# Three Dimensional Discrete Element Modelling of Open-Ended Tubular Pile Penetration in Weak Rocks

**by Xiangyu Zhang**

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**Doctor of Philosophy**

under the supervision of Behzad Fatahi and Hadi Khabbaz

University of Technology Sydney
Faculty of Engineering and Information Technology

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# CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Xiangyu Zhang declare that this thesis, is submitted in fulfilment of the requirements for the award of Ph.D. degree, in the School of Civil and Environmental Engineering at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

This research is supported by the Australian Government Research Training Program.

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(Xiangyu Zhang)

29 Feb 2020

To My Parents

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# List of Publications

- Published Journal Articles

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- Published Conference Papers

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# List of Abbreviations

API: American Petroleum Institute

BPM: Bonded Particle Model

CAPWAP: Case Pile Wave Analysis Program

CEL: Coupled Eulerian-Lagrangian

CPT: Cone Penetration Test

DEM: Discrete Element Method

DFN: Discrete Fracture Network

FEA: Finite Element Analysis

FEM: Finite Element Method

FinnRA: Finnish National Road Administration

FJM: Flat-joint Model

GSI: Geological strength index

HKU: Hong Kong University

ICP: Imperial College Pile

IFR: Incremental Filling Ratio

LCPC: Laboratoire Central des Ponts et Chausses

NGI: Norwegian Geotechnical Institute

PFC3D: Particle Flow Code in Three Dimension

PLR: Plug Length Ratio

RMR: Rocking mass rating

SJM: Smooth-joint Contact Model

USC: Unconfined Compressive Strength

UWA: University of Western Australia

# Nomenclature

The following notations are used in this research:

| | |
|---|---|
| $A$: | Constant; |
| $A^e$: | area of the element ($m^2$); |
| $A_p$: | gross end area of the pile ($m^2$); |
| $A_r$: | effective area ratio (non-dimensional); |
| $A_s$: | shaft area of the pile ($m^2$); |
| $A_{shoe}$: | area of the driving shoe ($m^2$); |
| $A^{sj}$: | area of the smooth-joint cross-section ($m^2$); |
| $B$: | Constant; |
| $C$: | Constant; |
| $c$: | undrained shear strength of soil (kPa); |
| $c_c$: | contact cohesion (Pa); |
| $D$: | pile diameter (m); |
| $D_{CPT}$: | cone diameter (m); |
| $D_{inner}$: | inner diameter of the pile (m); |
| $D_{outer}$: | outer diameter of the pile (m); |
| $D_r$: | relative density (non-dimensional); |
| $d_{50}$: | median particle diameter (mm); |
| $d_{max}$: | maximum diameter of the particles (mm); |
| $d_{min}$: | minimum diameter of the particles (mm); |
| $E_c$: | Young's modulus at each particle contact (Pa); |
| $E_f$: | Young's modulus values for jointed specimens (MPa); |

$E_i$: Young's modulus values for intact specimens (MPa);

$e$: void ratio (non-dimensional);

$F_n^{sj}$: normal force carried by the smooth-joint contact (N);

$F_n^{sj-\Psi}$: shear force due to dilation (N);

$F_s^{sj}$: shear force of smooth-joint contact (N);

$F_s^{sj-c}$: shear force determined by the imposed Coulomb limit (N);

$F_s^{sj-s}$: shear force determined by the force-displacement law (N);

$(F_n^{sj})_0$: initial normal force carried by the smooth-joint contact (N);

$\bar{F}_n^e$: normal force acting at the element (N);

$\bar{F}_s^e$: shear force acting at the element (N);

$f_{\mathrm{T}}(\sigma_{ci})$: correction factor for transition material (non-dimensional);

$f$: unit skin friction (kPa);

$f_{s-i}$: unit internal shaft friction (kN/m);

$f_{s-o}$: unit external shaft friction (kN/m);

$G$: operational shear modulus (GPa);

$g$: interface gap (m);

$H_Z$: embedded shaft length (m);

$H_i$: penetration depth (m);

$H_{plug}$: height of the rock plug (m);

$\Delta H$: change in pile penetration depth (m);

$h$: height of soil layer above the pile toe (m);

$I_{s(50)}$: point load strength index (MPa);

$I_{v0}$: relative void index (non-dimensional);

$I_{vy}$: relative void index at yield (non-dimensional);

$K$: coefficient of lateral earth pressure (non-dimensional);

$K_c$: a factor depend on yield stress ratio (non-dimensional);

$K_f$: coefficient of radial effective stress at failure (non-dimensional);

$K_s$: coefficient of horizontal stress of rock mass (non-dimensional);

$k^*$: normal-to-shear stiffness ratio (non-dimensional);

$k_n$: contact normal stiffness (Pa/m);

$k_{ns}$: contact normal stiffness for smooth-joint contact (Pa/m);

$k_s$: contact shear stiffness (Pa/m);

$k_{ss}$: contact shear stiffness for smooth-joint contact (Pa/m);

$L$: smallest characteristic model length (m);

$l_i$: soil plug length (m);

$\Delta l$: incremental change of plug length (m);

$m_b$, $m_i$, $s$, and $a$: original Hoek-Brown parameters;

$m_b^*$, $s^*$, and $a^*$: corrected Hoek-Brown parameters;

$N_c$: bearing capacity factor (non-dimensional);

$N_q$: bearing capacity factor (non-dimensional);

$N_\gamma$: bearing capacity factor (non-dimensional);

$P_a$: atmospheric pressure (kPa);

$p'_0$: effective overburden pressure (kPa);

$Q_{annular}$: resistance of the annular area (kN);

$Q_b$: ultimate resistance of the base (kN);

$Q_{base}$: resistance of the equivalent base (kN);

$Q_{bottom}$: bearing capacity of the soil beneath the plug base (kN);

$Q_{inner}$: bearing capacity of inner shaft (kN);

$Q_{outer}$: resistance of outer shaft (kN);

$Q_p$: ultimate resistance of the pile (kN);

$Q_{plug}$: bearing capacity of soil plug (kN);

$Q_s$: ultimate resistance of the shaft (kN);

$q$: unit end bearing capacity (kPa);

$q_c$: local CPT tip resistance (kPa);

$q_{uc}$: uniaxial compressive strength of the intact rock (MPa);

$R$: radius of the pile (m);

$R^*$: equivalent radius of the pile (m);

$R^A$: radii of the contacting particle A (m);

$R^B$: radii of the contacting particle B (m);

$R^{fj}$: radius of the flat-joint contact (m);

$R_{inner}$: inner radius of the pile (m);

$R_{outer}$: outer radius of the pile (m);

$r$: radial distance (m);

$\Delta r$: radial displacement (m);

$S_t$: clay sensitivity (non-dimensional);

$T$: tensile strength of the rock mass (MPa);

$t_{pile}$: thickness of the pile (mm);

$t_{pile}$: pile wall thickness (mm);

$UCS$: unconfined compressive strength (MPa);

$UCS_{RM}$: uniaxial compressive strength of rock mass (MPa);

$UCS_f$: unconfined compressive strength for jointed rock (MPa);

$UCS_i$: uniaxial compressive strength of intact rock material (MPa);

$W$: width of the base (m);

$W_p$: weight of the pile (m);

$Z$: depth (m);

$\alpha$: joint dip (degree);

$\beta$: adhesion factor (non-dimensional);

$\chi$: a multiplier (non-dimensional);

$\gamma$: effective density of the rock mass (kg/m$^2$);

$\delta$: friction angle between the soil and pile wall (degree);

$\delta$: friction angle between pile and soil (degree);

$\delta_{cv}$: interface angle of friction at failure (degree);

$\delta_f$: operational interface angle of frictional failure (degree);

$\Delta\delta_n^{sj}$: elastic portions of the normal displacement increment (m);

$\Delta\delta_s^{sj}$: shear displacement increment (m);

$\phi$: internal friction angle (degree);

$\emptyset_c$: contact friction angle (degree);

$\phi_{rc}$: contact residual friction angle (degree);

$\eta$: plugging coefficient (non-dimensional);

η: individual joint length (mm);

$\Psi$: dilation angle (degree);

$\lambda$: radius multiplier (non-dimensional);

$\mu_c$: contact friction coefficient;

$\mu_{cs}$: contact friction coefficient for smooth-joint contact;

$\sigma_1$: major principle stress (kPa);

$\sigma_3$: minor principle stress (kPa);

$\sigma_b$: normal stress on the notional surface (Pa);

$\sigma_c$: contact tensile strength (Pa);

$\sigma_{ci}$: uniaxial compressive strength (MPa);

$\sigma^e$: normal stress in the element (Pa);

$\sigma'_{rc}$: equalized radial effective stress (kPa);

$\sigma'_{rc}$: local radial effective stress (kPa);

$\sigma_{ten}$: tensile strength limit (Pa);

$\sigma'_{vo}$: in-situ initial vertical effective stress (kPa);

$\sigma'_{vy}$: vertical yield stress (kPa);

$\Delta\sigma'_{rd}$: increase in radial effective stress during pile loading (kPa);

$\tau_b$: shear strength of the contact (Pa);

$\tau^e$: shear stress in the element (Pa);

$\tau_f$: local shear stress (kPa);

$\tau_{lim}$: shear strength limit (Pa);

$\tau_{sp}$: shear strength of the element from slipping (Pa);

$\xi$: joint density ($m^2/m^3$);

$\omega$: joint aperture (mm);

# Abstract

Open-ended tubular piles, usually made of steel, are commonly used in offshore structures and bridge projects due to the high capacity and less required installation effort. Predicting the load – displacement response of the open-ended piles is of interest to many practicing engineers and researchers. Although the behaviour of the piles embedded in sands and clays has been studied extensively, clear and adequate recommendation is not currently available for predicting the load – displacement response of open-ended piles embedded in weak rocks. However, the increasing number of projects in Australia requires adopting the open-ended piles embedded in weak rock layers to sustain the axial and lateral structural loads. Current recommendations for the design of tubular piles in weak rocks are mainly based on the methods originally proposed for gravels, sands and clays, which cannot predict the shaft and base resistances of tubular piles in weak rocks accurately. Furthermore, the behaviour of weak rock masses is complex due to their characteristics, and the plugging mechanism of tubular piles influenced by the characteristics of the weak rock is not well understood. Therefore, there is a need to enhance the understanding of the load bearing mechanism of open-ended tubular piles embedded in weak rocks to optimise the construction cost and improve safety.

In this thesis, initially the effects of joint properties on the behaviour of weak rock masses are discussed. The discrete element method (DEM) is adopted which can simulate interacting rock grains. The interaction between grains is controlled by the adopted contact models. The flat-joint model that follows the elasto-plastic force-displacement constitutive law is employed in the analysis. Meanwhile, the discrete fracture network (DFN) along with the smooth-joint model are adopted to replicate the sliding of the joints. Initially, the effects of joint dip, joint density, joint aperture, and joint length on the mechanical behaviour of the

rock mass are investigated through simulating unconfined compressive strength and triaxial tests.

Moreover, this research provides an insight into the impacts of joint dip and joint density on the internal shaft friction of open-ended tubular piles through DEM analysis. The flat-joint and smooth-joint contact models are adopted to replicate the rock mass and the sliding of the joints, respectively. The push-up load tests are performed on the intact rock plug and jointed rock plug to analyse the effects of joints on the internal shaft frictions of tubular piles. It is noticed that the joints could reduce the capacity of the rock plug, and the joints parallel to the loading direction have the largest impact compared to other joint dips, where the joints parallel to the axial loading direction in the triaxial test do not result in the lowest strength. This indicates that the internal shaft friction of open-ended tubular piles is not solely a function of the rock strength, and the effects of joint properties need to be taken into consideration.

Furthermore, the axial load bearing mechanism of open-ended tubular piles penetrating into weak rock is discussed. The numerical modelling using the discrete element method is adopted since tubular pile driving involves extremely large displacements that DEM can accommodate. Effects of an inner driving shoe attached to the open-ended tubular pile on the load bearing mechanism is also investigated. The incremental filling ratio (IFR) and plug length ratio (PLR) are used to assess the plugging of the piles.  As expected, the base resistance can mobilise at the early stage of the pile penetration, while the internal and external shaft frictions increase continuously as the pile penetrates deeper. The unit internal shaft friction is mainly mobilised at the bottom portion of the rock plug due to the arching effect. Moreover, partial plugging is observed for both piles with and without driving shoe, and the correlations between IFR and PLR are proposed.