Sheet pile vibro-driving: Power pack-vibrator-sheet pile-soil interactions

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ABSTRACT: Performance of sheet pile vibro-driving results from power pack-vibrator-sheet pile-soil interactions. Numerous studies have dealt with pile-soil systems while a more limited number of studies have been conducted on the mechanisms of vibrator-pile-soil interplays. To the authors' knowledge however, none of the models currently available includes the influence of the power pack-vibrator interaction, although experimentally evidenced. This paper aims to discuss the interactions between the power pack, the vibrator and the pile-soil system during the vibro-driving process, from both theoretical and experimental approaches.

1 INTRODUCTION

Engineering issues related to vibratory driving of piles and sheet piles cover many facets including the long-term bearing capacity of the installed pile, its vibratory penetration resistance, the performance of vibrators and vibratory nuisance to the environment. Nowadays these issues are tackled independently from each other. Besides, most studies focus on the pile-soil interaction, without explicit consideration for the interaction between the pile and vibrator and/or power pack.

In this paper, an attempt is made to address these questions within a unique framework where the understanding of the power transfer mechanisms is the key. When focusing on power transfers, the vibro-driving process can be considered as an interaction between three systems:

- The hydraulic group (power pack) constitutes the source of power for the whole system.
- The vibrator provides the vibratory motion to the pile-soil system.
- The pile-soil system constitutes the main actor in the dissipation of power. Part of the power is absorbed in advancing the pile, and much of the remaining power is transmitted into the ground in the form of outgoing waves.

A comprehensive description of the vibratory equipment is first presented. Based on this description, current understanding of the different levels of interactions between power pack, vibrator, pile and soil is discussed, and illustrated with experimental data. Finally conclusions in terms of modeling implications are proposed.

2 VIBRATORY EQUIPMENT

The vibratory equipment mainly includes a power pack and a vibrator. The power pack (most often a hydraulic group) is essentially composed of a diesel motor coupled to a hydraulic pump. It constitutes the source of power for the whole system, from which the total power consumption can be evaluated. The power pack interacts via hydraulic hoses with the vibrator, essentially composed of a hydraulic motor activating the eccentrics that give the vibratory motion to the pile-soil system.

2.1 Power pack

The power pack can be an open or closed loop hydraulic system. In both cases, a diesel engine drives a hydraulic pump, which in turn drives the motor on the exciter. Frequency and torque can be varied either by using variable displacement pumps in the power pack or by varying the engine speed.

The diesel engine transmits a torque to the pump which depends on rotation speed. The pump converts the mechanical power from the torque and rotation being available at the shaft to pressurize a hydraulic fluid. Upon being pressurized, the fluid flows to the motor on the vibrator through the hoses and other in-line hydraulic components.

Volumetric pump-hydraulic motor systems are generally used because of several advantages: compact dimensions, highly accurate speed modulation, quick response and reversibility offered by pumps and/or hydraulic motors with variable displacement and intrinsic safety (Warrington,1992).

2.2 *Vibrator*

The motor converts the fluid power of the hydraulic system back into torque to turn the eccentrics. Most hydraulic vibratory hammers use fixed displacement hydraulic motors. This means that the available power varies proportionally with the speed: for a given hydraulic fluid pressure, the torque is essentially constant. The power available to the vibratory hammer is governed by the differential pressure between the input and output lines of the motor.

3 POWER PACK VS. VIBRATOR INTERACTIONS

3.1 *Theory*

The determining parameter in the power pack-vibrator interaction is the nominal frequency of the vibrator ω_o, which is related to the oil flow rate Q_m in the pump through the volume V_m of the pump.

$$\omega_o = Q_m/V_m \tag{1}$$

Knowing the efficiency curves of the hydraulic pump and the limit of pressure imposed on the system, the nominal frequency allows one to determine the characteristic curve of the pump (oil flow rate-oil pressure relationship), as illustrated in Fig. 1.

Based on this curve, the evolution of the actual vibratory frequency can be expressed in function of the power developed to rotate the eccentrics.

$$P_{group} = (p_{out} - p_{in}).Q.\cos\varphi \tag{2}$$

where:
P_{group}: power developed by the hydraulic pump [kW]
p_{out}, p_{in}: respectively the oil pressures leaving and entering the hydraulic pump [kPa]

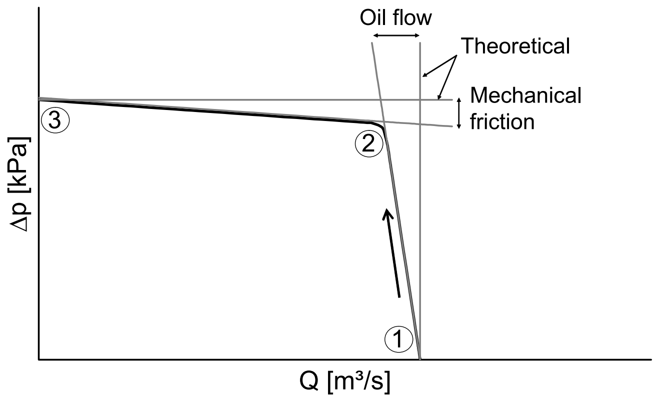


Figure 1. Typical characteristic curve for the hydraulic pump.

Q = oil flow rate [m/s]
Cos φ = efficiency factor [-]

The power demand upon starting the vibrodriving process is minimal and the hydraulic pump operates close to point ① in Fig. 1. As the pile penetrates into the soil, more power is required to overcome the increasing friction and the pressure differential increases towards point ③.

3.2 *Experimental illustration*

The vibrator-power pack interactions can be illustrated by experimental results obtained from two series of full scale driving tests. For both series of tests, oil flow rate and oil pressures have been measured at the output of the power pack (hydraulic pump), and accelerometers have been positioned on top of the sheet piles. The first series of tests have been conducted at Merville in France (Rocher-Lacoste & Gianeselli 2003); the second series of tests have been conducted at Limelette in Belgium in 2007. The information related to the driving equipment used for these tests is summarized in Table 1.

At Merville, a total of 13 different profiles have been vibro-driven. The evolution of dominant frequencies (derived from acceleration measurements) is presented in Fig. 2 in function of the penetration depth, along with the evolution of the power developed by the hydraulic group and calculated using equation (2). Up to a depth of 3.5 to 6.5 m (depending on the sheet piles), a slight decrease in dominant frequencies is observed, as

Table 1. Parameter of the vibrators

Site	Merville	Limelette
Vibrator	ICE 815	ICE 36RF-ts
Power pack	ICE 570	ICE 1000RF

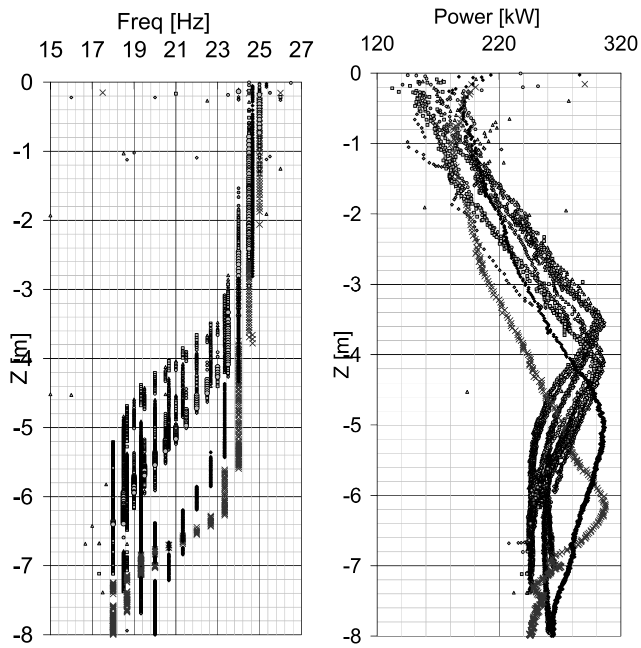


Figure 2. Evolution of – (a) dominant frequencies, (b) power developed by the power pack – in function of the penetration depth – Merville test site.

well as an increase in the power developed by the hydraulic group. This power development with penetration depth is required to overcome the increasing soil resistance. As can be explained by Fig. 1, an increase of the pressure demand in the system (Fig. 3) results in a slight decrease in oil flow rate due to oil leakage (Fig. 4).

At a depth within the 3.5–6.5 m range, the limit of pressure imposed for the power pack is approached (approximately 340 bars on Fig. 3): the power cannot further increase and the dominant frequencies start to significantly decrease. The operating point of the hydraulic pump (Fig. 1) starts moving from point 2 towards point 3. From combination of oil flow and oil pressure measurements obtained during the tests (Fig. 5 and Fig. 6), it is possible to explain the sharp decrease in frequency (or oil flow rate) once

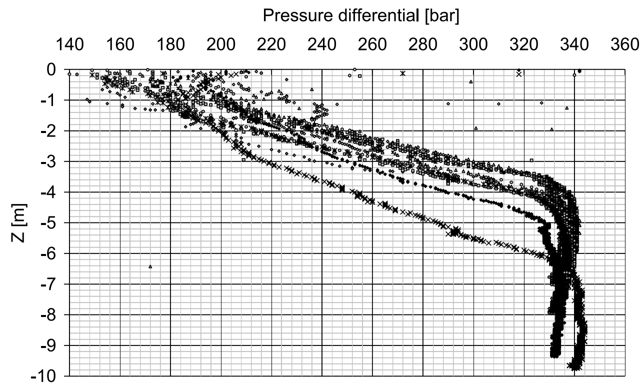


Figure 3. Oil pressure in function of penetration depth – Merville.

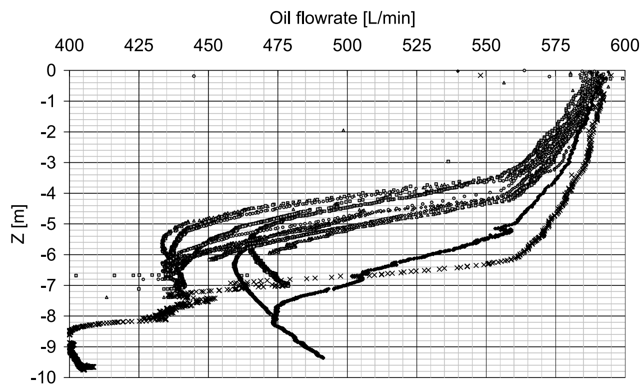


Figure 4. Oil flow rate in function of penetration depth – Merville.

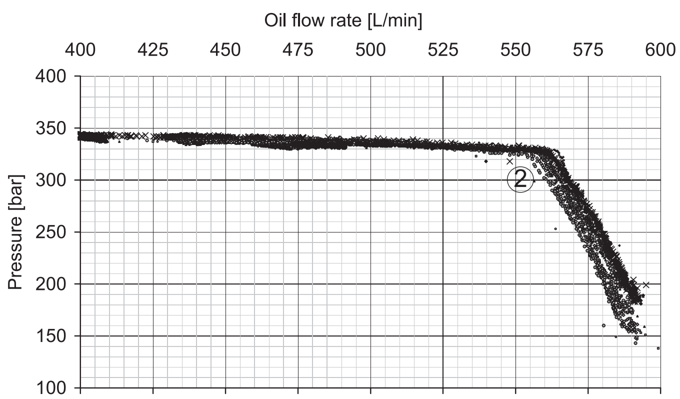


Figure 5. Oil flow rate vs. oil pressure relationship for the hydraulic pump, derived from experimental results – Merville.

the maximal power/pressure is reached. Fig. 5 is similar to the theoretical characteristic curve (Fig. 1). In Fig. 6, the oil flow rate is expressed as a function of the power developed by the power pack. From Fig.s 5 and 6, it can be observed that once the peak power is reached, a further increase in oil pressure (that cannot be prevented) results in a significant decrease in oil flow rate and thus in driving frequency.

Results from the test site of Limelette (2007) are presented for the comparison in Figs. 7 to 9. In this example, the dominant frequency has been voluntarily varied during the driving phase. Depending on the chosen frequency, different characteristic curves are obtained (Fig. 9).

Contrary to the results obtained at Merville, and for all the investigated frequencies, the power requirement is by far lower than the power available from the power pack and hydraulic pump. Therefore the vibratory parameters are not influenced by the limit of pressure of the power pack, and the frequencies show only a slight decrease with penetration depth.

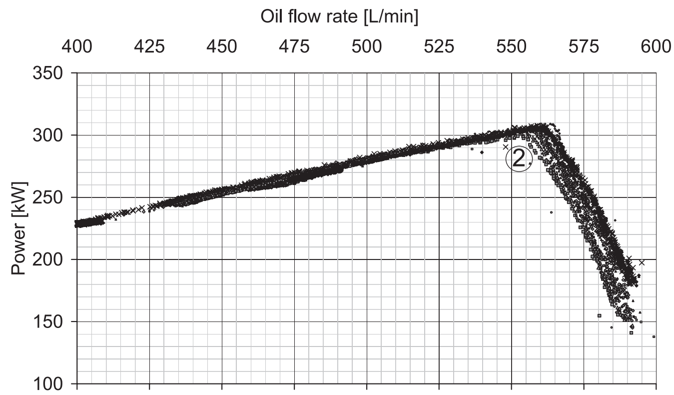


Figure 6. Oil flow rate vs. developed power relationship for the hydraulic pump, derived from experimental results – Merville.

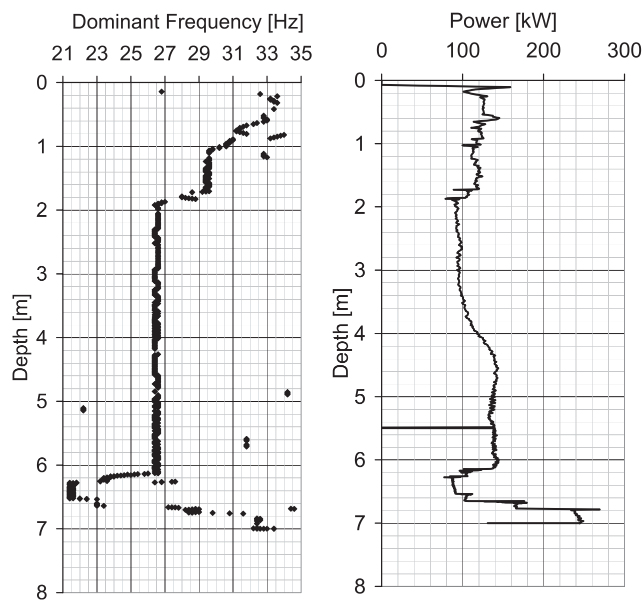
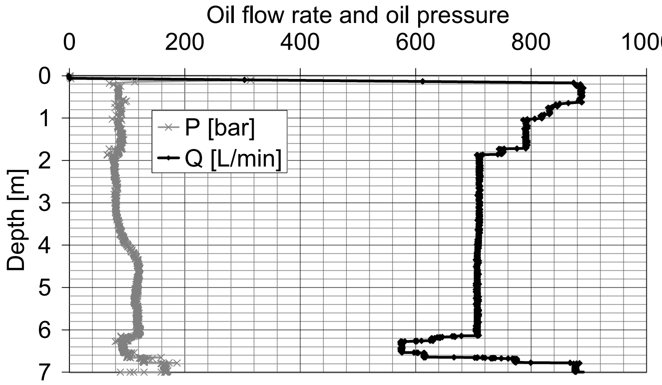


Figure 7. Evolution of – (a) dominant frequencies, (b) power developed by the power pack – in function of the penetration depth – Limelette test site (2007).



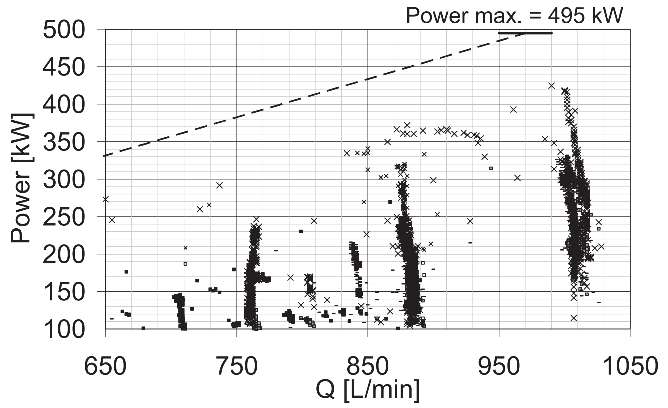


Figure 9. Oil flow rate vs. developed power relationship for the hydraulic pump, derived from experimental results – Limelette.

4 VIBRATOR VS. PILE-SOIL SYSTEM

The above examples show the possibility to predict the evolution of the actual vibratory frequency provided that the power needed to actuate the eccentrics can be evaluated. This required power is directly related to the interaction between the vibrator and the pile-soil system. A number of studies have been conducted on the vibrator-pile-soil interactions. Some of them are summarized below.

4.1 Vibrator-pile interaction

Sieffert (1980) has proposed analytical solutions to derive the power input supplied to the sheet pile and the average power dissipated by skin friction forces at the soil-pile interface. In further studies (Sieffert & Levacher 1982, Sieffert & Billet 1985, Billet & Sieffert 1985), he has completed its theoretical approaches with laboratory experimental investigations. The theoretical calculation of the different powers used required the knowledge of the deformation amplitudes and of the phases of each section of the sheet pile as well as the constitutive elements of the excitator.

Vipulananda et al. (1990) have proposed an empirical relationship (based on laboratory tests) between the power delivered to the pile head and the velocity of penetration v_p in function of the soil conditions (D_r, d_{10}, σ_h). The equations contain implicitly the effects of the interaction of the pile, driver, and soil, through power, velocity and acceleration terms and the soil coefficients and exponents.

Wong et al. (1992) have proposed a model for vibro-driving of rigid piles in sand, incorporating the interaction of the vibrator-pile-soil system. Based on the vibro-driving of a closed-ended pipe pile investigated using a large-scale laboratory testing system, the authors have observed that the measured maximum force at the pile head varied from test to test depending on the soil conditions. The contributions of bias weight and dynamic force transmitted to the pile head are therefore empirically modified through transmission ratios, T_B and T_D, that were determined experimentally to be functions of effective horizontal in situ stress, effective grain size of soil, and relative density of soil.

An experimental study of the power transfers during vibro-driving from the power pack to the sheet pile has been conducted by Whenham et al. (2006). Results came from two test campaigns (BBRI 2003 & 2004) where instrumented sheet piles have been installed and continuously monitored. The piles sheets were vibrated until refusal using a high frequency vibrator. Different approaches corresponding to different levels and assumptions in the global system were used to derive the power consumption during vibrodriving. The power developed by the hydraulic group and deduced from oil flow rate and oil pressure measurements is given in Fig. 10. The power transmitted to the top of the sheet pile (calculated from measurements obtained with strain gauges and accelerometers positioned on top of the sheet pile) is also shown in Fig. 10. Comparison of powers evaluated at different points within the system gives an insight into the power losses between the output of the power pack and the top of the sheet pile.

4.2 Pile-soil interaction

According to Westerberg et al. (1995), the interaction between pile and soil depends on the dynamic

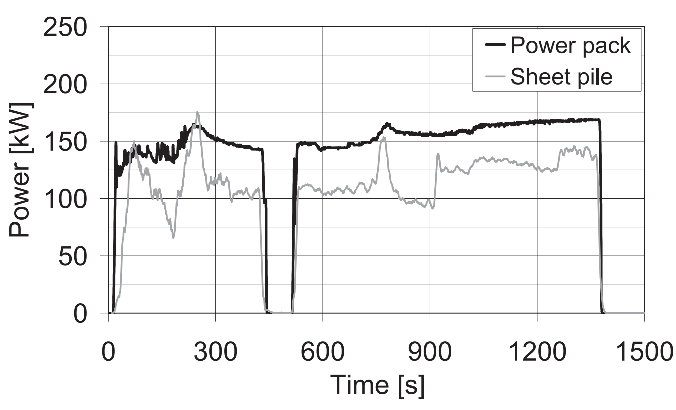


Figure 10. Power developed by the power pack and power transmitted to the top of the sheet pile as a function of time (Whenham et al. 2006).

properties (impedance) of the pile and the behaviour of the soil subjected to dynamic forces. For the assessment of dynamic pile-soil interaction during vibratory driving, resonance effects must also be taken into account. Besides, the location of the source of power transmission from the vibrating pile to the soil depends to a large extent on the soil layers through which the pile is driven.

Resonance between the soil and sheet pile has been studied a.o. by Smith & Po (1988), who tried to gain insight into probable resonance modes by studying the eigenmodes of undamped pile-soil idealization. According to Holeyman (2000), an apparent resonance of soil vibration may however be no more than the transient combination of increased rotation speed and soil degradation. At the beginning, the soil remains in contact with the slowly vibrating profile (coupled mode), and the transfer of power from the pile to the soil is nearly perfect. As the vibrator constantly accelerates, vibration levels tend to increase. However, as the soil begins to degrade, its shear modulus decreases and the specific shear impedance reduces, leading to loss in the power transfer. At that point, the coupling between soil and pile suffers some slippage, and therefore time lag. After a sufficient number of cycles, the soil has significantly degraded, and has entered into liquefaction. The shear modulus of the soil in contact with the profile is nearly zero, and very little power can pass through the fluidized surrounding zone. The soil in the vicinity of the profile cannot anymore follow the profile movement, from which it uncouples itself, resulting in a lower level of transmitted vibration.

Storz (1991) describes other phenomena influencing the soil-pile interaction when dominant tip resistance occurs. According to the author, if stationary solutions have the same frequency as the excitation, dominant tip resistance gives rise to bifurcation phenomena as period doubling, and assuming the limiting case of a Coulomb side resistance and impact type tip resistance, subharmonic and even chaotic motions. These kinds of movements were observable from results obtained at the test site of Montoir (Arnould et al, 2005).

5 POWER PACK VS. PILE-SOIL SYSTEM

To the writers' knowledge, none of the currently available modeling methods explicitly considers the influence of the power pack on the vibro-driving behaviour. However the power pack influences the operating parameters of the vibrator and therefore the pile movement and pile-soil interactions. In turn the soil parameters influence the vibrator power requirements and therefore the power pack parameters.

A more exact approach to deal with the soil-power pack interaction should account for the power pack-vibrator interaction combined with the vibrator-pile-soil interactions. However it is also possible to draw a direct relationship between the pile-soil system and the power pack through power considerations. In that case, the influence of the vibrator is simplified, and the characteristic curve of the hydraulic system is directly used to link the evolution of frequency with the power dissipated at the pile-soil interface, assuming constant eccentric moment.

As discussed below, a number of authors proposed various models (semi-analytical or numerical) to calculate the amount of power dissipated in the soil during a load cycle.

5.1 Dissipation of power at soil-pile interface

Trochanis et al (1987) have introduced a model based on a Winkler representation of the soil in order to study the hysteretic behaviour of a pile under arbitrary axial load. The model can account for cyclic quasi-static loading and material degradation using simple rules. It permits calculating the amount of power dissipated in the soil during a load cycle and establishes equivalent viscous damping coefficients for studying the dynamic response of driven piles.

Holeyman (1993) has suggested the use of a radial discrete model to calculate the vertical shear waves propagating away from the pile, using constitutive relationships that take into account main feature of soil cyclic behaviour. That model clearly separates geometric damping from the other power losses. It has been later improved by Vanden Berghe (2001).

Michaelides et al. (1998) focus upon the nonlinear soil response anticipated in the field and established the radial variation of soil properties based on commonly reported experimental data. Semi-analytical solutions have been presented for the corresponding impedance of the springs and dashpots used to represent soil in a Winkler-type analysis of axially vibrating piles. From these impedance values, the total power dissipated at the soil-pile interface can be derived. Besides, the description of the radial variation of soil properties

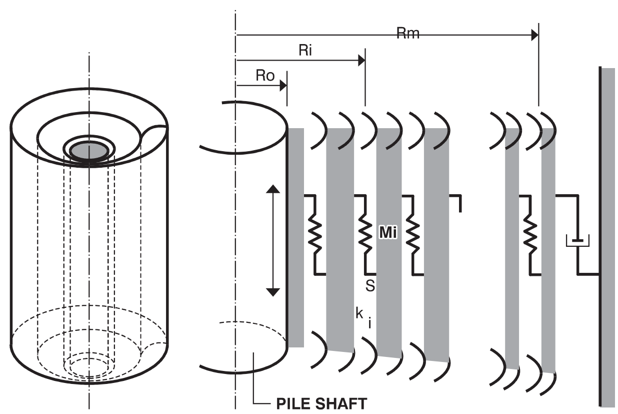


Figure 11. Radial 1-D model (Holeyman, 1993).

allows distinguishing the soil intrinsic power losses from the power losses due to geometric damping.

Ramshaw et al (2000) and Selby (2002) discuss approaches for predicting surface vibrations resulting from vibratory driving. The excitation to the system is by a vector of forces applied to the location of the outer surface of the pile. The total periodic force applied is taken as a percentage of the maximum dynamic force quoted in the manufacturer's literature, taking into account the power dissipation across the localized zone of liquefaction in the immediate proximity to the pile shaft. The surface velocities in both vertical and radial directions can then be displayed as standing waves, for comparison with site measurements of peak particle velocities at a small number of discrete points. The percentage of the input transferred into outgoing ground waves and used to achieve pile penetration can be estimated from back-analyses.

5.2 *Experimental illustration*

From the experimental results obtained during field tests performed for the National Project Vibropiling (at Merville & Montoir, see Arnould et al. 2006), Sieffert (2004) has computed the power dissipated at the pile-soil interface with a distinction between skin friction force and base resistance. At Montoir a close-ended tube (with a length of 32 meters) was driven in a sandy-clay soil down to 18 meters depth. At Merville an open tube and a double sheet pile were driven in Flanders clays. For the test site of Merville, Sieffert could compare these values with the power supplied by the power pack (from oil flow rate and oil pressure measurements).

A ratio of about 50–60% can be observed between the supplied power and the power dissipated along the pile-soil interface for the test site in Merville. At Merville (tertiary clay) the power dissipated along the shaft in higher than the power dissipated at the base. The opposite is observed at Montoir (sand).

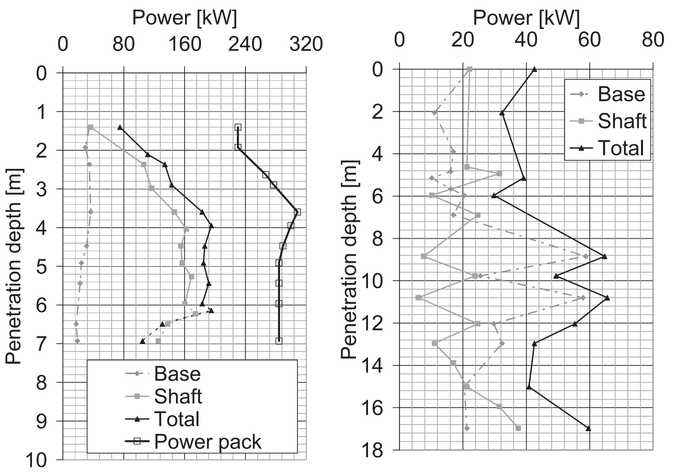


Figure 12. (a) Power developed by the power pack and dissipated by skin friction force and base resistance – Merville, (b) Power dissipated by skin friction force and base resistance – Montoir (Arnould et al., 2006).

6 CONCLUSIONS

From the considerations presented in this paper, it seems possible to:

- Estimate the power consumption during vibro-driving (from both a theoretical and experimental point of view);
- Improve current vibrodriving models which do not take into account the interactions between the power pack-vibrator-pile-soil actors.

Besides, as it should be possible to distinguish the power consumed to liquefy the soil from the power dissipated in outgoing waves, it can be hoped that power transfer analyses would also lead to improved methods for estimating the ground vibrations and bearing capacity.

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