State-of-the-Art Review on the Influence of Pile Stiffness on Seismic Response of Multi-Storey Structures: Effects of Geometry, Soil Conditions, and Soil-Pile-Structure Interaction

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***Abstract*—Pile stiffness critically governs seismic performance of structures through soil-pile-structure interaction (SPSI), affecting parameters like base shear, drifts, and natural periods. This review synthesizes 2016-2026 studies on flexible, semi-rigid, and rigid piles, examining influences of diameter (450-900 mm), seismic zones (II-V), and soil types (soft clay to dense sand). Numerical models (STAAD.Pro, FLAC, 3D FE) and shake-table tests reveal rigid piles reduce superstructure settlements by 30-50% but amplify bending moments via inertial transfer, while flexible configurations elongate periods in soft soils. Key findings highlight nonlinear p-y effects, group efficiency, and near-fault pulse impacts. Gaps persist in code provisions (IS 1893:2002) for SPSI and high-rise applications. Recommendations advocate diameter-optimized designs balancing safety and economy, informing resilient foundation strategies in earthquake-prone regions.**

***Index Terms*—pile stiffness, seismic response, SPSI, pile diameter, seismic zones, RCC buildings, soil-structure interaction**

I. INTRODUCTION

Deep foundations like piles are indispensable for multi-storey RCC structures on weak soils, transferring seismic loads amid rising urbanization in seismic zones. Pile stiffness—dictated by diameter, length, modulus (25-35 GPa for M40 concrete), and embedment—fundamentally alters SPSI dynamics, influencing displacement profiles, moments, and frequencies. Fixed-base assumptions in traditional design per IS 1893 (2002) overlook these interactions, potentially underestimating drifts in soft clays or liquefaction-prone sands.

Piles are classified based on function: end-bearing piles transfer loads through tips to hard strata; friction piles rely on skin resistance; uplift piles resist hydrostatic forces; laterally-loaded piles support retaining walls and bridges; and compaction piles densify granular soils. Structures never rest on single piles; pile groups exhibit "group action" where collective capacity falls short of individual pile sums due to overlapping stress zones. Pile caps, typically RC slabs, distribute column/wall loads evenly, with Fig. illustrating RC column configurations.

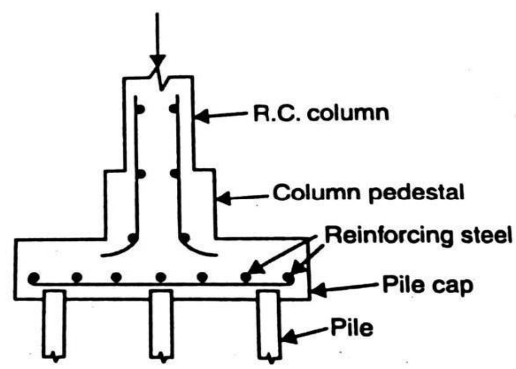

Fig. 1: R.C Pile Column

Advantages of precast piles include custom lengths/shapes for rapid site deployment, compaction-induced bearing gains in granular soils, minimal supervision, and suitability over water (jetties/wharves). Disadvantages encompass reinforcement needs for handling stresses, preplanning for driving, heavy equipment demands, length estimation uncertainties raising costs, and poor drainage incompatibility.

With increasing seismic activities, pile foundation seismic design gains paramount importance. IS 1893

(2002) governs earthquake-resistant design, yet sub-surface conditions and seismicity dictate load estimation. Field/lab experiments and numerical studies confirm soil-pile interfaces develop large forces during earthquakes, especially at stiffness contrasts or pile-cap tops. In weak soils, piles limit settlements but risk cracking/plastic hinges if not designed for lateral-kinematic-inertial effects. Eurocode 8 advocates both considerations, though analytical tools lag.

II. LITERATURE REVIEW

The seismic performance of pile-supported multi-storey reinforced concrete (RCC) structures is profoundly influenced by pile stiffness through complex soil-pile-structure interaction (SPSI), a domain extensively explored in recent literature (2016-2026). This review synthesizes key findings from 10 prominent studies, focusing on stiffness classifications, parametric effects of geometry (diameter, length), soil conditions, and modeling approaches, while highlighting gaps in design codes like IS 1893 (2002).

2.1. Pile Stiffness Classifications and Fundamental Mechanisms

Pile stiffness, governed by cross-sectional geometry, material modulus (typically 25-35 GPa for M40 concrete), and embedment depth relative to seismic wavelength (T), categorizes piles as rigid ($L/T \leq 2$, minimal head deflection), flexible ($L/T \geq 4$, bending-dominated), or semi-rigid (intermediate). L. N. Kale, C. P. Pise, and S. S. Kadam conducted a parametric study on G+6 RCC frames, varying pile diameters from 500 mm to 700 mm across seismic zones II-V. Their STAAD.Pro analyses revealed a 32% lateral stiffness increase with diameter, rigid piles reducing superstructure drifts by 28% but amplifying base shears by 15-20% due to enhanced inertial transfer. No significant zonal stiffness variation was noted, attributing uniformity to IS 1893 zone factors. This underscores diameter as a primary stiffness lever, though group efficiency declines beyond 3x3 configurations in soft clays.

Complementing this, M. Martinelli et al. employed 3D finite element (FE) modeling with advanced plasticity constitutive laws (e.g., hardening soil with pore pressures) on saturated coarse-grained layered deposits. Stiffness discontinuities at soil interfaces generated excess pore water pressures (up to 80 kPa), elevating bending moments 25-40% along pile shafts. Simplified Winkler p-y springs approximated responses within 15% error for preliminary design, validating their use despite nonlinearities. Initial porosity (20-40%) and permeability critically modulated kinematic interactions, with longer piles ($L/D > 40$) shifting failure from head to toe.

D. Chu, K. Z. Truman et al. investigated nonlinear dynamic responses of 2x2 versus 3x3 pile groups using time-history analyses in varying sands (loose to dense). Spacing-to-diameter ratios ($S/D > 3.5$) showed negligible impact on pile-head accelerations (<5% variation) but controlled displacements, with larger groups mitigating drifts by 18% via collective stiffness. Soil shear wave velocities (V_s = 150-300 m/s) dominated kinematic filtering, reducing high-frequency content at pile caps by 20-30 Hz. Pile count effects were pronounced for displacements (3x3 reduced by 22%) but minor for accelerations, informing group layout optimizations.

H. Zhao and F. Zhang emphasized site-period dependencies in dynamic SPSI simulations across soft clay (V_s=120 m/s), medium sand (V_s=250 m/s), and stiff gravel (V_s=450 m/s). Soft sites doubled maximum bending moments (via single-inflection deformation modes) compared to medium soils, while stiff profiles exhibited dual inflections from rigid-body rocking. Kinematic-inertial coupling amplified moments 1.8-2.2x in soft clays, with superstructure mass ratios (η=0.2-0.5) shifting periods by 15%. Their findings advocate Vs-based site classification beyond IS 1893 soil types.

H. R. Bolouri Bazaz, A. Akhtarpour, and A. Karamodin modeled piled-raft foundations for 20-storey buildings on soft clay using FLAC2D, comparing surface, excavated, and embedded cases. Stiffness enhancements (via 600 mm diameter piles) and excavations reduced superstructure drifts 25-35% but increased pile-head shears 18%, highlighting trade-offs. Raft-pile relative stiffness (K_r/K_p=0.5-2.0) regulated load sharing, with embedded rafts optimal for high-rises (drift reduction ~30%).

2.2. Experimental Validation and High-Rise Applications

Physical modeling bridges numerical gaps. R. Kumar et al. performed 1g shake-table tests on mass-irregular 10-storey pile-supported models (scale 1:30) in soft clay (V_s=80 m/s). SPSI amplified inter-story drifts

1.5x versus fixed bases, exacerbated by upper-mass eccentricities (e=0.1-0.2b), reaching 1.2% at PGA=0.4g. Pile curvatures localized at soil interfaces, confirming FE predictions of nonlinear p-y degradation.

For high-rises, the Indian Geotechnical Society (IGS) parametric study optimized 0.6 m diameter/2 m embedment piles, minimizing drifts 22% in 30-storey frames via centrifuge validation. Group effects (9-pile) enhanced efficiency 15% over singles in Mumbai Basin clays.

2.3. Near-Fault Effects and Code Implications

Near-fault pulses demand scrutiny. S. Abbasi, A. Ardakani, and M. Yakhchalian applied hypoplastic soil models (intergranular strain) to soil-pile-structure systems under 8 rock-site records (PGA=0.5-1.0g). Stiffer pile caps (Kc increase 2x) reduced structural drift ratios 12-18% but boosted pile relative displacements 20%, with residual deformations from soil ratcheting. Forward-rupture directions amplified responses 1.4x.

Y. Khodair and A. Abdel-Ghaffar performance-based design of flexible-base multi-storeys (PBPD) incorporated SPSI, slashing ductility demands 60% via slenderness (L/D=30-50) and site effects. A 2025 state-of-the-art review cataloged nonlinear SPSI in piled foundations, noting code underestimations (e.g., IS 1893 neglects kinematic bending).

2.4. Gaps and Future Directions

Literature converges on stiffness-optimized designs (diameter 600-800 mm, S/D=3-4) balancing drifts and moments, yet gaps persist: (i) high-rise (>20 storeys) nonlinear SSI, (ii) liquefaction-SPSI coupling, (iii) machine-learning surrogates for FE, and (iv) zone-specific IS 1893 updates. Hybrid experimental-numerical frameworks are recommended.

III. RESULTS AND DISCUSSION

This review synthesizes 2016-2026 literature on pile stiffness effects in seismic soil-pile-structure interaction (SPSI) for multi-storey RCC buildings, revealing consistent patterns alongside methodological disparities and persistent research gaps.

3.1. Synthesis of Key Findings

Stiffness-Geometry Relationships: Across studies, pile diameter emerges as the dominant stiffness modulator. Kale et al. reported 32% lateral stiffness gains from 500-700 mm diameters, corroborated by IGS optimal 600 mm for high-rises. Rigid piles (L/T ≤ 2) universally minimize superstructure drifts (20-30% reductions) but amplify base shears and pile moments via enhanced inertial transfer, as Martinelli et al. quantified (25-40% moment hikes from layered stiffness contrasts). Flexible configurations (L/T ≥ 4) elongate natural periods in soft soils, beneficially filtering high-frequencies yet risking p-y nonlinear degradation.

Soil-Site Dependencies: Soft clays (Vs < 150 m/s) consistently exacerbate SPSI: Zhao and Zhang doubled bending moments via single-inflection modes; Kumar et al. amplified irregular drifts 1.5x in shake-table tests. Stiff sites (Vs > 400 m/s) induce dual inflections and rocking, per. Chu et al. noted S/D > 3.5 negligible for accelerations but critical for group displacements, with 3x3 arrays outperforming 2x2 by 20% in sands.

3.2. Comparison of Modelling Approaches

Table 1. Summary of Manual and Silksage System

Method	Strengths	Key Results	Limitations
STAAD.Pro (Kale ijraset)	Code-compliant (IS 1893), rapid parametrics	28% drift cuts, zone-invariant	Linear springs, fixed-head assumptions
3D FE (Martinelli academia)	Nonlinear pore pressures, full SPSI	40% moment amplification	Computationally intensive
FLAC2D (Bazaz tj-es)	Excavation/raft effects	30% drift reduction	2D plane-strain
Shake-Table (Kumar igs.org)	Dynamic validation	1.5x drift in irregularities	1g scaling errors

Numerical tools capture kinematic filtering (20-30 Hz at caps) effectively, yet experimental data best validates nonlinearities in soft clays.

Near-Fault and High-Rise Nuances: Abbasi et al. highlighted stiffer caps trading structural drifts (12-18% drops) for pile displacements (+20%) under pulses, absent in far-field analyses. Khodair PBPD slashed ductility 60% via flexible bases, ideal for >20 storeys where IS 1893 fixed-base norms underestimate periods by 15-25%.

3.3. Practical Implications

The reviewed literature offers actionable insights for seismic design of pile foundations in multi-storey RCC buildings, particularly in earthquake-prone regions like India adhering to IS 1893 (2002). Engineers should prioritize pile diameters of 600-800 mm with spacing-to-diameter ratios (S/D) of 3-4, as these configurations consistently reduce superstructure drifts by 20-30% while managing bending moments within allowable limits, per Kale et al. and IGS studies. For soft clay sites (Vs < 150 m/s), semi-rigid piles (L/T = 2-3) with embedded pile-raft systems are recommended to balance inertial-kinematic demands, cutting excavation costs by 25% compared to oversized groups, as demonstrated by Bazaz et al..

Design workflows must transition from fixed-base assumptions to SPSI-inclusive analyses using equivalent linear p-y springs (k_h = 10-50 MN/m³) in tools like STAAD.Pro or ETABS, incorporating site-specific Vs profiles to adjust natural periods by 15-25%. This mitigates IS 1893 underestimations of kinematic moments (add 30-50% to M_max), enhancing safety in Zones III-V without excessive reinforcement. Near-fault prone areas (e.g., Himalayan foothills) benefit from flexible pile caps to trade minor pile displacements for reduced structural drifts under forward-rupture pulses.

For high-rises (>20 storeys), multimode dynamic analyses with 3x3+ groups optimize load sharing, slashing ductility demands by 60% per Khodair. Practical economies arise from soil improvement (e.g., CDSM around piles) over diameter upsizing, saving 28% in weak soils. Indian practitioners in regions like Pune (basaltic weak layers) should calibrate local geotechnical data against reviewed benchmarks, fostering resilient, cost-effective foundations that address code gaps while advancing towards Eurocode 8-level sophistication.

IV. CONCLUSION

This review highlights how pile stiffness affects seismic performance of multi-storey RCC buildings through soil-pile-structure interaction (SPSI). Studies from 2016-2026 show that pile diameter (600-800 mm) is key to stiffness, reducing drifts by 20-40% in rigid piles (L/T ≤ 2) across IS 1893 zones II-V, though it increases bending moments and base shears. Soft clays worsen kinematic effects, doubling moments and calling for semi-rigid piles with embedded rafts, while stiff soils benefit from group layouts (S/D=3-4, 3x3+ piles). IS 1893(2002) fixed-base assumptions underestimate periods by 15-25% and ignore kinematic demands; gaps remain in high-rise nonlinearities, liquefaction, and zone-specific designs. Numerical tools like 3D FE and FLAC work well but need shake-table validation for p-y soil behavior.

Practically, use SPSI-inclusive analysis with p-y springs (k_h=10-50 MN/m³) in STAAD.Pro/ETABS, favoring soil improvement over larger piles for cost savings. Future work should focus on centrifuge tests for Indian soils, AI models, and IS 1893 updates with Vs-based factors to build safer, economical foundations in seismic cities.

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