CHAPTER 6
Conclusions and Perspectives

1. Outline of the research

The main purpose of this research was to study the influence of the loading rate on the load-settlement relationship through the results of two testing procedures loading piles with variable durations (Static Load Test (SLT) → Dynamic Load Test (DLT)). Pile load test results belong to two national research programs organised by the BBRI and shortly described in chapter 3 of this thesis. The possibility to compare these measurements obtained on identical piles installed in the same well documented geotechnical environment could result in a better understanding of the loading rate effect within the range of high and low velocities covered by the testing procedures.

The objective was to refine the rheological parameters in relation to the sites investigated and with respect to the loading tests. The goal was also to find a characterisation of the pile/soil interaction system allowing to predict the load-settlement curves of each loading procedure by introducing the corresponding velocity history at the pile head.

This thesis includes a description of the load testing procedures and their main methods of interpretation plus a short description of the wave equation applied to pile dynamic analysis (chapter 1). The loading rate effects through the literature are investigated and approached according to the behaviour evaluation, to the description of this behaviour in simple and general formulations used in the dynamic piling practice and to the lumped models describing the rheologic soil response in terms of rational and fundamental geotechnical parameters (chapter 2).

Moreover, a complete analysis of the dynamic measurements of which the main results are summarized hereafter is presented in chapter 3.

The pile/soil interaction system is modelled by a non-linear mass/spring/dashpot system supposed to represent the pile, the soil and the constitutive relationships existing between them. These relationships account for the static and the so-called dynamic behaviour (chapter3). A back-analysis process based on a matching procedure between measured and computed curves (force/velocity) allows one to describe the pile/soil interaction in terms of constitutive and rheologic parameters based on the dynamic measurements. After optimisation of the matching procedure, the parameters obtained are used to simulate the “static” load-settlement curve to be compared with the measured one.

However, there is a large amount of parameters to be optimised. Since the original procedure performed the matching “manually” by modifying some parameters one by one, it was wished to refine the optimisation phase and to transform it into an automatic process. This will was supported by the requirement to have an impartial, objective and rapid method to optimise all the parameters in the same time. This method was developed and its satisfactory performance was assessed as described in chapter 4. A hierarchy of the parameters based on their relative weight in the optimisation process was highlighted allowing a powerful optimisation by sorting and optimising the parameters by level of influence.

But the strict results of these optimisations resulted in the need of the modification of the basic pile/soil interaction modelling: the pile and the soil have to be differentiated using two degrees of freedom to allow an independent motion of each in case of slippage at their interface. Indeed, the classical model behaved as a moving pile embedded in a motionless soil. Consequently, the pile/soil interaction links the generated stress to the pile motion without considering any slippage at their interface. It has been shown that this constraint results in a questionable optimisation of the initial stiffness and of the unloading parameters (chapter 4) and influences the ultimate soil resistance optimisation.

Chapter 4 provides also a complete back-analysis of the dynamic tests performed on prefabricated piles in both sites of Sint-Katelijne Waver and Limelette. The results are commented and the simulations compared to the static load settlement curves. These analysis are carried out with the model where the soil is motionless and the motion lead by the pile. So these conclusions are still influenced by the unloading phase.

Since the loading stiffness and the ultimate resistance are directly involved in the simulation of the static load settlement curve, it was required to develop a pile/soil model authorizing the slippage at the interface between the pile and the soil (DDOF model – chapter 5). Moreover, a general study of this slippage event was also undertaken in a simplified but complete model (the Cylindrical model – chapter 5) with the aim to describe the spreading of this behaviour in the close vicinity of the pile. Unfortunately, a lack of time prevented the implementation of these models into the general pile/soil system impeding a complete analysis of real dynamic measurements.

The main conclusions of this research are listed by chapter followed by the main practical contributions and the prospective, summarized and described.

2. Conclusions

2.1. The literature review

The literature review presents mainly the loading rate effects occurring during the failure. This affect is described according to a power law of the velocity of the moving body. The exponent of the power law is generally fixed to 0.2 and the rheologic parameter varies with the author, the procedure or the type of soil and testing.

A small analysis has highlighted the danger to reference the relationships describing the loading rate effect to a given velocity considered as the static test reference velocity. This implies a negative influence in the case where the studied velocity is lower than the reference one. A complete loading history where the velocity starts from 0, reaches its maximum value and goes back to zero provides such a case.

The literature presents very little information about the influence of the loading rate during the loading and the unloading stages. The main results concern the failure, namely under large strains and stresses.

The observed trend of the loading rate effect is commonly described by a generic parameter: the rheologic parameter J (Smith, Coyle & Gibson, Case method, …). Despites the fact that many authors tried to correlate this parameter with soil type or other quantities, no satisfactory conclusions can be drawn and one often imposes to confirm the proposed values of J by a field verification under the same loading conditions and by testing a similar foundation.

The models describing the terms of the rheologic soil reaction with rational parameters (primarily of the friction modeling) give a strong importance to the geometric damping. This term is directly influenced by the rate of static soil mobilization and the underlying degradation of the tangent modulus. This term leads quickly the soil to failure in the range of high velocities (like the DLT). Theoretically, the radiation term vanishes when the slippage occurs but since the static soil mobilization is not complete, and the tangent modulus not completely degraded yet, the radiation term does not disappear and still influences the rheologic stress evaluation. That implies the addition of a term assuming to generate an additional stress due to the loading rate in the range of large strain to compensate the vanishing of the radiation term (namely the velocity dependent stress).

2.2. The model and the dynamic measurements analysis

The analysis is mainly focused in the friction modeling. The terms of the rheologic stress include a static, a radiation and a viscous component. These elements are summed and limited by a value (the ultimate rheologic stress) dependent of the velocity and the ultimate static stress. A study showed the influence of the radiation term in the range of the dynamic velocities especially for the stiffness of the stress-displacement curve. At the beginning of the loading, this term is the main component of the rheologic stress due to the rapid increase of velocity and the small mobilized displacement. The failure occurs quickly and the passage to the failure mode is marked by an angular break that might be interpreted as a quake but that is strictly determined by the dynamic behavior. When the static mobilization increases, the importance of the radiation term decreases the degradation while the viscous term (proportional to the velocity and the static mobilization) becomes more important.

The analysis of the measurements of the dynamic load tests showed that there is a link between the maximum settlements, the permanent settlements of the pile head and the drop heights. A critical drop height is defined. If the drop height is smaller than this limit, no permanent settlements occur, if it is higher, the pile significantly settles down. The maximum settlements measured are also influenced because the difference between both settlements is almost constant (= rebound) for a drop height beyond the critical one. The analysis of the maximum quantities (force measured, pile head velocity, energy transmitted to the pile) shows a similar result. There are critical quantities defining the permanent settlement of the pile. For a same pile of similar length, both sites present similar trends and different values. The summary of these quantities is given in Table VI-1. There is a pronounced difference between the clay and the sand.

	Sint Katelijne Waver	Limelette
Critical Drop Height [m]	0.5 – 0.7	1.3 – 1.4
Critical Maximum Velocity [m/s]	1.2 – 1.4	1.5 – 1.6
Critical Maximum Force [MN]	1.9 – 2.0	1.75 – 1.8
Critical Energy [MNm]	0.007	0.012 – 0.03

Table VI-1: Summary of the critical quantities to get significant permanent settlement (prefabricated pile 11 & 13 m long)

The analysis of the Boom clay site measurements including two DLT campaigns separated by one year does not show any marked differences. The analysis of the Bruxellian sand site measurements including the results of two different piles does not show any marked differences.

The relationships between the drop height & the settlements and the enthru & the settlements follow a similar trend: a concave-convex relationship for the permanent and maximum settlements, respectively (Figure VI-1). The relationships between the velocity and the settlements and the force measured and the settlements follow also a similar trend: the superposition of two straight lines with their crossing corresponding to the start of the permanent settlement generation (Figure VI-1).

The expected relationships between maximum quantities (force-velocity related to the nominal pile impedance; and transmitted energy-drop height related to the efficiency of the dropping system) are confirmed and allow one to characterize the quality of the signals (eccentricity).

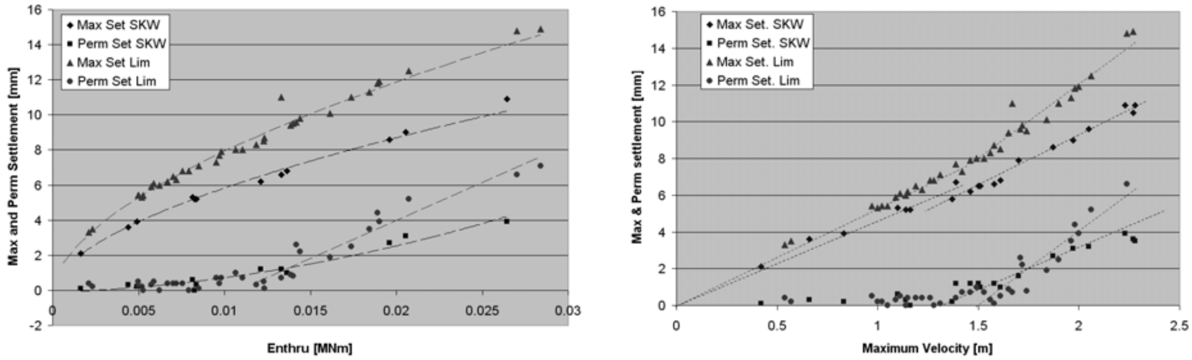


Figure VI-1 : Relationships between quantities based on the dynamic measurements

2.3. The back analysis and the optimisation procedure

This part of the research aims to automate the main step of the analysis process of the dynamic measurements: the back analysis and the optimisation procedure of the matching between measured and modelled dynamic curves (force and pile head velocity). The dynamic data are dealt with by extracting the pile/soil interaction parameters and by sorting them according to their static or dynamic influence. This treatment is called the back-analysis and the procedure followed to achieve it is an optimisation between the measured and the modelled pile/soil response. After that, the static load-settlement curve is simulated based on the interaction modelling assessed.

The principles of the matching procedure, the details and the requirements to have an objective and rapid method to perform the back analysis are presented. The method developed is based on the multi dimensional parameter perturbation sensitivity analysis (Berzi, 1999). It consist in exploring the close vicinity of a point (defining a combination of n parameters in their R^n space) in order to obtain a new combination improving the matching quality. This process is followed until a stop criterion is achieved (success or end of process). The final combination is considered as the solution of the back-analysis.

The implemented method allows to obtain a solution that minimizes the gap between measured and calculated pile/soil responses (force or pile head velocity) and authorizes a sensitivity analysis of this solution around it. Consequently, the parameters can be classified according to their relative weight in the matching procedure. Figure VI-2 presents two sensitivity analysis of parameters and the influence of their variation (Δp/p) on the matching quality factor D(p). A sorting is performed into the set of parameters allowing a sequential optimisation. All the parameters are firstly used to give a first step to the process. Aftewards, the most influential are successively retrieved to allow the optimisation of the less influential parameters. The parameters leading the process are the static soil reaction ones (ultimate resistance, thickness of the layers), the rheologic ones are less influential.

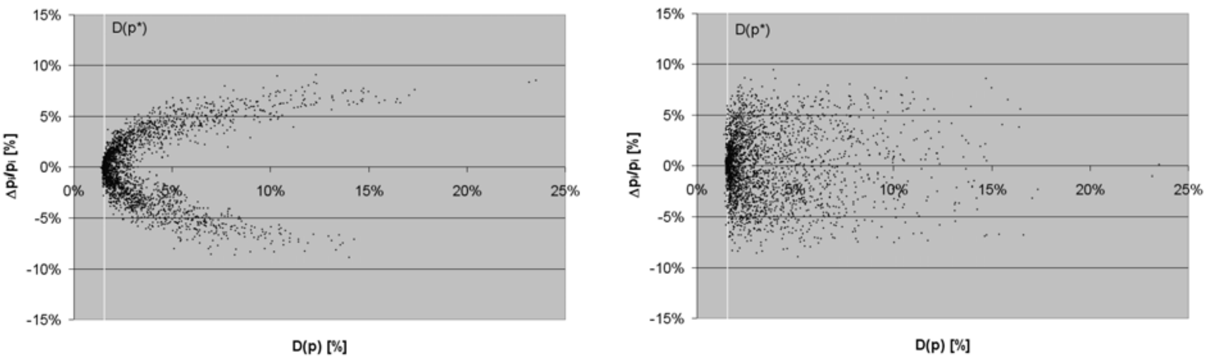


Figure VI-2 : Influential parameter and non influential parameter

The back-analysis has been carried out on the dynamic measurements performed in Sint Katelijne Waver and Limelette. The matching procedure succeeds in all cases but the back-analysis results are less reliable. The systematic analysis has shown that profiles of the soil resistance were respected in comparison with the CPT ones used as reference. But the net values are wrongly influenced by a bad modelling of the loading and unloading initial shear modulus. The reason of that is found to be the motion coupling of pile and soil enforcing the follow-up of the settlement path by the constitutive stress-displacement relationships without any possibility of slippage between pile and soil. The main consequence is that the initial shear modulus G_i and the ratio of modulus G_2/G_i get small and unrealistic values. Unfortunately, the stiffness parameters influence greatly the simulation of the static load-settlement curve. So, a modification of the pile/soil system modelling is required. The slippage between pile and shaft must be authorized and both motions have to be independent during its occurrence.

However, the systematic back-analysis brings results of interest:

- The highlighting of the prior mobilization of the shaft friction before the base resistance and the confirmation of the settlement of this mobilization as about 1 to 1.5 % diameter of the pile;
- The ratio of the base/shaft friction capacities for both sites (Boom clay and Bruxellian sand) as observed with the static load tests;
- The respect of the expected profile given by the CPT;
- A first indication of the rheologic parameters values for both types of soil:

J value	Sint Katelijne Waver	Limelette
Shaft damping factor	0.6 $s/m^{0.2}$	0.1 to 0.75 $s/m^{0.2}$
Base damping factor	1.75 s/m	0.9 s/m

<u>Table VI-2</u> : First estimation of the rheologic parameters

- The simulations of the static load settlement curves agree with the measured ones but are probably influenced by the pile/soil motion coupling.

Finally, one can points out that the load rate effects are more developed in clay compared to the sand environment. It can be observed that a good matching is not a sufficient condition to have a good back-analysis result. Guides must orientate the matching. The first and the most important one is the comparison with a relevant geotechnical information about the soil environment. Automatic guides can be implemented, but the most reliable is the human control of a seasoned engineer.

2.4. The slippage event at the pile shaft

In order to authorize the pile to slip into the soil when a certain resistance is exceeded along the pile shaft as required by the conclusions of chapter 4, two new pile/soil systems are proposed to dissociate the pile and the soil referentials:

- The DDOF[1] model;
- The Cylindrical model.

[1] Double Degree Of Freedom Model

The DDOF model only considers the soil reaction in the direct vicinity of the pile shaft and is modelled by a non linear static term, a velocity dependent term for the internal dissipation of energy into the soil (the viscous term) and a radiation term. The three terms are function of the soil motion. The ultimate rheologic resistance of the soil is function of the ultimate static shear stress and of the interface velocity (difference between pile & soil velocities) which is nil when pile and soil are coupled and variable when the slippage occurs. During the slippage, the soil motion is evaluated so that the soil reaction perfectly balances the ultimate rheologic resistance of the soil. The results allow to discern the pile penetration and the penetration velocity defined as the difference of settlements and velocities between pile and soil, similarly to a model described by Paquet in 1988.

The DDOF model keeps the advantages of the SDOF model (size, simplicity, time computing) and allows to distinguish the pile and soil displacement histories in order to fulfil the requirements of the chapter 4. The soil motion (shape, maximum and permanent values), and consequently, the pile penetration are strongly influenced by the choice of the ultimate static resistance of the soil and by the value of the damping parameters $J_{(s)}$.

The Cylindrical model describes the soil reaction by mean of concentric cylinders surrounding the pile. The last ring closes the model by an absorbing boundary respecting the theory of Novak et al, 1978. The Cylindrical model allows the computing of the displacements and the stresses induced in the soil due to a dynamic pile sollicitation. The static soil reaction is completed by a viscous term function of the relative velocity between soil elements and the geometry of the model is supposed to represent the radiation term usually modelled in the 1D pile/soil system. The loading rate influence is also marked in the ultimate rheologic resistance of the soil which is also function of the interface velocity.

Firstly validated with the theoretical approach of Novak et al., 1978. the model is used to study the slippage occurring at the interface between pile and soil. If only the static terms of the soil reaction are used, the slippage is confined to the sole interface between the pile and the soil. On the other hand, if the velocity dependent terms are added to the static soil reaction, it appears that the slippage can spread out to a certain range around the pile (between soil elements). This thickness is function of the ultimate static resistance of the soil, of the rheologic parameters and of the initial shear modulus of the soil. The development of the slippage beyond the pile/soil interface is due to the velocity dependent terms and especially to the viscous term.

Moreover, the slippage is not modelled as an insurmountable barrier but acts as a filter defined by the ultimate soil resistance and stiffness and the rheologic parameters: the smallest the ultimate soil resistance and the faster the mobilization of the soil, the less the transmitted information to the soil.

3. Contributions of the research

The definition of the different terms intervening in the loading rate effect are defined and described. The strict overview of the loading rate influence was investigated through literature. The importance of the radiation term is highlighted and the need of better knowledge of its evolution with the static and dynamic soil resistance degradation is pointed out. The traditional attempt to classify the rheologic parameter J (from Smith, Case method, or Coyle-Gibson approaches) with the type of soil must be avoided.

A systematic analysis of the dynamic measurements provides informations about the pile/soil response in function of the maximum force, energy and velocity needed to significantly settle down the pile. The type of soil differentiates also the observed results. This can be applied directly to the driving analysis. The energy and the settlements can be used to compare the different loading procedures.

The back-analysis and optimisation modules allow to automate and accelerate an objective analysis of the dynamic measurements. The proposed method authorizes to check the given solution by a sensitivity inspection of its close vicinity. Statistics become conceivable. The sorting of parameters give the opportunity to refine the less influential of them.

The matching procedure is successful in all cases but the analysis of the optimised parameters brings out the requirement of the slippage in the pile/soil modelling. This improvement could result in a better knowledge of the pile/soil interaction and also of the behaviour of the soil reaction at the end of each blow (with a special attention to the residual stresses along and beneath the pile).

The models developed or improved in order to authorize the slippage between the pile and the soil show results of interest:

- The distinction of both soil and pile motions with a light and reliable model;
- The relationships between the soil parameters (resistance, rheologic) and the generated soil motion;
- The possible spreading of the slippage zone under dynamic conditions;
- The transmission of movement through the failure surface.

All these results must be confirmed and refined with real measurements or specific tests.

4. Perspectives

Since almost all the results available in the overview of the loading rate effect in literature concern the ultimate rheologic resistance of the soil and a relatively high level of velocity, it is required to investigate the intermediate ranges of velocity and strain. The path is of the same importance than the failure mode. It is needed to investigate the low range of velocity and the low level of static mobilization. The type of soil must be also widened. Major part of the studies concerns a clayey soil or a mix of sand and clay. The other types of soil are concerned by the influence of the loading rate and must be investigated.

Finally, it was observed that the influence of the loading rate is composed of different terms. However, generally, the tests undertaken give a global coefficient, dependent of the velocity, including all the influences. It is required to perform tests allowing to point out each term independently, with the minimum of interference. The viscous term is often neglected or set to a low contribution. However, its importance is highlighted by the increase of soil resistance with the velocity in the vicinity of the failure where the radiation is theoretically vanished. A proposition would be to study this component by performing the same test on the same sample of soil saturated with many fluids of gradual viscosity. It is also of importance to carry out tests where the inertial effects are removed or evaluated with precision.

The synthetic analysis on the loading rate effect performed in chapter 3 pointed out the existence of a marked threshold between the description of the soil reaction and the failure mode in the friction modelling. Laboratory tests allowing the highlighting of this threshold and its characterization with regard to the soil parameters and without influence of inertial effects are wished. The comparison of tests performed with a constant level of energy transmitted but a variable velocity is another way of investigation of the loading rate effect.

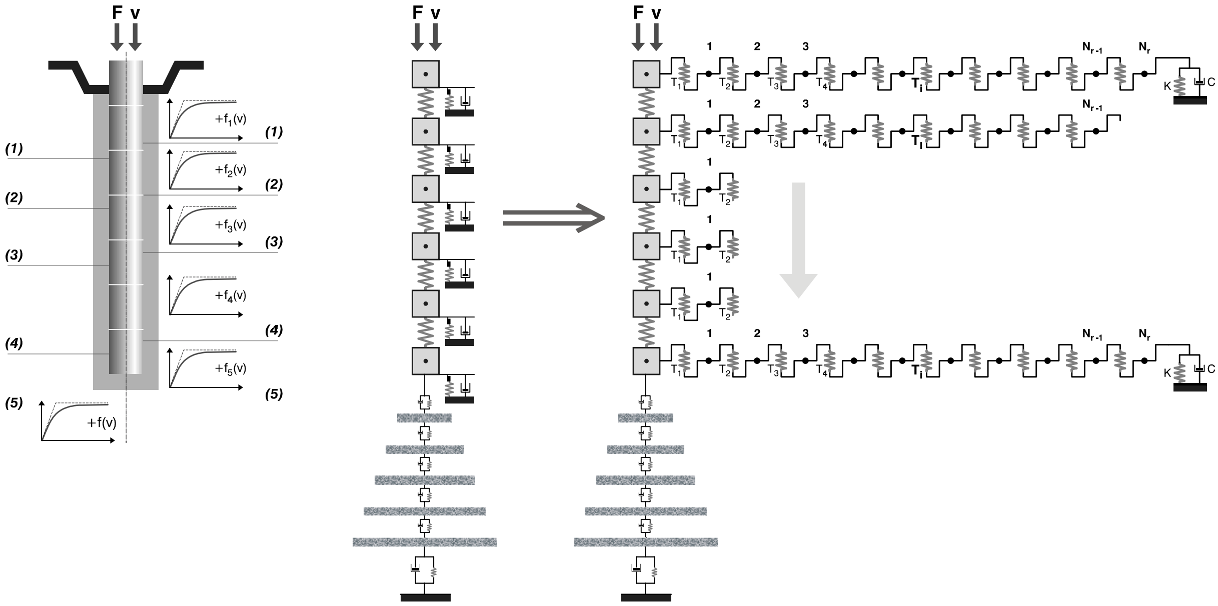
The results obtained after analysis of the dynamic measurements must be confirmed with a larger sample of data coming from another piles (diameter and length) in different sites. The critical quantities and the beginning of a significant permanent settlement must be related to the quake analysis for both pile resistance components: the base resistance and the shaft friction. There is an equilibrium between the base and the integrated shaft quakes. The understanding of this behaviour must take into account the slippage at the interface between pile and soil, the residual stresses, the initial and the unloading stiffness of the different stress-displacement relationships.

The implementation of the back-analysis module highlights the need of the slippage possibility. This must to be implemented in the general pile/soil system. The sensitivity analysis authorizes the development of statistic tools on the back-analysis results beside the geotechnical sources of information (correlation of profiles, link $\Delta p/p - D(p)$ and static load settlement simulation). All these tools could better the process toward the best geotechnical solution.

The complete set of dynamic measurements of a complete sequence of DLT tests could also be used as one sole signal to be studied and optimised in order to describe the pile/soil interaction system accounting for all the tests carried out.

Concerning the slippage event, the first action of importance to be continued is to complete the pile/soil model by implementing the DDOF model into the system described in chapter 3 and to perform back-analysis of real dynamic measurements with the algorithm developed in chapter 5.

A more complete model could be also put together by merging both models presented in chapter 5. The pile/soil model is described by the DDOF model, and the soil description is described by the Cylindrical model connected to the preceding (Figure VI-3). The results could differentiate the pile and the soil motions and evaluate the soil behaviour in the direct vicinity of the pile and in the far field allowing the comparison with measurements obtained from transducers installed on the field (geophones, …).



<u>Figure VI-3</u> : Complete model to be implemented

The analysis of the slippage allowed one to highlight the requirement to differentiate the rheologic terms with respect to the relevant velocity (pile, soil, interface). Since there is too little information available in literature about this differentiation, it could be interesting to confirm the simulation observations by real measurements. In corollary, both damping factors, J & Js, used in the ultimate rheologic soil resistance and in the viscous term must be differentiated due to the difference in the behaviours described. If the first damping factor (J) is easier to estimate by measuring the failure under dynamic solicitation, the second parameter (J_s) requires more refinements.