"Loading rate effects on pile load-displacement behaviour derived from back-analysis of two load testing procedures"

Charue, Nicolas

ABSTRACT

Soils, like several other materials, exhibit strong time-dependent behaviour which can be evidenced in terms of creep or strain-rate effects. The degree of this rheological behaviour varies with the type of soil, its structure, and with the stress history. This effect is exacerbated in pile load testing where the procedure duration tends to be shortened under increasing time pressures. The modelling needed to interpret the results therefore becomes more and more complex, including soil viscosity, wave radiation into the soil and other significant phenomena. The objective of the research reported herein is to refine the rheological parameters characterizing the influence of the loading rate within the framework of a relevant pile/soil interaction model fed with dynamic measurements acquired during pile Dynamic Load Tests (DLTs). The final goal is to predict and simulate the quasi-static pile load settlement curve. The pile/soil interaction system is described by a non-linear mass/spri...
This thesis was supervised by:

Prof. dr. ir. A. Holeyman, Université catholique de Louvain (Belgium)

Members of the Jury:

Prof. dr. ir. J.-D. Legat, President Université catholique de Louvain (Belgium)
ir. F. De Cock, co-advisor Geo.be (Belgium)
Prof. dr. ir. R. Frank; co-advisor CERMES

Prof. dr. ir. J.-F. Thimus Laboratoire Central des Ponts & Chaussées (France)
ir. D. Vié Université catholique de Louvain (Belgium)

C.E.B.T.P. (France)
Loading rate effects on pile load-displacement behaviour derived from back-analysis of two load testing procedures

Thesis presented for the degree of Doctor in Applied Sciences

by

Nicolas CHARUE

October 2004
This research, during the last four years, would not have been possible without the help, encouragements and support of many people. I would like to thank them with my sincere gratitude.

Special thanks go to my adviser, Professor Alain Holeyman (UCL), who initiated and supported this research. He gave me the opportunity and trust to perform this research in the institution of UCL. His encouragements, comments, numerous ideas and permanent optimism helped me all through my work. He transmitted me the need to completely understand what I was looking for and found out, and the freedom to organize my work around my centres of interest in an accurate, creative and autonomous way. His numerous comments about the present document were an essential guide to this final version.

Profuse thanks go equally to ir. Flor De Cock (GEO.BE, Belgium) and to Professor Roger Frank (CERMES, France) for their involvement in my thesis steering committee. I had the opportunity to share my research process with a very active committees, internationally recognized for its competence in the deep foundation arena. Moreover, one or two meetings per year framed my research with long and interesting discussions. These meetings brought every time a lot of comments and new ideas that pushed the research forward. They also spend their precious time to comment the submitted text and help me to organize the writing process.

I would also like to warmly thank Professor Jean-Francois Thimus (UCL) and ir. Dominique Vié (C.E.B.T.P., France) for their participation to the jury of this thesis. The time needed to read, comment the text and their participations to the defences were highly appreciated.

I would like to extend my gratitude to the Dean of the faculty of Applied Sciences (UCL), Professor Jean-Didier Legat, for honouring my jury by presiding it.

A special thank goes to the Belgian Building Research Institute (BBRI) allowing us to use data of two national projects focused on the design methods and the installation influence of screwed pile in two types of soil encountered in Belgium. The extraordinary amount of data including a huge geotechnical survey and the load tests results was the foundation of this research. A particular thank is given to ir Noël Huybrechts for his help, comments and availability at any moment and to Rosario Bonsangue and Christian Verbeke for technical support during the data measurements.

The environment where this research was achieved has to be highlighted. The Université catholique de Louvain and particularly the Civil and Environmental Engineering Department is a remarkable and
comfortable place where every scientist could find the adequate conditions to perform his job. This is due to the quality and the comfort of the installation but also and especially to the human being quality of the people who are working there. The friendly atmosphere of work and the team spirit existing between all the members of the Laboratory of Civil Engineering and the Civil and Environmental Engineering Department was an appreciated environment and a precious help contributing to the accomplishment of the present research. Each of them must be thanked for that. I would like to specially express my gratitude for the "Measurement" section of the laboratory composed of Alex Bertholet and André Renard, and to Eric Dupuis who responded with patience to many practical and stupid questions during all my work. I would like also to express my thanks to our secretaries, Marie-Rose Bodart-Decelle and Viviane Misson-Delmarcelle for their permanent help and support. Finally, Jean-François Vanden Berghe who preceded me in the PhD experience was a great guide and a very good officemate in the first year of this research. Thanks to him.

I am indebted to the University of Western Ontario (London-Canada) that hosted me for 5 months and made available the exchange with researchers from other institutions. I want to thank first Professor Hesham El Naggar who accepted me and helped me scientifically and practically during my stay. Besides, I would like to extend my gratitude to the staff of the Geotechnical Centre and especially to Mohamed Sakr who guides and helped me everyday.

All my gratitude is also going to Nicolas Bronchart, a very good friend, who reviewed all the text in order to correct my mistakes. His precious contribution was more than just correcting errors. His review increased significantly the quality of the text. In the same way, I would like to extend my gratitude to all the persons who helped me by reviewing the text of the thesis: in particular Flor De Cock, Roger Frank, Alain Holeyman and Céline Paulus. The final result is also richly illustrated by pictures and pictograms drawn by the "artist" of the department: José Flemal. I would thank him for his availability and pleasure to work with.

I gladly acknowledge the different funds that helped me to work without having to worry about material concerns. During the first year, the research was funded by the Fonds special de recherche (FSR) of UCL. The next three years were supported by BBRI and the Belgian Federal Ministry of Economic Affairs through two national research programs: Screw piles in sand (Biennale 2000-2002) and Harmonization of pile design method (Biennale 2002-2004). In that regard, the support provided by ir Christian Legrand, Head of the Infrastructure Division of the BBRI, is fully acknowledged. The stay at the Canadian University was supported by the “bourse of excellence” of the Belgian French Community.

I would like to give special thanks to the Laboratory of Civil Engineering, and particularly to its director, ir Albert Mertens de Wilmars to allow me to finish this work calmly and serenely.

And last but not least, I would like to thank my parents whose presence and support were never missing during the last 30 years. I am extremely grateful to them and indebted for all they did.

To all my friends and parents who never stopped to support me in my research, sincerely thanks to them.

Finally, extremely warm thanks go to Céline without whom the end of this thesis would have been much more difficult or simply impossible. I thank her for her daily encouragements and supports, for her patience, for her presence in the difficult periods and for her confidence in my abilities. Thanks to be there.
Soils, like several other materials, exhibit strong time-dependent behaviour which can be evidenced in terms of creep or strain-rate effects. The degree of this rheological behaviour varies with the type of soil, its structure, and with the stress history. This effect is exacerbated in pile load testing where the procedure duration tends to be shortened under increasing time pressures. The modelling needed to interpret the results therefore becomes more and more complex, including soil viscosity, wave radiation into the soil and other significant phenomena. Within this framework, it would be interesting to study the influence of the loading rate on the load-displacement behaviour of the pile through the results of two testing procedures loading piles with variable duration (Static Loading Test (SLT) used as reference and Dynamic Load Test (DLT)). Based on these data issued from two national research programs organised by the Belgian Building Research Institute (BBRI), the objective of the research reported herein is to refine the rheological parameters characterizing the influence of the loading rate within the framework of a relevant pile/soil interaction model fed with dynamic measurements acquired during pile Dynamic Load Tests. The final goal is to predict and simulate the quasi-static pile load settlement curve.

After an overview of the loading rate effects in the literature through the experimental and modelling aspects, the dynamic data measured on field are analysed. It has been observed that some relationships exist between maximum quantities such as: energy transmitted to the pile, pile head velocity and force and the settlements (maximum and permanent) measured after a sequence of blows during a DLT event. These relationships are similar for the sandy and clayey sites and repeatable in time. It has been found that there are some critical quantities (correlated with the hammer drop height) from which a significant settlement of the pile is possible while the pile does not settle if these quantities are not exceeded.

The pile/soil interaction system is described by a non-linear mass/spring/dashpot system supposed to represent the pile and the soil, with constitutive relationships existing within and between them. These relationships account for the static and the dynamic or rheologic behaviour. A back-analysis process based on a matching procedure between measured and computed curves (force and 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. The matching procedure is based on an automatic multi dimensional parameter perturbation analysis. Since the parameters influence the system response with a relative weight, they are sorted in order to optimise all the parameters by successively retrieving the most influential ones and working on the remaining ones.

The back-analysis performed on dynamic measurements of both sites of Sint-Katelijne Waver (B) and Limelette (B) are generally successful but the obtained pile/soil system description appears to be unrealistic for some of the parameters. Consequently, the pile/soil model has been readjusted in order to account for the slippage between pile and adjacent soil along the pile shaft. This refinement increases the number of degrees of freedom needed to describe the pile/soil system but brings deeper insight into the behaviour of an interfacing zone of limited thickness surrounding the pile shaft.
Résumé

Le sol, comme bon nombre de matériaux, est fortement influencé par le facteur temps. Cette influence s’exprime par des propriétés de fluage et de relaxation ainsi que par une dépendance vis-à-vis de la vitesse de déformation. Ce comportement rhéologique varie en fonction du type de sol, de sa structure et de son histoire de chargement. Ce caractère est fortement marqué dans les résultats d’essais de mise en charge de pieux effectués à différents vitesses de chargement.

Si la durée de mise en charge tend à être raccourcie pour des raisons de rendement, le travail de modélisation nécessaire pour interpréter les résultats devient de plus en plus complexe du fait des facteurs mis en jeu tels que la viscosité du sol ou le rayonnement des ondes dans le sol. C’est dans ce contexte que s’inscrit cette recherche dont l’objet réside dans l’analyse de l’influence de la vitesse de mise en charge d’un pieu sur sa courbe de chargement. Des données issues de deux campagnes nationales d’essais organisées par le Centre Scientifique et Technique de la Construction (CSTC) et provenant de deux procédures de mises en charge à vitesses différentes (mises charge statique et dynamique) sont utilisées. L’objectif est de quantifier et de caractériser les paramètres rhéologiques définissant l’influence de la vitesse de mise en charge dans un modèle pieu/sol cohérent et, sur base des mesures de chargement dynamique, de simuler la courbe quasi-statique de charge-enfoncement du pieu étudié.

Premièrement, une étude de la littérature traitant du sujet tant sur les aspects expérimentaux que modélisatoires est proposé. Ensuite, une analyse des données dynamiques mesurées est effectuée et des relations particulières entre grandeurs physiques maximum sont mises en lumière. Ces grandeurs sont soit la vitesse particulaire de la tête du pieu, soit l’onde de force la traversant ou soit l’énergie transmise au pieu. Elles sont liées aux enfoncements maximum et permanent du pieu suite au coup donné. Ces relations montrent qu’il existe des seuils, appelés valeurs critiques, au dessus desquelles l’enfoncement permanent devient significatif alors que pour des valeurs inférieures, aucun enfoncement permanent n’est observable.

Le modèle d’interaction pieu/sol est décrit par un système de masses/ressorts/amortisseurs non linéaires modélisant le pieu, le sol et les relations constitutives les liant. Ces relations rendent compte des comportements statique et dynamique. Un processus d’analyse inverse basé sur l’ajustement de signaux mesurés (signaux dynamique et cinématique en tête de pieu) et calculés permet de décrire l’interaction sol/structure au moyen des paramètres constitutifs et rhéologiques du sol. Ainsi
l’optimisation de cet ajustement de courbes implique que la description du modèle pieu/sol y résultant est satisfaisante. La courbe de mise en charge statique correspondante peut être simulée et comparée à celle mesurée lors de l’essai de mise en charge statique.

La phase d’ajustement est basée sur une analyse stochastique des paramètres décrivant le système pieu/sol. Comme chaque paramètre a une influence relative sur la réponse du système, une classification est opérée de manière à optimiser tous les paramètres et à retirer successivement les plus influents pour pouvoir optimiser les paramètres restant. L’analyse inverse effectuée sur les enregistrements des deux sites (Sint-Katelijne-Waver (B) et Limelette (B)) donne de bons résultats en terme d’ajustement mais ne permet pas de caractériser correctement et physiquement le modèle pieu/soil utilisé. Ce modèle a donc dû être modifié pour tenir compte du glissement à l’interface pieu/sol le long du pieu. Cette amélioration du modèle n’est pas sans conséquence sur le nombre de degrés de liberté et donc sur la complexité du modèle et permet d’étudier en détail le comportement du sol dans une zone d’épaisseur limitée entourant latéralement le pieu.
# Table of Contents

Acknowledgements
Abstract
Résumé
Table of Contents

**Chapter 0: Introduction**

**Chapter 1: Load Testing Procedures: Description and Methods of Interpretation**

1. Introduction I-1
2. The Static Loading Test I-2
   2.1. Definitions and characteristics I-2
   2.2. Measurements I-3
   2.3. Interpretations of the results I-4
3. The Dynamic Loading Test I-5
   3.1. General presentation I-5
   3.2. Definitions and characteristics of the Dynamic Load Test I-7
<table>
<thead>
<tr>
<th>Chapter 2: Loading Rate Effect and Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
</tr>
<tr>
<td>2. Definitions</td>
</tr>
<tr>
<td>3. The global damping parameter J</td>
</tr>
<tr>
<td>3.1. The Smith approach</td>
</tr>
<tr>
<td>3.2. The J values and the evolution of the relationship</td>
</tr>
<tr>
<td>3.3. Attempt of classification of J</td>
</tr>
<tr>
<td>3.4. Conclusions</td>
</tr>
<tr>
<td>4. Analytically based models</td>
</tr>
<tr>
<td>4.1. Shaft friction models</td>
</tr>
<tr>
<td>4.2. The base models</td>
</tr>
<tr>
<td>4.3. Conclusions</td>
</tr>
<tr>
<td>5. The loading rate study through the literature</td>
</tr>
<tr>
<td>5.1. Linear velocity relationships</td>
</tr>
<tr>
<td>5.2. Complex velocity relationships</td>
</tr>
<tr>
<td>5.3. Loading Rate Conclusions</td>
</tr>
<tr>
<td>6. Conclusions</td>
</tr>
<tr>
<td>6.1. Approach low and large strains</td>
</tr>
<tr>
<td>6.2. Approach low and large velocities</td>
</tr>
<tr>
<td>6.3. Clay and sand particularities</td>
</tr>
</tbody>
</table>
Chapter 3: Pile/Soil Interaction Model & Dynamic Signal Analysis

1. Introduction  III-1
2. Presentation of the model  III-2
   2.1. Global model description  III-2
   2.2. Pile/soil interaction model  III-4
   2.3. Algorithms – scheme of resolution – SLT simulation  III-14
   2.4. Decomposition of the rheologic shaft friction stress into static and velocity dependent terms  III-14
3. Dynamic load test measurement: project description and signal analysis  III-20
   3.1. The Screw Pile projects  III-20
   3.2. Pile presentation  III-28
   3.3. Relationships between maximum quantities  III-29
   3.4. Visualisation of the dynamic motion signal along the pile  III-41
   3.5. Signal quality check  III-43
4. Conclusions  III-48

Chapter 4: Back-analysis and optimisation

1. Introduction  IV-1
2. The back-analysis system used in the dynamic pile testing analysis  IV-1
   2.1. Principle  IV-1
   2.2. Used signals and quality criterion  IV-3
   2.3. Results and comparison of signals  IV-6
   2.4. Pile/soil system input  IV-8
3. Automatic optimisation system  IV-11
   3.1. Requirement  IV-11
   3.2. Literature  IV-13
   3.3. Algorithm  IV-15
   3.4. Uniqueness of the back-analysis response  IV-19
Chapter 5: The Slippage Event

1. Introduction

2. The DDOF Model
   2.1. Description
   2.2. Algorithm
   2.3. Simplified pile/soil model
   2.4. Analysis of the DDOF Model results
   2.5. Influence of a variation of $\tau_{ult,stat}$
   2.6. Influence of a variation of the rheologic parameter $J$
   2.7. Influence of the differentiation of $J$ and $J_s$
   2.8. Comparison with the SDOF model

3. The Cylindrical model
   3.1. Description
   3.2. Algorithm
   3.3. Validation of the model
   3.4. Results
   3.5. Depth of the slippage zone
   3.6. Detail of the slippage process: about the spreading of the slip zone

4. Conclusions
Chapter 6: Conclusions and Perspectives

1. Outline of the research VI-1
2. Conclusions VI-3
3. Contributions of the research VI-7
4. Perspectives VI-8

References

List of Symbol