Ground vibrations due to pile and sheet pile driving
– prediction models of today

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ABSTRACT

As part of a construction work pile and sheet pile driving unavoidably generates vibrations. As of today construction works are often located in urban areas and along with society’s increasing concern of environmental impact the need for vibration prediction prior to construction is of immediate interest. This study presents a review of the prediction models existing today. For prediction of ground vibrations from pile and sheet pile driving there are roughly three different types of models; empirical models, theoretical models and engineering models. A prediction model should be reliable in all cases where it is meant to be used. It is also important that it is relatively easy to use and that the input data is easily obtained. This study concludes that, as of today, there is a lack of such a model. Today’s models either lack in reliability or require great amounts of input data, knowledge and skills as well as time and money. The findings within this study constitute the initial part of an on-going research project at the division of Soil- and Rock Mechanics at the Royal Institute of Technology in cooperation with the Development Fund of the Swedish Construction Industry and NCC Construction Sweden.

Keywords: Ground vibrations, pile driving, vibration prediction, pile, sheet pile, prediction model

1 INTRODUCTION

Construction work and especially the driving of piles and sheet pile has for a long time been one of the most important sources for vibrations in urban areas. The induced vibrations can have a negative impact on the surroundings. As a consequence of society’s increased concern of environmental impact and the fact that construction projects more often are located in urban areas and close to existing structures, vibration assessment and prediction has become of immediate interest.

The prediction of the vibration level in a construction project can have important economic and technical consequences. Unnecessarily conservative estimations will increase costs, may limit the choice of construction methods and delay the project. If, on the other hand, the vibration level is underestimated, it might lead to...
damaged structures, disturbed occupants and suspension of the construction work.

Today an estimation of expected vibration level is usually based upon experience or field test measurements. This study presents a review of the existing prediction models for vibrations caused by pile and sheet pile driving and is part of an on-going research project aiming for better prediction and understanding of ground vibrations induced by pile and sheet pile driving.

2 BASIC THEORY

In order to estimate the effect of pile/sheet pile driving it is necessary to consider the entire vibration transfer process from the source to the damage object. The process is divided into three main parts; vibration source, wave propagation in soil and damage object (Figure 1). Vibrations are generated by the driving equipment (impact or vibratory) and are transmitted through the pile cap and further into the pile. There is an interaction between the soil and the pile shaft and pile toe, leading to vibrations being transmitted into the ground. From thereon vibrations propagate through soil and eventually interact with possible damage objects.

Figure 1. Schematic illustration of the vibration transfer during pile driving.

At the pile-soil interface vibrations from the pile are transmitted to the soil as different waves and wave fronts (Figure 2). At the pile toe spherical wave fronts of both P- and S-waves are created. From the shaft a conical wave front is created consisting of S-waves. As the wave fronts reach the ground surface part of the vibration energy is transferred to surface (R-)waves.

As waves propagate through the soil attenuation takes place in the form of geometrical and material damping. Geometrical damping is caused by the energy spreading over an increasing soil volume, and material damping is due to internal friction and hysteresis. The total attenuation of vibrations propagating in soil is usually approximated by the following relationship:

\[
A_2 = A_1 \left( \frac{r_2}{r_1} \right)^{-\alpha} e^{-\alpha(r_2-r_1)}
\]

where

- \(A_1, A_2\) = vibration amplitude at distance \(r_1\) respectively \(r_2\) from the source
- \(\alpha\) = absorption coefficient (m\(^{-1}\)) depending on soil material and vibration frequency
- \(n = \frac{1}{2}\) for surface waves, 1 for body waves, 2 for body waves along the surface

3 CURRENT PREDICTION MODELS

The magnitude of induced vibrations in a specific project can be measured fairly well in the field...
but the prediction of its magnitude prior to driving is very insecure. Several examples can be found in literature stating that as of today there is little guidance to be found regarding how practising engineers can make a prediction of the vibrations during a pile or sheet pile driving work (e.g. [2], [3], [4], [5], [6], [7] and [8]).

The existing prediction models are in this study divided into three different categories depending on their approach:

- Empirical models – based on empirical knowledge from former measurements and experience of piling works
- Theoretical models – based on theoretical knowledge usually consisting of numerical models
- Engineering models – a mix of empirical, theoretical and engineering knowledge (sometimes also called mixed-approach models)

3.1 Empirical models

Even if there are no generally accepted methods for predicting vibrations during pile- and sheet pile driving, there exist a lot of measurements and empirical knowledge.

In 1967 Wiss [9] discovered that the vibration magnitude due to pile driving varied with the amount of energy transmitted to the soil, the soil properties and the distance from the source. Wiss [9] then concluded that the particle velocity varied with the square root of the energy of the hammer. Attewell & Farmer [1] proposed that, for practical estimates of vibrations due to pile driving, the vibration intensity attenuates directly with distance from the pile and that the geological character of the ground can be ignored. Hence, in 1973 Attewell & Farmer [1] presented one of the first empirical prediction models where they suggest that the vertical peak particle velocity, \( v \), is given according to the general formula:

\[
v = k \left( \frac{\sqrt{W_0}}{r} \right)^x
\]

where

- \( k \) = empirically determined constant (-)
- \( W_0 \) = input energy (hammer energy) (J)
- \( r \) = horizontal distance between pile and monitoring point (m)
- \( x \) = empirically determined index (-)

From field measurements [1] claimed that the results correlate quite well with setting \( k = 1 \) and \( x = 1 \), however, they suggested that \( k = 1.5 \) is used for practical conservative prediction of ground vibrations due to pile driving. The energy based relationship in Eq. (2) has since been developed by various researchers proposing values for \( k \) and \( x \) ([10], [11], [2], [12], [13] and [14]).

Attewell et al. ([11] and [15]) found that a quadratic regression curve was a better fit to measurements of ground vibrations due to pile driving than the former used linear regression curve in Eq. (2). The developed model proposes the following equation for the prediction of vibration velocity due to pile driving:

\[
\log v = k + m \log \left( \frac{\sqrt{W_0}}{r} \right) + n \log^2 \left( \frac{\sqrt{W_0}}{r} \right)
\]

where

- \( k, m \) and \( n \) = constants of proportionality (-)

Constants \( k, m \) and \( n \) are functions of the soil conditions at the site of pile driving and the driving method. Suggested values for the constants are published in [15].

Svinkin [16] presented a development of the energy based relationship founded on determination of the vibration velocity at the pile head, and from that computed the ground vibrations. In Eq. (2) \( x \) is set as 1 and \( k \) is equal to the pile vibration at the pile head, \( v_p \).

3.2 Theoretical models

Theoretical models use a different approach for the prediction of vibrations than the one used in empirical models. Theoretical models are usually based on numerical or analytical modelling using different computer programs. Davis [8] listed several numerical methods which can be
used for prediction of ground vibrations, the most common are:

- Finite Difference Time-Domain Method (FDM)
- Finite Element Method (FEM)
- Boundary Element Method (BEM)

FDM can take layering and anisotropy of the soil into account; however, there is uncertainty in the loss of energy due to material damping. Another drawback of the FDM is that it requires high levels of mathematical skills from the user [8]. FEM is commonly used for the modelling of problems in soil and rock materials. There are a number of commercial computer programs based on FEM (Plaxis being the most common among geotechnical engineers). BEM is somewhat more limited in its use than FEM and FDM due to its need for reformulation of the partial differential equations. To overcome the limitations with BEM the soil immediately next to the source can be modelled with FEM while the rest of the propagation path can be modelled using a coupled BEM model. For the modelling of ground vibration problems with infinite domains BEM is considered to be better than FEM regarding efficiency, accuracy and user friendliness [8].

Theoretical models often consist of sub-models for the pile, the soil and sometimes also for damage objects. The sub-models are modelled separately and thereafter connected to make the prediction [17]. Several of the existing prediction models mix different numerical methods in their prediction models (e.g. [3] and [18]).

Whenham [19] has listed several publications where numerical methods have been used to predict the vibrations induced by pile driving. From that list modifications and additions have been made resulting in Table 1.

### 3.3 Engineering models

Engineering models mix different approaches in the same model to make a prediction. Jongmans [4] presented an engineering model that aims towards reconstructing the whole vibration signal generated during pile driving. The model consists of two parts; the first part is based on the use of geophysical prospecting to represent the response of the site (Green’s function) and the other part is an equivalent source function idealising energy transmission from pile toe to soil.

A model presented by Svinkin [21] uses the concept of the impulse response function to model the soil behaviour. The impulse response function is determined by setting up an experiment in which known magnitudes of impact are applied on the site of interest. Once the impulse response function is known the dynamic loads for pile driving are computed by wave equation analysis. Duhamel’s integral is then used to find the predicted vibrations.

In 2008 Massarsch & Fellenius [20] introduced a model for estimating vibrations from impact pile driving. The method includes the force applied to the pile head, the dynamic stresses in the pile and the dynamic resistance along the pile toe and pile shaft.

### 4 COMMENTS ON CURRENT PREDICTION MODELS

#### 4.1 Empirical models

Hope & Hiller [22] draw the conclusion that prediction models not taking soil conditions into consideration are less accurate than prediction models taking soil conditions into account. Several others ([21], [23] and [20]) are critical towards empirical relationships for estimation of ground vibration as they do not take soil conditions into account in an adequate way. According
to [4] it is likely that soil conditions affect not only the vibration magnitude but also its frequency content and wave form. Hope & Hiller [22] and Massarsch & Fellenius [20] showed that the empirical approach is too crude for reliable analysis of ground vibrations and that some of the relationships assumed in these empirical models are invalid.

However, according to [11] and [24] it is quite reasonable that ground vibrations due to pile driving can be estimated by the use of empirical methods. They stated that empirical methods are the most sensible and suitable for use on site. In [23] it is also reasoned that empirical models have their limitations, nevertheless, they are easy to apply and thus valuable for piling practitioners.

4.2 Theoretical models

Athanasopoulos & Pelekis [23] believed that theoretical models are capable of modelling the whole vibration problem and producing predicted vibration levels. Svinkin [21] stated that analytical prediction models usually give good agreement between predicted and measured vibrations for a certain site. However, designing the models takes a lot of time and knowledge in order to get the calculations right. A theoretical model is in most cases strongly influenced by the user and his/her expertise and knowledge, which affects the predicted vibrations [17]. Making reliable predictions also requires detailed input data that in many cases needs to be estimated.

4.3 Engineering models

The advantage of Jongmans’ model is that it takes the site characteristics into account [4]. The model presented by Massarsch & Fellenius [20] also considers soil conditions in the form of soil resistance. And Svinkin [21] stated that the advantage of the impulse response function is that it reflects real soil behaviour without the need for investigations of the soil properties.

The engineering models presented in section 3.3 all include soil conditions in one way or another; however, they lack validation in the form of comparison to vibration levels measured in the field.

4.4 Reliability of prediction models

One of the main conclusions in the study of [17] was that the uncertainty in vibration prediction generally is quite large; however, using sophisticated FEM-models reduced the uncertainty compared to expert judgement. Another conclusion was that the user of the prediction model has a huge influence on the outcome of the prediction.

Hope & Hiller [22] presented a review of the prediction models available at that time, focusing on vibrations from impact pile driving. They showed that the accuracy of the existing prediction models were limited. Most prediction models presented considerably over-estimated the vibration magnitudes at distances less than 11 m from the pile. In [19] predicted vibrations from the Attewell et al. model ([11] and [15]) were compared with measured results showing that the model over-predicted the actual vibrations with a factor of 2 to 10. Nevertheless, most prediction models are intentionally conservative.

In order to highlight the complexity of the problem and the difficulty in prediction, a relative comparison between the Attewell & Farmer-model (Eq. 2) and the Attewell et al.-model (Eq. 3) has been conducted within this study. The comparison showed that when using the same input data ($W_0 = 5000$ J and $r = 15$ m) predicted vibration levels were $7.1$ mm/s respectively $3.4$ mm/s. The other models all require the assumption of large amounts of different input data making a relative comparison insignificant.

5 CONCLUSIONS

A prediction model should be reliable in all cases where it is meant to be used. It is also important that it is relatively easy to use, the mathematical operations should not take days to execute and the input data should be readily available. This study shows that, as of today, such a model is lacking. Current empirical models have the advantage that they are easy to use and require relatively small amounts of input data, however, they cannot be considered reliable as they tend to highly overestimate the vibration level. Today’s theoretical prediction models seem to be some-
what more reliable, but instead they require great amounts of input data, knowledge and skills as well as time and money. The engineering models lack validation in order to be considered reliable; however, they seem to have the potential of producing a prediction model satisfying the above criteria.

A prediction model simple enough to be used by practising geotechnical engineers yet sophisticated enough to reliably predict vibrations will hopefully be available in the future. In order to get there further research clarifying how to better quantify the vibration actually transferred from the pile to the soil and also how to better incorporate soil conditions into a prediction model is required.

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