UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Assessment of Seismic Behaviour of Large LNG Tanks Considering Soil-Foundation- Structure Interaction

by Noor Sharari

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, **Noor Sharari,** declare that this thesis, is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, 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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Noor Sharari
Sydney, November 2021

Sincerely Dedicated to

My Father and Mother

Ibrahim & Mountaha

I owe you two my life and all the success

My husband Hussam, thank you for being with me during this journey

Saad and Hamad my sweethearts

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LIST OF NOTATIONS

$A_g(t)$	Horizontal ground acceleration
A_{loop}	Area of one hysteresis loop
A^{ff}	Area of influence of free-field elements
C_b	Outward wave speed at the lateral boundaries of a numerical model
C_{con}	Sloshing period coefficient
$C_h(T)$	Spectral shape factor
C_{imp}	Acceleration coefficient
Ck	Initial kinematic hardening modulus
C_l	Coefficient of impulsive period
cp	Dilatational (pressure) speed
Cs	Kinematic hardening modulus for steel
c_{sv}	Shear wave speeds
Cu	Undrained shear strength of soil
D	Tank diameter
D_K	Building damping ratio
dt	Tensile damage parameter
dc	Compressive damage parameter
d_s	damping of the infinite boundary in the normal directions
d_p	damping of the infinite boundary in the shear directions
E_0	Intial elastic stiffness of concrete
E_c	Elastic modulus of the concreter
E_s	Elastic modulus of the 9% Ni steel
E_{soil}	Modulus of elasticity of soil
E_r	Elastic modulus of the rebar
F	Yield surface function
$F_{boundary}$	Resultant normal force acting on an interface element
$f(\sigma - \alpha)$	Equivelant Mises stress
f_{bo}	Biaxial compressive yield strengths
f_{co}	Uniaxial compressive yield strengths

F^{ff}	Force generated in the free-field element
f'_c	Concrete compressive strength
f_y	Tensile yield stress
f_{ult}	Ultimate tensile strength
G_{inf}	Infinite element shear modulus of soil
G_{max}	Maximum shear modulus of soil
G_{sec}	Secant shear modulus of soil
G_{tan}	Tangent shear modulus of soil
h	Overclosure or gap level
H	Height of tank
H_{con}	Convective mass height
H_{imp}	Implusive mass height
H_L	Fluid design level
$\grave{I}_1, I_1$	Modified Bessel functions of order 1 and its derivative
I_g	Reduction factor modulus
K_c	Tensile to the compressive meridian ratio
K_{con}	Convective mode spring stifness
K_h	Horizontal stiffness for SFSI system
K_r	Rotational stiffness for SFSI system
M_{con}	Covective mass
M_{imp}	Implusive mass
M_{fod}	Foundation mass
M_{total}	Liquid mass
$(N_1)_{60cs-Sr}$	Equivalent SPT value
N_{max}	Coffiecient for fualt distance
P	Contact pressure
PGA	Peak ground acceleration
p_{con}	Convective pressure
$p_i and\ p_{imp}$	Impulsive pressure
$\bar{p}$	Hydrostatic stress
$\bar{q}$	Von Mises effective stress
R	Return period factor

R^2	Coefficient of determination
R_{tank}	Tank radiuos
r	Cylindrical coordinates of tank
S	Deviatoric stress tensor
S_r	Residual shear strength
t	Time
T	Structure period
T_{imp}	Impulsive natural period
T_{imp}^{*}	Impulsive natural period with SFSI effect
T_{con}	Convective natural period
t_u	Equivalent uniform thickness of the tank wall
ν	Poisson's Ratio
V_s	Shear wave velocity
Z	Hazard factor
z	Cylindrical coordinates of tank
$\langle\cdot\rangle$	Macaulay bracket
α	Back stress
α^{dev}	Devatoric part of back stress tensor
α^{s}	Back stress at large plastic strains
$\alpha_{damping}$	Rayleigh coefficients viscous damping
$\beta_{damping}$	Rayleigh coefficients viscous damping
$\dot{\bar{\varepsilon}}^{pl}$	Equivalent plastic strain rate
$\bar{\varepsilon}_c^{in}$	Inelastic crushing strain
$\bar{\varepsilon}_c^{pl}$	Compressive plastic strain
$\bar{\varepsilon}_t^{cr}$	Cracking strain
$\bar{\varepsilon}_t^{pl}$	Tensile plastic strain
$\dot{\varepsilon}^{pl}$	Plastic flow rate
ε_t^{pl}	Tensile plastic strain
ε_c	Compressive strain
ε_{eng}	Nominal strain values
ε_t	Tensile strain

ε_{true}	True (logarithmic) strain
ϵ	Eccentricity of plastic potential surface
γ_k	Hardening modulus decreasing rate
γ_{ref}	Refernce shear strain
γ	Cyclic shear strain
γ_l	Non-diamntional factor
ρ	Fluid density
ρ_{soil}	Soil density
ρ_c	Concrete density
ρ_r	Steel rebar density
ρ_{steel}	Ni steel desity
γ_k	Hardening modulus decreasing rate
δ	Elongation
ξ	Non-dimensional coordinates
$\xi_{damping}$	Soil damping
ξ_{max}	Maximum damping ratio
ς	Non-dimensional coordinates
$\bar{\sigma}_{max}$	Maximum principal effective stress
$\bar{\sigma}_c$	Effective compressive stress
$\bar{\sigma}_t$	Effective tension stress
σ_c	Compression stress
σ_{eng}	Nominal stress- strain values
σ_t	Tensile stress
σ_{t0}	Tensile stress at failure
σ_{true}	Cauchy stress
σ_{ult}	Ultimate stress
$\acute{\sigma}_{vc}$	Effective vertical stress
σ_y	Yield stress
$\sigma\|_0$	Initial yield stress
θ	Cylindrical coordinates of tank
τ	The shear stress
$\tau_{critical}$	Critical contact shear stress

τ_{rev}	Shear stress at the reversal point
ψ	The dilation angle
μ	Friction coefficient

ABSTRACT

During the past decades, demand for Liquefied Natural Gas (LNG) tanks has increased. Indeed, the LNG is cleaner and cheaper fuel for power generation compared to oil and coal. The LNG industry is growing rapidly, and many LNG tanks are constructed in seismically active coastal regions; hence, potential damage or leakage due to cracking triggered by an earthquake can result in destructive environmental and safety issues. These LNG tanks are usually built near the seashore to reduce the cost and increase the flexibility of LNG transportation and storage. Often the foundation soil in coastal regions is not capable of bearing the load of such heavy structures. Thus usually, deep foundations are used to support these tanks. Indeed, pile foundations are commonly used for these large tanks to transfer the load to competent ground layers and control the settlement. Generally, assessing the seismic resilience of these critical infrastructures is essential to ensure the availability and security of services during and after large earthquakes. Considering the complexity of the seismic analysis and design of such structures due to the Fluid-Structure Interaction (FSI) and Soil–Foundation-Structure Interaction (SFSI) effects, advanced modelling and analysis are required.

This thesis conducts the three-dimensional fully nonlinear coupled SFSI and FSI numerical simulations for LNG tanks using the direct method. The nonlinear time history analysis and free vibration analysis are conducted to assess the seismic safety and dynamic characteristics of LNG tanks under different pile foundation types and liquefiable soil deposits. The fluid-structure interaction effects are captured using a mechanical model, which captures both convective and impulsive hydrodynamic components. Nonlinear kinematic hardening soil model adopted in this study is also

verified and implemented to capture the hysteretic damping of the soil and the variation of the shear modulus with the cyclic shear strain developed in the soil. Infinite boundary elements are assigned to the numerical model, and proper interface elements, capable of modelling sliding and separation between the foundation and soil elements, are considered. This thesis conducts the numerical analyses with the help of the High-Performance Computer (HPC) at the University of Technology Sydney (UTS), taking a few weeks to a month for a single analysis to run due to the complexity of the system.

To assess the effect of different pile foundation options on the seismic response of LNG tanks, different pile foundation types, including an end-bearing pile foundation and a pile-raft foundation with two different frictional pile lengths, are investigated. The results show the importance of the SFSI effect in evaluating the seismic response of LNG tanks built on pile foundations. Furthermore, the significant effect of the deep foundation system choice on the dynamic response of the LNG tanks is highlighted. Indeed, the seismic analysis and the design of LNG tanks in practice need to carefully consider the SFSI effects implementing direct method of analysis to ensure both kinematic and inertial interactions are captured accurately when analysis LNG tanks on pile foundations. Moreover, the numerical results show that presence of liquified soil layer alter the dynamic properties of LNG tank by lengthen the natural period and increase the damping of the LNG tank, soil, and foundation system. In addition, the presence of liquified soil layer significantly reduces the impulsive forces applied on LNG tank wall, while no significant change is observed for the convective forces. Hence, presence of the liquefied soil layer can absorb the seismic energy and reduce the seismic forces transferred to the superstructure. The predictions show that with increasing the thickness of the liquefied soil layer, the kinematic interaction increases, directing more seismic forces to the piles supporting the LNG tank, which can potentially result in yielding and failure of the piles.