

**Effects of Foundation Characteristics and Building
Separation Gap on Seismic Performance of Mid-rise
Structures Incorporating Soil-Foundation-Structure-
Interaction**

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

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Sydney, July 2017

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ABSTRACT

Seismic waves travel many kilometres and pass through soil layers close to the ground surface before hitting the structures. The seismic induced dynamic behaviour of structures built on soft soil is highly dependent on the soil properties and the foundation type due to their interactions during an earthquake event. The design of building structures needs to consider seismic soil-foundation-structure interaction, where the building responses vary significantly depending upon the fixity of the base condition due to the interaction between the ground and the foundation as well as the building structures. This interaction is called “Seismic Soil-foundation-structure-interaction” (SSFSI). For a typical soil and foundation, SSFSI analysis shows lower natural frequency of the structural system and higher effective damping ratio compared to the traditional analysis with fixed base condition. This can considerably alter the response of the building frames under the seismic excitations by influencing the structural demand of the building as well as amplifying the lateral deflections and inter storey drifts of the superstructure. This phenomenon is highly influenced by the foundation type (i.e. shallow and deep foundation) and may change the performance level of buildings in the performance based design approach. Therefore the interaction should be considered in design of buildings subject to seismic activities so as to provide a safe and cost effective structural system.

In this study, a rigorous numerical modelling approach was developed and used to build numerical tests for different foundation types and sizes as well as the pounding effects between buildings. The results consisted of lateral deformation, inter-storey drifts, levelling shear forces of the structures, foundation rocking, impact force and pile responses. These parameters cover a wide range of earthquake inputs and foundation characteristics.

The first step was that the soil-pile-interaction numerical behaviour was investigated in a case study of lateral loaded pile considering the shear plastic deformation of the layered sloping ground including sand and clay layers. Appropriate subroutines were adopted to simulate the soil-pile-interaction which included the incorporation of gapping and sliding (in normal and tangential directions) at the interface. A wide range of parameters for this numerical modelling was validated through comparison with an array of a full-scale lateral loaded pile experiments.

Secondly, dynamic characteristics of soil-foundation-structure system were investigated for seismic response of a mid-rise moment resisting building on shallow foundation under four well-known earthquakes. By adopting a direct calculation method, the numerical model can perform a fully nonlinear time history dynamic analysis for three-dimensional numerical model with different foundation sizes where the infinite boundary, sliding and separation in soil-foundation was taken into account. In addition, the influence of foundation sizes on natural frequency and structure response spectrum was also studied. The results confirmed that when the size of shallow foundation is reduced, the natural period would lengthen, the base shear would reduce significantly while the lateral deformation, inter-storey drift and foundation rocking would increase.

Thirdly, the comprehensive pile foundation investigation concludes that the type and size of a pile foundation that supports mid-rise buildings in high-risk seismic zones can alter the dynamic characteristics of the soil-pile-foundation system during an earthquake due to soil-structure-interaction. It is not true to believe that longer piles can provide safer condition under earthquake loading. In fact, by increasing the length of floating piles the structure undergoes more maximum lateral deflection, more inter-story drift and more total maximum levelling shear force but less foundation rocking. This can be explained due to the fact that longer pile foundation has higher contact surface with surrounding soil which enable them to absorb extra seismic energy. This finding can be the recommendation for design engineers that the pile should not lengthen too much to reduce the seismic effects.

Finally, the separation gap between moment resisting and two shear wall braced buildings on pile foundation under seismic loading was studied. The result from this numerical modelling showed that pounding impact influences the distribution of shear force which disturbs the natural vibration and in extreme case, causes collapse. The outcome of this study provides essential insight to geotechnical and structural engineers when designing neighbouring structures in earthquake prone areas.

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LIST OF ABBREVIATIONS

| Full text | Abbreviation |
|---|--------------|
| American Society of Civil Engineers design code | ASCE |
| Boundary element method | BEM |
| Building Seismic Safety Council | BSSC |
| Complete quadratic combination | CQC |
| Earthquake design category | EDC |
| Earthquake Wave Equation Analysis for Piles | EQWEAP |
| Federal Emergency Management Agency | FEMA |
| Global Positioning System | GPS |
| International Building Code | IBC |
| Linear dynamic procedure | LDP |
| Linear static procedure | LSP |
| National Earthquake Hazards Reduction Program | NEHRP |
| National Computational Infrastructure | NCI |
| Nonlineal dynamic procedure | NDP |
| Nonlinear static procedure | NSP |
| Seismic Soil-foundation-structure-interaction | SSFSI |
| Seismic soil–pile–structure interaction | SSPSI |
| Single degree of freedom | SDOF |
| Soil-foundation-structure interaction | SFSI |
| Soil-pile-structure interaction | SPSI |
| Soil–structure-interaction | SSI |
| Structure-soil-structure-interaction | SSSI |
| Thin layer method | TLM |

LIST OF NOTATIONS

| | |
|---------------------------|--|
| $a(t)$ | raw data record |
| $a_c(t)$ | corrected acceleration record |
| $a_0(t)$ | acceleration correction |
| $2a$ | width of the foundation |
| A | Area, foundation width, cohesion |
| A_{loop} | area of the hysteresis |
| $[A]$ | Damping matrix |
| B | width of the pile |
| B_b | width of building |
| B_f | width of foundation |
| B_s | width of soil model |
| c | damping coefficient, soil cohesion |
| c_h | damping coefficient in horizontal direction |
| c_θ | damping coefficient in rotation direction |
| \bar{c} | equivalent damping coefficient |
| C_1, C_2, C_3, C_k | modification factor for pseudo lateral load, constant |
| c' | cohesion, effective cohesion |
| c_p, c_s | velocities of the normal wave and shear wave |
| CL | clayey soil |
| $[C]$ | damping matrix |
| D | diameter of pile |
| <i>Drift</i> | maximum inter-storey drifts of the building |
| d_p, d_s | distributed damping in the normal and shear directions |
| d_c | decay coefficient |
| d_{i+1}, d_i | Deflection at level $(i + 1)$ and (i) |
| $d_i(t)$ | deflection history at level (i) |
| E | Young's modulus, modulus of elasticity of concrete |
| E_a, E_b, E_c, E_d, E_e | Soil classification according to AS1170.4 (2007) |
| E_s | soil subgrade reaction |
| E_p | Young's modulus of pile |

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|-----------------|---|
| E_x | soil reaction |
| F | force |
| F_x | vertical distribution of seismic force at each level |
| f | natural frequency |
| f_1, f_2 | first and second mode frequencies in Rayleigh damping |
| f'_c | compressive strength of concrete |
| f_n | natural frequency of mode n |
| f_y, f_{sy} | yield strength |
| G | shear modulus, permanent action |
| G_0 | average shear modulus |
| G_{max} | maximum shear modulus |
| G_{sec} | secant shear modulus |
| G_{tan} | tangent shear modulus |
| H | height of the structure, shear force, soil thickness, soil height |
| H_s | height of soil model |
| h | clearance or gap, height of level |
| h_s | floor slab thickness |
| h_f | foundation thickness |
| I | moment of inertia |
| I_p | moment of inertia of pile |
| I_x, I_y | moment of inertia about x axis and y axis |
| IE | bending stiffness of the beam |
| k | stiffness |
| k_h | stiffness in horizontal direction |
| k_i | soil resistance in segment (i) |
| k_y | lateral stiffness |
| k_θ | stiffness in rotation direction, rocking stiffness |
| \widetilde{k} | equivalent stiffness |
| \overline{k} | stiffness of the structure fixed at the base |
| $[K]$ | stiffness matrix |
| L | length |

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|----------------------------|--|
| L_b | length of building |
| L_f | length of foundation |
| L_{FE} | length of finite element section |
| L_{INF} | length of infinite element section |
| m | mass |
| M | bending moment |
| $[M]$ | mass matrix |
| M_w | moment magnitude of earthquake in Richter scale |
| P | lateral load |
| p | load, contact pressure |
| p_i | load in segment (i) |
| P_0 | amplitude of harmonic force |
| P_x | axle force from structure applied to pile head |
| PI | plasticity index |
| PGA | peak ground acceleration |
| q_s | lateral distributed load from soil to the pile |
| q_y | lateral distributed load along the beam |
| Q | Impose Action, shear force along the pile |
| R_{int} | reduction factor |
| r_{in} | inner radius of the pile |
| r_{out} | outer radius of the pile |
| $SDOF$ | single degree of freedom |
| S | slope (or rotational deflection) of the pile, distance |
| S_a | response spectrum acceleration, spectral acceleration |
| S_{DS} | design earthquake motion |
| s_i | minimum distance between adjacent structure at level (i) |
| S_u | undrained shear strength |
| $(S_u)_{soil}$ | undrained shear strength of soil |
| $[(S_u)_{int}]$ | reduce shear strength at the interface |
| SD | separation gap |
| Δ | lateral deflections in $P - \Delta$ effect |
| Δ_{i1}, Δ_{i2} | lateral deflections of neighbouring structures |

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|---------------------------------------|--|
| T | fundamental period |
| \widetilde{T} | effective fundamental period |
| T_0 | characteristic period of the response spectrum |
| T_1 and T_2 | limits of a time interval |
| t | time |
| u_0 | structural distortion |
| u_t^0 | total initial lateral displacement |
| u_t | total lateral displacement |
| \widetilde{u}_g | equivalent input motion |
| u_i, u_j | material particle displacement |
| $u_i(t)$ | horizontal displacement history at level (i) |
| $u_0(t)$ | horizontal displacement history at level (0) |
| \ddot{u}_i | material particle acceleration |
| V | pseudo lateral load, shear force |
| V_S | shear wave velocity |
| V_{S0} | average shear wave velocity |
| $v_c(t)$ | corrected velocity record |
| W | total dead load and anticipated live load |
| \overline{W} | total dead load and anticipated live load of structure fix at base |
| W_D | dissipated energy |
| W_S | the maximum strain energy |
| x_i | position of pile at segment (i) |
| Y | deflection, pile deflection |
| y_i | deflection in segment (i) |
| z_i | depth of soil at segment (i) |
| α, β | mass damping coefficient and stiffness damping coefficient |
| γ | shear strain, unit weight |
| $\dot{\gamma}_1$ and $\dot{\gamma}_2$ | two local slip velocity components |
| γ_c | cyclic shear strain, shear strain |
| γ_{max} | maximum shear strain |
| $\dot{\gamma}_{eq}$ | equivalent slip rate |
| ε | strain of concrete material |

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|----------------------------|--|
| ε_{yield} | strain at yield point |
| Z | damping ratio |
| Θ | angle |
| μ | coefficient of friction |
| μ_r, μ_p | residual coefficient of friction, peak coefficient of friction |
| ν | Poisson's ratio |
| ξ_0 | hysteretic damping |
| \bar{E} | damping ratio |
| $\bar{\xi}$ | equivalent damping ratio |
| ρ | density, mass density |
| σ, σ' | normal stress, effective normal stress |
| σ_y, σ_{yield} | yield stress of concrete material |
| τ | shear strength |
| τ_1 and τ_2 | two orthogonal components of shear stress |
| τ_{cr}, τ_{crit} | critical shear stress |
| τ_{eq} | equivalent shear stress |
| τ_c | shear stress |
| φ, φ' | internal frictional angle, effective internal frictional angle |
| ψ | dilation angle |
| ω, ω_0 | natural frequency |
| ω_i, ω_j | natural angular frequency for mode (i) and (j) |
| $\bar{\omega}$ | equivalent natural frequency |
| ϕ, ϕ and ϕ' | friction angle and effective friction angle |