

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

By

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of the requirement for the degree of  
**Doctor of Philosophy**

School of Civil and Environmental Engineering  
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## **CERTIFICATE OF ORIGINAL AUTHORSHIP**

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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.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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(Ruoshi Xu)

Sydney, June 2018

*To My Dearest Family*

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## LIST OF PUBLICATIONS RELATED TO THIS RESEARCH

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### **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.
2. **Xu, R.** and Fatahi, B. 2018. Influence of Geotextile Arrangement on the Seismic Performance of Mid-Rise Buildings Subjected to MCE Shaking. *Geotextiles and Geomembranes*, 46(4), 511-528.
3. Fatahi, B., Van Nguyen, Q., **Xu, R.** and Sun, W.-j. 2018. Three-Dimensional Response of Neighboring Buildings Sitting on Pile Foundations to Seismic Pounding. *International Journal of Geomechanics*, 18, 04018007. DOI: 10.1061/(ASCE)GM.1943-5622.0001093.

### **Peer-reviewed Conference Papers**

4. **Xu, R.** and Fatahi, B. 2018. Assessment of Soil Plasticity Effects on Seismic Response of Mid-Rise Buildings Resting on End-Bearing Pile Foundations. *GeoChina 2018*. Hangzhou, Zhejiang, China. (Accepted).
5. **Xu, R.** and Fatahi, B. 2018. Effects of Pile Group Configuration on the Seismic Response of Buildings Considering Soil-Pile-Structure Interaction. *GeoShanghai International Conference 2018*. Shanghai, China.

6. **Xu, R.**, Li, D. and Fatahi, B. 2017. Effects of Soil Stiffness on Seismic Response of Buildings Considering Soil-Pile-Structure Interaction. 19th International Conference on Soil Mechanics and Geotechnical Engineering (19ICSMGE). Seoul, Korea.
7. **Xu, R.**, Fatahi, B. and Hokmabadi, A. S. 2016. Influence of Soft Soil Shear Strength on the Seismic Response of Concrete Buildings Considering Soil-Structure Interaction. GeoChina 2016. Jinan, Shandong, China.
8. **Xu, R.** and Fatahi, B. 2015. Three Dimensional Numerical Analysis of Seismic Soil-Structure Interaction Considering Soil Plasticity. 6th International Conference on Earthquake Geotechnical Engineering (6ICEGE). Christchurch, New Zealand.

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## LIST OF NOTATIONS

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$\phi'$	Effective friction angle of soil
$\gamma$	Shear strain in hysteretic damping algorithm
$\gamma_c$	Critical shear strain
$\gamma_{soil}$	Unit weight of soil
$\varepsilon$	Axial strain developed in geosynthetic layer
$\varepsilon_u$	Strain developed in geosynthetic layer at ultimate tensile strength
$\varepsilon_{yield}$	Yield strain of structural member
$\theta, emb$	Rotation of an embedded foundation
$\theta$	Rotation of a surface foundation
$\theta_v$	Angle between the axis of the concrete compression strut and the longitudinal axis of a structural member
$\nu_{geo}$	Poisson's ratio of geosynthetic layer
$\nu$	Poisson's ratio of soil
$\tilde{\xi}$	Equivalent damping ratio of a SDOF system considering SFSI
$\xi$	Damping ratio due to one hysteresis loop
$\xi_\theta$	Damping ratio of a structure due to foundation rotation
$\xi_h$	Damping ratio of a structure due to foundation horizontal movement
$\rho_{conc}$	Density of concrete
$\rho_{geo}$	Density of geosynthetic layer
$\rho_{pile}$	Density of a pile
$\rho_{reo}$	Density of steel reinforcement
$\rho_{soil}$	Density of soil
$\sigma$	Stress developed in a structural member

$\sigma_{yield}$	Yield stress of a structural member
$\sigma_n$	Additional normal stress vectors added due to interface stress initialisation
$\sigma_{si}$	Additional shear stress vectors added due to interface stress initialisation
$\tau_c$	Critical shear stress
$\tilde{\omega}$	Equivalent natural frequency of a SDOF system considering SFSI
$\omega_0$	Natural frequency of a fixed-base system
$\omega_s$	Natural frequency of a structure
$\omega_\theta$	Natural frequency of a structure due to foundation rotation
$\omega_h$	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
$A_{max}^f$	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 matrix 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

$c_\theta$	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 matrix of a soil-foundation-structure system
$\bar{K}$	Dynamic stiffness of a foundation
$\bar{K}_{u,emb}$	Lateral dynamic stiffness of an embedded foundation
$\bar{K}_u$	Lateral dynamic stiffness of a foundation
$\bar{K}_{v,emb}$	Normal dynamic stiffness of an embedded foundation
$\bar{K}_v$	Normal dynamic stiffness of a foundation
$\bar{K}_{\theta,emb}$	Rotational dynamic stiffness of an embedded foundation
$\bar{K}_\theta$	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
$K_\theta$	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
$k_\theta$	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
$\hat{M}(z)$	Dimensionless normalised bending moment
$[M]$	Mass matrix 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 structural member
$N$	Applied normal force
$PI$	Plasticity index
$PL$	Plastic limit
$P_x$	Axial load in a pile
$p$	Pressure applying on soil
$\hat{Q}(z)$	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 acceleration at the base boundary of a soil-foundation-structure system
$\tilde{u}_g$	Equivalent input motion of a SDOF system considering SFSI

$\Delta\ddot{u}_g$	Earthquake acceleration increment at the base boundary 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
$\Delta u_{si}$	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

$\Delta z_{min}$	Smallest width of an element in the normal direction
$t$	Time
$\Delta t_{dyn}$	Dynamic time increment/step

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## ABSTRACT

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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 sensible 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 permanent 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 arrangement of the reinforcement 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.