Full scale sheet pile vibro-driving tests

Essais de vibrofonçage en vraie grandeur

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ABSTRACT

Full-scale experimental tests have been performed to study the installation of sheet piles using vibro-driving techniques. The tests took place at the Belgian Building and Research Institute (BBRI) test site located in Limelette, Belgium in October 2007. The main objective of the tests was to characterize sheet pile vibrodriving as a whole process by involving energy consumption records together with stress wave measurements on the sheet pile and soil particle velocity measurements at the soil surface and at depth. Another objective of the tests was to quantify the lateral vibrations undergone by the sheet pile during the vibro-driving process. This paper gives an overview of the measurements performed and of the obtained results.

RÉSUMÉ

Des essais en vraie grandeur ont été réalisés pour étudier la mise en place de palplanches par vibrofonçage. Les tests ont eu lieu en octobre 2007 sur le site du Centre Scientifique et Technique de la Construction (CSTC) situé à Limelette, en Belgique. L'objectif principal des essais était de caractériser le processus de vibrofonçage en enregistrant les paramètres de consommation d'énergie et de propagation d'onde dans la palplanche, ainsi que les vitesses particulaires du sol, en surface et en profondeur. Un autre objectif était de quantifier les vibrations latérales subies par la palplanche pendant le vibrofonçage. Cet article donne un aperçu des mesures réalisées et des résultats obtenus.

Keywords : vibratory driving, full scale tests, instrumentation, energy consumption, lateral vibrations, sheet pile behaviour

1 INTRODUCTION

Although the vibratory driving technique is one of the most common way to drive a pile or sheet pile into the ground (at least in soft soil conditions), little is mastered by the engineer when it comes to addressing issues such as the vibratory penetration resistance of the installed pile, the performance of vibrators or vibratory nuisance to the environment. Because of the difficulty to accurately represent the mechanisms at play, experimental observations, by preference by means of extensively instrumented real scale driving tests, constitute a valuable tool to tackle these issues.

Early full scale programmes have been conducted by Barkan (1963) and Davisson (1970). More recently, full scale experimental results have been published in (BBRI 1994, Viking 2002, Holeyman et al. 2002, Gonin et al. 2006, Whenham et al. 2006, Meijers 2007). In BBRI 2004, results from 21 test sites located in Belgium have been compiled, with penetration velocity records, acceleration and strain measurements on the sheet piles. The BBRI research program led to the development and validation of two analytical models with the aim to predict drivability and/or vibration nuisance in the surroundings (Holeyman & Legrand 2004). In Viking (1999), results of 2 full-scale field tests (located in Sweden) have been published, along with comparisons with two prediction models (Vanden Berghe & Holeyman 1997, Vanden Berghe 2001). Both the driveability and the ground vibrations generated during driving were continuously monitored, as well as both the axial and lateral accelerations of the sheet pile. In the proceedings of the TRANSVIB 2002 & 2006 conferences (Holeyman et al. 2002, Gonin et al. 2006), experimental results from 3 test sites obtained within the framework of a French National Project on Vibratory Driving have been presented. Pile penetration velocities, soil resistance parameters and soil vibrations were continuously monitored. Whenham et al. (2006) have proposed a detailed analysis of a full scale sheet pile driving test, with focus on the question of energy consumption during the sheet pile vibrodriving process. Meijers (2007) has detailed a large scale test performed in The Nederlands with focus on soil vibrations and settlements.

The present paper gives an overview of full-scale experimental tests performed at the test site of Limelette (Belgium) to study specific questions such as the influence of vibratory parameters and sheet pile profile movements on the vibratory penetration resistance of piles, the performance of vibrators, and vibratory nuisance to the environment. A series of 11 driving and extraction tests have been conducted. The same fully instrumented sheet pile (double crimped pile) was used for all the tests, but different driving parameters were adopted for the vibrator (driving frequencies varying from 20 to 38Hz, displacement amplitudes varying from 1.4 to 4.5mm), as well as different clamping systems (simple or double clamps).

2 GEOTECHNICAL CONTEXT

A Cone Penetration Test with electrical cone (CPT-E) was performed in the axis of each test position, before and after the sheet pile driving and extraction tests. The objective was to observe a potential soil densification due to the vibrodriving

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process. Figure 1 shows the locations of the tests on a site plan. CPT-E profiles are given in Figure 2, along with the soil profile as interpreted from the CPT-E as well as additional borings carried out at short distance from the test site. Cone tip penetration resistances do not show any variation after completion of the tests, while the friction ratios seem to be reduced 3 months after the driving process (Figure 2). No soil related rational explanation could be found for this decrease in soil friction, except a possible deviation in the calibration of the friction transducers. This illustrates the difficulty to obtain reliable friction measurements with a cone penetration test.

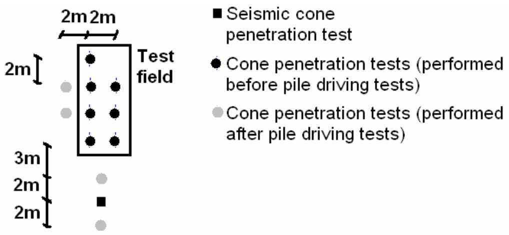

Figure 1. Implantation of the CPTs and sheet pile driving tests

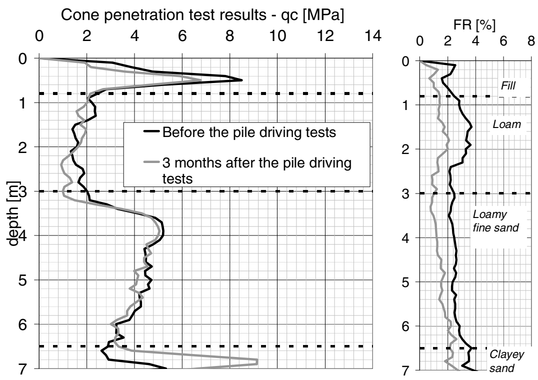

Figure 2. CPT results

Seismic Cone Penetration Tests (SCPT) have also been performed to derive small shear modulus profiles (Figure 3).

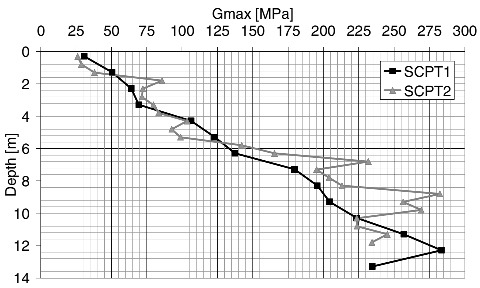

Figure 3. Small strain shear modulus deduced from seismic cone penetration tests results

The groundwater was reported by previous researches to be approximately at 60m depth.

3 INSTRUMENTATION AND MONITORING

The objectives of the instrumentation were to monitor the main field-related parameters influencing the driveability performance of the sheet pile and the vibratory nuisance to the environment. A special attention was put on energy consumption and influence of lateral movements of the sheet pile on the driving process. Measured parameters are listed in Table 1 together with the associated instrumentation and sampling rates. Instrumentation of the sheet pile included accelerometers positioned along 3 mutually-perpendicular directions (x,y,z) and longitudinal strain gauges set both in line and eccentrically with respect to the neutral axis of the sheet pile. Figure 4 shows the position of the transducers placed on the sheet pile as well as a description of the sheet pile and vibratory equipment.

Table 4. Measured parameters together with the associated instrumentation and sampling rates

Parameter	Instrumentation	Sampling rate
Suspension (holding) force	Force transducer designed by the BBRI	0.5 Hz
Accelerations on the sheet pile	Piezoelectric accelerometers	4096 Hz
Strains (Forces) on the sheet pile	Strain gauges	4096 Hz
Oil flow and oil pressures (in & out) from the hydraulic group	External equipment manufacturer	1 Hz
Soil particle acceleration (at the ground surface)	Piezoelectric accelerometers	2000 Hz
Soil particle acceleration (at depth)	Piezoelectric accelerometers (in the seismic cone)	1000 Hz
Soil particle velocities (at the ground surface)	Geophones	300-2000Hz

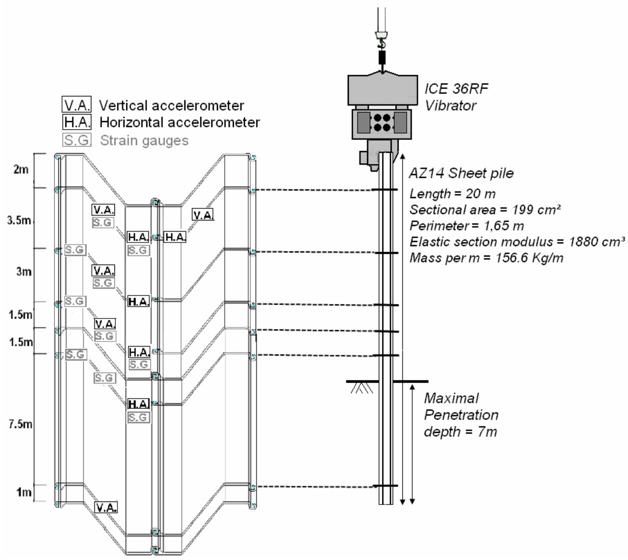

Figure 4. Position of the transducers on the sheet pile along with sheet pile and vibratory equipment

An example of the collected test results is shown in Figure 5 (test Hd). The driving frequency was intentionally varied during the driving process of that particular test. The variation of the driving frequency is depicted along with the corresponding sheet pile penetration velocity and energy consumption.

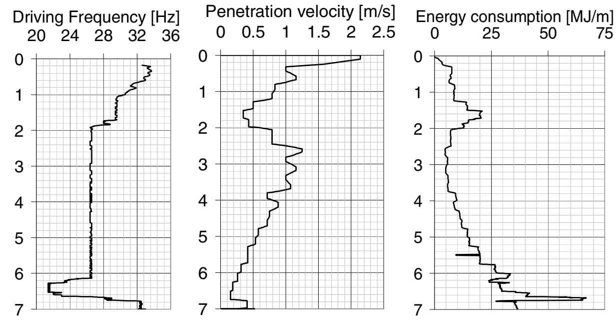

Figure 5. Driving frequency, penetration velocity and energy consumption for test Hd (as functions of the penetration depth)

Test Hd records indicate that refusal was achieved at 6.4m depth when the driving frequency was equal to 20Hz, but that penetration could be continued when the frequency was increased up to 32Hz. This illustrates the effect of the driving frequency on the refusal depth. The driving frequency is not the only parameter that influences the penetration velocity of the sheet pile; also the holding force and soil properties play a significant role.

Energy consumption is directly related to the penetration velocity. Although the power consumption linearly increases with the driving frequency when using a hydraulic group (see Holeyman & Whenham 2008), in the above example, the positive influence of the driving frequency on the sheet pile penetration velocity governs the energy consumption profile.

Details of interpreted accelerometer signals for the same test are provided in Figures 6 & 7. Accelerometers positioned along the vertical direction show a frequency content diagram highly dominated by the driving frequency applied by the vibrator. Variations in the acceleration amplitudes with the penetration depth can be directly related to the variations in driving frequency (figure 5). Comparison of the vertical accelerations obtained at different distances from the sheet pile top does not show significant differences. Elastic properties of the sheet pile however cannot be neglected as they influence the transmission of the driving force from the vibrator to the sheet pile (see Figure 8). In the frequency diagram of the horizontally directed accelerometers, harmonic frequencies are much more developed, possibly indicating that the vibrations never achieved a steady state condition in the horizontal direction. Profile of horizontal accelerations can also be related to the variation of the driving frequency. Besides, horizontal accelerations depend on the distance from the sheet pile top. It can be globally observed that the amplitudes of horizontal accelerations are far from negligible when compared to that of the vertical ones.

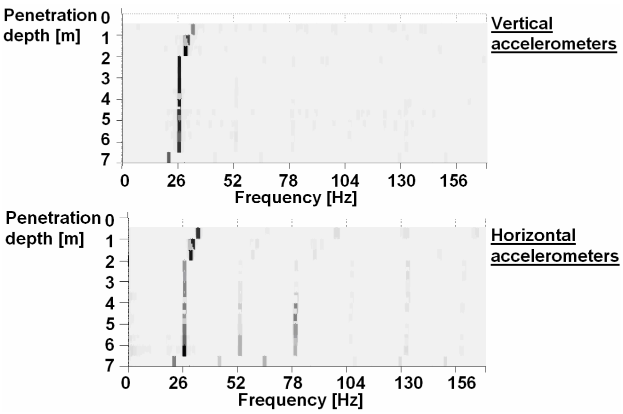

Figure 6. Spectral analysis of vertical & horizontal sheet pile accelerations at 2m, 5.5m & 8.5m from top of the sheet pile (Hd test)

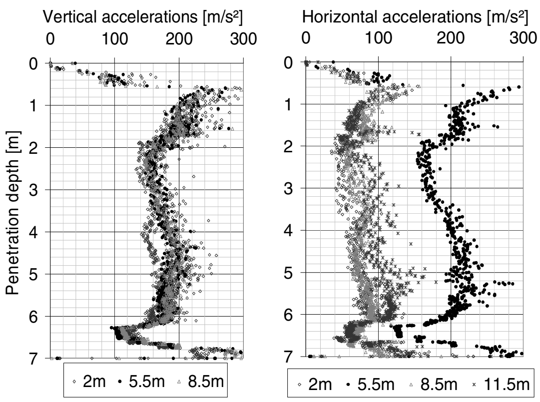

Figure 7. Vertical & horizontal acceleration amplitudes of the sheet pile measured at 2m, 5.5m and 8.5m from top of the sheet pile (Hd test)

Results obtained from the strain gauges transducers are presented in Figure 8. The theoretical "static" part of the driving force (deduced from the suspension force exerted by the crane on the vibrator) is compared with the average part of the forces measured at different levels on the sheet pile (and corrected by the pile weight). The alternating part of the measurements is compared with the vibratory force theoretically transmitted to the top of the sheet pile, assuming (a) that the pile behaves as a rigid body and (b) that the pile behaves as an elastic body. The sheet pile behaviour is far different from that of a rigid body. This is due to the high flexibility of the sheet pile and to its slenderness as compared to the heavy vibrator used for the tests.

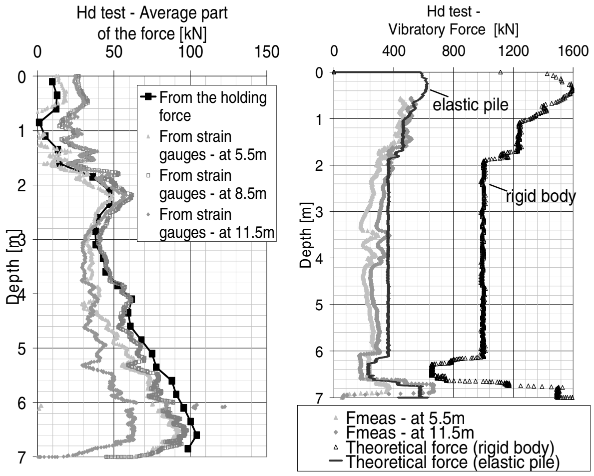

Figure 8. Strain gauges transducers results (measurements performed at 5.5m, 8.5m and 11.5m from the sheet pile top) as a function of the penetration depth

Bending moments can be deduced from the strain gauges (total stresses) positioned eccentrically from the neutral axis are presented in Figure 9.

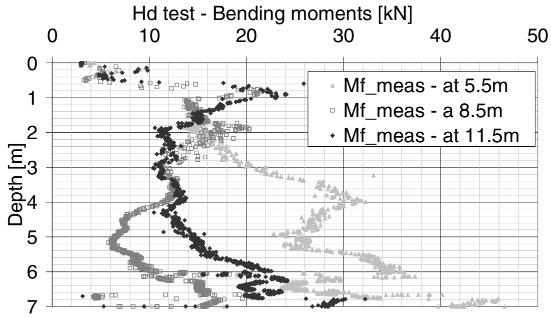

Figure 9. (Total) Bending moments deduced from strain gauges measurement performed at 5.5m, 8.5m and 11.5m from the sheet pile top (as a function of the penetration depth)

Monitoring of the surrounding soil consisted mainly of soil-particle velocity and radial vibration measurements recorded both at the ground surface and at depth using SCPT equipment, at distances varying from 3m up to 40m from the sheet pile. A dual seismic cone provided vibration measurements from various depths in the soil. Figure 10 presents geophones and accelerometers measurements obtained for the same test Hd, both in the vertical and horizontal directions. Variation of soil particle velocities results from a combination of variations in soil resistance, driving frequency and penetration velocity. An increase in soil resistance as well as a decrease in penetration velocity clearly leads to increased soil particle velocities. The influence of the driving frequency depends on the site stratification and soil properties and is therefore much more difficult to characterize.

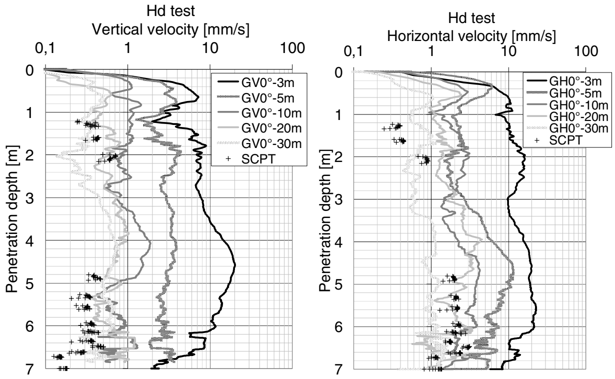

Figure 10. Soil particle velocities measured for test Hd. GV(H)-…m = Geophone measuring the vertical (horizontal) direction, at a distance of m from the sheet pile. The SCPT measurements have been performed at a distance of 9m from the pile, at a depth of 3.9m.

4 GENERAL OBSERVATIONS

Beside obtaining experimental data to be compared with improved vibrodriving prediction models taking into account more accurate sheet pile and vibrator-power pack properties, the objectives of the tests were to investigate the influence of driving parameters on the sheet pile penetration velocity and energy consumption.

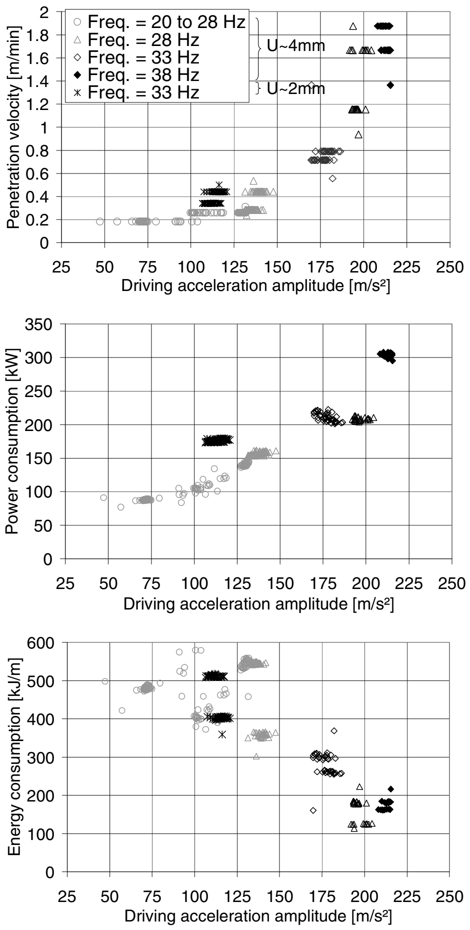

Figure 11. Penetration velocity, power and energy consumption obtained for the 11 driving tests as a function of the driving acceleration amplitude (for a pile penetration depth between 6 to 6.5m)

For example, Figure 11 depicts the influence of the driving acceleration amplitude on sheet pile penetration velocity and energy consumption, as deduced from a global analysis of the results collected from the 11 tests performed. In spite of the power consumption rise related to an increase in acceleration amplitude (in particular if obtained from a higher driving frequency), the resulting increase in penetration velocity leads to lower global energy consumption.

5 CONCLUSIONS

The aim of this paper was to give a general overview of measurements performed within the framework of a full scale sheet pile test campaign, conducted at the test site of BBRI (Belgium). A large number of measurements have been acquired to characterize the sheet pile behaviour as well as the energy consumption during the vibrodriving process. Such results will be used to validate improved vibratory driving prediction models that should include a better description of the sheet pile and vibrator-power pack behaviour as well as an evaluation of the energy consumption related to the driving process.

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