6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Vibration Transfer During Sheet Pile Driving – A Full-Scale Field Test

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ABSTRACT

Vibration transfer between sheet pile and soil during vibratory driving is commonly modelled using theory developed for impact pile driving. However, field observations and previous literature show that a driven sheet pile vibrates both vertically and horizontally. A transfer of vibrations to adjoining sheet piles in the sheet pile wall can also be observed. Results from a full-scale field test are presented showing that driven sheet piles vibrate both horizontally as well as vertically and that vibrations to a high degree are transferred to adjoining sheet piles. Based on the results it is suggested that the common vibration transfer model is modified to better capture the real behavior of the driven sheet pile and the adjoining sheet pile wall.

Introduction

Stockholm is currently one of the fastest growing capitals in Europe. New infrastructure and housing are constructed close to existing structures and on land with poor ground conditions. Consequently piles and sheet piles are often a necessity in urban construction projects. However, pile and sheet pile driving give rise to undesirable vibrations that both disturb humans and may inflict damage on property (Wiss; 1967; Hintze et al., 1997; Hope & Hiller, 2000).

New and stricter design codes have emphasized lower limits regarding induced vibrations related to foundation work such as pile and sheet pile driving. The challenge for the contractor is to predict levels of anticipated vibrations at an early stage of a foundation project. An important part in predicting vibrations due to pile and sheet pile driving is to acknowledge the vibration transfer between pile/sheet pile and soil.

The existing model for vibration transfer during vibratory sheet pile driving originates from impact pile driving (Attewell & Farmer, 1973; Martin, 1980; Woods, 1997; Athanasopoulos & Pelekis, 2000). When sheet piles are vibratory driven it can be observed in the field that the driven sheets vibrate both vertically as well as horizontally and that the entire sheet pile wall is set into motion during driving. In literature there are two publications of measurements showing the horizontal motion of the sheet pile (Viking, 2002; Whenham et al., 2009). For a better understanding of the transfer of vibration between sheet pile and soil during vibratory driving this paper investigates the current model for vibration transfer between sheet pile and soil. Results from a full-scale field test are used to verify if modification of the existing model is necessary to better capture the actual behavior of the driven sheet pile and the adjoining sheet pile wall during vibratory driving.

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Vibration Transfer between Pile/Sheet Pile and Soil

Transfer of vibration from pile to soil is commonly described using the concept of two vibration sources, the shaft and the toe, see Figure 1a). Along the shaft S-waves are generated due to friction and propagate outwards from the pile in conical wave fronts. At the toe both P- and S-waves arise, propagating outwards in spherical wave fronts as the pile penetrates into the soil. This conceptual model for vibration transfer originates from impact driven piles (Attewell & Farmer, 1973; Martin, 1980). Over the years the model has been adopted to also apply for vibratory driven sheet piles (Woods, 1997; Athanasopoulos & Pelekis, 2000). However, there are several differences in the vibration transfer process when piles are impact driven and sheet piles are vibratory driven (Deckner, 2013). For example, vibratory driving does not induce a propagating wave in the pile, as opposed to impact driving. Therefore, it has been argued that the conical shape of the wave front propagating from the shaft should instead be cylindrical (Woods, 1997).

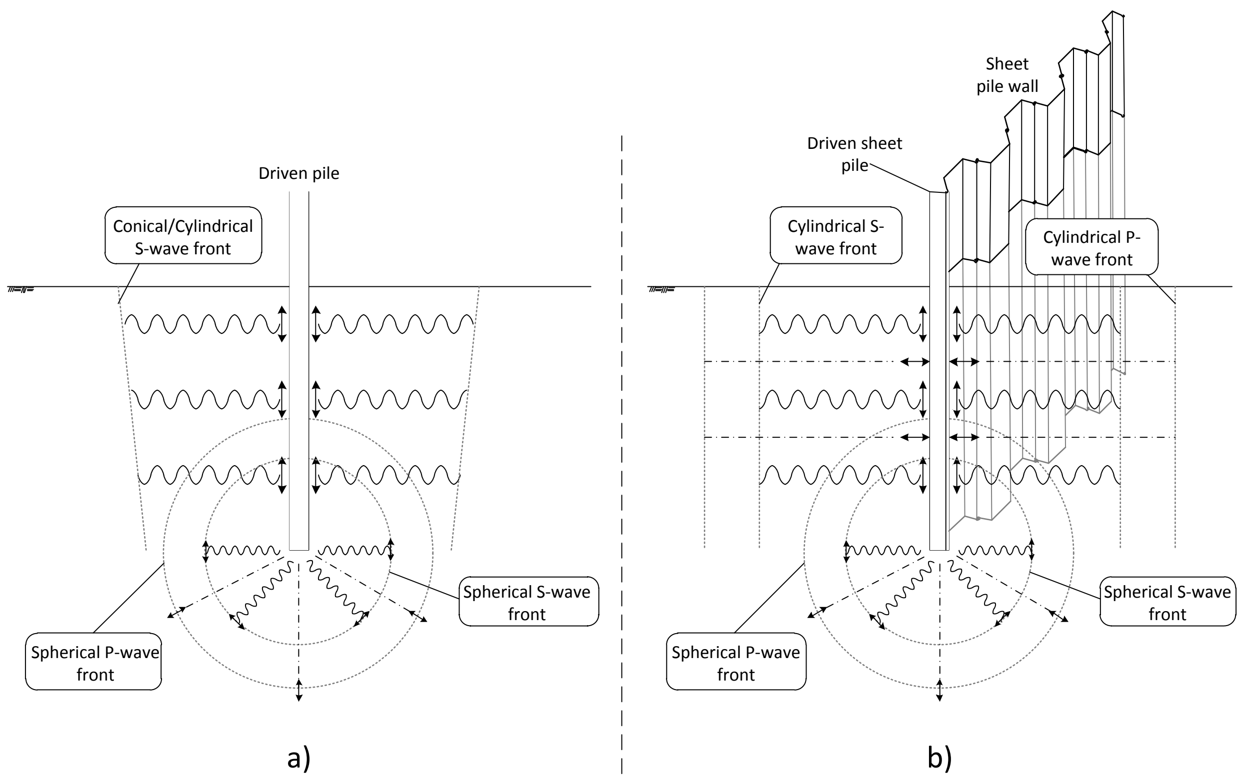

Figure 1. a) Vibration transfer during pile driving, originating from Attewell & Farmer (1973), b) Modified model of vibration transfer during vibratory sheet pile driving.

During vibratory driving the vibrator is constructed to move the sheet pile solely in the vertical direction (Woods, 1997). However, when sheet piles are vibratory driven into the soil it can in the field be observed that the relatively slender cross-sections vibrate horizontally as well as vertically. Two field measurements have previously been performed on sheet piles during vibratory driving; see Viking (2002) and Whenham et al. (2009). Both of these studies show that the sheet pile vibrates extensively in the horizontal longitudinal direction during driving. An extensive horizontal motion would cause the sheet pile to hit the soil along the shaft. The impact would give a compression wave (P-wave) propagating away from the sheet pile shaft. Figure 1b) illustrates the effect of the horizontal motion; a cylindrical P-wave front propagating outwards from the shaft.

During sheet pile driving individual sheet piles are driven in interlock in order to create a sheet pile wall. As a sheet pile is driven in interlock vibrations are transferred both to the soil and to adjoining sheet piles. If the vibration of the adjoining sheet pile wall is extensive it will contribute to the transfer of vibrations to the surrounding soil during driving. Therefore, it is reasonable to say that the adjoining sheet pile wall should be included in the vibration transfer model, see Figure 1b).

Full-Scale Field Test

A full-scale field test was performed in Solna, a suburb to Stockholm, Sweden. In total seven sheet piles were driven and accelerations were measured on three of the sheet piles as well as at different depths in the ground at different distances from the sheet pile line. A thorough description of the field test can be found in Guillemet (2013).

Sheet pile accelerations were measured at three positions (top, middle and toe) on three sheet piles, using triaxial accelerometers. A plan view of the driven sheet piles is presented in Figure 2a), a side view showing the position of sensors as well as soil profile is illustrated in Figure 2b) while Figure 2c) shows a photo of the field test. The sheet piles driven during the field test were used Larssen 603. The five initial sheet piles (SP1-SP5) were 13.8 m long and driven to bedrock and the last two (SP6, SP7) were 11 m long and driven into the moraine. The driving equipment consisted of a Liebherr piling- and drilling rig (LRB 125 XL) equipped with a high frequency vibrator (Liebherr 1100H). The field test was divided into seven measurement series (series 1-7) each corresponding to the driving of one sheet pile, driving of SP1 = series 1 etc.

Results

Results from the full-scale field test of vibratory driven sheet piles are presented to verify the modification of the vibration transfer model. To determine if the horizontal vibration of the driven sheet pile is sufficient to contribute to the vibration transfer the vibrations in the longitudinal and transversal directions of driven sheet piles are investigated. Figure 3 shows acceleration measured on SP4 during series 4 as acceleration envelopes (one absolute maximum value per second). The accelerations are shown in the vertical, longitudinal and transversal direction. It can be seen that the acceleration in the horizontal and especially longitudinal direction are as large as the vertical accelerations in the top acceleration transducer (SP4-1). In SP4-3 the vertical accelerations are considerably higher, something that can be due to stress waves in the sheet pile due to impact against the soil at the toe, as discussed in Viking (2002). The increase in acceleration between 80 and 90 seconds is consistent with the time of driving when the sheet pile toe enters the moraine layer. The main frequency of the recorded accelerations generally corresponds to the driving frequency of 35 Hz. In Table 1 maximum accelerations for the driven sheet piles are summarized. It is clear that the maximum acceleration is considerable in all three directions.

Table 1. Maximum accelerations measured on sheet piles during driving in the three perpendicular directions, - = no record of that sensor.

Series	Sensor	Vertical $a_{V,max}$ (g)	Longitudinal $a_{L,max}$ (g)	Transversal $a_{T,max}$ (g)
1	SP1-1	56.0	56.7	21.5
	SP1-2	-	17.0	27.4
	SP1-3	77.5	50.7	59.1
2	SP2-1	38.4	52.3	12.1
	SP2-2	-	28.4	11.3
	SP2-3	52.0	32.3	28.3
4	SP4-1	48.9	45.3	31.2
	SP4-2	-	39.3	19.6
	SP4-3	78.0	21.5	12.9

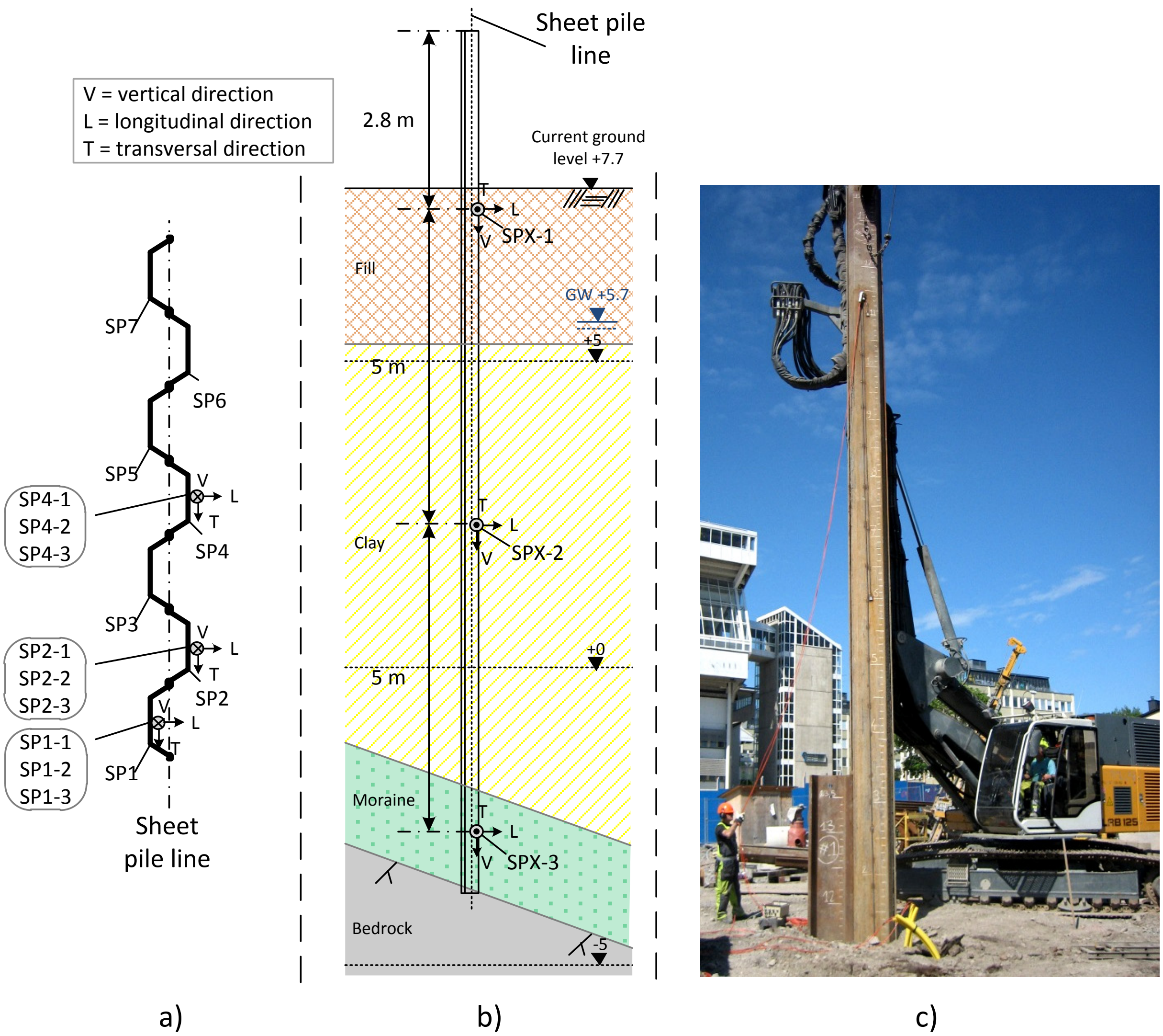

Figure 2. Field test setup of sheet pile instrumentation from a) above, b) from the side and c) photo showing the driving of SP2. A Characteristic soil profile is illustrated in b).

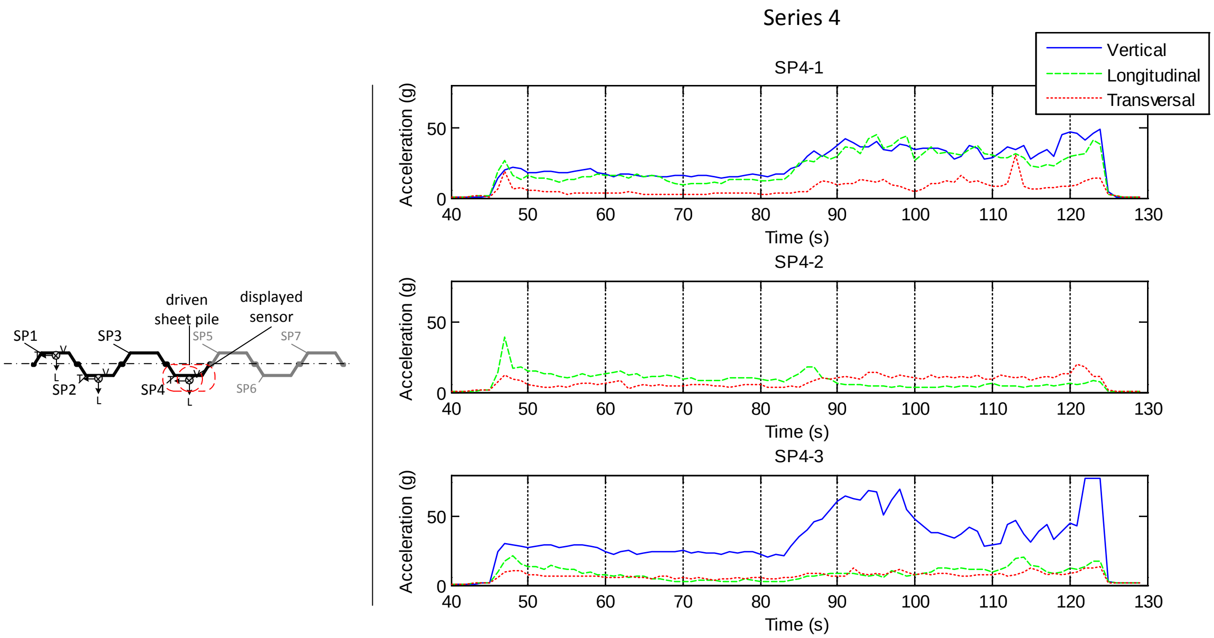

Figure 3. Acceleration envelopes of SP4 during series 4. There is no record of the vertical component in SP4-2.

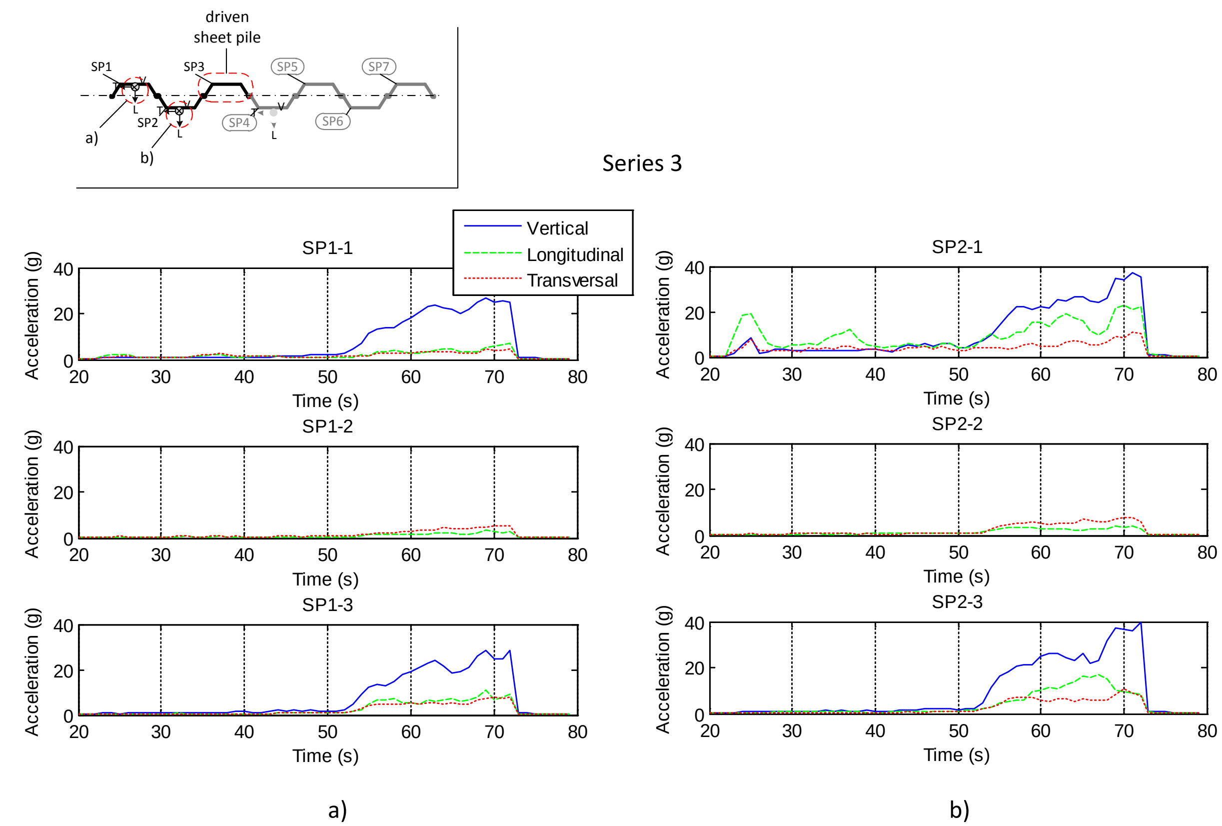

Figure 4. Acceleration envelopes of a) SP1 and b) SP2 during series 3. There is no record of the

vertical component in SP1-2 and SP2-2.

To investigate vibration transfer to adjoining sheet piles, accelerations on installed sheet piles were recorded during driving in several series. In Figure 4 accelerations recorded on SP1 and SP2 during series 3 are shown. The accelerations are relatively high both on SP1 and SP2. In Figure 5 accelerations recorded on SP1 during series 7 are shown. The magnitude of the accelerations is small compared to the accelerations in Figure 4.

Table 2 includes a compilation of PPA's (peak particle acceleration as maximum instantaneous resultants) for the top and toe sensors on installed sheet piles during driving of sheet piles further along the sheet pile wall. From the results it can be deduced that it is not conclusive that the sheet pile closest to the driven sheet pile experiences highest vibration. However, it is evident that the adjoining sheet piles vibrate with considerable magnitude, which could add to the transfer of vibrations to the soil.

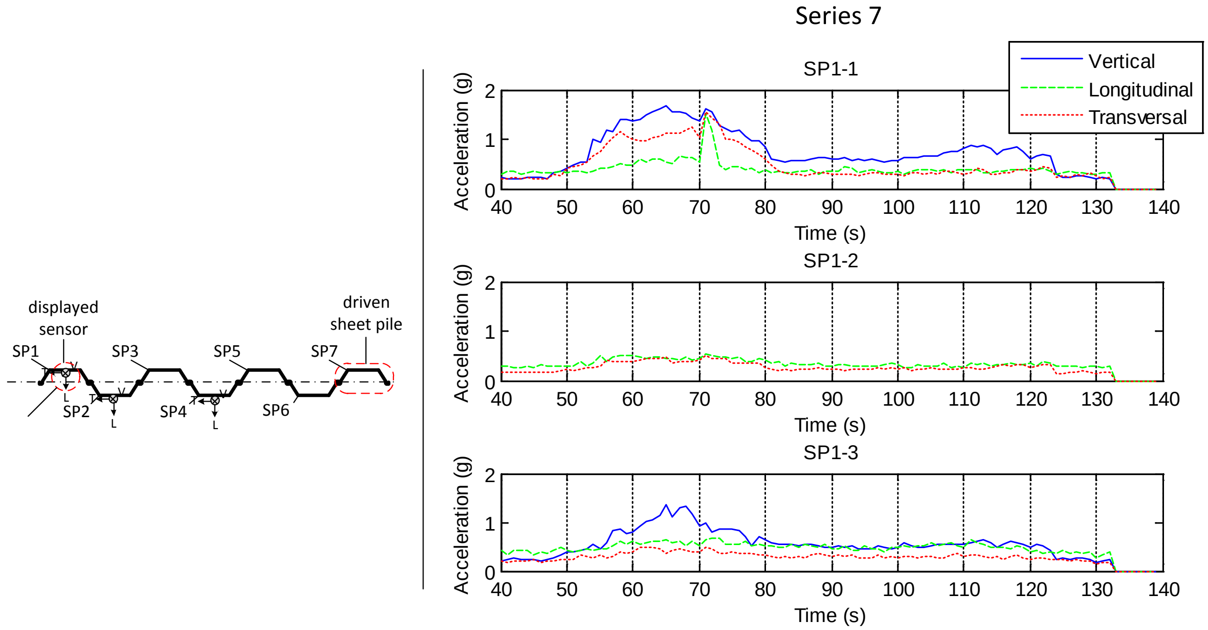

Figure 5. Acceleration envelopes of SP1 during driving of SP7. There is no record of the vertical component in SP1-2.

Table 2. Maximum PPA of sensors on installed sheet piles during driving of different series. - = no record in that series.

Sensor	**PPA (g)**			
	Series 3	**Series 5**	**Series 6**	**Series 7**
SP1-1	26.6	30.7	44.1	1.9
SP1-3	28.9	10.4	4.7	1.4
SP2-1	37.1	23.0	-	-
SP2-3	40.3	24.1	-	-
SP4-1	-	80.0	-	-
SP4-3	-	68.4	-	-

Discussion

The model in Figure 1a) has been used to visualize vibration transfer from sheet pile to soil during vibratory driving. Experience from construction projects and from literature (Viking, 2002; Whenham et al., 2009) shows that the sheet pile vibrates extensively in the horizontal direction during driving. Field observations also indicate that vibrations are transferred to adjoining sheet piles during driving.

The results from the full-scale field test clearly show that the driven sheet pile vibrates in the horizontal directions. The results also indicate that adjoining sheet piles vibrates extensively during driving. Nevertheless, the results from this field test indicate that it is not likely to believe that the whole sheet pile wall contributes to transferring vibrations to the soil.

If the results from this study are compared with the model in Figure 1a) it appears that a modification of the model is necessary to capture the true behavior of a vibratory driven sheet pile and the adjoining sheet pile wall. It is suggested that a cylindrical P-wave front emanating from the shaft is added to account for the horizontal motion of the sheet pile during driving, see Figure 1b). The results from this study are not conclusive regarding whether the adjoining sheet pile wall contributes to the vibration transfer to the soil or not. The results show that vibrations are transferred to adjoining sheet piles to a high degree, however, further studies are needed to investigate if the entire sheet pile wall contributes to vibration transfer to the soil.

The vibrator only moves the sheet pile in the vertical direction during driving; nevertheless it is evident that the sheet pile vibrates extensively in the horizontal directions as well. The horizontal motion is probably caused by some kind of bending. In Viking (2002) it is discussed that the bending is caused by clamping the sheet pile eccentrically during driving. Another possible reason is that the vibration mode of the sheet pile is affected by the driving frequency, causing the sheet pile to bend during driving. However, the natural frequency of the embedded pile would differ during driving as it penetrates further into the soil. Further research is needed to investigate the cause of the horizontal motion of the sheet pile during vibratory driving.

Conclusions

In the present paper attention has been focused on vibration transfer between sheet pile and soil during vibratory driving. This vibration transfer has until now been described using the conceptual model for vibration transfer that originally was developed for impact driven piles. A new way of looking at vibration transfer from sheet pile to soil during vibratory driving is presented. Results from a full-scale field test are shown to verify the theory.

From the study the following conclusions can be drawn:

- During vibratory driving the driven sheet pile vibrates extensively in the horizontal directions.
- Vibrations are to a high degree transferred to adjoining sheet piles in the sheet pile wall.
- A cylindrical P-wave front emanating from the shaft should be added to the model of vibration transfer during vibratory sheet pile driving.

Experience from the field and former studies (e.g. Athanasopoulos & Pelekis, 2000; Viking 2002; Whenham et al., 2009) have shown that in reality vibratory sheet pile driving is complex, containing a huge number of varying parameters. However, an improvement of the vibration transfer process is one step of making the complex process more understandable. A better understanding of the vibration transfer process can lead to a better control of the induced ground vibrations in the future, which is vital for the construction industry.

Acknowledgments

The authors wish to acknowledge the financial supporters of this research project; the Development Fund of the Swedish Construction Industry (SBUF), NCC Construction Sverige AB, Hercules Grundläggning AB and KTH Royal Institute of Technology.

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