Pile Driving Vibrations and Building Damage

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. Many countries have national or international standards for assessing the risk of vibration damage to buildings. Since these standards are often prepared by engineers with little to no geotechnical knowledge, the effects of ground conditions on vibration propagation and damage to building foundations are generally not recognized. In addition 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 they are founded on loose granular soils. When seeking guidance in geotechnical literature, little to no information can be found regarding methods to assess permissible levels of ground vibrations with respect to risk for settlement.

This article summarizes a paper presented at the DFI/EFFC International Conference on Piling and Deep Foundations in Sweden in May titled: "Ground Vibrations from Pile and Sheet Pile Driving Part 1 – Building Damage." Here the authors focus 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, prevalent in urbanized areas. Sheet piles are commonly used as support for deep excavations. While piles are commonly installed by impact driving, vibrators are frequently used for driving (and extracting) 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, the vibration frequency is also important. When the dominant frequencies of the generated vibrations coincide with the resonance frequency of buildings or building elements, the risk of building damage increases.

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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 that can be chosen and modified by the operator. The 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 amplification effect can be used to increase the efficiency of deep vibratory compaction systems, by means of "resonance compaction."

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 thus depend 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 to know the location of hard soil layers through which the pile will be driven since they may give rise to strong ground vibrations.

Building Damage Due to Vibrations

In assessing the risk for damage to a building due to pile-driving induced vibrations, it is important to 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. Damage to buildings and their foundations can be related to four different damage categories (see Figure 1). Damage Category I comprises static ground movements, which can occur in the vicinity of deep excavations. The installation of

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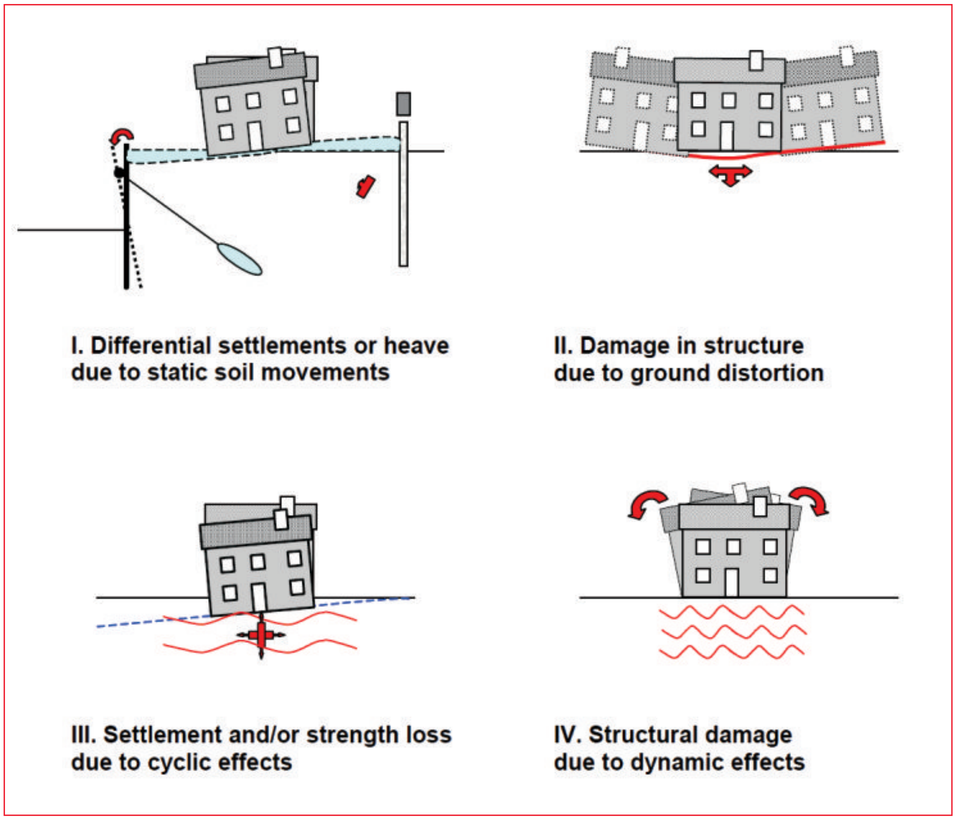


Figure 1. Damage mechanisms due to driving of piles or sheet piles

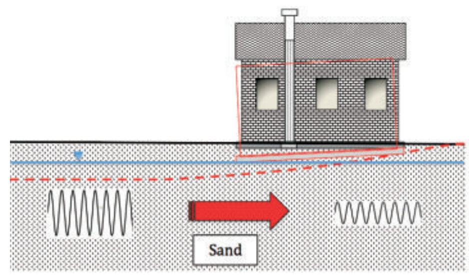
displacement piles can also give rise to heave and lateral displacements, which can damage buildings. Another possible source of static soil movement can be from the vibration-triggered movement of adjacent slopes or excavations with low factor of safety. Damage Category II is caused by ground distortion. 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. Damage Category III is due to settlement caused by ground vibrations. Settlement due to vibrations is largest in loose, granular soils, such as sand and silt. Differential settlements are more critical than total settlement. Damage Category IV comprises building damage caused by dynamic effects in the building itself, which is the only damage category typically considered in vibration standards.

Ground conditions play an important role when assessing the risk of damage due to pile-driving induced vibrations (see Figure 2). One example 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. Another case is a building founded on 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. Another example is a building that 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.

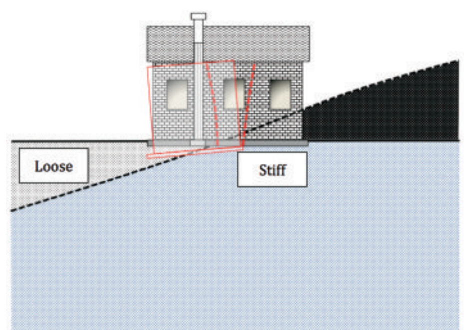
Settlement Due to Vibration

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. 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. There is a need for guidance documents that can be used by the practicing engineer to assess the risk of settlements.

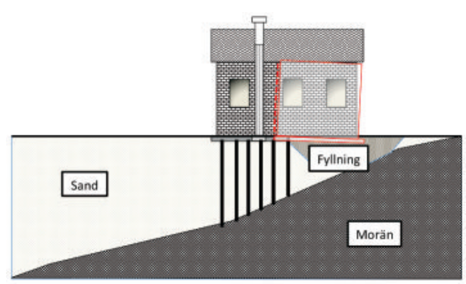
The first step is to determine vibration limits below which the risk of settlement is negligible. It is possible to determine critical vibration levels, which are based on the shear strain level generated by ground vibrations. When vibrations pass through



a) Variation of vibration amplitude with distance from source



b) Variable ground conditions below building



c) Mixed foundation

Figure 2. Foundation conditions that may result in total and differential settlement

material, strain is induced. Strain, ε, caused by propagation of a compression wave (P-wave) can be determined if the particle velocity, v_P, measured in the direction of wave propagation, and the wave speed, c_P are known.

$$\varepsilon = \frac{v_P}{c_P}$$

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

$$\gamma = \frac{v_S}{c_S}$$

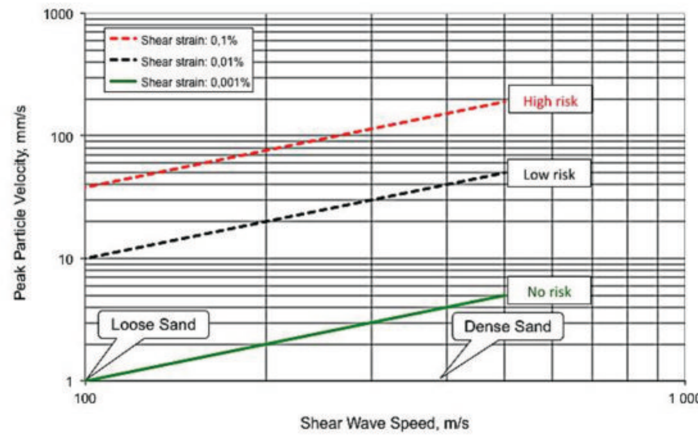


Figure 3. Assessment of settlement risk in sand

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 will occur and, therefore, the vibrations will not generate an increase of pore water pressure in water-saturated sands. It has been shown that soil disturbance will not occur if shear strain are below a threshold value of $\gamma_t \approx 0.001\%$. When this level is exceeded, the risk of particle rearrangement and thus settlement increases (see Figure 3). At a shear strain level of 0.01%, vibrations can start to cause settlement, and this value should not be exceeded. Significant risk of settlements exists when the shear strain level exceeds 0.1%. It is important to note that shear modulus and shear wave speed are affected by shear strain. The shear wave speed decreases with increasing shear strain and 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.

In the following example, piles are driven in the vicinity of a building founded on medium dense sand. It is assumed that the sand has an average shear wave speed of 200 m/s (656 ft/s). From Figure 3 it is possible to determine the three damage threshold levels: no risk (0.001% shear strain) = 2 mm/s (0.08 in/s); low risk (0.01% shear strain) = 20 mm/s (0.8 in/s); and high risk (0.1% shear strain) = 75 mm/s (2.9 in/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.

Conclusions

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 most building vibration standards. Differential settlements of the ground below a building are often the main reason for damage in building foundations, 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. Another important aspect which frequently is overlooked is the type of building foundation. Of particular significance 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 (328 ft/s), settlements are unlikely to occur when the peak particle velocity is below 1 mm/s (0.04 in/s) However, the risk of settlement increases when the peak particle velocity exceeds about 10 mm/s (0.4 in/s). In the case of important projects, pile driving tests and vibration monitoring will provide valuable information.

For additional information, please refer to the conference proceedings for the complete paper as well as the companion paper: "Part 2 – Review of Vibration Standards." Printed proceedings are available at http://www.dfi.org/publications.asp?goto=100#P100 for $145 for members or $195 for nonmembers.