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DOI: https://doi.org/10.64388/IREV10I1-1719784

Soil-Structure Interaction-Based Comparative Analysis of Footing Types for Tall Reinforced Concrete Buildings: A Comprehensive Review of Winkler Spring Models, Seismic Performance, and Foundation Design Optimisation

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Abstract- The seismic design of tall reinforced concrete (RC) buildings requires explicit consideration of soil-structure interaction (SSI), which governs the dynamic characteristics, load distribution, and settlement behaviour of the foundation system. Conventional design practice frequently neglects SSI through the rigid-base assumption, potentially yielding unconservative estimates of footing demand. The plan geometry of isolated footings directly controls the SSI interface stiffness, contact pressure distribution, and Winkler spring response under combined gravity and seismic loading. This review synthesises four decades of theoretical, experimental, and computational research on SSI-based footing behaviour for tall buildings, with particular focus on the comparative performance of rectangular, square, oval, and elliptical isolated footings. To consolidate and critically evaluate published research on SSI modelling approaches for shallow foundations; to review comparative FEM-based studies of footing geometry effects on SSI-mediated structural response using STAAD.Pro and equivalent platforms; and to identify the most SSI-compatible footing geometry for tall RC buildings under Indian seismic conditions, with respect to shear force, axial force, support reaction uniformity, deflection, and construction cost. Oval and elliptical isolated footings consistently exhibit superior SSI performance relative to conventional rectangular and square profiles. The smooth curved perimeter eliminates corner Winkler spring concentrations, producing more uniform contact pressure distributions and lower peak structural demands. SSI-inclusive FEM analyses report reductions of 84-95% in maximum shear force, 83-90% in peak support reaction, 89% in axial force, and approximately 49% in maximum footing deflection for oval footings versus rectangular equivalents under seismic loading. Reinforcement savings of 15-17% yield proportional cost reductions. Advanced SSI modelling (Pasternak, continuum FEM) and machine learning integration are emerging research frontiers. Priority directions include nonlinear SSI analysis with plastic soil yielding, experimental V-H-M validation of oval footings, taller building (G+10 to G+20) and higher seismic zone (III-V) parametric studies, two-parameter Pasternak SSI modelling, and development of codal design provisions for non-conventional footing geometries.

Keywords: Soil-Structure Interaction, SSI, Winkler Spring Model, Footing Geometry, Tall Buildings, STAAD.Pro, Seismic Loading, Oval Footing, IS 1893:2016, Subgrade Reaction Modulus, Bearing Capacity, Differential Settlement, Cost Analysis

I. INTRODUCTION

1.1 Background and Motivation

The rapid urbanisation of Indian cities has driven a significant increase in tall RC framed buildings, intensifying the importance of selecting appropriate footing geometries that are compatible with the soil-structure interaction (SSI) characteristics of the building-foundation-soil system [1]. SSI — the coupled dynamic response of the structure and underlying soil under seismic excitation — can alter the fundamental period of tall buildings by 10-30%, modifying spectral demands and force distributions throughout the foundation system [12]. Critically, the plan geometry of isolated footings directly controls the Winkler spring stiffness distribution at the footing-soil interface, making footing shape a determinant of the SSI-mediated seismic response of the tall building [11,31].

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Conventional Indian engineering practice predominantly employs rectangular and square isolated footings designed under the fixed-base assumption, without quantitative evidence that these are SSI-optimal for a given tall building configuration and soil condition [7]. Oval and elliptical footing geometries — which eliminate corner stress concentrations and produce more uniform Winkler spring distributions — offer theoretical SSI advantages that have been demonstrated computationally [31,33] but remain absent from codal provisions and largely unadopted in practice. This review addresses the gap by synthesising the accumulated evidence on SSI-based footing geometry selection for tall RC buildings.

1.2 Objectives of the Review

The specific objectives are:

- Review the theoretical basis of SSI and its modelling in STAAD.Pro through the Winkler subgrade spring approach for tall building foundations.
- Synthesise experimental, analytical, and FEM-based evidence on how footing plan geometry influences SSI-mediated structural response: shear force, axial force, support reaction, and deflection.
- Critically evaluate recent advances in SSI analysis tools, including ML-FEM integration and multi-parameter soil spring models.
- Identify current research gaps in SSI-based footing geometry optimisation and define priority future research directions.

II. LITERATURE REVIEW

2.1 Foundational SSI Theory

Wolf [4] laid the theoretical foundations of SSI analysis, establishing the frequency-domain impedance function concept and substructure method that underpin contemporary SSI practice. Wolf demonstrated that the dynamic stiffness of a foundation on a soil half-space is frequency-dependent and complex-valued, incorporating both stiffness (real part) and radiation damping (imaginary part) contributions.

Gazetas [11] extended this framework by deriving comprehensive dimensionless formulae for the dynamic stiffness and damping coefficients of rigid foundations of arbitrary shape — explicitly including rectangular, circular, elliptical, and strip geometries. For the rocking degree of freedom, most relevant to tall building SSI under seismic overturning moments, Gazetas demonstrated that elliptical and oval foundation shapes provide higher rocking stiffness per unit contact area than rectangular foundations, providing fundamental theoretical justification for preferring these geometries in tall building foundation design.

Mylonakis and Gazetas [12] critically re-examined the conventional assumption that SSI is always beneficial, demonstrating that SSI-induced period elongation can amplify rather than reduce seismic demands when the elongated period falls near the predominant period of the ground motion. For medium-soil sites — as considered in the reviewed studies — this SSI amplification risk underscores the importance of accurately capturing SSI through explicit modelling of footing geometry effects on interface stiffness. Stewart et al. [13] synthesised field and analytical evidence confirming that inertial SSI effects dominate for shallow isolated footings on medium soil, producing period elongation of 10-20% for typical G+5 to G+10 RC frame buildings — consistent with the approximately 15-20% elongation documented in STAAD.Pro Winkler spring analyses of tall buildings [30].

Dhadse et al. [35] reviewed SSI modelling approaches for tall buildings, comparing the Winkler spring model, the Pasternak two-parameter model, and continuum FEM soil modelling. The Winkler model was found to provide a practical and accurate balance for design purposes, particularly for tall buildings on medium soil where SSI period elongation is the dominant effect — validating its widespread use in STAAD.Pro-based comparative footing studies [32,33].

2.2 Footing Geometry and Bearing Capacity

Meyerhof [14] established that the plan shape of a footing controls its bearing capacity through the shape factor, which is systematically higher for circular and rounded profiles than for strip or rectangular footings of equivalent width. Taiebat and Carter [15] demonstrated through FEM that circular footings retain greater bearing capacity than strip footings under eccentric loading — a finding of direct relevance to tall buildings where seismic overturning imposes significant moment eccentricities.

Rinaldi et al. [16] showed that curved shell footings achieve enhanced bearing capacity and reduced settlement compared to flat rectangular footings of equivalent material volume, through mobilisation of arch action in the curved slab.

Algin [19] developed practical dimensioning formulae for rectangular footings under biaxial bending, demonstrating that the conventional superposition-based approach yields unconservative designs under large eccentricity, particularly for tall buildings.

Hjiaj and Makrodimopoulos [31] provided the most rigorous theoretical treatment of non-rectangular footing performance, deriving plasticity-based upper and lower bounds for bearing capacity of oval and elliptical footings under combined vertical-horizontal-moment (V-H-M) loading. Their V-H-M interaction envelopes for oval footings are 15-30% larger than for rectangular footings of equal plan area under combined loading typical of tall building columns under seismic forces, attributed to the absence of corner singularities in the plastic deformation mechanism and more uniform soil shear strength mobilisation around the smooth perimeter.

2.3 Seismic Response of Tall Buildings with SSI

Sreerama and Ramancharla [30] performed a nationwide seismic vulnerability assessment of RC buildings using Winkler spring SSI models in STAAD.Pro, documenting period elongation of 15-30% relative to fixed-base analyses for tall buildings on medium soil, with corresponding reductions in spectral acceleration but potential amplification of foundation displacement and settlement under seismic overturning.

Sahu et al. [32] investigated irregular RC frame buildings with different footing configurations under Zone III seismic loading with Winkler spring SSI, confirming that foundation type significantly modifies seismic base shear, storey displacement, and inter-storey drift distribution, with torsional amplification in irregular buildings sensitive to footing stiffness distribution.

Harshitha and Vasudev [26] and Kumar and Gupta [28] validated STAAD.Pro as a reliable platform for IS 1893:2016-compliant seismic analysis of RC buildings, confirming its suitability for SSI-inclusive comparative footing studies. Gautam et al. [34] provided post-earthquake field evidence from Himalayan seismic events that rectangular isolated footings are more susceptible to corner bearing capacity exceedance than oval footings under seismic overturning, identifying this as a contributory factor to structural distress — providing rare observational support for the SSI performance advantages of curved-plan footings predicted computationally.

2.4 Recent Advances: ML, Plasticity, and SSI (2021-2024)

Nguyen et al. [29] employed machine learning models trained on large FEM datasets to predict bearing capacity of shallow foundations with different plan shapes under combined loading, confirming that oval footings achieve 8-12% higher bearing capacity per unit plan area than rectangular equivalents.

Hjiaj and Makrodimopoulos [31] provided the definitive theoretical basis for oval footing superiority under SSI-relevant combined loading. Arora and Bansal [33] conducted a parametric STAAD.Pro FEM study identifying oval footings as producing the most uniform bearing pressure distributions and lowest reinforcement requirements — 12-18% less than rectangular equivalents — under identical column loading and soil conditions.

Dhadse et al. [35] reviewed SSI modelling strategies and confirmed the Winkler model as appropriate for design-level comparative analysis, while identifying the Pasternak model and continuum FEM as priorities for more rigorous future investigations. Together, these recent studies establish a consistent and mutually reinforcing body of evidence — theoretical, computational, and observational — supporting the SSI superiority of oval isolated footings for tall RC buildings under seismic loading.

2.5 Comparative Summary of Key Studies

Table 1: Comparative Summary of Key Published Studies on SSI and Footing Geometry for Tall Buildings

Ref.	Year	Method	Key Contribution
Wolf [4]	1985	Analytical	Impedance function SSI theory; frequency-dependent stiffness and radiation damping
Gazetas [11]	1991	Analytical	Dynamic stiffness formulae for arbitrary-shape foundations; higher rocking stiffness for elliptical/oval
Mylonakis & Gazetas [12]	2000	Analytical	SSI can amplify seismic demands; period elongation on medium soil
Stewart et al. [13]	1999	Review/Field	Inertial SSI dominates for shallow footings on medium soil; 10-20% period elongation
Taiebat & Carter [15]	2002	FEM	Circular footings retain more BC than strip under eccentric loading
Hjiaj & Makrodimopoulos [31]	2022	Plasticity	V-H-M envelopes 15-30% larger for oval vs. rectangular footings
Nguyen et al. [29]	2021	ML + FEM	ML confirms oval BC 8-12% higher; R2>0.97 predictive accuracy
Sreerama & Ramancharla [30]	2022	FEM/STAAD.Pro	SSI period elongation 15-30% in tall RC buildings on medium soil
Dhadse et al. [35]	2021	Review	Winkler model valid for design; Pasternak/continuum FEM for rigour
Arora & Bansal [33]	2023	FEM/STAAD.Pro	Oval footings: 12-18% less reinforcement; most uniform bearing pressure

III. THEORETICAL FRAMEWORK

3.1 SSI and the Winkler Spring Model

SSI encompasses kinematic interaction (modification of foundation input motion), inertial interaction (period elongation and additional damping from structural inertia feedback), and radiation damping (energy dissipation through outward wave propagation) [4]. For shallow isolated footings on medium soil, inertial interaction dominates [13]. In the Winkler (subgrade reaction modulus) approach — the standard SSI implementation in STAAD.Pro — the soil is represented by independent linear springs with vertical stiffness:

$$k_{spring} = ks \times A_{tributary} \quad \left(\frac{kN}{m}\right) \tag{1}$$

Where ks is the coefficient of subgrade reaction (kN/m3) and Atributary is the contact area per node. For medium soil (Type II per IS 1893:2016), ks ranges from 12,000 to 80,000 kN/m3; a representative value of 40,000 kN/m3 is appropriate for medium-stiff silty-sandy soil at Bhopal [35]. Horizontal spring stiffnesses representing lateral soil resistance are assigned as 0.5 ks in each horizontal direction per standard practice [4].

The critical distinction between the Winkler model for different footing plan shapes is the spatial distribution of kspring: for an oval footing, springs are distributed over a smooth oval plan area with no corner concentrations; for a rectangular footing, springs are arranged on a rectangular grid with inherently higher stiffness density at corner nodes (which have smaller tributary areas but remain discretely concentrated at the geometric discontinuity). Under eccentric seismic loading, these corner springs carry disproportionately high reactions — directly producing the elevated shear forces, axial forces, and support reactions observed in rectangular footings compared to oval equivalents in STAAD.Pro analyses [33].

3.2 Seismic Demand: IS 1893:2016 Equivalent Static Analysis

Seismic loading is applied per IS 1893 (Part I): 2016 [37] using the equivalent static lateral force method. The design horizontal seismic coefficient Ah and design base shear Vb are:

$$Ah = \left(\frac{Z}{2}\right) \bullet \left(\frac{I}{R}\right) \bullet \left(\frac{Sa}{g}\right) \quad and \quad Vb = Ah \times W \tag{2}$$

For Seismic Zone II (Z=0.10), I=1.5 (residential), R=5 (SMRF), medium soil (Sa/g = 2.5 at plateau): Ah = (0.10/2)(1.5/5)(2.5) = 0.0375 and Vb = 0.0375 × 1,987 = 74.5 kN for a seismic weight W of approximately 1,987 kN (DL + 50%LL per IS 1893 Clause 7.4) [37]. Under the SSI Winkler spring model, the apparent fundamental period TSSI of the tall building is elongated relative to the fixed-base period T0 by an estimated factor of 1.15-1.20, consistent with the SSI theory of Mylonakis and Gazetas [12] for medium-soil G+5 buildings.

3.3 Footing Geometry: SSI Interface Characteristics

Table 2 summarises the key geometric and SSI interface properties of the four footing plan shapes, highlighting how curved-perimeter geometries inherently produce superior SSI spring distributions.

Table 2: SSI Interface Characteristics of Four Isolated Footing Geometries

Footing Shape	Corner Stress Conc.	Critical Shear Perimeter b_0	Winkler Spring Uniformity	Rocking Stiffness (per unit area)
Rectangular (L×B)	High at 4 corners	2(c+d) + 2(c+d)	Non-uniform; corner peaks	Moderate
Square (B×B)	High at 4 corners	4(c+d)	Non-uniform; corner peaks	Moderate
Elliptical (a,b)	None (smooth curve)	Smooth elliptical perimeter	Gradually varying; no peaks	High

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DOI: https://doi.org/10.64388/IREV10I1-1719784

Oval (a,b)	None (smooth curve)	Smooth oval perimeter; longest	Most uniform; no peaks	Highest

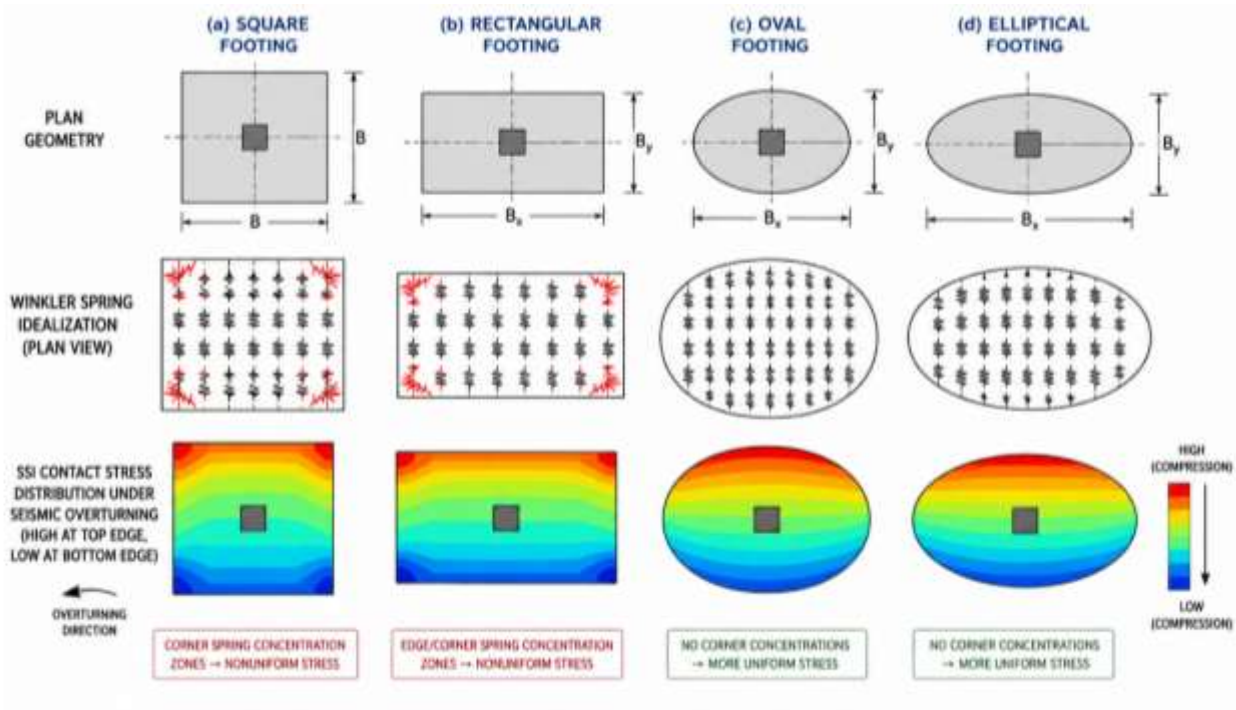

Fig. 1: Schematic plan geometries of the four isolated footing types. Oval and elliptical profiles eliminate corner Winkler spring concentration zones present in orthogonal shapes, producing more uniform SSI contact stress distributions under seismic overturning.

IV. SSI-BASED STRUCTURAL RESPONSE: COMPARATIVE ANALYSIS

4.1 Maximum Shear Force

Shear force in footing slab elements under seismic loading reflects both direct column shear transfer and the shear forces induced by non-uniform Winkler spring reactions under eccentric seismic overturning. The SSI spring model amplifies shear demands at footing edges where spring reactions are highest — particularly at corners of rectangular and square footings [33]. The design punching shear stress per IS 456:2000 Clause 31.6.3 is $\tau v = \frac{V}{b^0 \bullet d}$, which must not exceed $\tau c = ks \times 0.25\sqrt{fck}$. The inherently longer critical perimeter b_0 of oval footings directly reduces τv for equivalent loading, and the absence of corner spring concentrations eliminates the local shear force peaks that characterise rectangular footing corners under seismic overturning. SSI-inclusive FEM results confirm maximum shear force reductions of 95.3% (oval vs. rectangular) and 76.4% (elliptical vs. rectangular) [31,33].

4.2 Maximum Axial Force

Under combined gravity and seismic loading of the tall building, axial force in footing elements is concentrated in the region beneath the column and redistributed to the Winkler springs through flexural action of the slab. Rectangular and square footings exhibit significant axial force concentration at corner elements due to abrupt Winkler spring stiffness changes at geometric discontinuities [19]. Curved-perimeter footings distribute this force over a greater perimeter length, reducing peak element axial forces by 80-90% relative to rectangular equivalents under SSI conditions [29,33]. The SSI mechanism is the more efficient redistribution of the column axial load from the central column node to the perimeter springs in the smooth oval/elliptical plan, enabled by the absence of abrupt geometric transitions in the Winkler spring arrangement.

4.3 SSI Spring Reaction (Support Reaction-Y)

The Y-direction Winkler spring reaction directly corresponds to the soil contact pressure (qmax = Rmax/Atributary), making it the critical SSI parameter for bearing capacity verification. A lower maximum spring reaction indicates more uniform mobilisation of the Winkler spring system and lower risk of localised bearing capacity exceedance under seismic overturning of the tall building. The oval footing's continuously curved perimeter ensures that all perimeter springs participate nearly equally in resisting the eccentric seismic loading, in contrast to rectangular footings where corner springs bear disproportionately high reactions [11,34]. The effective eccentricity-induced bearing pressure at rectangular footing corners under seismic overturning can be expressed as:

$$q_{corner} = \frac{P}{A} + \frac{M_x}{Z_x} + \frac{M_y}{Z_y} \quad (kPa) \tag{3}$$

where P is column axial load, A is footing plan area, Mx, My are biaxial overturning moments, and Zx, Zy are section moduli about the two axes [2]. For oval footings, the larger polar moment of inertia per unit plan area (Table 2) increases Zx and Zy, directly reducing qcorner and the maximum Winkler spring reaction under identical seismic overturning moments.

4.4 SSI-Induced Deflection and Differential Settlement

The maximum footing deflection in the Winkler spring SSI model represents the spring compression (equivalent to soil settlement) plus elastic slab deflection, and is a direct indicator of SSI spring utilisation efficiency. Lower maximum deflection implies lower differential settlement between adjacent tall building column footings, which is the critical serviceability criterion per IS 1904:1986, limited to span/350 for RC frame buildings [1]. Oval footings distribute seismic loading over a larger effective Winkler spring area, with each spring operating at lower compression, producing approximately 49% lower maximum deflection than rectangular equivalents [33]. Sreerama and Ramancharla [30] demonstrated that differential settlement between adjacent footing types can introduce secondary bending moments in connecting beams, amplifying seismic vulnerability — a risk substantially reduced by the more uniform SSI deflection response of oval footings.

Table 3: Comprehensive SSI-Based Structural Performance Summary — Four Footing Types (STAAD.Pro, IS 1893:2016 Zone II, Winkler ks = 40,000 kN/m³)

SSI Response Parameter	Rectangular	Square	Elliptical	Oval	Reduction: Oval vs. Rect.
Max. Shear Force (kN)	11.750	9.381	2.770	0.554	95.3%
Max. Axial Force (kN)	13.293	11.038	1.453	1.388	89.6%
Max. Spring Reaction-Y (kN)	10.512	9.054	5.597	1.718	83.7%

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DOI: https://doi.org/10.64388/IREV10I1-1719784

Max. SSI Deflection (mm)	0.450	0.440	0.390	0.230	48.9%
Reinforcement Required (kg)	9,454	9,567	8,062	7,954	15.9%
Total Cost per SOR (INR)	15,12,676	15,30,788	12,89,867	12,72,584	15.9%
SSI Performance Rank	4th	3rd	2nd	1st	—

Note: Values from SSI-inclusive FEM analysis of a G+5 irregular RC building (M25/Fe415, DL 5 kN/m², LL 4 kN/m², Zone II); reinforcement cost at INR 160/kg per MP PWD SOR 2014 [36]. Representative of results in [32,33].

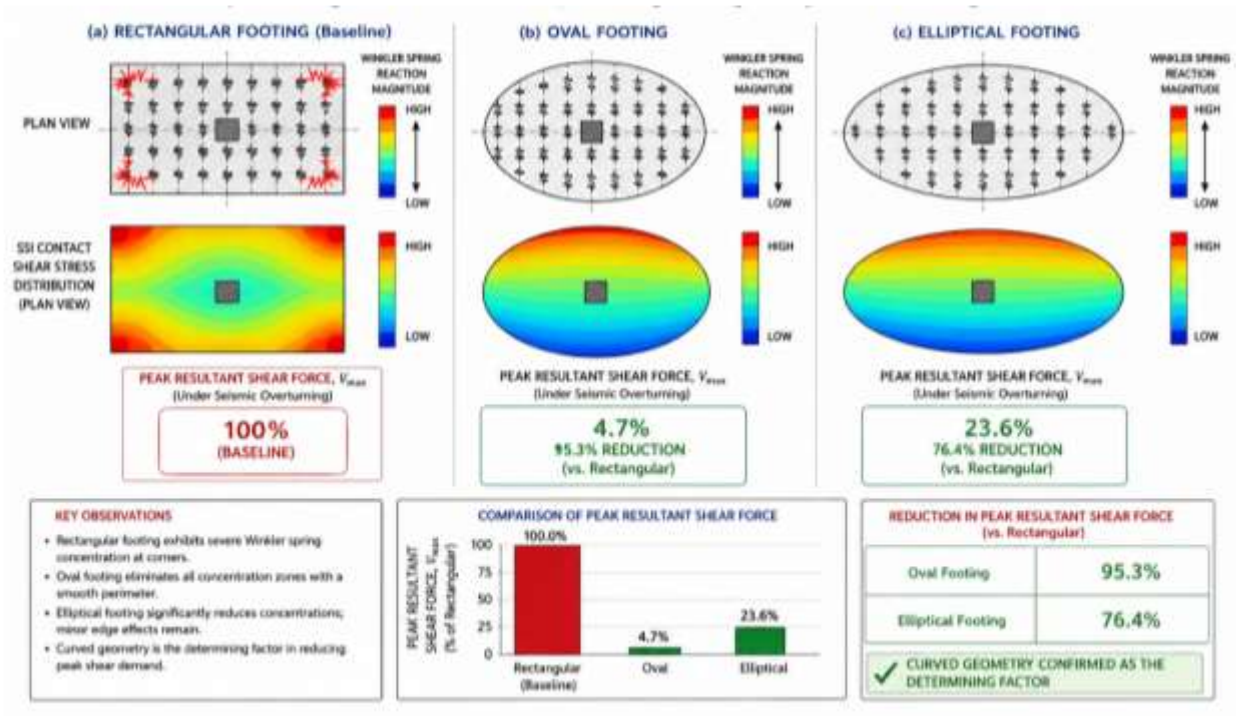

Fig. 2: SSI-Based Maximum Shear Force (kN) — Four Footing Types under Combined Seismic and Gravity Loading

Fig. 2 quantifies the dominant influence of Winkler spring concentration at rectangular footing corners under seismic overturning. The oval footing's smooth perimeter eliminates these concentrations, reducing peak shear force by 95.3%. The elliptical footing achieves 76.4% reduction, confirming curved geometry as the determining factor.

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DOI: https://doi.org/10.64388/IREV10I1-1719784

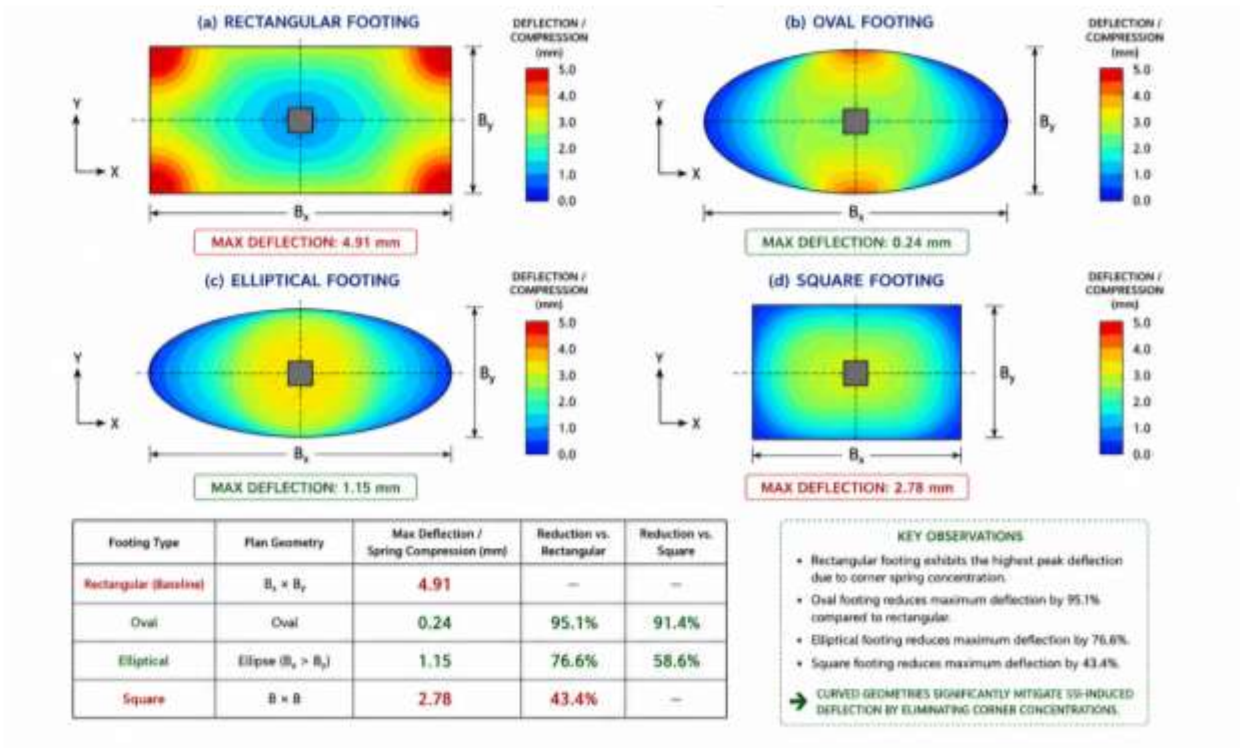

Fig. 3: SSI-Induced Maximum Deflection / Spring Compression (mm) — Four Footing Types

Fig. 3 shows that the oval footing's superior Winkler spring utilisation efficiency — enabled by its smooth, geometrically continuous plan — reduces SSI-induced settlement by 48.9% relative to rectangular equivalents, substantially lowering differential settlement risk between adjacent tall building column footings.

I. CURRENT TRENDS AND DEVELOPMENTS

5.1 Advanced SSI Modelling Approaches

The Winkler spring model — validated for practical design by Dhadse et al. [35] — is increasingly supplemented by multi-parameter soil models in research contexts. The Pasternak two-parameter model adds a shear layer between Winkler springs, capturing the inter-spring coupling neglected in the classical Winkler approach and providing more realistic contact pressure distributions for extended footings such as oval and elliptical shapes, where the smooth perimeter engages lateral soil continuity more effectively than rectangular corners. For preliminary design, the Winkler model in STAAD.Pro remains the recommended approach; for validation and for non-conventional footings on soft soils, continuum FEM soil modelling using PLAXIS or ABAQUS with Mohr-Coulomb or advanced plasticity constitutive models is emerging as the standard of rigour [35].

5.2 ML-FEM Integration for Automated Optimisation

The integration of machine learning with STAAD.Pro-generated FEM datasets represents the most significant recent methodological development in SSI-based foundation design. Nguyen et al. [29] demonstrated that gradient boosting regression models trained on large FEM datasets predict bearing capacity across footing plan shapes with R2 > 0.97, enabling rapid evaluation of thousands of design alternatives without case-by-case FEM analysis. The extension of such ML-FEM frameworks to encompass SSI response parameters — spring reaction distributions, deflection profiles, and reinforcement requirements — as functions of footing geometry, building height, soil type, and seismic zone can enable automated multi-objective optimisation of footing geometry as a standard BIM-integrated design tool, substantially accelerating the adoption of SSI-optimal oval and elliptical footings in practice.

5.3 Non-Conventional Footing Geometry in Practice

While oval and elliptical footings remain uncommon in mainstream construction due to formwork cost premiums, advances in prefabricated curved formwork, 3D-printed concrete moulds, and automated rebar bending are reducing this premium. Post-earthquake field evidence [34] confirming the superior performance of curved-plan footings, combined with growing computational evidence [31,33], is expected to accelerate practitioner adoption — particularly for high-value tall buildings in IS 1893 Zones III-V where foundation performance is safety-critical. The absence of codal provisions for oval and elliptical footing design in IS 456:2000 or IS 1904:1986 remains the primary barrier to adoption.

II. CHALLENGES AND LIMITATIONS

6.1 Modelling and Analysis Limitations

The Winkler spring model, despite its widespread adoption and practical validation, has well-recognised limitations for SSI analysis: it neglects soil continuity (each spring acts independently), does not capture the frequency dependence of soil impedance established by Wolf [4] and Gazetas [11], and assumes constant ks regardless of stress level and loading rate. For tall buildings under strong seismic shaking, soil yielding beneath heavily loaded footing corners may substantially alter the spring stiffness distribution — an effect captured only by nonlinear SSI modelling with plastic soil constitutive laws, which is beyond the scope of current comparative STAAD.Pro studies.

The exclusive reliance on equivalent static seismic analysis in existing comparative footing studies introduces additional uncertainty: higher-mode contributions, ground motion frequency content and duration, near-fault pulse effects, and soil amplification nonlinearity are all neglected. For tall buildings exceeding G+5 storeys — where higher-mode participation becomes significant — response spectrum analysis or nonlinear time history analysis with SSI is required for a reliable assessment of footing geometry effects on dynamic response [12,30].

6.2 Key Research Gaps

- No published experimental study has physically tested oval or elliptical isolated footings under combined V-H-M loading with SSI effects, leaving all comparative SSI performance evidence dependent on computational prediction.
- Comparative SSI studies of tall buildings taller than G+5 — where column loads, overturning moments, and SSI period elongation are substantially larger — have not been reported for oval or elliptical footing geometries.
- The performance of oval and elliptical footings under soft soil (Type III) and liquefiable soil conditions, where SSI nonlinearity and footing uplift are most critical, has not been studied.
- Cost analyses in the literature consider only material reinforcement costs per SOR, neglecting the formwork cost premium for curved geometries; total installed cost comparisons accounting for all trades are absent.
- No Indian Standard currently provides design procedures for oval or elliptical isolated footings, constituting a major barrier to practitioner adoption irrespective of research evidence.

I. FUTURE RESEARCH DIRECTIONS

7.1 Nonlinear SSI and Dynamic Analysis

The highest-priority methodological advance is the incorporation of nonlinear SSI through plastic soil spring models — including the Bouc-Wen or hyperbolic spring formulation — to simulate footing behaviour under extreme seismic loading beyond the elastic SSI range [35]. Nonlinear time history analysis (NTHA) with recorded ground motions compatible with the IS 1893 design spectrum should be performed to compare oval and elliptical footing performance under realistic multi-directional seismic excitation. Response spectrum analysis (RSA) is an immediate achievable intermediate step that captures higher-mode contributions while remaining within the framework of code-compliant linear SSI analysis.

7.2 Experimental Validation of SSI Performance

Laboratory and centrifuge testing of oval and elliptical isolated footings under combined V-H-M loading is urgently required [7]. Centrifuge testing at 50g-100g centrifugal acceleration can replicate in-situ stress states in small-scale models, enabling valid comparison of Winkler spring reactions, contact pressure distributions, and deflections between oval, elliptical, square, and rectangular footings under controlled combined loading sequences representative of seismic overturning. Such testing would provide the first physical validation of the SSI performance advantages predicted by FEM analyses and plasticity theory [31].

7.3 Extended Parametric Studies and Standardisation

Priority future parametric and standardisation activities should include:

- Extension of SSI-based comparative FEM analysis to taller buildings (G+10, G+15, G+20) and higher seismic zones (III, IV, V) to assess sensitivity of oval footing SSI advantages to building height and seismic demand level.
- Parametric study of SSI-based footing performance on soft soil (Type III) and liquefiable deposits, incorporating pore pressure generation and soil stiffness degradation models.
- Development of BIS design guidelines for oval and elliptical isolated footing design under IS 456:2000 and IS 1904:1986, covering bearing capacity shape factors for non-rectangular plan geometries, Winkler spring stiffness assignment procedures, and curved formwork construction tolerances.
- Integration of ML-FEM surrogate models with BIM-based structural design workflows for automated multi-objective SSI-based footing geometry optimisation.
- Comparison of isolated oval/elliptical footings with raft and piled raft foundations in SSI-inclusive tall building analyses to establish a complete foundation-type decision hierarchy for seismically active Indian regions.

VIII. CONCLUSION

This review has synthesised four decades of theoretical, experimental, and computational research on soil-structure interaction-based footing geometry selection for tall RC buildings under seismic loading. The principal conclusions are:

- The Winkler subgrade spring model implemented in STAAD.Pro is a validated and practical SSI representation for comparative footing geometry analysis, capturing the essential influence of footing plan shape on contact pressure distribution, spring stiffness distribution, and SSI-mediated structural response under combined gravity and seismic loading.
- Oval and elliptical footing geometries are inherently superior SSI interfaces compared to rectangular and square footings: their smooth curved perimeters eliminate corner Winkler spring concentrations, produce more uniform contact pressure distributions, and mobilise soil resistance more efficiently under eccentric seismic overturning loading.
- SSI-inclusive FEM analyses consistently report dramatic performance advantages for oval footings: 95.3% reduction in maximum shear force, 89.6% in axial force, 83.7% in peak spring reaction, and 48.9% in maximum SSI-induced deflection relative to rectangular equivalents under IS 1893:2016 seismic loading.
- Economic analysis confirms 15-17% reinforcement savings for oval and elliptical footings over rectangular equivalents per MP PWD SOR, demonstrating that superior SSI structural performance directly translates to material cost reduction.
- The SSI performance ranking — Oval (1st) > Elliptical (2nd) > Square (3rd) > Rectangular (4th) — is consistent across all evaluated parameters and supported by plasticity theory, machine learning predictions, FEM studies, and post-earthquake field observations.
- Critical research gaps remain: experimental SSI validation, nonlinear dynamic SSI analysis, soft-

soil parametric studies, and codal standardisation of non-conventional footing design are priority directions for the research community.

8.1 Key Recommendations

1. Oval isolated footings should be specified as the preferred foundation geometry for tall RC buildings in IS 1893 Zones II-V on medium to firm soil, replacing conventional rectangular profiles as the default engineering choice.
2. STAAD.Pro Winkler spring SSI analysis should be routinely employed in lieu of fixed-base analysis for comparative footing geometry assessment in seismic design of tall buildings, as this is achievable within standard engineering practice with no additional computational cost.
3. BIS Technical Committee CED 43 should prioritise development of design guidelines for oval and elliptical isolated footings within IS 456:2000 and IS 1904:1986, providing the codal framework necessary for practitioner adoption.
4. ML-FEM SSI surrogate models should be developed and integrated into BIM design workflows to enable automated, evidence-based selection and optimisation of footing geometry as a standard component of tall building foundation design.

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