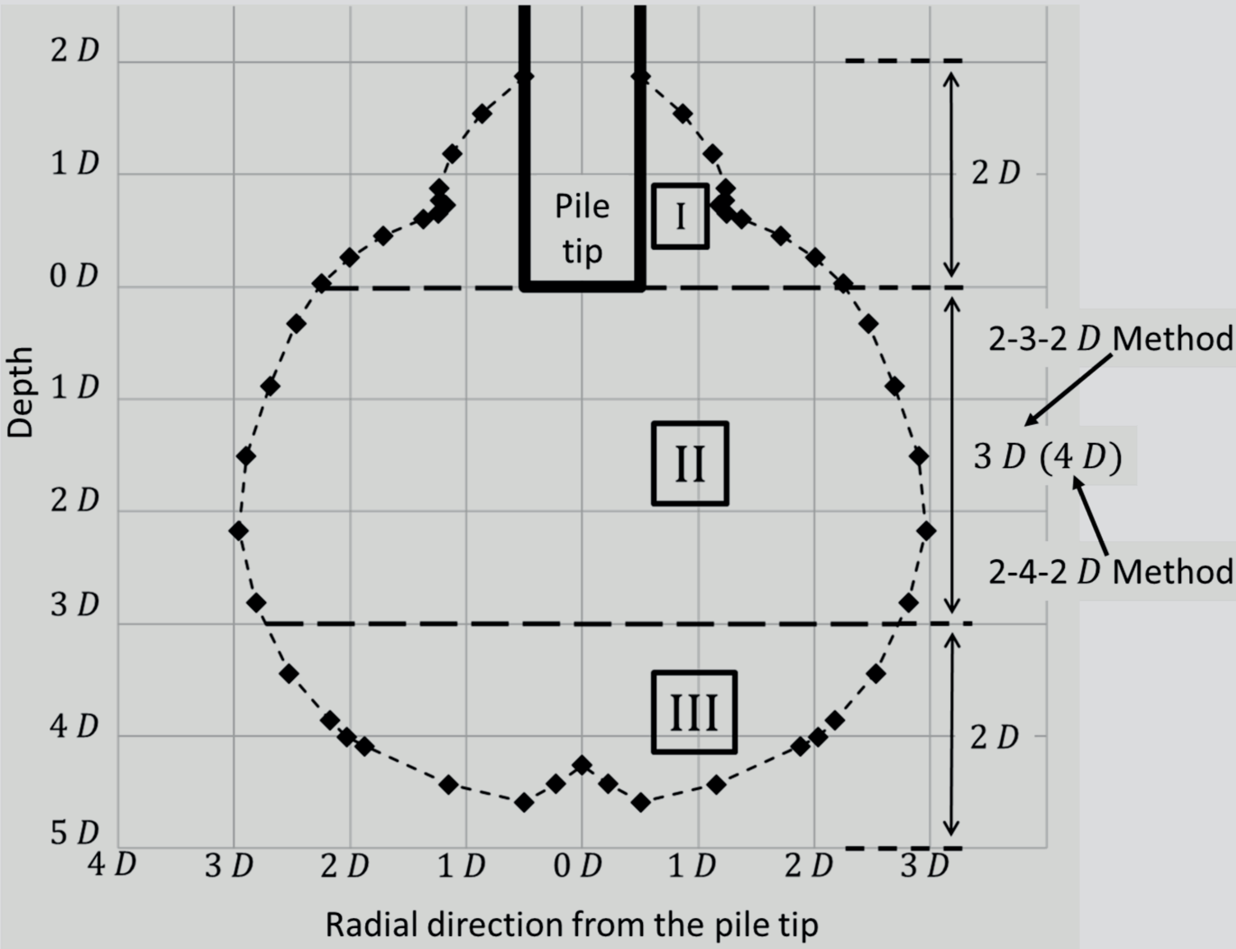
IMPROVED DESIGN METHODS FOR THE BEARING CAPACITY OF FOUNDATION PILES



Shilton RICA

UNIVERSITY OF LUXEMBOURG

PhD-FSTC-2019-58

Faculty of Science, Technology and Communication

DISSERTATION

IMPROVED DESIGN METHODS FOR THE BEARING CAPACITY OF FOUNDATION PILES

Presented on 17/09/2019 in Luxembourg
to obtain the degree of

DOCTEUR DE L'UNIVERSITÉ DU LUXEMBOURG

by

Shilton RICA
Born on 7th of September 1992 in Laç (Albania)

DISSERTATION DEFENSE COMMITTEE

Chairman:	Prof. Dr. Ing. Markus SCHÄFER, *Professor in Structural Engineering and Composite Structures* *University of Luxembourg*
Vice-Chairman:	Prof. Dr. Ing. Andreas ZILIAN, *Professor in Engineering science: Statics and structural analysis* *University of Luxembourg*
Dissertation supervisor:	Prof. Dr. Ir. Stefan VAN BAARS, *Professor of Geotechnical Engineering* *University of Luxembourg*
Member:	Prof. Ken GAVIN, *Professor of Subsurface Engineering* *Technique University of Delft*
Member:	Prof. Dr. Stefan JUNG, *Dr. Jung+ Lang Ingenieure Gmbh Geotechnik und Umwelt,* *Professur Geotechnik und Baustofftechnologie an der Hochschule für Technik und wirtschaft des Saarlandes*

Shilton Rica

Improved Design Methods for the Bearing Capacity of Foundation Piles

Shaker Verlag
Düren 2019

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Luxemburg, Univ., Diss., 2019

Printed in Germany.

ISBN 978-3-8440-7069-9

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Abstract

Pile foundations are often used for civil structures, both offshore and onshore, which are placed on soft soils. Nowadays, there are many different methods used for the prediction of the pile bearing capacity. However, the resulting design values are often different from the values measured at pile load field tests. A reason for this is that there are many pile installation effects and (unknown) soil conditions which influence the pile bearing capacity. Another problem is that for many pile load field tests in the past, the residual stresses at the pile after pile installation, have been ignored unfortunately. This ignoring leads to a measured tip bearing resistance which is lower than the real tip bearing resistance (capacity), and a measured pile shaft friction which is higher than the real pile shaft friction.

The main aim of this thesis is, to come to a better understanding of the pile performance and especially the pile bearing capacity. In order to achieve this aim, many numerical loading simulations were computed for small displacements with the Finite Element Model Plaxis and many existing pile design methods have been studied. The pile installation process itself was modelled and simulated with the help of the material point method, MPM, which is able to handle large displacement numerical simulations. The used version of this MPM method was recently developed at the research institute Deltares in the Netherlands.

The results from the MPM simulations showed that there is a big difference between the bearing capacity of a pre-installed pile (no installation effect are taken into account) and the bearing capacity of a pile where the installations effects are taken into account. This proves in a numerical way the importance of the pile installation effects on the pile bearing capacity. However, the MPM numerical simulations were done only for jacked piles. Therefore, impact piles, vibrated piles etc., were not simulated. For this reason, there is not a detailed numerical study for the effect of each installation method specific on the pile bearing capacity. The fact that the installation effects, in general, has an important influence on the pile bearing capacity was already proven by field tests and centrifuge tests, and has been published before by several authors.

The performed numerical simulations show that during the loading and failure of a pile, a balloon shaped plastic zone develops around the pile tip, which is in fact the failure mechanism. A better understanding of this zone could lead to a better estimation of the pile tip bearing capacity because the size and position of this plastic zone are directly related to the pile tip bearing capacity. Therefore, this plastic zone has been studied for different soil and pile parameters. Also, the influence of each parameter has been studied and discussed. A similar balloon shaped plastic zone was found for both small and large displacement simulations.

The tip bearing capacity of a pile is regarded to depend only on the soil in a certain zone around the pile tip. This zone is called the influence zone. The influence zone is found to be similar to the plastic zone of a pile tip. Therefore, the influence of a soft soil layer, near the influence zone of the pile tip, has also been studied. The numerical results have been validated with laboratory tests made by Deltares. The influence zone is roughly from 2 times the pile diameter, D, above the pile tip, to 5 or 6 times D below the pile tip.

Laboratory tests, using the direct shear test machine, have been performed in order to define the difference between the soil-pile friction angle and the soil-cone friction angle. The tests were done for different surface roughnesses and for three different sand types. The results were compared with the roughness of the sleeve of the Cone Penetration Test (CPT) apparatus.

Based on the numerical simulations and the laboratory tests of Deltares, a new design method has been proposed for the estimation of the pile bearing capacity. This method has as main input value, the CPT results, therefore it is a CPT-based design method. The proposed method has been validated using pile field tests that were performed in Lelystad in the Netherlands.

During this research, several axial and lateral pile field tests were performed at the West Coast of Mexico. Their results have been reported and discussed in the appendices.

Acknowledgements

First, I am very grateful to my supervisor Prof. Van Baars for the endless support. His helpful comments, advice and encouragement throughout the duration of my research were crucial in succeeding my dissertation.

I would also like to thank Dr. Stefan Jung for our fruitful discussions, for his valuable comments, and the opportunity to attend pile installation projects on site in Mexico.

In addition, Prof. Andreas Zilian, the vice-chairman of my PhD defense, has provided interesting remarks on all meetings that we have had during my research.

Furthermore, I wish to thank Prof. Markus Schäfer for being the chairman of my PhD defense. I am grateful for his help and encouragement.

Special thanks goes to Prof. Ken Gavin from the Technical University of Delft for accepting to be part of the evaluation committee.

I would like to thank Prof. Stephan Leyer for being my administrative supervisor during the last period of my research.

During this period, I had the pleasure two participate on different pile installation and pile tests on the construction site in the Netherlands in collaboration with Tahl Tekofsky, Guido Meinhardt and Harrie Dieteren. I am indebted with them for their help and exchange.

Peter Buch and Roland Wulkow were my greatest support during the period of the pile tests in Mexico.

I would like Dr. Vahid Galavi and Dr. Mario Martinelli for their support on the numerical simulations during my stay at Deltares research institute in Delft.

Moreover, I thank my colleges and friends for making stay at the University of Luxembourg even more pleasant.

Finally, I am very thankful to my family for being close to me and supportive. I would like to express my greatest gratitude to my wife Borana, and daughter Lura, for their love and constant support during all the late nights and early mornings, and for keeping me sane over the past few years.

Shilton RICA

Luxembourg, September 2019

Contents

List of Abbreviations and Symbols

Abbreviations	**Definition**
CPT	Cone Penetration Test
CEM	Cavity Expantion Method
DEM	Discrete Element Method
FDM	Finite Difference Method
FEM	Finite Element Method
ICP	Imperial College Pile
IP	Installed Pile
LCPC	Laboratoire Central des Ponts et Chausées
LE	Lagrangian –Eulerian
MPM	Material Point Method
MPT	Menard Pressiometer Test
MSL	Main Sea Level
MTD	Marine Technology Method
NEN	Nieuwe Europese Normen (Dutch engineering norms)
NGI	Norwegian geotechnical Institute
PE	Photo-Elasticity
PFEM	Particle Finite Element Method
PIV	Particle Image Velocimetry
PRT	Press-Replace Technique
PBP	Pre-Boring Pressiometers
SBP	Self-Boring Pressiometers
SPT	Standard Penetration Test
UWA	University of western Australia
WIP	Wished In Place
Px	Pixel (from PIV measurements)
c^{te}	constant

Latin Symbols	**SI**	**Definition**
A_{si}	[m^2]	The shaft area of the pile within the i-th soil layer
$A_{s,i}^{a}$	[m^2]	The shaft surface along the pile length above the neutral plane
$A_{s,i}^{b}$	[m^2]	The shaft surface along the pile length below the neutral plane
A_t	[m^2]	The section area of the pile tip
a, b (a x b)	[m]	The dimensions of a squared cross-section
B	[m]	The width of the strip foundation
b_a, b_b	[m]	The distances above and below the pile tip (Menard-penetrometer)
C_{CPT}	[-]	The correlation factor of the pile shaft friction regarding the CPT shaft
C_{D_R}	[-]	The factor depending on relative density of the soil at the pile tip
C_{load}	[-]	The factor for pile load (compression/tension)
C_{mat}	[-]	The factor for pile material (steel/concrete)
C_{sig}	[-]	The factor depending on effective stresses in the soil at the pile tip
C_{tip}	[-]	The factor for closed- or open-ended pile tip
C_u	[-]	The coefficient of uniformity from the sieve tests
c	[MPa]	The soil cohesion
c_D^i, c_L^i	[-]	The factors depending on the pile parameters (for D = c^{te} and L=c^{te})
D	[m]	The pile diameter
D_{ch}	[m]	The chamber diameter (laboratory tests)
D_R	[- or %]	The relative density of sand before cone (pile) penetration
D_{50}	[m]	The grain diameter of 50 % of grains in the soil sample from the sieve test
d_c	[m]	The diameter of the central cell
d_{CPT}	[m]	The cone penetrometer diameter
E	[MPa]	The Young's modulus of the soil
E_p	[MPa]	The pressiometric stiffness modulus (Menard test)
E_{ws}	[MPa]	The Young's modulus of the thin weak soil layer

e_{min}	[-]	The minimum possible void ratio of the soil sample
e_{max}	[-]	The maximum possible void ratio of the soil sample
F_s	[kN]	The pile shaft friction
$F_{s,c}$	[kN]	The calculated pile shaft friction
$F_{s,m}$	[kN]	The measured pile shaft friction
F_t	[kN]	The pile tip bearing capacity
$F_{t,c}$	[kN]	The calculated pile tip bearing capacity
$F_{t,m}$	[kN]	The measured pile tip bearing capacity
$F_{tot,c}$	[kN]	The total calculated pile bearing capacity
$F_{tot,head}$	[kN]	The measured pile bearing capacity at the pile head
$F_{t,m(t)}$	[kN]	The measured pile tip bearing capacity t-time after installation
$F_{t,m(t_0)}$	[kN]	The measured pile tip bearing capacity directly after installation
f	[-]	The friction number from CPT measurements
$f(\dots)$	[-]	This represents a function of …
f_b, f_s	[-]	Empirical bearing capacity factors
f_t/f_c	[-]	The ratio of tension over compression regarding the pile capacity
G	[MPa]	The shear modulus of the soil
H_{pile}	[m]	The depth of the pile tip in the soil (from the soil level)
H_{ch}	[m]	The height of the chamber (laboratory tests)
h	[m]	The high above the pile tip
h_d	[m]	The penetration depth in end-bearing layer
h_{ws}	[m]	The thickness of the thin weak soil layer
K_0	[-]	The coefficient of the lateral earth pressure coefficient
K_a	[-]	The active earth pressure coefficient
K_p	[-]	The passive earth pressure coefficient
k	[-]	The cavity parameter (for cylindrical or spherical cavity)
k_p	[-]	The limit pressure coefficient (pile installation method and the soil type)
L	[m]	The pile length, below the ground soil level.
L_c	[m]	The critical depth of pile tip
l_c	[m]	The length of the central cell (Menard test)
m	[-]	The operative flow number for the plasticity zone
N_q, N_c, N_γ	[-]	The surcharge, the cohesion and the self-weight bearing capacity factor
p	[MPa]	The limit pressure, Prandtl's wedge
p_{atm}	[MPa]	The atmospheric pressure
p_0	[MPa]	The natural pressure of the soil at rest
p_L	[MPa]	The limit cavity pressure, cavity expansion theories
p_l	[MPa]	The limit cavity pressure (Menard test)
$p_{l;i}$	[MPa]	The limit value of the i-th measurement of the pressiometer
$p_{l;avg}$	[MPa]	The average value of the limit pressure
p_{ref}	[MPa]	The reference stress (equal to 1 atmosphere = 0.1 MPa)
p'	[MPa]	The effective mean stresses of the soil at the pile tip
q	[MPa]	The surcharge
q_c	[MPa]	The cone resistance (unit CPT tip bearing capacity)
q_t	[MPa]	The unit pile tip bearing capacity
$q_{t_{resid}}$	[MPa]	The residual unit pile tip bearing capacity (after pile installation)
$q_{t,0.1}$	[MPa]	The unit pile tip bearing capacity for a $10\ \%\ D$ displacement of pile head
$q_{c,weak}$	[MPa]	The cone resistance of the weak layer
$q_{c,hard}$	[MPa]	The cone resistance of the hard layer
$q_{c;avg}$	[MPa]	The average value of q_c values within an influence zone
$q_{c;i;avg}$	[MPa]	The average value of q_c values in area i =(I, II, III), Koppejan method
q_{t_M}	[MPa]	The unit pile tip bearing capacity according to Menard method
R_B	[m]	The radius of the hardly deformed soil around the pile (installation)
R_c	[m]	The radius of the cavity zone

R_p	[m]	The radius of the plastic zone
R_{inter}	[-]	The parameter of the friction coefficient for the soil-pile interface
r_0	[m]	The distance from the centre of the pile/cone tip
Sr	[-]	The degree of the soil saturation
s	[-]	The shape factor of the pile tip
s_q, s_c, s_γ	[-]	The surcharge, the cohesion, the self-weight shape factor of the pile tip
V_0	[m^3]	The volume of the cell at rest condition (Menard test)
V_c	[m^3]	The initial volume of the central cell (Menard test)
V_m	[m^3]	The mean value of the volume of the cell (Menard test)
W	[kN]	The self-weight of the foundation pile
w	[m]	The pile head displacement/settlement
z_b	[m]	The depth of pile embedment into hard layer

Greek Symbols

α, β	[-]	Empirical parameters
α_t	[-]	The pile tip factor (depending on the pile, soil, installation method etc.)
α_s	[-]	The pile shaft factor (depending on the pile, soil, installation method etc.)
β_t	[-]	The pile tip factor accounting for the shape of the pile tip
γ_{soil}	[kN/m^3]	The unit self-weight of the soil (in natural condition)
γ_{water}	[kN/m^3]	The unit self-weight of the water
γ_{sat}	[kN/m^3]	The unit self-weight of the saturated soil
γ_{min}	[kN/m^3]	The minimum possible unit self-weight of the soil
γ_{max}	[kN/m^3]	The maximum possible unit self-weight of the soil
γ'	[kN/m^3]	The effective self-weight of the soil
δ_f	[°]	The interface friction angle at failure
$\delta_{soil-cone}$	[°]	The friction angle between the soil and the CPT-cone shaft
$\delta_{soil-pile}$	[°]	The friction angle between the soil and the pile shaft
Z	[-]	The factor representing the pile installation effects
θ_c	[°]	The half of the apex angle of the cone (CPT)
v	[-]	The Poisson's ratio
λ	[-]	The shear stress ratio, $\lambda = \tau/\sigma$, regarding the direct shear test
$\lambda_{c,i}$	[-]	The constant/residual shear stress ratio, regarding the direct shear test
μ	[-]	The coefficient depending on the radius of the plastic zone
π	[-]	The "pi" number, which is equal to 3.14159...
σ'_v, σ'_h	[MPa]	The vertical and the horizontal initial effective stresses
$\Delta\sigma_{rd}$	[MPa]	The change in radial stress during loading
τ_s	[MPa]	The shaft friction
$\tau_{s,i}$	[MPa]	The unit shaft friction of the i-th soil layer
$\tau_{s,i}^a$	[MPa]	The residual unit shaft friction above the neutral plane
$\tau_{s,i}^b$	[MPa]	The residual unit shaft friction below the neutral plane
τ_{sf}	[MPa]	The local shear stress at failure
τ_u or τ_{soil}	[MPa]	The shear strength of the soil
τ_{soil}^{max}	[MPa]	The maximum shear strength of the soil
τ_s^{CPT}	[MPa]	The CPT-cone shaft friction
τ_{s,i_M}	[MPa]	The unit pile shaft resistance of the i-th soil layer according to Menard test
ρ_s	[kN/m^3]	The density of the soil grains
ϕ	[°]	The friction angle of the soil
ϕ_{peak}	[°]	The residual friction angle of the soil
ϕ_{resid}	[°]	The residual friction angle of the soil
ϕ_T	[°]	The friction angle of the soil near the penetrometer tip
ϕ_{ws}	[°]	The friction angle of the thin weak soil layer
ψ	[°]	The dilatancy angle of the soil
ψ_T	[°]	The dilatancy angle of the soil near the penetrometer tip