Novel Application of Geosynthetics in Seismic Protection of Buildings Considering Soil-Foundation-Structure Interaction

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

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(Ruoshi Xu)

Sydney, June 2018

To My Dearest Family

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LIST OF PUBLICATIONS RELATED TO THIS RESEARCH

Journal Articles

1. **Xu, R.** and Fatahi, B. 2018. Geosynthetic-Reinforced Cushioned Pile Foundation with Controlled Rocking for Seismic Safeguarding of Buildings. Geosynthetics International. DOI: 10.1680/jgein.18.00018.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF NOTATIONS

ϕ'	Effective friction angle of soil
γ	Shear strain in hysteretic damping algorithm
γ_c	Critical shear strain
γ_{soil}	Unit weight of soil
ε	Axial strain developed in geosynthetic layer
ε_u	Strain developed in geosynthetic layer at ultimate tensile strength
ε_{yield}	Yield strain of structural member
θ, emb	Rotation of an embedded foundation
θ	Rotation of a surface foundation
θ_v	Angle between the axis of the concrete compression strut and the longitudinal axis of a structural member
ν_{geo}	Poisson's ratio of geosynthetic layer
ν	Poisson's ratio of soil
$\tilde{\xi}$	Equivalent damping ratio of a SDOF system considering SFSI
ξ	Damping ratio due to one hysteresis loop
ξ_θ	Damping ratio of a structure due to foundation rotation
ξ_h	Damping ratio of a structure due to foundation horizontal movement
ρ_{conc}	Density of concrete
ρ_{geo}	Density of geosynthetic layer
ρ_{pile}	Density of a pile
ρ_{reo}	Density of steel reinforcement
ρ_{soil}	Density of soil
σ	Stress developed in a structural member

σ_{yield}	Yield stress of a structural member
σ_n	Additional normal stress vectors added due to interface stress initialisation
σ_{si}	Additional shear stress vectors added due to interface stress initialisation
τ_c	Critical shear stress
$\widetilde{\omega}$	Equivalent natural frequency of a SDOF system considering SFSI
ω_0	Natural frequency of a fixed-base system
ω_s	Natural frequency of a structure
ω_θ	Natural frequency of a structure due to foundation rotation
ω_h	Natural frequency of a structure due to foundation horizontal movement
ARR	Area replacement ratio
A	Contact area of an interface element
A_b	Foundation area
A_g	Gross cross sectional area of a structural member
A_{loop}	Area of one hysteresis loop
A_{pile}	Total area of piles
A_{raft}	Area of foundation raft
A_{reo}	Area of reinforcement
A_{soil}	Areas of soil
A_{st}	Cross sectional area of longitudinal tensile reinforcement
A_{sv}	Gross sectional area of shear reinforcement
A_w	Total area of side wall contacting with soil
A_i	Representative area associated with an interface element
A^{ff}	Area of influence of free-field elements
A^f_{max}	Maximum face area associated with tetrahedral sub-elements

a_s	Curve fitting parameter for SIG-III model
a_{PGA}	Peak ground acceleration of applied earthquake
B	Foundation width
B'	Half width of a foundation
BCR	Bearing capacity ratio
b_s	Curve fitting parameter for SIG-III model
b	Length of a geosynthetic layer
b_m	Width of a element cross section
b_w	Width of a cross section of a structural member
$[C]$	Damping matrx of a soil-foundation-structure system
$\tilde{c}_u$	Lateral dynamic damping coefficient of a foundation
$\tilde{c}_v$	Normal dynamic damping coefficient of a foundation
$\tilde{c}_\theta$	Rotational dynamic damping coefficient of a foundation
C	Damping coefficient of a foundation
C_b	Outward wave speed at the lateral boundaries of a numerical model
$C_r(\omega)$	Radiation damping coefficient of a foundation
$C_{ru,emb}$	Lateral radiation damping coefficient of an embedded foundation
C_{ru}	Lateral radiation damping coefficient of a foundation
$C_{rv,emb}$	Normal radiation damping coefficient of an embedded foundation
C_{rv}	Normal radiation damping coefficient of a foundation
$C_{r\theta,emb}$	Rotational radiation damping coefficient of an embedded foundation
$C_{r\theta}$	Rotational radiation damping coefficient of a foundation
$\tilde{c}$	Equivalent damping of a SDOF system considering SFSI
c	Damping coefficient of a fixed-base system
c'	Effective cohesion of soil
c_h	Translational damping coefficient of a SDOF system

c_θ	Rotational damping coefficient of a SDOF system
d_0	Distance from the extreme compressive fibre of the concrete cross section to the centroid of the outermost layer of tensile reinforcement
d_i	Building deflection at the i_{th} level
d_{i+1}	Building deflection at the $(i+1)_{th}$ level
d_{pile}	Diameter of a pile
E_R	Elastic modulus of a geosynthetic layer
E_c	Modulus of elasticity of concrete
E_s	Modulus of elasticity of steel reinforcement
E_{soil}	Modulus of elasticity of soil
E_{unref}	Elastic modulus of unreinforced sand
E_{ref}	Elastic modulus of reinforced sand
EI	Bending stiffness of pile
f'_c	Characteristic compressive strength of concrete
f_{cmi}	In-situ compressive strength of concrete
f_{cv}	Concrete shear strength
f_{sy}	Yielding strength of steel reinforcement
F_n	Resultant normal force acting on an interface element
F^{ff}	Force generated in an free-field element
${F^{(t+\Delta t)}}_n$	Normal force vectors generated on the interface element at time $(t+\Delta t)$
${F^{(t+\Delta t)}}_{si}$	Shear force vectors generated on the interface element at time $(t+\Delta t)$
G	Shear modulus of solid element
G_{max}	Maximum shear modulus of soil
G_{sec}	Secant shear modulus of soil
G_{tan}	Tangent shear modulus of soil

h	Height of a structure
h_g	Spacing between geosynthetic layers
h_m	Height of an element cross section
$h\theta$	Structural lateral displacement due to foundation rocking
I	Moment of inertia of a cross section
I_b	Moment of inertia of a foundation
I_{cr}	Moment of inertia of a cracked cross section
J	Tensile stiffness of a geosynthetic layer
$[K]$	Stiffness matrx of a soil-foundation-structure system
$\overline{K}$	Dynamic stiffness of a foundation
$\overline{K}_{u,emb}$	Lateral dynamic stiffness of an embedded foundation
$\overline{K}_u$	Lateral dynamic stiffness of a foundation
$\overline{K}_{v,emb}$	Normal dynamic stiffness of an embedded foundation
$\overline{K}_v$	Normal dynamic stiffness of a foundation
$\overline{K}_{\theta,emb}$	Rotational dynamic stiffness of an embedded foundation
$\overline{K}_\theta$	Rotational dynamic stiffness of a foundation
$\tilde{k}$	Equivalent stiffness of a SDOF system considering SFSI
K	Bulk modulus of solid element
K_s	Static stiffness of a foundation
K_u	Lateral static stiffness of a foundation
K_v	Normal static stiffness of a foundation
K_θ	Rotational static stiffness of a foundation
$k(\omega)$	Dynamic stiffness coefficient of a foundation
k	Stiffness of a fixed-base system
k_h	Translational stiffness of a SDOF system
k_n	Normal spring stiffness

k_s	Shear spring stiffness
k_u	Lateral dynamic stiffness coefficient of a foundation
k_v	Normal dynamic stiffness coefficient of a foundation
k_θ	Rotational dynamic stiffness coefficient of a foundation
k_{re}	Coefficient of soil reaction
L_1	Curve fitting parameter for default model
L_2	Curve fitting parameter for default model
L'	Half-length of a foundation
LL	Liquid limit
$\widehat{M}(z)$	Dimensionless normalised bending moment
$[M]$	Mass matrx of a soil-foundation-structure system
M	Applied bending moment
$M_{max}(z)$	Maximum bending moment imposed on a pile at the depth z
M^p	Plastic moment capacity for flexural structural members
M_s	Secant modulus in hysteretic damping algorithm
M_t	Tangent modulus in hysteretic damping algorithm
m	Mass of a fixed-base system
N^*	Axial compressive force applied on a cross section of structual member
N	Applied normal force
PI	Plasticity index
PL	Plastic limit
P_x	Axial load in a pile
p	Pressure applying on soil
$\widehat{Q}(z)$	Dimensionless normalised shear force
$Q_{max}(z)$	Maximum shear force imposed on a pile at the depth z
q_R	Bearing capacity of a geosynthetic reinforced foundation

q_u	Ultimate bearing capacity of an unreinforced foundation
Q	Applied lateral force
R_r	Reinforcement ratio
S	Dynamic impedance of a foundation
S_s	Shear strength of interfaces
S_a	Spectral acceleration
S_u	Undrained shear strength of soil
s	Centre-to-centre spacing of shear reinforcement
$\widetilde{T_n}$	Natural period of a system considering soil-foundation-structure interaction
T	Tensile stress developed in a geosynthetic layer
T_x	X component of tensile stress developed in a geosynthetic layer
T_y	Y component of tensile stress developed in a geosynthetic layer
T_n	Natural period of a system
T_s	Tensile strength of interface
T_u	Ultimate tensile strength of a geosynthetic layer
t_{geo}	Thickness of a geosynthetic layer
$\{\ddot{u}\}$	Nodal acceleration in a soil-foundation-structure system
$\{\dot{u}\}$	Nodal velocity in a soil-foundation-structure system
$\{\Delta\ddot{u}\}$	Nodal acceleration increment in a soil-foundation-structure system for a small time step
$\{\Delta\dot{u}\}$	Nodal velocity increment in a soil-foundation-structure system for a small time step
$\{\Delta u\}$	Nodal displacement increment in a soil-foundation-structure system for a small time step
$\{u\}$	Nodal displacement in a soil-foundation-structure system
$\ddot{u}_g$	Earthquake accelaration at the base bourndary of a soil-foundation-structure system
$\tilde{u}_g$	Equivalent input motion of a SDOF system considering SFSI

$\Delta \ddot{u}_g$	Earthquake accelaration increment at the base bourndary of a soil-foundation-structure system for a small time step
u_f, emb	Lateral displacement of an embedded foundation
u_g	Depth of the first geosynthetic layer
u_f	Lateral displacement of a surface foundation
u	Structural distortion
u_0	Displacement of a base relative to a free-field motion
u_g	Displacement of a free-field motion
u_t	Total lateral displacement of the system
u_n	Absolute normal penetration of the interface node
Δu_{si}	Incremental relative shear displacement vector of an interface element
V^*	Base shear including soil plasticity
V	Base shear excluding soil plasticity
V_{se}	Volume of a tetrahedral sub-element
V_{La}	Lysmer's analog wave velocity
V_s	Shear wave velocity of soil
V_u	Shear strength of a structural member
v, emb	Vertical displacement of an embedded foundation
v	Vertical displacement of a surface foundation
v^m	Velocities of solid elements at lateral boundaries
v^{ff}	Velocities of free-field elements
W_D	Absorbed energy in one hysteresis loop
W_S	Maximum strain energy created by one hysteresis loop
w	Soil deformation in winkler model
x_0	Curve fitting parameter for SIG-III model
y	Lateral deflection of a pile at point x along the length of the pile

Δz_{min}	Smallest width of an element in the normal direction
t	Time
Δt_{dyn}	Dynamic time increment/step

ABSTRACT

The structural, geotechnical and earthquake engineering designs under earthquakes are gradually moving from strength-based seismic design to performance-based seismic design (PBSD). Indeed, seismic design of structures is moving from imposing limits on forces and moments acting on the structures and foundations, to performance-based seismic design allowing more sensiable evaluation of building performance during and after earthquakes with different severity levels. Generally, in PBSD, the conventional prohibitions are released to the extent that maximum and permanent displacements and rotations are kept within acceptable limits, while no structural failure or collapse is allowed. Foundation rocking is a common phenomenon observed during earthquakes. The rocking induced foundation uplifting and soil yielding can function as energy dissipaters to absorb seismic energy and prevent it from being fully transmitted to the superstructures. However, the permeant foundation rotation and settlement are the issues produced by this foundation movement. On the other hand, employing end-bearing pile foundations may result in enormous shear forces developed in the structure and at the connection between the foundation slab and pile heads, as the foundation rocking mechanism is prevented.

In this study, a geosynthetic reinforced composite soil (GRCS) foundation system is proposed to resolve the rocking induced issues for shallow foundations. In addition, a geotextile reinforced cushioned pile foundation is recommended to extend the use of foundation rocking as an energy dissipater to pile foundations. Thus, design engineers can have a broader choice of foundation system for the seismic safeguarding of buildings. To evaluate the seismic performance of the proposed foundation systems, a fully nonlinear three dimensional numerical model is developed to perform time history analysis considering seismic soil-foundation-structure interaction employing FLAC3D software. Hysteretic damping of the soil is implemented to represent the variation of the shear modulus reduction factor and the damping ratio of the soil with the cyclic shear strain, while a Mohr-Coulomb constitutive model is used to simulate the plastic deformation of the soil. Free-field boundary conditions and rigid boundary condition are assigned to the lateral boundaries and the bottom boundary of the model, respectively.

Appropriate interfaces are considered between foundation (shallow foundation or piles) and soil to capture possible separation/gapping and sliding. Apart from those, soil-geosynthetic interfaces are also modelled to consider possible sliding and pull-out of the reinforcement layers. Real earthquake records are used as input accelerations applied at the base of the model.

Firstly, an investigation about the impact of dynamic soil properties including Plasticity Index and undrained shear strength on the seismic performance of the superstructures supported by a shallow foundation and an end-bearing pile foundation is carried out. The results indicate that extreme care is required to treat these soil properties to obtain reasonable predictions. In addition, the influence on the soil-foundation-structure system brought by the pile configuration is studied and the numerical predictions shows that the response of the system is sensitive to the pile configuration and therefore it should be chosen wisely to optimise the design.

Furthermore, a three dimensional numerical model simulating a mid-rise building resting on proposed geosynthetic reinforced composite soil (GRCS) foundation is developed to evaluate the influence of the proposed foundation system on the seismic response of mid-rise buildings. In addition, a parametric study is conducted to investigate the impact on the superstructures brought by the arrangement of geosynthetic reinforcement layers focusing on the stiffness, length, number and spacing of the layers. The results indicate that the GRCS foundation can enhance the structural seismic performance from unacceptable to acceptable provided that the arrangement of reinforcement layers is well designed. Eventually, the seismic response of a superstructure supported by a geotextile reinforced cushioned pile foundation consisting of a reinforced interposed layer to bridge between the foundation slab and pile heads is studied. The predictions indicate that the proposed cushioned pile foundation can considerably reduce the structural demands of buildings and piles while control the building deformation within acceptable criteria and consequently, the proposed geotextile reinforced cushioned pile foundation can offer an alternative option for the seismic protection of buildings.

Therefore, in practice, Plasticity Index and undrained shear strength of soil should be considered when numerical analysis is required. In addition, pile configurations should be considered carefully to achieve optimised foundation design. Furthermore, a geosynthetic reinforced composite soil (GRCS) foundation system can provide design engineers with an alternative option to limit excessive settlement, and maximum and residual inter-storey drifts induced by seismic loading; this foundation option can be optimised by analysing the arrangment of the reinfocement layers including their material stiffness, length, spacing and number of the layers with great care. Moreover, for buildings requiring pile foundations, a geotextile reinforced cushioned pile foundation can offer design engineers another solution to control the shear forces that develop in a superstructure, as well as reducing the structural demand of the pile foundations.