ABSTRACT

Physical Testing of Jack-Up Footings on Sand Subjected to Torsion

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With approximately 100 terra cubic feet (TCF) of gas estimated to be available on the North-West Shelf and the large quantity of oil in that region, the use of self-elevating mobile units such as jack-ups will be in great demand. Because of their economic importance in developing these resources, their safe use and reliability is critical. Jack-ups perform drilling in water depths up to 120 m. At such depths, the magnitude of loads acting on the three legs is substantial and becomes a combined load on the foundation. These include vertical (V), horizontal (2 orthogonal H_1 and H_2), moment (2 orthogonal M_1 and M_2), and torsional (T) loads. To incorporate this, an adequate foundation model with six degrees of freedom needs to be investigated. The main aim of this thesis is to examine the vertical and combined torsion load displacement behaviour. The thesis concentrates on footings on sand in an attempt to verify an existing three-dimensional plane strain formulation (known as 'Model C' for six degrees of freedom) in the Vertical load V – Torsion T space.

This thesis presents the experimental results of various size circular footings (20, 30, 40, and 50 mm radius) when subjected to vertical and torsional loads on dense and loose silica sand. Further, other common test procedures performed to determine the sand properties, such as sieve analysis, minimum and maximum density tests, and direct shear box tests are described. The test results include pure vertical-loading tests, vertical-torsion sideswipe tests (V-T space), and a radial displacement test in the V:T plane. Based on the experimental test results, Model C for six degrees of freedom in the V-T space was experimentally verified. Various model parameters, such as yield surface size in the V:T plane, have been defined and modifications to the existing model suggested. Based on these suggestions, successful retrospective numerical simulation of the experiments was performed.

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Dear Sir

It is with great pleasure that I submit this thesis entitled "Physical Testing of Jack-Up Footings on Sand Subjected to Torsion" as a partial requirement for the double degree of Bachelor of Science and Bachelor of Engineering (Civil).

Yours sincerely

Joseph Cheong

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"For God so loved the world that he gave his one and only Son, that whoever believes in him shall not perish but have eternal life." (John 3:16)

TABLE OF CONTENTS

NOMENCLATURE

Notation used in thesis. Symbols have been placed under chapter headings.

Chapter 1:

H	horizontal load
H_1, H_2	orthogonal horizontal loads
M	moment load
M_1, M_2	orthogonal moment loads
R	radius of a circular footing
T	torsional load
u	horizontal footing displacement
u_1, u_2	orthogonal horizontal footing displacements
V	vertical load
w	vertical footing displacement
θ	rotational footing displacement
θ_1, θ_2	orthogonal rotational footing displacements
θ_t	torsional (rotational) footing displacement

Chapter 2:

a	eccentricity of yield surface
A	surface area of the footing
b_c, b_γ, b_q	base inclination factors
B	footing width or diameter
c	cohesion (also shear strength, s_u)
d	(as prefix) increment in value
d_c, d_γ, d_q	depth factors
f	yield function
f_p	factor determining limiting magnitude of vertical load as $w_p \rightarrow \infty$
g	plastic potential function
g	dimensionless shear modulus factor
g_c, g_γ, g_q	ground inclination factors
G	representative elastic shear modulus
h_0	dimension of yield surface (horizontal)
$h_{0\,peak}$	horizontal dimension for the yield surface at peak bearing capacity
H	horizontal load
H_0	maximum horizontal load
H_1, H_2	orthogonal horizontal loads
i_c, i_γ, i_q	load inclination factors
k	initial plastic stiffness
k^e	elastic vertical stiffness
k'	rate of change in association factors
k_c	dimensionless elastic stiffness factor (horizontal/moment coupling)

k_h	dimensionless elastic stiffness factor (horizontal)
k_m	dimensionless elastic stiffness factor (moment)
k_t	dimensionless elastic stiffness factor (torsion)
k_v	dimensionless elastic stiffness factor (vertical)
m_0	dimension of yield surface (moment)
M	moment load
M_1, M_2	orthogonal moment loads
N_c, N_γ, N_q	bearing capacity factors
p_a	atmospheric pressure
q	overburden (surcharge pressure = γz)
q_{ult}	ultimate bearing capacity
Q	general deviator force
r	radius at the surface of a partially penetrated conical footing
R	radius of a circular footing
s_c, s_γ, s_q	shape factors
s_{fp}	dimensionless scaling factor in the "combined" strain hardening law
t_0	dimensionless variable that determines the size of the yield surface in the $T/2R$ plane and is the value of $T/(2RV_0)$ at the maximum T
$t_{0\,peak}$	torsional dimension for the yield surface at peak bearing capacity
T	torsional load (torque)
u	horizontal footing displacement
u_1, u_2	orthogonal horizontal footing displacements
V	vertical load
V_0	maximum vertical load capacity when all other loads are not present (eg $H = 0$, $M = 0$, $T = 0$)
V_0'	maximum vertical load for the current plastic potential shape
V_{peak}	maximum vertical load bearing capacity, i.e. peak value of V_0 in strain hardening law
V_{ult}	ultimate vertical load (= $q_{ult}A$)
w	vertical footing displacement
w_p	plastic component of the vertical penetration (also w^p)
w_{pm}	value of the plastic component of the vertical penetration at the peak value of V_0 (i.e. at V_{peak})
z	depth of a foundation below the lowest adjacent surface

α	footing roughness
α_h, α_m	horizontal and moment association factor respectively
$\alpha_{h\infty}$, $\alpha_{m\infty}$	association factor as horizontal displacement or rotation tend to infinity respectively
β	cone apex angle
β_1	curvature factor for yield surface (low stress)
β_2	curvature factor for yield surface (high stress)
β_3	curvature factor for plastic potential (low stress)
β_4	curvature factor for plastic potential (high stress)
ϕ	friction angle
γ	effective unit weight
λ	multiplication factor determining the magnitude of plastic displacement increments
ν	Poisson ratio

θ	rotational footing displacement
θ_1, θ_2	orthogonal rotational footing displacements
θ_t	torsional (rotational) footing displacement
σ_f	failure stress
σ_g	yield stress
σ_y	first yield stress

Superscripts:

e	elastic
p	plastic

Chapter 3:

d_{50}	maximum particle size of the smallest 50 per cent of the sample
e	void ratio
e_{max}	maximum void ratio
e_{min}	minimum void ratio
G_s	specific gravity
I_d	density index (also called relative density)
I_R	relative dilatancy index
p'	mean effective stress

ϕ	friction angle
ϕ'_{cv}	critical state friction angle
ϕ'_{peak}	peak friction angle
ρ_d	dry density
σ_n'	constant normal stress
σ_v'	effective vertical stress
τ	shear stress (= horizontal load / area)
τ/σ_n'	shear stress ratio

Chapter 4:

Y	horizontal displacement
Z	vertical displacement

Chapter 5:

d	(as prefix) increment in value
d_{50}	maximum particle size of the smallest 50 per cent of the sample
f	yield function
f_p	factor determining limiting magnitude of vertical load as $w_p \rightarrow \infty$
g	plastic potential function
G	representative elastic shear modulus

h_0	dimension of yield surface (horizontal)
H	horizontal load
I_d	density index (also called relative density)
k	initial plastic stiffness
k^e	elastic vertical stiffness
k_v	dimensionless elastic stiffness factor (vertical)
M	moment load
N_γ	bearing capacity factor (self-weight)
q	overburden (surcharge pressure = γz)
Q	general deviator force
r	auxiliary parameter
R	radius of a circular footing
t_0	dimensionless variable that determines the size of the yield surface in the $T/2R$ plane and is the value of $T/(2RV_0)$ at the maximum T
$t_{0\,peak}$	torsional dimension for the yield surface at peak bearing capacity
T	torsional load
T_m	maximum value of T
V	vertical load
V_0	maximum vertical load capacity when all other loads are not present
V_0'	maximum vertical load for the current plastic potential shape
V_{peak}	maximum vertical load bearing capacity, i.e. peak value of V_0 in strain hardening law
w	vertical footing displacement
w_p	plastic component of the vertical penetration (also w^p)
w_{pm}	value of the plastic component of the vertical penetration at the peak value of V_0 (i.e. at V_{peak})
z	depth of a foundation below the lowest adjacent surface

α	footing roughness
α	angle of "theoretical" plastic displacement direction vector
α_h, α_m	horizontal and moment association factor respectively
α_t	torsion association factor
β_1	curvature factor for yield surface (low stress)
β_2	curvature factor for yield surface (high stress)
β_3	curvature factor for plastic potential (low stress)
β_4	curvature factor for plastic potential (high stress)
ϕ	internal friction angle
ϕ'_{cv}	critical state friction angle
ϕ'_{peak}	peak friction angle
γ	effective unit weight
η	angle of "experimental" plastic displacement ratio (Eqn 5.21)
λ	multiplication factor determining the magnitude of plastic displacement increments
θ_t	torsional (rotational) footing displacement
θ_t^p	plastic component of torsional (rotational) displacement
σ	vertical stress
σ_{max}	maximum vertical stress
τ	shear stress

Superscripts:

e	elastic
p	plastic
t	total

Chapter 6:

f_p	factor determining limiting magnitude of vertical load as $w_p \rightarrow \infty$
g	dimensionless shear modulus factor
G	representative elastic shear modulus
k	initial plastic stiffness
k'_t	rate of change of association factor α_t
k_t	dimensionless elastic stiffness factor (torsion)
k_v	dimensionless elastic stiffness factor (vertical)
N_γ	bearing capacity factor (self-weight)
p_a	atmospheric pressure
R	radius of a circular footing
t_0	dimensionless variable that determines the size of the yield surface in the $T/2R$ plane and is the value of $T/(2RV_0)$ at the maximum T
T	torsional load
V	vertical load
V_0	maximum vertical load capacity when all other loads are not present
V_{peak}	maximum vertical load bearing capacity, i.e. peak value of V_0 in strain hardening law
w	vertical footing displacement
w_p	plastic component of the vertical penetration (also w^p)
w_{pm}	value of the plastic component of the vertical penetration at the peak value of V_0 (i.e. at V_{peak})

α_m	moment association factor
α_t	torsion association factor
$\alpha_{t\infty}$	association factor as torsional (rotational) displacement tend to infinity
β_1	curvature factor for yield surface (low stress)
β_2	curvature factor for yield surface (high stress)
β_3	curvature factor for plastic potential (low stress)
β_4	curvature factor for plastic potential (high stress)
γ	effective unit weight
η	angle of “experimental” plastic displacement ratio (Eqn 5.21)
θ_t	torsional (rotational) footing displacement
θ_t^p	plastic component of torsional (rotational) displacement

Chapter 7:

H	horizontal load
M	moment load

R	radius of a circular footing
t_0	dimensionless variable that determines the size of the yield surface in the $T/2R$ plane and is the value of $T/(2RV_0)$ at the maximum T
T	torsional load
V	vertical load
V_0	maximum vertical load capacity when all other loads are not present
α_t	torsion association factor
β_3	curvature factor for plastic potential (low stress)
β_4	curvature factor for plastic potential (high stress)

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