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Automated procedure of pile dynamic test signal matching

Procédure automatique d'ajustement de signaux d'un essai de chargement dynamique de pieux

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ABSTRACT

Within the framework of the analysis of a pile dynamic load test, a widely used method is the signal matching procedure between measured and calculated signals. The method requires that the soil parameters are iteratively adjusted in the pile-soil model until a reasonable agreement is found between calculated and measured pile top force and velocity records. The number of unknowns (the soil parameters) depends on the variability of the soil, the pile and soil discretization and the complexity of the used pile/soil interaction model. A direct consequence of these multi-parameters adjustments is the time consumed in computational efforts or independently required expert interpretation. The present paper describes an automated method that simplifies the complexity of the signal matching analysis by giving a starting point for the optimisation procedure based on the geotechnical information available. The general algorithm is exposed, the different parts detailed and illustrated by a pile dynamic test analysis.

RÉSUMÉ

L'ajustement des signaux mesurés et calculés est une méthode très répandue dans le traitement des essais de mise en charge dynamique de pieux. le processus requiert que les paramètres constitutifs du sol soient ajustés itérativement jusqu'à ce que les signaux de force et de vitesse mesurés correspondent au mieux avec les signaux issus du modèle numérique. Le nombre d'inconnues de cette analyse inverse dépend de la variabilité du sol, de la discrétisation choisie et de la complexité du modèle pieu/sol et influence directement le temps nécessaire pour réaliser l'analyse. Cet article décrit une méthode automatique qui simplifie le processus général d'analyse. Un point de départ basé sur les données géotechnique disponibles oriente la convergence. Le cadre, l'algorithme et les parties constitutives de cette méthode sont explicitées et illustrées par un exemple concret.

1 INTRODUCTION

The signal matching procedure between measured and calculated signals is widely used to analyse pile dynamic load test results. The soil parameters are iteratively adjusted until a reasonable agreement is observable between measured and simulated pile top signals (force and velocity). A method allowing to find automatically a solution for the signal matching procedure is presented here. It allows also to check the solution sensitivity in the near field of parameters by a systematic and stochastic approach. The solution is compared to the static load test result.

1.1 *Pile Dynamic Load Test*

The objective of dynamic load testing consists in predicting pile capacity and pile/soil interaction from hammer blows during driving and/or restrike of an instrumented pile (figure 1).

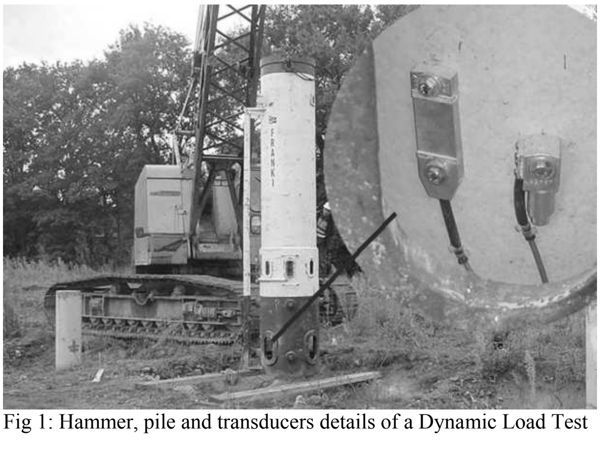

Fig 1: Hammer, pile and transducers details of a Dynamic Load Test

The transducers are generally twofold: accelerometers to measure the pile head vertical acceleration and strain gauges to measure vertical strain in the local section due to the impact transmitted by the falling mass. Acceleration is transformed in pile head velocity and displacement while strains result in transmitted force (figure 2).

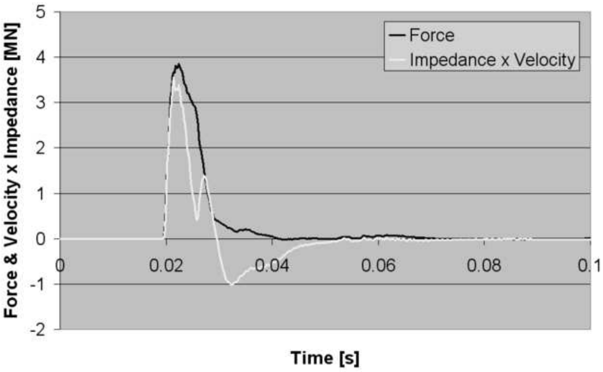

Fig. 2: Measured signals during a DLT event.

Due to the viscous effect superposed to the static soil reaction and due to wave equation phenomena, post-treatment and assessments are required to predict the static pile load-settlement behavior. Numerous methods such as driving formulae, visual inspection of the blows and the pile settlement, signal processing by using the specific theory of the wave equation, and numerical models increase the complexity of the analysis but improve the quality of the interpretations.

This research uses a detailed numerical model to describe the pile/soil interaction by a computer simulation.

1.2 *The pile-soil interaction model*

The dynamic pile/soil interaction is described by a non-linear mass/spring/dashpot system representing the pile and the soil with constitutive relationships existing within and between them. The soil behaviour is described for both shaft and base reactions using an approach suggested by Holeyman (1984). These relationships account for the static and the dynamic behaviours. The parameters of these relationships define the system and an explicit algorithm allows to simulate the motion and dynamic fields for each node and each time step.

However, this characterization must be limited in order to reduce the complexity of the analysis. A good knowledge of the pile/soil environment and an appropriate discretization of the soil layers can reduce the number of unknowns and decrease the computational efforts. The classification of the parameters in function of their reliability and their order of certainty (figure 3) focuses the back analysis on the soil and rheological parameters.

Parameter classification

Fixed parameters	Fixed to variable parameters	Unknowns
• Pile material density • External pile geometry • Tests data • Time increment • Analysis duration	• Wave propagation velocity in pile • Burried pile geometry (length, base diameter) • Soil data well-known (soil density, Poison's ratio) • Pile/soil interaction (relationships, …)	• Soil reaction parameters: Ultimate resistance (τ_{ult}, σ_{ult}) Shear and compression modulii (G_i, E_i) • Rheological parameters (J, N)

Fig 3 : Classification of the parameters according to their reliability

The optimization of these parameters based on a back-analysis process fed with dynamic measurements allows one to characterize the pile/soil interaction and to simulate the "static" load-settlement curve.

2 THE AUTOMATED SIGNAL MATCHING PROCEDURE (NUSUM-UCL)

The main principle of the back analysis uses the fact that the pile/soil interaction model is able to calculate the system response for a given impulse. This input signal is an event measured during a dynamic test. The pile response is compared to the measured one and the gap between curves is considered as a measure of the imperfection of the simulation. The smaller the difference or the gap between signals, the better becomes the calculated response and the closer the pile/soil model gets to the real interaction (figure 4). The gap, called D(p), is function of the set of parameters (p) and must be minimized. The main goal is to adjust the soil parameters in order to fulfil this criterion. The inputs used are successively the measured force and the measured velocity. The system responses are the velocity and the force to be compared with the measured ones.

Consequently, if the pile/soil response is known, simulations of the pile under other loading scenarios are possible.

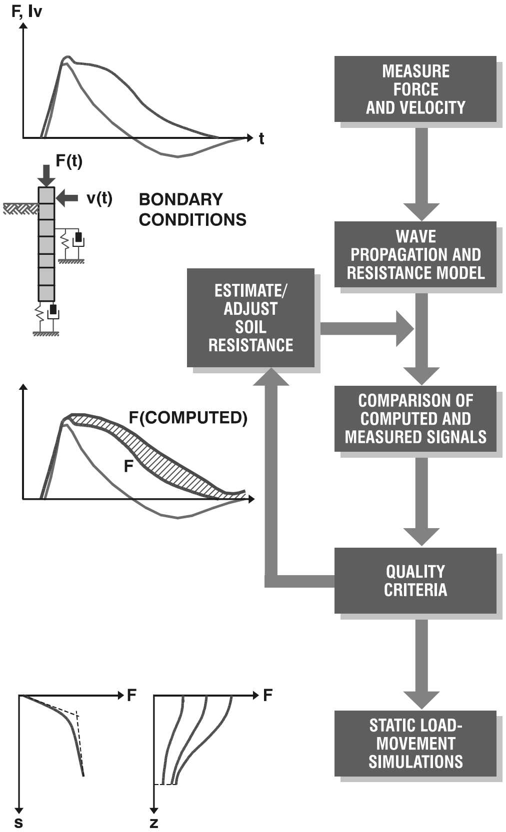

Fig 4 : Resolution algorithm (NUSUMS – Holeyman, 1992)

2.1 *Description of the method and algorithm*

Since the modification of one parameter modifies the system response and the influence of the other parameters, there is a need to investigate all the parameters at the same time and to follow the best way to reach the solution in function of the parameters variability. Since the optimisation requires a large number of iterations and small modifications of each parameter in order to reach a stable and correct solution, an automated approach is also required. Finally, the desire to study the path followed, the sensitivity of the pile/soil response to particular modifications implies the need of an impartial process.

All these requirements result in the setting up of a new approach based on an automated and stochastic parameter perturbation analysis.

Initially based on a method used by Berzi (1996) to analyse the sensitivity about the neighbourhood of an optimal solution, the method suggested herein explores systematically the close vicinity of the parameters and computes for each combination of the parameters (p) the pile/soil response in terms of D(p).

The exploration is made randomly but is characterized by the distance of investigation Δ and the number of combinations k. The combination p' minimizing the value of D(p) is found to be the new starting point of the next optimisation step. Figures 5 and 6 illustrate this algorithm.

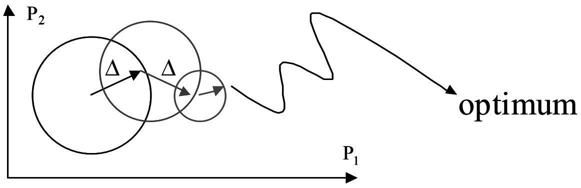

Fig 5: Schematic procedure for two parameters

Conditions can be applied to the choice of the radius Δ, the number of combinations k before a change of starting point and to the criterion to choose the best intermediate combination (p'). Statistical, geotechnical and physical considerations are currently planned to be implemented to steer the process.

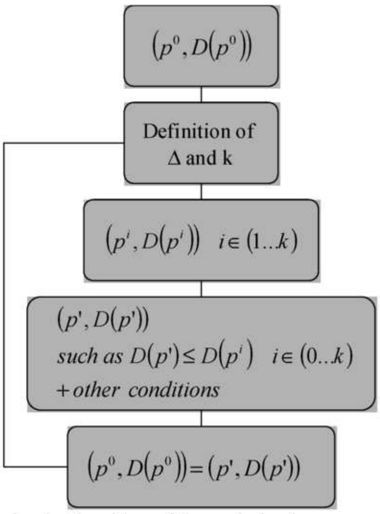

Fig. 6: Algorithm of the optimization process

This method, open and explicit, allows one to store the evolution of the optimization in order to check the variation of each parameter. The simultaneous upgrade of the parameters respects their relative influence and allows one to control the path followed. However, the stochastic approach requires a large number of combinations which could be considered as a waste of time. There is also no certainty that the best solution is not a local minimum in the set of possible D(p). A post-analysis of the path followed by the optimization and a human evaluation of the optimization results can reduce the risks linked to these disadvantages.

2.2 *Link with geotechnical information*

According to the algorithm presented on figure 5, the method needs a starting point. This point defines the *a priori* knowledge of the pile/soil system. Since the quality of the optimisation is directly linked to the physical reliability of the parameters, it has been observed that the best way to start the optimisation process was to use the geotechnical information available. *In situ* or laboratory tests results, experience or literature information give the best starting point possible. Consequently, the parameters remain in their reasonable physical ranges. On the opposite, to start with an unrealistic combination implies a non acceptable solution or a non convergence. Figure 7 shows the starting point used for the ultimate shaft resistance in the case study presented hereafter.

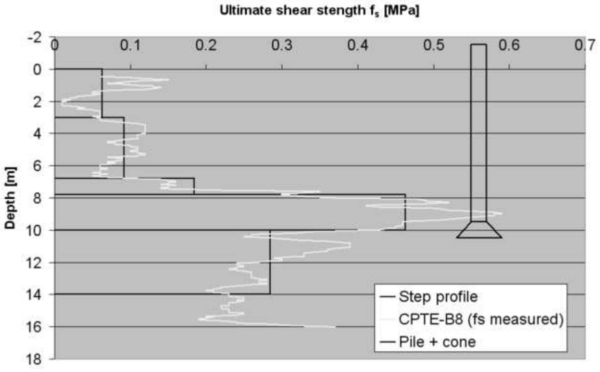

Fig 7 : Starting point of the matching procedure (ultimate shear resistance of the soil)

The average (in 5 layers) local friction comes from a Cone Penetration Test performed with an electrical cone but is only a starting point aiming to profile the shaft resistance with depth, not to give the ultimate values.

2.3 *Case study*

Within the framework of a national research program organised by the Belgian Building Research Institute (BBRI) in order to establish the performance of different types of cast-in-place ground displacement screwed piles (Holeyman (2001) and Huybrechts (2003)), identical concrete prefabricated concrete piles have been driven and tested statically and dynamically. The narrow site where these tests were carried out has been widely investigated from a geotechnical point of view. Since the soil environment and the pile characteristics are similar, the results of both loading procedures can be compared with large confidence. The piles are 11 m long with a square section of 35x35 cm². The piles are embedded in a dense layer of Bruxellian sand covered by 8 meters of quaternary silty loam as illustrated by figure 7. The groundwater was not encountered.

The Static Load Test consists of a sequence of about 10 load steps of 1 hour each to reach the anticipated failure load. The Dynamic Load Test consists in a sequence of blows of variable height. A 4 tons mass is dropped from 0.4m to 2m on the pile head. The varying energy transmitted to the pile allows one to mobilize different levels of soil resistance along the pile shaft and beneath the base. Each blow is studied independently with the same starting point based on the geotechnical information (see figure 7). Table 1 gives the detail of the heights of drop for a selection of studied blows, the maximum settlement reached during the loading and the results of the matching procedure in terms of minimized gap (D(p)). The analysis is carried out on a signal duration of 25 travels of the wave into the pile, namely 0.065 s. The parameters chosen for the optimization are the ultimate soil resistance, the shear and compression initial moduli, the thickness of the soil layers and the rheological parameters J and n according the Coyle and Gibson approach (1969):

$$\tau_{rheol} = \tau_{stat} \cdot \left(1 + J \cdot v^n\right)$$

- τ_{rheol} & τ_{stat} : rheological and static soil reaction [MPa];
- J & n : rheological parameters [s/m^{-n}, -];
- v : pile velocity [m/s]

Table 1: Summary of the analyzed blows and of the reached settlements

	Drop Height [m]	Max Settlement [m]	D(p) [%]
B8-001	0.4 m	0.0033 m	0.74%
B8-002	0.6 m	0.0054 m	0.98%
B8-003	0.8 m	0.0062 m	0.89%
B8-007	1.2 m	0.0077 m	1.18%
B8-011	1.6 m	0.0094 m	1.2%
B8-015	2 m	0.0119 m	0.91%

Figures 8 & 9 give the result of the matching process for the blow B8-015 for the signals of force and velocity. D(p) is the sum of the normalized gaps of these signals.

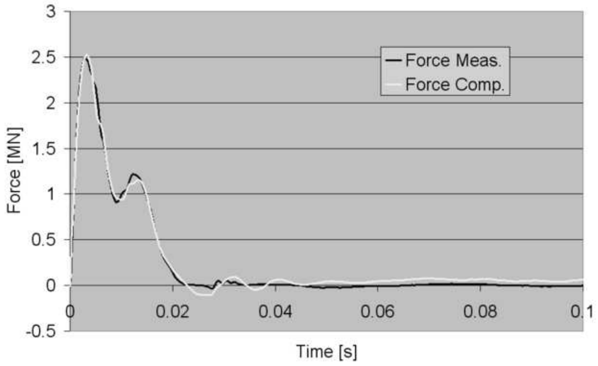

Fig 8 : Measured and computed signals of force after optimization

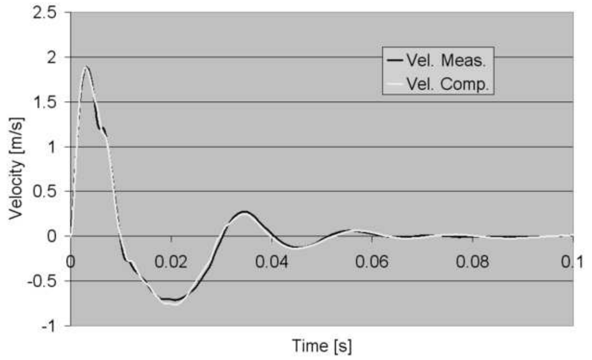

Fig 9 : Measured and computed signals of velocity after optimization

It is seen that the results respect the measured trends for both dynamic and kinetic signals until complete attenuation. The maximum and final settlements were also correctly simulated.
After optimization, the load settlement curve of the corresponding quasi static load test can be simulated (figure 10). This curve is valid up to the maximum settlement occurring during the corresponding DLT test. Most of the simulations respect the first part of the SLT trend (stiffness, …). The most energetic DLT simulations deviate from the reference curves. This is due to a modeling weakness (Charue, 2004) which is not presented here.

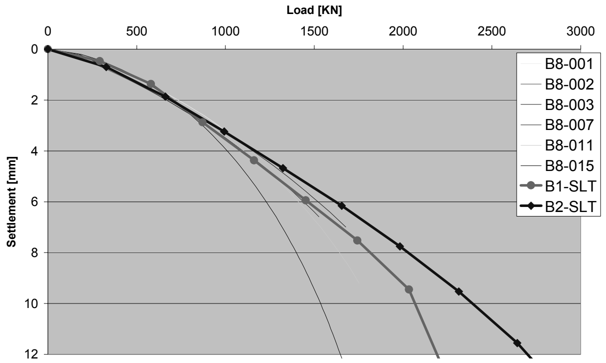

Fig 10 : Measured and computed load-settlement curves from SLT and DLT tests.

2.4 *Sensitivity analysis*

Following the same technique, it is possible to analyse the sensitivity of each parameter and to sort them according to their relative influence onto the matching process. Figures 11 & 12 highlight the direct influence of the variation of some of the parameters upon the matching quality. The parabola on figure 11 expresses a direct link between this parameter and the matching success. At the same time, an other parameter shows a cloud identifying the absence of relationship (figure 12).

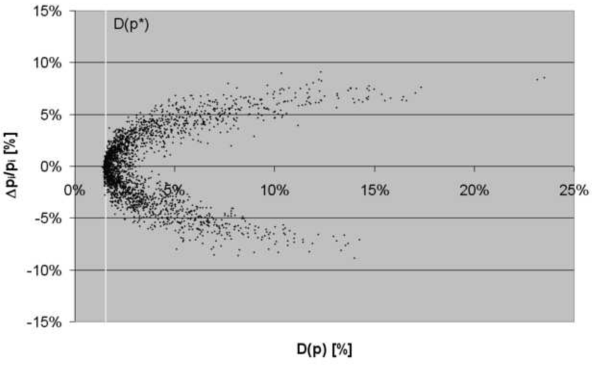

Fig 11 : Influence of the variation of an influential parameter on D(p)

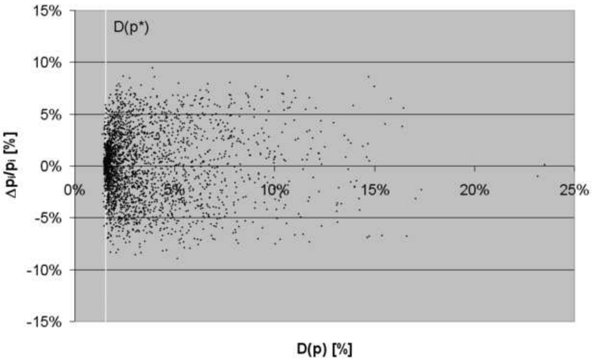

Fig 12 : Influence of the variation of a non-influential parameter on D(p)

Since the parameters influence the system response with a relative weight, they are sorted in order to optimize all the parameters by successively retrieving the most influential ones and working on the remaining ones. This results in a more efficient optimization where all the parameters can be refined.

3 CONCLUSIONS

An automated procedure of pile dynamic test signal matching has been set up. This algorithm allows one to characterize the pile/soil interaction system in terms of parameters and to simulate the load-curve of other loading scenarios. The stochastic method used to optimise the variables investigates all the parameters at the same time with respect to their own variability in an impartial and rapid process. A particular attention can be given to the sensitivity of each parameter. This influence can be used in order to improve and to refine the optimisation.

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