced in gravel and sand than in silt and is even smaller in clay. The effect must be appraised when determining the shear wave speed at a given strain level. Based on Eq. 2, and taking into account the reduction in shear wave speed with shear strain level, Massarsch (2002) proposed a simple chart (Figure 3) showing the relationship between vibration velocity (particle velocity) and shear wave speed due to ground vibrations for three different levels of shear strain in relation to the risk for settlement in sand.

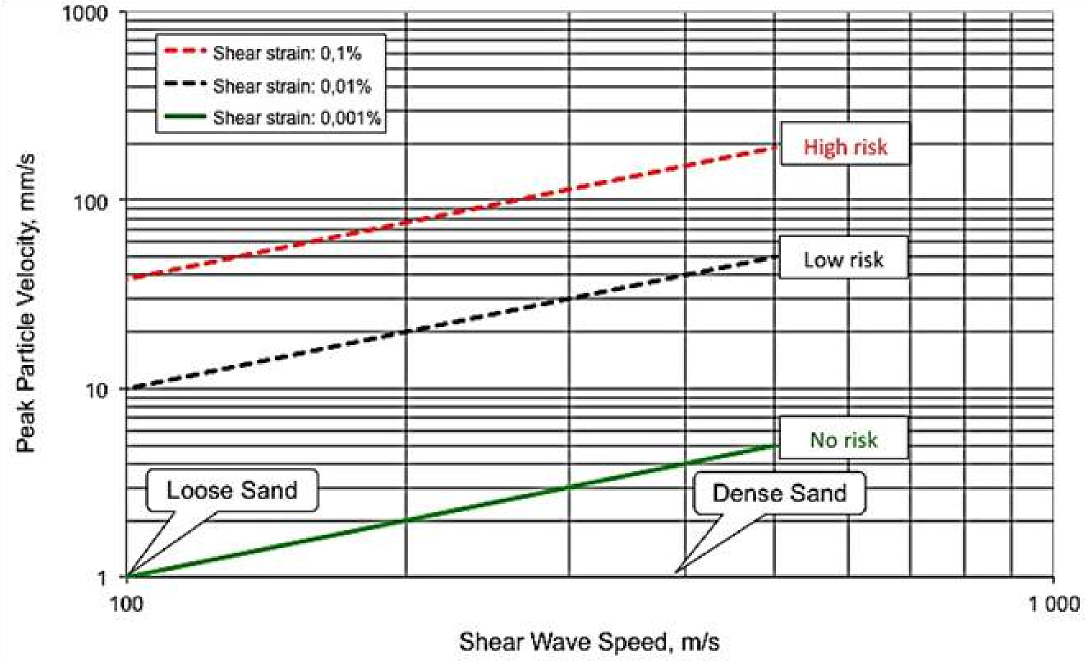


Figure 3 Settlement risk in sand as function of shear wave speed and vibration velocity

In the following example, piles are driven in the vicinity of a building founded on medium dense sand. It is further assumed, that the sand has an average shear wave speed of 200 m/s. It should be noted that the peak particle velocity, which is relevant for settlement, should be measured perpendicular to the direction of vibration propagation. From Figure 3 it is now possible to determine the three damage threshold levels; no risk (0.001 % shear strain; $10 \cdot 10^{-6}$ με): 2 mm/s; low risk (0.01 % shear strain; ; $100 \cdot 10^{-6}$ με): 20 mm/s; and high risk (0.1 % shear strain; ; $1{,}000 \cdot 10^{-6}$ με): 75 mm/s. In practice, a planning engineer can require pile driving tests, where the expected vibration levels can be determined as a function of pile penetration depth and at different distances. This information can be used to assess the risk level with respect to settlement in the sand. If the predicted vibration level exceeds the "low risk" level, a detailed monitoring program should be implemented. This simple example illustrates that it is possible to assess the risk of settlement when sandy soil is subjected to ground vibrations. Of course, a more detailed analysis can be performed which also takes into account other important factors, such as number of vibration cycles etc. However, for many practical purposes, a simple assessment of the settlement risk in combination with field monitoring will suffice.

3.2 Estimation of Settlement Adjacent to Pile Driven in Sand

Vibrations, which are caused by driving piles into dry or permeable soils, can cause settlements. The magnitude of settlement depends on several factors, such as soil type and stratification, groundwater conditions (degree of saturation), pile type, and method of pile installation (driving energy). For estimating settlements in a homogeneous sand deposit adjacent to a single pile, Massarsch (2004b) proposed the basic procedure, illustrated in Figure 4.

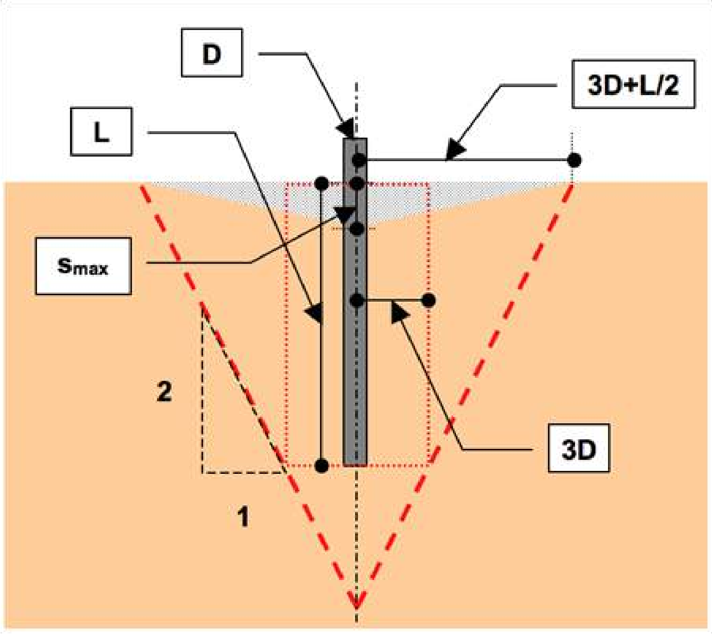


Figure 4 Basic method of estimating settlements adjacent to a single pile in homogeneous sand.

It is assumed that the most significant densification due to pile driving occurs within a zone corresponding to three pile diameters around the pile being driven. The volume reduction resulting from ground vibrations will cause significant settlements in a cone with an inclination 2(V):1(H), with its apex at a depth of 6 pile diameters below the pile toe. Thus, the settlement trough will extend a distance of 3D + L/2 from the centre of the pile, with maximum settlement at the centre of the pile. Maximum and average settlements (s_{max} and s_{avg} (m)) settlement can be estimated using the Eq. 3 relationship, for an appropriate value of the soil compression factor, α (Table 1).

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

Table 1 shows compression factors, based on experience from soil compaction projects, which are applicable to driving in very loose to very dense sand. The intensity of ground vibrations can be assessed based on vibration levels indicated in Fig. 3.

TABLE 1 Compression factor, α, for sand based on soil relative density and level of driving energy.

Ground Vibrations:	Low	Medium	High
Soil Density	- - - - - Compression factor, α - - - - -		
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

Assume that a concrete pile with diameter D = 0.3 m and an effective pile length L = 10 m is installed in a deposit of medium dense sand. The pile is driven using an impact hammer, and pile penetration is normal (stiff layers requiring high driving energy are assumed not to be present). The compression value for medium dense sand and average driving energy according to Table 1 is α = 0.010. The maximum settlement adjacent to the pile, and the average surface settlement of the cone are 118 mm and 39 mm, respectively. The radius of the settlement cone of the ground surface footprint is estimated to 5.9 m, resulting in an average surface inclination of 1:50 (0.118/5.90).

4. CONCLUSIONS AND SUMMARY

Driving of piles or sheet piles can cause damage to building foundations or installations in the ground, such as sewage pipes and tanks. Some of the observed damage may not directly be related to vibrations but to static ground movement. Vibrations can cause settlement in loose granular soils, a fact which is not appreciated in building vibration standards. Differential settlements of the ground below a building are often the main reason for damage in building foundations, from where damage can propagate up the building structure and be interpreted as vibration damage. Therefore, it is important that the risk of settlement in granular soils due to ground vibrations is included in a risk analysis. An important aspect, which frequently is overlooked in a vibration risk analysis, is the type of building foundation. Of particular importance is the vulnerability of buildings with mixed foundations where one part of the building is founded on stiff ground or piles, and the other part on soft or loose soil.

A basic method is proposed to estimate the risk of settlement due to ground vibration in granular soils. Even in very loose sand and silt with a shear wave speed of about 100 m/s, settlements are unlikely to occur when the peak particle velocity is below 1 mm/s. However, the risk of settlement increases when the peak particle velocity exceeds about 10 mm/s. In the case of important projects, pile driving tests and vibration monitoring will provide valuable information.

Settlement around a pile driven into sand can be estimated based on a simplified concept. Average and maximum settlements can be estimated for loose to dense, granular soils by selecting a compression factor. Also the intensity of driving can be taken into account, selecting the level of pile driving energy.

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