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Major vibration source during vibratory sheet pile driving – shaft versus toe

Principale source de vibration pendant vibrofonçage des palplanches

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ABSTRACT: Due to increasing demand to maintain vibration levels below strict limits during construction, it is important to develop a better understanding of how vibrations emanate from the shaft and the toe during vibratory sheet pile driving. It is still unclear whether it is the shaft or the toe that contributes the most regarding induced ground vibration levels. A sheet pile shaft has a significantly larger area compared to the toe area. It is therefore expected that the shaft would contribute the more significantly. However, results from full scale field studies have shown that the sheet pile toe also has a large influence on ground vibration levels as the toe passes measurement points buried in the ground close to the vibrodriven sheet piles. This paper employs a numerical model developed to investigate the hypothesis that most of the ground vibrations emanate from the shaft during vibratory sheet pile driving. The results indicate during driving in clay the contribution from the toe and shaft to ground vibration depends on the sheet pile penetration depth, with the shaft dominating vertical ground vibrations for large penetration depths.

RÉSUMÉ: En raison de la demande croissante de maintenir des niveaux de vibration inférieurs aux limites strictes pendant la construction, il est important de mieux comprendre comment les vibrations pendant du vibrofonçage de palplanche émanent de la tige aussi bien que du pied. Il ne toujours pas certain si c'est la surface ou le pied de la planplache qui provoque le plus de vibrations dans le sol. La surface vertical de la palplanche est beacoup plus grande que celle du pied. On pourrait donc s'attendre que la surface provoque plus de vibrations au sol. Mais les essaias à grande échelle ont montré que le pied avait également une grande influence lorsque le pied dépassaient les points de mesure enterrés près des palplanches vibrantes. Cet article décrit l'utilisation d'un modèle numérique pour étudier l'hypothèse des vibrations dans le sol. Les résultats montrent que l'hypothèse ne peut pas être confirmée; il est plutôt indiqué que la tige et le pied tout ensemble provoque le plus de vibrations dans le sol.

Keywords: sheet pile; vibratory driving; ground vibrations; numerical modelling

1 INTRODUCTION

Vibratory driven sheet piles are widely used as retaining walls. However, the installation method induces ground vibrations, which may adversely affect buildings or structures and cause disturbance for humans. Due to an increasing demand to maintain vibration levels below strict limits during construction, it is important to develop a better understanding of how vibrations are transferred from the driven sheet pile to the soil in the ground. While it is generally accepted that vibrations emanate from the sheet pile shaft as well as the toe (Attewell & Farmer, 1973; Athanasopoulos & Pelekis, 2000), it is still unclear whether it is the toe or the shaft that contributes most significantly to induced vibration levels in the ground.

The sheet pile shaft has a significantly larger area compared to the toe area. While it might be expected that the shaft would contribute more significantly, results from full scale studies have shown that the sheet pile toe has large influence on ground vibration level when it passes measurement points buried in the ground close to the driven sheet pile (Deckner et al., 2015).

The aim of the present paper is to investigate the hypothesis that most of the vibrations in the ground emanate from the shaft during vibratory sheet pile driving. This is investigated by using a three-dimensional finite element approach developed by the authors. The numerical model is unique in that it contains true sheet pile geometry, as well as in the way it is handling the complexity of the sheet pile-soil interaction and the large strains induced by the driving.

2 NUMERICAL MODELLING

Here follows a brief description of the numerical model employed to investigate the hypothesis that the shaft is the major contributor to induced ground vibrations during vibratory driving. In this paper focus is placed on describing the actions performed to distinguish between shaft-related and toe-related vibrations.

The three-dimensional finite element model is set up in the commercial software COMSOL® Multiphysics and consists of the driven sheet pile and the surrounding soil, see Figure 1a. The model is developed to simulate a performed full scale field test, which is thoroughly described in Deckner et al. (2015). The sheet pile geometry corresponds to the true geometry of a Larssen 603 profile with a length of 13.8 m. The soil is divided into four horizontal layers; an upper fill layer (2.5 m), a clay layer (7.5 m), and a moraine layer (1.5 m) upon bedrock, see Figure 1a. Material data used in the model is compiled in Table 1. Along the boundaries of the model perfectly matched layers (PMLs) are used to avoid reflection of waves back into the model.

The model accounts for the effects of slippage, large strains in the soil along the shaft and large strains together with loss of contact below the toe.

During driving large strains are induced in the soil close to the sheet pile (Clough & Chameau, 1980; Holeyman et al., 2013). Slippage occurs along the shaft when the surrounding soil no longer can follow the motion of the sheet pile, which then starts moving relative to the soil (Novak & Sheta, 1982; Michaelides et al., 1998; Whenham, 2011). Below the toe there is likely instead a loss of contact between sheet pile toe and soil, when the sheet pile moves upwards in each cycle.

Table 1. Material data used in the model.

Material	**Density** ρ **(kN/m^3)**	**Poisson's ratio** ν **(-)**	**Shear modulus** G **(MPa)**
Sheet pile	78.5	0.33	75 200
Fill	18	0.33	40
Clay	18	0.485	14 + 1.2 MPa/m
Moraine	19	0.485	280
Bedrock	26	0.33	10 000
Fill – *Low G-zone*	18	0.33	0.035
Clay – *Low G-zone*	18	0.485	0.0175

The large strains, the slippage and the loss of contact affect the transfer of vibrations from sheet pile to soil to a large extent (Deckner, 2017). To account for this the soil is divided into different zones. Closest to the sheet pile there is a zone called *Low G-zone*, which stretches about 100 mm around the shaft and below the toe, see Figure 1b. *Low G* stands for a low shear modulus (*G*). The shear modulus is an important parameter when it comes to a soil's ability to transfer vibrations.

In the soil outside the zones with low stiffness, an equivalent linear approach is used to account for the reduction of shear stiffness with increasing shear strain (Lysmer et al., 1975).

The dynamic load generated by the vibratory driving is modeled by a load on top of the sheet pile to simulate the driving force. The load is added as a vibratory load of 928 kN and a point mass of 2980 kg to account for the vibrating mass. The calculations are performed in the frequency domain and the studied frequency of 35 Hz corresponds to the driving frequency.

3 ANALYSES

To analyze the transfer of vibrations to the soil and whether it is the toe or the shaft that contributes the most calculations have been performed for the following three cases; **Case 1 –** vibrations from shaft, **Case 2 –** vibrations from toe and **Case 3** – reference case. The three cases are described below.

3.1 Case 1 – Vibrations from shaft

In Case 1 we model vibrations from the shaft and omit contribution from the toe. To avoid transmission of vibrations from the toe the soil in the *Low G-zone* below the toe, is replaced by a void, since no waves are transmitted at a solid-to-void interface (Richart et al., 1970), see Figure 2a. The void is given a very low Young's modulus of 1 Pa, thus the toe is practically incapable of transferring vibrations to the surrounding soil, due to very low stress in the soil below the toe.

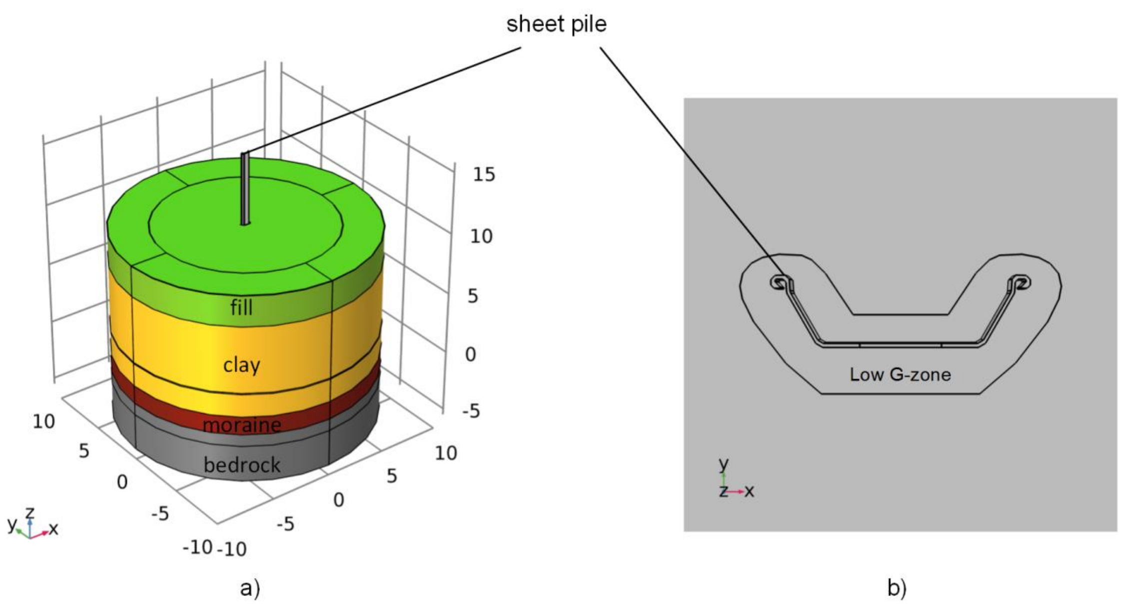

Figure 1. Geometry of the numerical model, in (a) the different soil layers are visible and in (b) the Low G-zone around the shaft is seen from above.

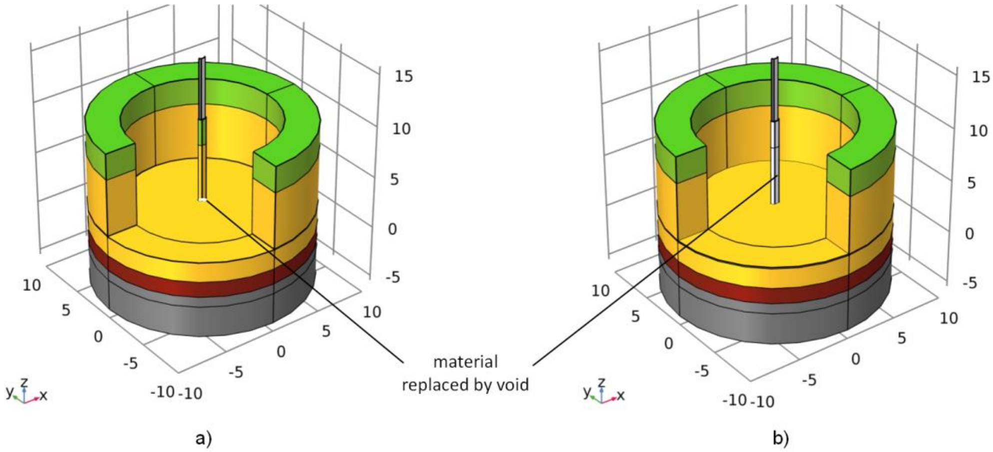

Figure 2. Zones replaced by void, (a) below the toe and (b) around the shaft. Observe that parts of the geometry have been hidden.

3.2 Case 2 – Vibrations from toe

In Case 2 vibration transmission is restricted to the toe by giving the *Low G-zone* around the shaft a very low Young's modulus of 1 Pa, see Figure 2b.

3.3 Case 3 – Reference case

Results from Case 1 and 2 are compared to a model of "normal" sheet pile driving procedure, a reference case. In the reference case soil is present both below the sheet pile toe as well as along the shaft, meaning that vibrations can be transferred from sheet pile to soil both at the toe and along the shaft.

4 RESULTS AND DISCUSSION

In this section results from Case 1, Case 2 and Case 3 are presented and discussed. This study is limited to a single penetration depth. The sheet pile is wished-in-place to a depth where the sheet pile toe is eight meters below the ground surface. Thereafter the load is applied, and the results are derived for that penetration depth.

In Figure 3 vertical vibration amplitudes in the soil, expressed as velocities, are displayed. To enhance visibility, it is the logarithm of the vibration amplitudes that is plotted. Figure 3a shows Case 1 – vibrations from shaft, Figure 3b shows Case 2 – vibrations from toe and Figure 3c shows Case 3 – reference case. As can be seen no waves emanate from the toe in Figure 3a and almost no waves emanate from the shaft in Figure 3b, indicating that the usage of void to restrict vibration transmission works as expected. In Figure 4 horizontal vibration amplitudes are displayed in the same manner.

In order to study the contribution from the shaft respectively the toe to the total ground vibration level the vibration level calculated from Case 1 and Case 2 is compared to the vibration level calculated from Case 3. Ideally vibrations from the shaft (Case 1) would add to the vibrations from the toe (Case 2) and give a total vibration level corresponding to the level from Case 3.

When doing this kind of comparison, it is also important to look at the vibrations of the sheet pile. Preferably the vibration of the sheet pile should be approximately the same in all three cases to know that the vibration source is the same. A comparison of the vibration amplitude at the top of the sheet pile is done in Table 2. As can be seen the difference in vibration level is only around 4% and can thus be considered to give a fair comparison between the three cases.

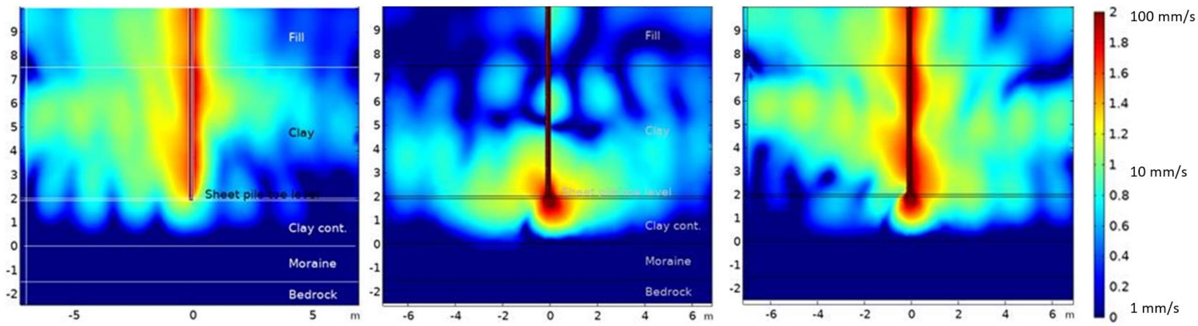

Figure 3. Vibration amplitudes in the vertical (z-) direction for (a) Case 1, (b) Case 2 and (c) Case 3.

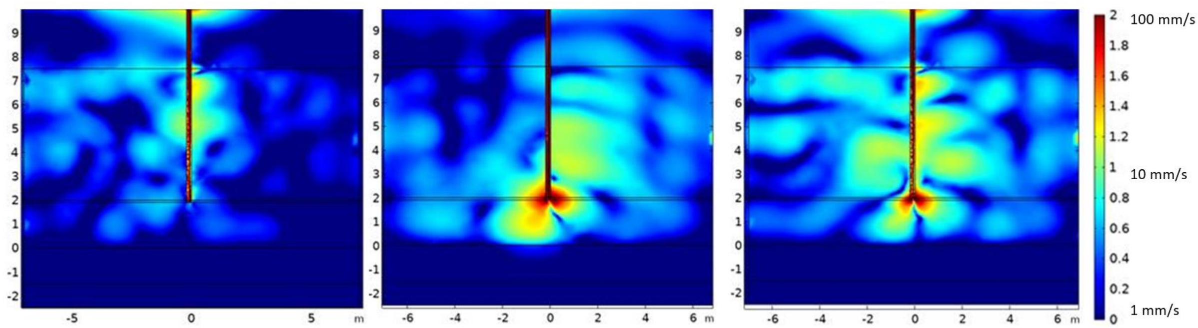

Figure 4. Vibration amplitudes in the horizontal (y-) direction for (a) Case 1, (b) Case 2 and (c) Case 3.

Table 2. Vertical vibrations from top, middle, and toe of the sheet pile, expressed as accelerations.

	Acceleration amplitude (m/s^2)		
	Top	Middle	Toe
Case 1	285	276	252
Case 2	284	278	262
Case 3	283	277	257

Even though the vibration amplitudes are derived from a non-linear calculation, Figure 3 and 4 show that Case 3 is approximately the sum of Case 1 and 2.

The non-symmetrical vibration pattern in the soil comes from the use of a true sheet pile geometry. If e.g. a pipe pile is vibratory driven the wave pattern would probably be more symmetrical.

Regarding the vertical vibration amplitudes, see Figure 3, both the shaft and the toe contributes significantly to the vibration level in the soil. The toe contributes more to vibrations at depth while the shaft seems to contribute more to vibrations closer to the ground surface.

When studying the horizontal vibration amplitudes, see Figure 4, it appears that the toe contributes more to the vibration level in the soil than the shaft. It appears that the vibrations from the toe in Figure 4b is travelling towards the surface, indicating that the horizontal vibrations emanating from the toe would contribute to the vibration level on the ground surface.

It is likely that for a shallow penetration depth the toe will mostly contribute to the vibrations and with increasing penetration depth the shaft would dominate the contribution to the ground vibration level. If the toe would penetrate a stiffer soil layers or hit blocks it is likely that the toe's contribution to the ground vibration level will increase and it might also cause damage to the sheet pile. However, to fully confirm this a larger model would be necessary as well as the study of several different penetration depths.

5 CONCLUSIONS

In this paper the major vibration source during vibratory sheet pile driving is investigated using a three-dimensional finite element model.

The results of presented numerical study provides a better understanding of the transfer of vibrations from sheet pile to soil.

It can be concluded that the attempt to numerically control the vibration source on the sheet pile by replacing the soil with a void below the toe respectively around the shaft is successful.

From the analysis of the results it can be concluded that the hypothesis that the shaft is the major contributor to vibration level in the ground cannot be neither confirmed nor rejected. During vibratory driving in clay the contribution from toe and shaft to ground vibration depends on the sheet pile penetration depth. The results indicate that the shaft is the major contributor to vibration level in the ground when large parts of the shaft has penetrated the ground. The toe causes most of the ground vibrations for shallow penetration depths.

To fully study the contribution from the toe respectively the shaft a model including a larger soil volume would be necessary. I would also be useful to study further the contribution from the different parts of the sheet pile at different penetration depths. Further studies are needed in other ground conditions, e.g. driving the toe through stiffer soil deposits or hitting blocks may cause larger ground vibrations.

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7 REFERENCES

Athanasopoulos, G.A., Pelekis, P.C. 2000. Ground vibrations from sheetpile driving in urban environment: measurements, analysis and effects on buildings and occupants, *Soil Dynamics and Earthquake Engineering* **19**, 371-387.

Attewell, P.B., Farmer, I.W. 1973. Attenuation of ground vibrations from pile driving, *Ground Engineering* **3**, 26-29.

Clough, G.W., Chameau, J-L. 1980. Measured Effects of Vibratory Sheetpile Driving, *Journal of Geotechnical Engineering Division* **106**, 1081-1099.

Deckner, F. 2017. *Vibration transfer process during vibratory sheet pile driving – from source to soil*, Doctoral thesis, KTH Royal Institute of Technology, Stockholm, Sweden.

Deckner, F., Viking, K., Guillemet, C., Hintze, S. 2015. Instrumentation System for Ground Vibration Analysis During Sheet Pile Driving, *Geotechnical Testing Journal* **38**, 893-905.

Holeyman, A., Bertin, R., Whenham, V. 2013. Impedance of pile shafts under axial vibratory loads, *Soil Dynamics and Earthquake Engineering* **44**, 115-126.

Lysmer, J., Udaka, T., Tsai, C-F., Bolton Seed, H. 1975. FLUSH A computer program for approximate 3-D analysis of soil-structure interaction problems, Report No. EERC 75-30, University of California, USA.

Michealides, O.D., Bouckovalas, G., Gazetas, G. 1998. Non-linear soil properties and impedances for axially vibrating pile elements, *Soils and Foundations* **38**, 129-142.

Novak, M., Sheta, M. 1982. Dynamics response of piles and pile groups, *Proceedings of the*

2nd International Conference on Numerical Methods in Offshore Piling, 489-507.

Richart, F.E., Woods, R.D., Hall, J.R. 1970. *Vibrations of Soils and Foundations*, Prentice-Hall, Engelwood Cliffs, USA.

Whenham, V. 2011. *Power transfer and vibrator-pile-soil interactions within the framework of vibratory pile driving*, Doctoral thesis, University of Louvain, Belgium.