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Effect of Soil-Structure Interaction Effects and Mitigation Strategies for RC Structures - A Review

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Abstract

Soil-structure interaction (SSI) significantly influences the seismic performance of structures, necessitating advanced modeling and mitigation strategies to address dynamic responses across various structural configurations and soil types. This review synthesizes recent research on SSI effects in reinforced concrete (RC) frames, tall buildings, and subway stations, employing nonlinear finite element modeling, shaking table tests, and probabilistic fragility analyses. Studies highlight that SSI alters natural frequencies, damping, and seismic demands, with structure-soil interaction (SSI) reducing exceedance probabilities for immediate occupancy, life safety, and collapse prevention in RC frame clusters, though pounding and post-earthquake tilt pose challenges. Inter-story isolation in high-rise buildings mitigates displacements but requires optimization for low shear wave velocity soils. Soil-pile foundation-structure interaction (SPFSI) reduces global ductility in RC frames and wall-frames, particularly in softer soils, necessitating adjusted seismic response factors. Tuned mass dampers (TMDs) and semi-active TMDs (STMDs) effectively reduce torsional irregularities and roof drifts in tall buildings, with STMDs offering superior robustness against parameter variations. Base isolation and viscoelastic dampers further mitigate SSI effects in mid-rise and soft-story buildings, respectively, though site amplification can increase vulnerability if neglected.

Keywords: Soil-structure interaction (SSI), Reinforced Concrete (RC), Soft-Story buildings, Soil-pile foundation-structure interaction (SPFSI), Tuned mass dampers (TMDs)

INTRODUCTION

Seismic design of structures has evolved significantly, with increasing recognition of soil-structure interaction (SSI) as critical factors influencing dynamic responses. SSI accounts for the interplay between a structure and its underlying soil, altering natural frequencies, damping, and seismic demands. This review compiles findings effects of SSI on RC frames, tall buildings, subway stations, and mitigation strategies like tuned mass dampers (TMDs), base isolation, and inter-story isolation. The studies utilize nonlinear finite element modeling, shaking table tests, and probabilistic fragility analyses to explore seismic performance across various soil types and structural configurations.

Jishuai Wang at al. [1] conducted probabilistic seismic fragility assessments on clusters of typical 3-, 6-, 9-, and 12-story RC frames on medium-stiff clay soil, using nonlinear high-fidelity FE models in OpenSees, incorporating structure-soil-structure interaction (SSSI) with and without pounding, compared to fixed-base and soil-structure interaction (SSI) cases. Incremental dynamic

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analysis (IDA) and Latin hypercube sampling (LHS) account for uncertainties in structural properties and 40 ground motions. Results show SSSI reduces exceedance probabilities for immediate occupancy (IO), life safety (LS), and collapse prevention (CP) states in no-pounding scenarios (up to 12% median capacity increase), making fixed-base/SSI assumptions conservative. For pounding (3- and 12-story pair), SSSI minimally affects median capacities but elevates LS/CP probabilities at low intensities while reducing them at high intensities.

Sitong Fang et al. [2] evaluates the seismic performance of inter-storey isolation systems in super high-rise buildings (e.g., 411-m case study) under soil-structure interaction (SSI), using a lumped parameter sway-rocking (SR) model to derive dynamic characteristics like natural frequencies and displacement transfer ratios. Parametric analyses examine soil shear wave velocity (Vs) and damping ratios (5-25%) Figure 1.

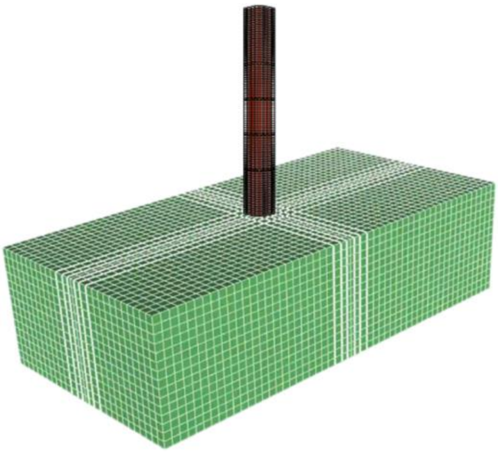


Figure 1. 3D visualization of soil-structure interaction [2].

Findings show inter-storey isolation effectively reduces displacements and Park-Ang damage indices, but high-damping systems increase displacement/damage on low-Vs soils; non-isolated structures see damping ratio increases with decreasing Vs, while isolated ones exhibit decreases at higher damping. Recommendations emphasize optimizing designs for SSI effects.

Yangzhou Wu et al. [3] develops an iterative static analysis method to efficiently compute effective frequencies and modes dominating seismic responses of aboveground structures in 3D soil-structure interaction (SSI) systems, bypassing full modal analysis of soil-dominated modes. Parametric studies examine impacts of site shear wave velocity and adjacent underground structures (e.g., tunnels) on these frequencies Figure 2.

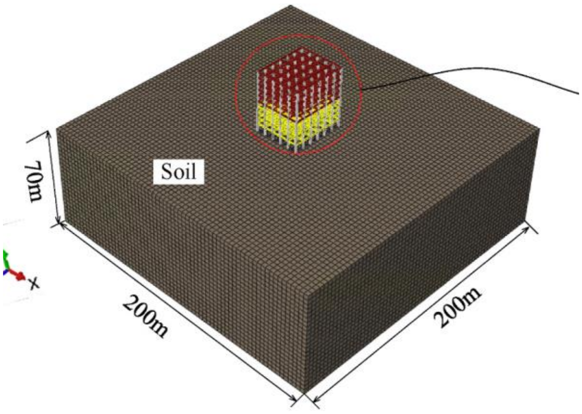


Figure 2. Finite element model of a frame structure-foundation-soil system [3].

A response spectrum method (RSM) incorporating these effective parameters is proposed for seismic design, with numerical examples (e.g., 5-15 story buildings) validating its accuracy (errors <3%) against time-history analyses under artificial and real earthquakes.

Nishant Sharma et al. [4] examines the impact of soil-pile foundation-structure interaction (SPFSI) on the inelastic response and ductility capacity of 3-12 story RC frame and wall-frame buildings using nonlinear finite element pushover analyses in ABAQUS. Models incorporate pile inelasticity, soil nonlinearity (via Drucker-Prager), and varying sand densities (loose to dense) Figure 3.

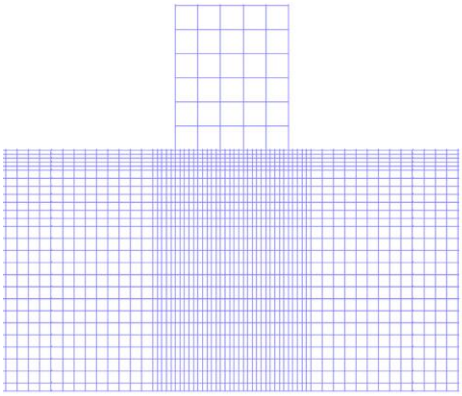


Figure 3. Adopted non-uniform optimized meshing [4].

Key findings: SPFSI induces foundation rocking and inelastic pile rotations (correlated with compressive loads), increasing yield/ultimate drifts but reducing global ductility (μ_c = Δ_u / Δ_y) by up to 12% for frames and 39% for wall-frames, especially in softer soils and taller/wider configurations. Recommends adjusting seismic response reduction factors and further experimental studies.

Gholamreza Keyvani Hafshejani et al. [5] examines the seismic response of two adjacent irregular RC structures (6- and 10-story) at varying embedment depths (0-3m) and distances (2-10m) using 3D Abaqus simulations incorporating soil-structure interaction (SSI). Nonlinear dynamic analyses under El Centro earthquake reveal that increasing distance reduces displacements, accelerations, and stresses, while greater depths amplify responses due to soil stiffening; maximum SSI effects occur at minimum distance and surface level (84.4% increase), with depth variations mitigating effects (31.2% to 19.2% reduction). Results emphasize considering embedment in SSI for urban designs Figure 4.

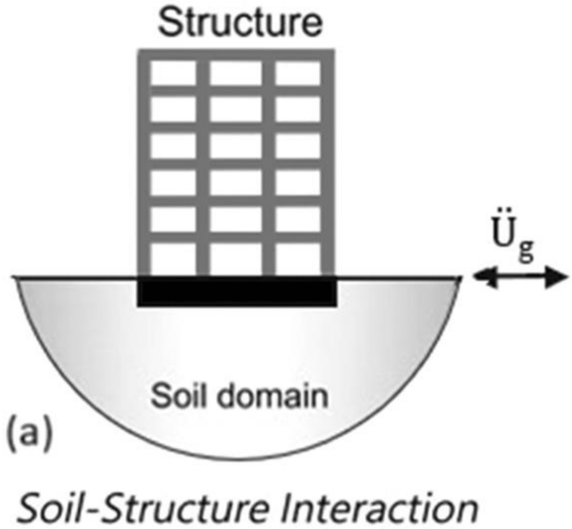


Figure 4. Illustration of the substructure method for SSI analysis [5].

Ibrahim Oz et al. [6] evaluates the effectiveness of tuned mass dampers (TMDs) in mitigating torsional irregularity (ηbi > 1.2) in a 9-story L-shaped RC building under soil-structure interaction (SSI) on ZC (moderate) and ZD (soft) soils, using nonlinear time-history analyses with 15 bidirectional ground motions in SAP2000. Substructure modeling captures SSI effects, showing amplified torsional responses (up to 25% ηbi increase) on soft soils. TMD implementation reduces upper-story torsional demands by over 12% on ZD soils, with fragility curves confirming lower exceedance probabilities, highlighting TMD's role in seismic design for irregular RC structures Figure 5.

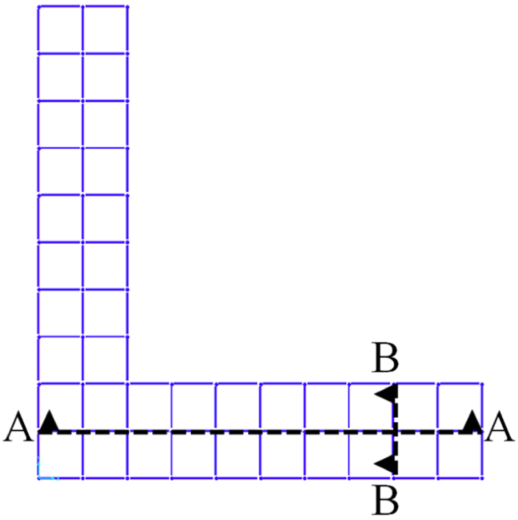


Figure 5. Plan views of the investigated L-shaped structure.

Liangkun Wang et al. [7] proposes a semi-active tuned mass damper (STMD) with real-time adjustable mass (via pumping liquid/sand) and eddy current damping ratio (via air gap actuation) for seismic response control of tall buildings, addressing uncertainties in structural models and SSI that cause detuning in passive TMDs. A combined output-signal-based algorithm using wavelet transform for frequency identification and LQR for damping optimization enables self-tuning. Preliminary SDOF analyses under harmonic/sweep excitations show STMD with dual adjustments outperforms variable-damping-only versions under stiffness detuning. Applied to a 40-story benchmark high-rise with four SSI soil types, nonlinear time-history simulations demonstrate STMD reduces roof drifts and accelerations by 20-40% more effectively than optimized passive TMDs, enhancing robustness against ±15% parameter variations. This research paper proposes a semi-active tuned mass damper (STMD) with variable mass (via liquid/sand pumping) and eddy current damping (via adjustable air gap) for seismic response control of tall buildings, accounting for soil-structure interaction (SSI). It employs a combined output-signal-based algorithm using wavelet transform for real-time frequency retuning and adaptive damping adjustment Figure 6.

Preliminary harmonic/sine-sweep analysis on a SDOF structure demonstrates STMD's superiority over variable-damping-only devices, mitigating detuning effects. Applied to a 40-story benchmark building with four SSI soil types, nonlinear time-history analyses show STMD reduces peak displacements by 20-40% more effectively than optimized passive TMD, with enhanced robustness to ±15% stiffness variations.

Jishuai Wang et al. [8] investigates seismic soil-structure interaction (SSI) in typical 3, 6, and 9 story RC frame clusters on medium clay soil using high-fidelity nonlinear finite element models in Open Sees, with uncertainties addressed via Latin hypercube sampling under 40 code-specified earthquakes (east-west excitation). Compared to soil-single structure interaction (SSI), SSSI reduces maximum story drifts (up to 10%) and base shear (up to 15%) in most scenarios due to adjacent structures acting as tuned mass dampers and foundation impedance amplification Figure 7.

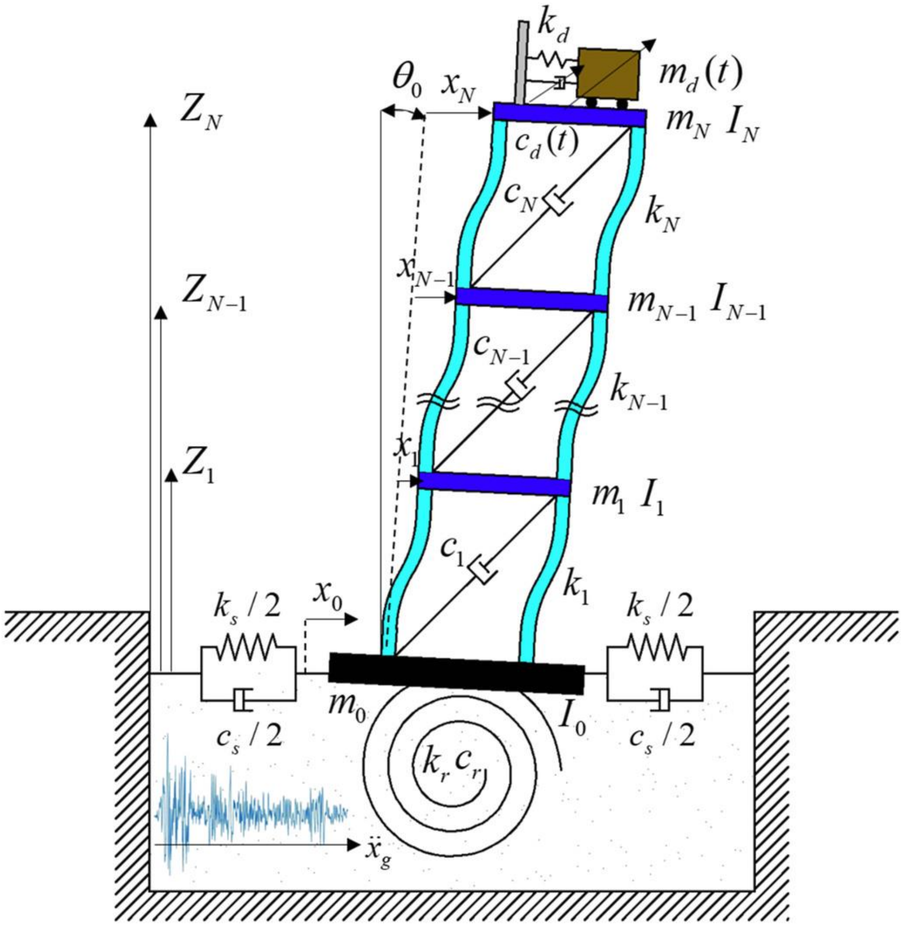
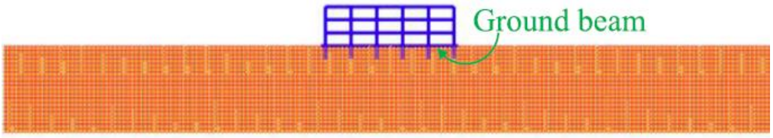
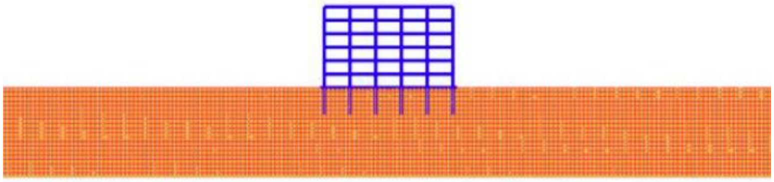


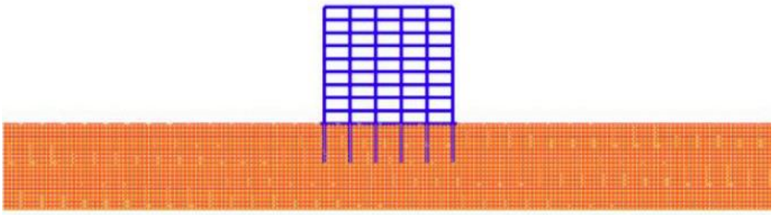
Figure 6. Schematic diagram of tall building with STMD considering SSI [7].



(a) SSI system of 3-story RC frame



(c) SSI system of 6-story RC frame



(e) SSI system of 9-story RC frame

Figure 7. Numerical models of the SSI systems [8].

However, SSSI increases post-earthquake tilt in edge structures (up to 0.02 radians), particularly for taller buildings on softer soils, suggesting conservative design without SSSI but necessitating deeper/wider foundations to mitigate tilt.

Sunny Mishra and Avik Samanta [9] examines the seismic response of 9-story RC buildings with shear walls and infill walls on soft soil in Patna, India (high seismicity zone), using nonlinear time-history analyses in SAP2000 under 24 scaled PEER ground motion pairs. Four models compare fixed/flexible bases with/without shear walls: bare frames show SSI amplifies peak displacements, accelerations, inter-story drifts, and ductility due to base flexibility; shear/infill walls enhance stiffness, reduce fundamental periods, and mitigate responses (up to 50% drift reduction), more effectively for fixed bases. Key insights: SSI heightens vulnerability on soft soils (low Vs), ductility correlates with building aspect ratio, and drifts concentrate in lower/mid stories, emphasizing SSI consideration for open-ground-story designs.

Hamid Asadi-Ghoozhdi et al. [10] evaluates the nonlinear soil-structure interaction (SSI) effects on seismic responses of 5- and 10-story vertically irregular RC moment frames with tall ground stories (height ratios 1.25-2), using beam on nonlinear Winkler foundation (BNWF) modeling for shallow foundations on sandy soils (classes D/E) and nonlinear dynamic analyses under 15 far-fault earthquakes. Key parameters include irregularity ratio, soil type, and foundation vertical safety factor (FSv=2-6). Findings show SSI reduces drifts in lower stories (more on soft soils), with lower FSv decreasing demands but increasing transient/residual settlements; correlations link max drifts to foundation behavior for regular/irregular structures.

Davide Forcellini [11] develops analytical fragility curves to assess soil-structure interaction (SSI) effects on the seismic vulnerability of a 20-story building on pile foundations, using 3D nonlinear dynamic analyses in OpenSees. It incorporates soil hysteresis and plasticity via Pressure Independent Multi-Yield models and structural deterioration with Ibarra-Medina-Krawinkler hysteretic behavior, under 7 scaled ground motions. Key findings highlight SSI's dual role: beneficial through period elongation and reduced roof accelerations, but detrimental via site amplification from kinematic/inertial interactions, increasing inter-story drifts and exceedance probabilities (up to 19% at complete damage for 0.5g SA). Neglecting SSI underestimates system vulnerability.

Mohammad Seddiq Eskandari Nasab et al. [12] investigates the impact of soil-structure interaction (SSI) on the seismic performance and retrofit of soft first-story buildings, using a five-story RC case study modeled in OpenSees. It employs the beam on nonlinear Winkler foundation (BNWF) approach for SSI, Square-Root-Impedance (SRI) for site amplification, and viscoelastic dampers (VEDs) installed vertically for retrofit. Nonlinear dynamic analyses across soil types (SB to SE) show that SSI amplifies responses, especially on soft soils (SD/SE), increasing inter-story drifts beyond 1.5% limits. VEDs effectively reduce drifts and failure probability (by up to 60% in fragility analysis), highlighting the need to consider SSI in retrofit designs for soft soils.

Luis Eduardo P´erez-Rocha et al. [13] analyzes the effects of soil-structure interaction (SSI) on the seismic response of base-isolated mid-rise buildings (10-15 stories) on soft soils, focusing on Mexico City sites with narrow-band spectra from the 1985 earthquake. A discrete shear-building model with linear elastic elastomeric bearings and flexible foundations (shallow or pile) is used, incorporating non-classical damping and site-specific synthetic accelerograms. Parametric studies of base shear spectra reveal that SSI amplifies responses in non-isolated structures but base isolation effectively reduces detrimental SSI effects and inter-story drifts when the site dominant period is longer than the superstructure's fixed-base fundamental period (e.g., 1-1.5 s) [14–16].

CONCLUSION

Incorporating SSI into seismic design is essential for accurate prediction of structural responses, particularly on soft soils where amplification is pronounced. Mitigation strategies like base isolation, inter-story isolation, TMDs, STMDs, and VEDs significantly enhance seismic performance, with STMDs offering superior adaptability to SSI uncertainties. Design practices must account for soil nonlinearity, foundation behavior, and adjacent structure effects, supported by advanced modeling and probabilistic approaches, to optimize safety and resilience in diverse structural systems.

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