

Seismic Behavior of Pipe Rack Structures and Foundation Aspects Considering Soil–Structure Interaction: A Comprehensive Review

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Abstract— Pipe rack structures are critical nonbuilding systems in petrochemical plants, refineries, and LNG terminals, where they support extensive piping networks and process equipment. Their seismic behavior is more complex than conventional building structures due to mass irregularities, structural–piping interaction, and soil–structure interaction (SSI). This paper presents a comprehensive review of the seismic behavior of pipe rack structures with emphasis on SSI effects and foundation aspects.

The review of recent studies indicates that SSI significantly modifies structural response by altering natural frequency, damping, and displacement demands. While SSI may reduce pipeline stresses by up to 40–45% due to a seismic isolation effect, it can increase inter-storey drift and fragility of structural frames. Foundation flexibility, uneven settlement, and boundary conditions of piping systems are identified as critical factors influencing seismic performance. In particular, pipe boundary conditions can increase collapse probability from 0% to 59%, highlighting major modeling uncertainty.

Different SSI modeling approaches, including Winkler Spring models, nonlinear soil models, continuum finite element methods, and lumped parameter models, are critically evaluated. The study identifies significant research gaps, including lack of integrated studies combining pipe rack systems with SSI, uneven settlement, torsional effects, and foundation variability. The paper concludes that performance-based design approaches and efficient SSI modeling techniques are essential for improving seismic safety and resilience of industrial pipe rack systems.

Index Terms— Pipe rack structures, soil–structure interaction, seismic response, foundation stability, fragility analysis, industrial structures

I. INTRODUCTION

Pipe rack (PR) structures are essential components of industrial facilities such as petrochemical plants, oil refineries, and LNG terminals. These structures support pipelines, cable trays, and equipment at multiple levels above ground, forming the backbone of material transport systems. Unlike conventional buildings, pipe racks exhibit complex structural behavior due to open-frame configurations, irregular mass distribution, and interaction with piping systems. During earthquakes, pipe rack structures are subjected to dynamic forces influenced not only by structural properties but also by the supporting soil. Soil–structure interaction (SSI) plays a significant role in modifying seismic response by altering stiffness, damping, and natural frequencies. Conventional design approaches often assume fixed-base conditions, neglecting soil flexibility, which can lead to inaccurate predictions of seismic demand.

In addition to SSI, foundation-related aspects such as bearing capacity, sliding, overturning, and uneven settlement significantly influence seismic performance. Uneven settlement can introduce torsional effects and amplify structural damage, especially in soft soil conditions. Furthermore, interaction between pipe racks and supported piping systems adds another layer of complexity to seismic behavior.

Although several studies have investigated SSI effects in various structural systems, limited research has focused specifically on pipe rack structures considering combined effects of SSI, foundation

variability, and interaction with piping systems. This paper aims to critically review existing literature, identify research gaps, and provide insights for improved seismic design of

II. BACKGROUND: PIPE RACK STRUCTURES AND CODE PROVISIONS

A. Pipe rack structures are open-frame systems constructed using steel or reinforced concrete, designed to support pipelines, cable trays, and process equipment above ground level for operational efficiency, safety, and maintenance accessibility. Structurally, these systems consist of:

(i) moment-resisting or braced frames in the transverse direction, (ii) pinned beam–column connections in the longitudinal direction using struts, and (iii) vertical and horizontal bracing systems to resist lateral loads and stabilize the structure.

This inherent directional asymmetry results in significantly different seismic demand and load-resisting mechanisms along the two principal axes, which are not adequately captured by conventional equivalent-static analysis methods. Steel is the most commonly used material in coastal industrial environments due to its corrosion resistance and constructability, whereas reinforced concrete is preferred in certain cases for improved fire resistance and durability.

The structural complexity of pipe racks is primarily governed by the equipment and piping systems they support. Components such as horizontal pressure vessels, vertical columns, and multiply supported pipelines introduce substantial and often asymmetric mass distribution. Studies have shown that pipe contents alone may contribute up to 60–70% of the total seismic mass at intermediate levels, resulting in vertical irregularities in stiffness and strength distribution. These irregularities promote higher-mode effects and may induce torsional response, particularly in the absence of rigid floor diaphragms.

B. Dynamic Analysis Methods

The seismic assessment of pipe rack structures is typically performed using three principal analysis methods: (i) Equivalent Lateral Force (ELF) method, (ii) Response Spectrum Analysis (RSA), and (iii) Nonlinear Response History Analysis (NRHA).

The ELF method, commonly prescribed in design codes such as ASCE 7, provides a simplified approach but is often inadequate for irregular structures. Comparative studies indicate that ELF-based analysis may underestimate seismic demands by approximately 20–40% when compared to NRHA, especially for multi-level and irregular pipe rack systems.

RSA offers improved accuracy by incorporating modal contributions; however, it may still fail to capture nonlinear behavior under strong ground motion. NRHA, on the other hand, provides the most realistic representation by accounting for material nonlinearity, geometric effects, and time-dependent seismic loading.

For advanced seismic performance evaluation, Incremental Dynamic Analysis (IDA) is widely adopted, as it enables assessment of structural response over a range of seismic intensity levels.

An additional complexity in pipe rack systems arises from the interaction between the structural frame and supported piping systems. The dynamic response of the system is influenced by the relative stiffness of pipes, supports, and the rack structure. Coupled finite element models have demonstrated that when the natural frequencies of pipes coincide with those of the supporting structure, resonance effects may occur, significantly amplifying pipe stresses. Furthermore, pipe support conditions (anchored, guided, or with expansion joints) result in different force transfer mechanisms and must be carefully considered in analysis.

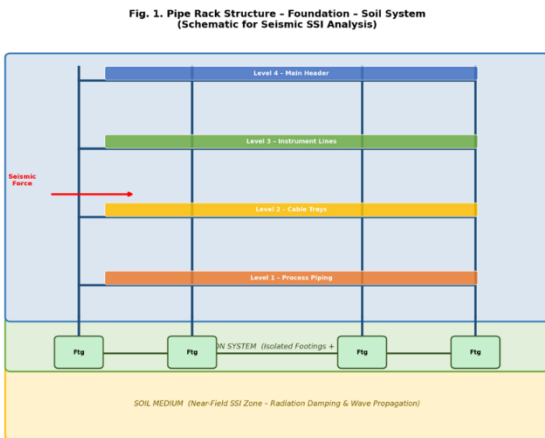
C. Code Provisions and Their Limitations

Current seismic design standards provide limited and often inadequate guidance for pipe rack–piping systems. The ASCE/SEI 7-22 standard classifies industrial process structures under Risk Categories III or IV and includes provisions for nonbuilding structures in Chapter 15. Additionally, Chapter 19 introduces simplified SSI effects through base shear reduction factors (up to 30%) and modified damping values. However, these provisions are primarily developed for conventional building structures and may not accurately represent the kinematic and inertial interaction effects in pipe rack systems, particularly for shallow foundations.

Eurocode 8 (EN 1998-1) does not explicitly address pipe rack structures, treating them under general irregular structures with simplified analysis

approaches. EN 1998-4 provides guidelines for tanks, silos, and pipelines individually but does not consider their combined interaction when supported on pipe racks. Furthermore, pipeline design under EN 13480-3 is based on allowable stress principles, limiting pipe stresses to elastic range. This requirement often leads to overly stiff pipe rack designs, resulting in conservative and uneconomical solutions.

ASCE provisions allow dynamic decoupling between pipe racks and supported equipment when the equipment mass does not exceed 25% of the total system mass. However, this criterion oversimplifies the interaction by neglecting important factors such as pipe stiffness, connection rigidity, and multiple-support excitation effects. Studies have shown that such assumptions can result in significant overstrength in pipe rack systems, with the probability of exceeding critical limit states being substantially lower than design expectations.



III. SOIL-STRUCTURE INTERACTION: THEORY AND MODELING APPROACHES

A. Theoretical Background

Soil-structure interaction (SSI) is governed by two primary mechanisms: kinematic interaction (KI) and inertial interaction (II). Kinematic interaction arises due to the inability of a rigid or semi-rigid foundation to fully follow free-field ground motion, resulting in wave scattering and attenuation of high-frequency components. In contrast, inertial interaction is caused by inertia forces generated within the vibrating superstructure, which induce additional foundation translations and rotations. Together, these mechanisms modify both the effective seismic input and the

impedance characteristics (stiffness and damping) of the soil-foundation system.

For isolated footings supporting pipe rack columns, soil impedance functions depend on parameters such as shear modulus (G), Poisson's ratio (ν), footing geometry, and loading frequency. Since dynamic stiffness and radiation damping are frequency-dependent, the use of constant (static) spring values represents a simplification, generally acceptable only for low-frequency structures (fundamental period $T > 0.5$ s).

Incorporation of soil flexibility leads to period elongation, typically increasing the natural period by a factor of 1.15–1.45 for pipe racks on medium-dense soils. This results in a reduction of spectral acceleration demand (approximately 10–29%) but an increase in displacement demand (approximately 11–43%), which is critical for serviceability and piping integrity considerations.

B. Winkler Spring Models

Winkler-type Spring-dashpot models are the most widely used SSI representation in engineering practice due to their simplicity and computational efficiency. In this approach, the soil-foundation system is idealized using discrete springs and dashpots calibrated from impedance functions derived for an elastic half-space, commonly based on the formulations of Gazetas.

In practical applications, such as the study by Di Sarno and Karagiannakis, the foundation is represented by a set of lumped springs corresponding to translational and rotational degrees of freedom. This method is particularly suitable for integration with commercial structural analysis software.

However, a major limitation of the Winkler approach is the assumption of linear, homogeneous soil behavior, which restricts its ability to capture nonlinear soil response, strain-dependent stiffness degradation, and energy dissipation under strong seismic excitation.

C. Nonlinear Soil Models

To address the limitations of linear models, nonlinear soil constitutive relationships are employed. The Ramberg-Osgood (RO) model is commonly used to simulate nonlinear stress-strain behavior of soils. In this approach, shear modulus degradation ($G-\gamma$) and damping variation ($D-\gamma$) curves are calibrated based

on empirical formulations, such as the modified Ishibashi–Zhang relationships.

Nonlinear SSI models enable realistic representation of soil hysteresis behavior and energy dissipation under cyclic loading. Studies indicate that incorporating soil nonlinearity reduces variability in seismic response and provides more reliable fragility predictions compared to linear models. However, these models require detailed soil characterization and increased computational effort.

D. Continuum Finite Element Models

Continuum-based finite element (FE) modeling represents the most rigorous approach for SSI analysis.

In this method, the soil domain is discretized using solid elements, allowing simulation of spatial variability, stress distribution, and complex deformation patterns.

For example, studies have modeled soil domains extending several times the foundation dimensions to minimize boundary effects, with appropriate boundary conditions such as viscous dampers to simulate infinite soil media. Contact elements or nonlinear springs are often used at the soil–foundation interface to represent separation and sliding behavior.

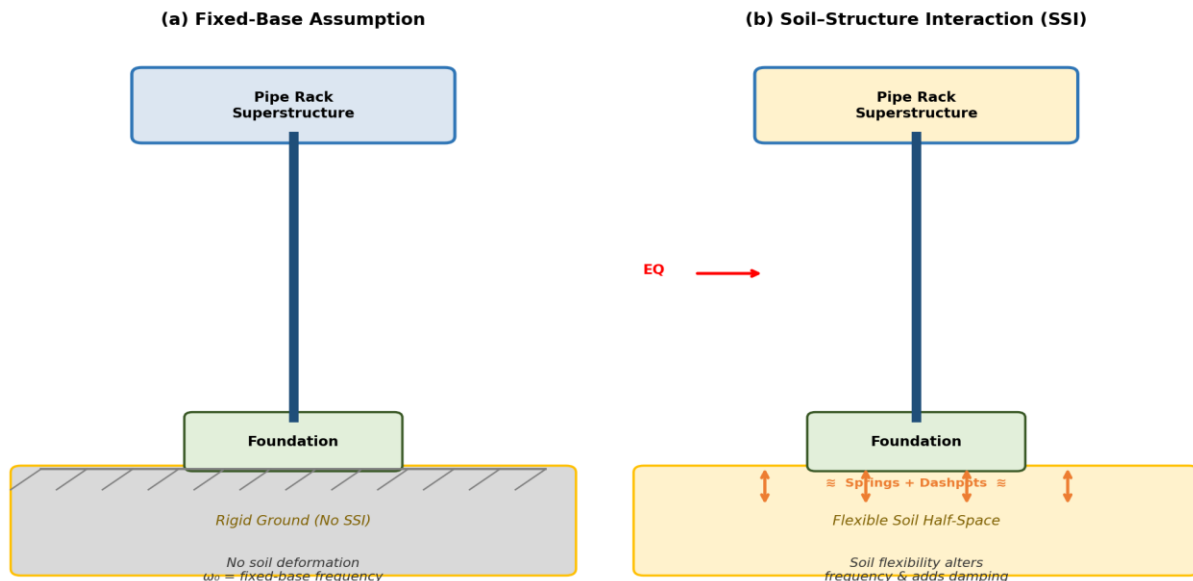
Although this approach provides high accuracy, it is computationally intensive and may not be practical for routine design applications.

Table I summarizes and compares the four SSI modeling approaches reviewed.

Comparison of SSI Modeling Approaches Reviewed in the Literature

Approach	Model Type	Software	Key Feature	Limitation
Winkler Springs	Linear spring-dashpot	ABAQUS	Computationally efficient; compatible with standard FE codes	Linear soil; homogeneous half-space; no nonlinearity
Ramberg–Osgood	Nonlinear hysteretic	SeismoSoft	Captures soil nonlinearity, G – γ degradation, energy dissipation	Simplified boundary; no liquefaction; calibration-intensive
Solid FE Continuum	Full 3D continuum	SAP2000	Spatially variable soil; realistic deformation; captures torsion	Very high computational cost; limited scalability for probabilistic analysis
Lumped Parameter (LPM)	Frequency-domain calibrated	TREMURI / Custom	Efficient; captures radiation damping; practical for fragility analysis	Visco-elastic only; no soil yielding; calibration needed per site

Fig. 2. Soil-Structure Interaction Mechanism in Pipe Rack Seismic Analysis



IV. FOUNDATION ASPECTS AND SEISMIC STABILITY

A. Foundation Types for Pipe Racks

The selection of foundation type plays a critical role in the seismic performance of pipe rack structures. In competent, non-liquefiable soil conditions, isolated pad (spread) footings are most commonly used due to their simplicity and cost-effectiveness. However, when column spacing is limited, soil bearing capacity is low, or differential settlement needs to be controlled, alternative foundation systems such as combined footings, strap footings, and mat foundations are adopted.

In soft or liquefiable soil conditions, pile foundations are generally preferred to ensure adequate load transfer and stability. The choice of foundation type significantly influences the soil–structure interaction (SSI) behavior of the system. Studies on similar structural systems have shown that different foundation configurations (e.g., spread footings, pile groups, and anchored foundations) produce distinct variations in acceleration, displacement, and overall seismic response, highlighting the importance of foundation selection in design.

B. Bearing Capacity Under Seismic Loading

Seismic forces introduce combined vertical, horizontal, and moment loads on foundations, resulting in eccentric and inclined stress distributions. The effective footing area method is commonly used to account for eccentric loading by reducing the actual footing area to an equivalent central area.

Under combined loading conditions involving axial load (N), lateral force (H), and overturning moment (M), the effective bearing area may be reduced by approximately 30–60% of the gross footing area in high seismic zones. As a result, foundations may reach their bearing capacity limit at seismic intensities lower than the design level. Additionally, in cohesive soils, cyclic loading leads to degradation of soil strength, further reducing bearing capacity. Therefore, appropriate reduction factors must be incorporated in design to account for cyclic and dynamic soil behavior.

C. Overturning Stability

Overturning is often the governing failure mode for isolated foundations supporting tall and slender pipe

rack structures. The overturning stability ratio (OSR), defined as the ratio of stabilizing moment to overturning moment, must exceed a minimum value specified by design codes (typically 1.5 as per ASCE 7).

For low-rise pipe racks (height $H < 6$ m), overturning stability is generally not critical. However, for multi-level pipe racks (height $H > 15$ m) with significant pipeline loads, the OSR may reduce considerably under strong seismic excitation. In such cases, the OSR may fall below acceptable limits (e.g., below 1.2 under maximum considered earthquake conditions), necessitating design modifications such as increasing footing size, providing tie beams, or adopting pile foundations.

It is also observed that while SSI tends to reduce base shear, it simultaneously increases displacement, thereby increasing the overturning moment arm. This effect may reduce overall stability, particularly in soft soil conditions.

V. CRITICAL REVIEW OF KEY STUDIES

A. Seismic Assessment of Steel Pipe Racks with SSI (Di Sarno and Karagiannakis, 2020a)

Di Sarno and Karagiannakis (2020) performed a nonlinear seismic assessment of steel pipe rack–piping systems considering SSI and dynamic interaction. SSI was modeled using Winkler springs, and Incremental Dynamic Analysis (IDA) was conducted using multiple earthquake records. The study reported a 6–14% increase in structural periods and a significant reduction (40–45%) in pipeline stresses due to soil isolation effects. However, structural displacement increased, and the system exhibited high overstrength, indicating conservatism in current design codes.

B. Seismic Fragility of Pipe Rack–Piping Systems with SSI (Di Sarno and Karagiannakis, 2020b)

In a subsequent study, fragility analysis incorporating uncertainties such as pipe boundary conditions and soil nonlinearity was performed. It was found that pipe boundary conditions have a dominant influence, with collapse probability increasing from 0% to 59%. SSI reduced variability in response, while near-field earthquakes produced more critical demands compared to far-field motions.

C. Seismic Response of RC Frames with Uneven Foundation Settlement and SSI (Shang et al., 2023)
Shang et al. (2023) investigated reinforced concrete frames under SSI and uneven foundation settlement. Results showed that differential settlement significantly amplifies seismic response, with inter-storey drift increasing up to 2.7 times compared to SSI alone. Additionally, torsional effects were observed due to asymmetric settlement, highlighting the importance of considering settlement effects in structural analysis.

D. Effect of SFSI on Seismic Response of Wind Turbines (Austin and Jerath, 2017)

Austin and Jerath (2017) studied wind turbine structures with different foundation systems. SSI was found to increase displacement (4–11%) and reduce natural frequency. However, its effect was relatively small in frequency-based designs. The study emphasized that foundation type significantly influences seismic response and that simplified SSI models may be adequate in certain cases.

E. Seismic Response of URM Buildings with SFSI Using Lumped Parameter Models (Bracchi et al., 2026)

Bracchi et al. (2026) introduced lumped parameter models (LPM) for SSI analysis. Results showed that SSI has a moderate and intensity-dependent effect on structural response, with minimal influence on capacity but noticeable changes in fragility. LPM was identified as an efficient and practical alternative to complex finite element models.

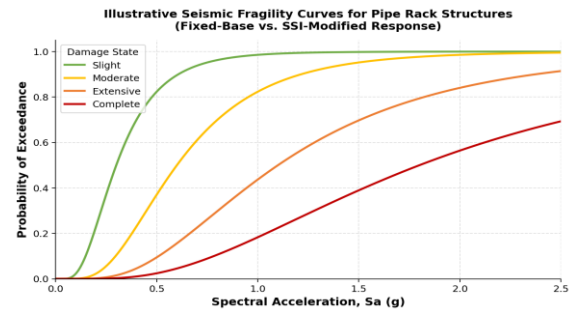
VI. FRAGILITY ANALYSIS OF PIPE RACK SYSTEMS

Fragility analysis provides a probabilistic framework to estimate the likelihood of a structure exceeding specific damage states under seismic loading. For pipe rack systems, key engineering demand parameters

(EDPs) include inter-storey drift ratio (IDR) for structural response and stress or plastic strain for piping components. Most studies employ Incremental Dynamic Analysis (IDA) with spectral acceleration $Sa(T_1)$ as the intensity measure, and develop lognormal fragility functions.

An important observation is that the dispersion parameter (β) is highly sensitive to modeling assumptions. Incorporation of nonlinear soil behavior reduces variability in response compared to linear SSI models, indicating that accurate soil modeling improves reliability of fragility predictions.

Steel pipe racks generally exhibit higher fragility capacity due to their ductility. However, equipment anchorage failure is often the governing damage mode at lower seismic intensities (below 0.5g), occurring prior to structural damage. SSI exhibits a dual effect on fragility behavior: it shifts fragility curves toward higher intensity levels (beneficial for piping systems), while increasing displacement demands that may affect post-earthquake functionality.



VII. COMPARATIVE ANALYSIS AND SYNTHESIS

The five studies reviewed provide a multi-faceted understanding of SSI effects across different structural systems. Table II synthesizes key characteristics and findings to facilitate cross-study comparison.

Table II
Comparative Summary of Reviewed Studies

Study	Structure Type	SSI Model	Analysis Method	SSI Effect	Key Finding
Di Sarno & Karagiannakis [5] (2020a)	Steel PR + piping	Winkler springs (linear)	IDA + fragility curves	Increases IDR; isolates pipes	Pipe stress reduces 40–45%; $SaR/SaR,d$ drops from 1.84 to 1.67; high overstrength in rack

Di Sarno & Karagiannakis [6] (2020b)	RC PR + piping	Ramberg–Osgood nonlinear springs	IDA + uncertainty analysis + fragility	Reduces fragility dispersion; increases beam fragility	Pipe BC: CLS fragility 0%→59%; nonlinear SSI reduces IM dispersion
Shang et al. [13] (2023)	RC frame with USF	Solid FE continuum	Time-history (10 records, 3 intensities)	Amplifies drift, damage, and torsion	Inter-story drift up to 274.8% greater with USF; torsional amplification critical at upper stories
Austin & Jerath [17] (2017)	Wind turbine (3 sizes, 4 foundations)	K-model + explicit FE	Modal + time-history; experimental validation	Minor effect for frequency-based design	SSI increases acceleration 8–13% and displacement 4–11%; K-model is adequate for engineering use
Bracchi et al. [14] (2026)	URM masonry building	Lumped Parameter Models (LPM)	Pushover + multi-stripe dynamic	Slight reduction in vulnerability at high IM	LPM efficient for SFSI; radiation damping insensitive to seismic intensity level

First, the effect of SSI is not uniform; it depends on structural type, foundation system, soil conditions, and seismic intensity. While SSI reduces pipe stresses, it may increase structural displacement and damage. Studies also show that SSI effects can vary from beneficial to negligible or even adverse depending on system characteristics.

Second, modeling assumptions and boundary conditions significantly influence system response. In particular, pipe support conditions have been shown to drastically alter fragility behavior, indicating that SSI

effects cannot be assessed independently of modeling uncertainties.

Third, soil nonlinearity plays a crucial role in seismic response. Nonlinear soil models reduce dispersion in fragility predictions compared to linear models, resulting in more reliable and consistent response estimation.

Finally, foundation variability and uneven settlement remain critical but underexplored factors. Their combined influence with SSI especially in inducing torsional response has not been adequately studied for pipe rack systems, representing a major research gap.

Table III
Summary of Relevant Code Provisions for Pipe Rack SSI Design

Standard	Region	Pipe Rack Classification	SSI Provisions	Key Limitation
ASCE/SEI 7-22	USA	Nonbuilding structure similar to building; Risk Category III/IV	Chapter 19: base shear reduction up to 30%; effective damping adjustment	SSI method developed for buildings; shallow lightly embedded PR footings may not qualify
EN 1998-1 (Eurocode 8)	Europe	Informative Annex E; industrial irregular structure; $q = 2.0\text{--}4.0$	No dedicated SSI provisions for industrial structures; relies on EN 1998-5 for foundations	No pipe rack-specific guidance; EN 1998-5 SSI provisions limited to general buildings
ASCE Petrochemical Guidelines (2011)	USA	Dedicated pipe rack provisions; load combinations; damping values	No explicit SSI adjustment; references ASCE 7 for SSI	Decoupling criterion (25% weight ratio) oversimplifies piping interaction
IS 1893 Part 4 (2015)	India	Industrial structures including stack-like structures	Limited SSI provisions; references national annex	No pipe rack-specific SSI guidance; limited applicability to coastal soft-soil sites
EN 13480-3	Europe	Pipeline component design (allowable stress)	None (pipeline code only)	Keeps pipes below yield → promotes conservative overdesign of rack structure

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

The comprehensive review of existing literature reveals that, while the seismic response of pipe rack superstructures and the broad principles of SSI are well-documented, several specific areas remain inadequately addressed:

- Fully coupled SSI-fragility frameworks for pipe rack structures are absent from the literature. No published study provides SSI-informed fragility curves derived from properly calibrated, coupled structural–geotechnical models using ground-motion suites representative of near-fault and long-period motions.
- The effect of bidirectional seismic loading on foundation stability has received limited attention. Pipe racks are susceptible to combined transverse and longitudinal seismic action; current stability checks are predominantly uniaxial.
- Nonlinear soil behavior under cyclic loading, including stiffness degradation, pore pressure buildup in saturated sands, and cyclic mobility, is rarely incorporated into pipe rack seismic analyses despite its demonstrated importance in case histories.
- Longitudinal seismic demand on bracing systems and anchor rods is systematically underemphasized in both research and code provisions.
- Operational variability in mass distribution arising from varying pipe fill levels, equipment on/off states, and thermal expansion states has not been rigorously incorporated into probabilistic seismic performance assessment frameworks.
- Foundation-level soil–pipe interaction, where pipes buried near or at grade interact with the soil independently of the rack structure, represents an unquantified additional failure pathway.

Future research should prioritize the development of open-source numerical frameworks combining nonlinear structural analysis (OpenSees or equivalent) with fully coupled SSI soil domains using advanced constitutive models (e.g., PM4Sand for liquefiable soils). Machine-learning surrogate models trained on large IDA datasets offer a promising pathway for efficient probabilistic fragility assessment that accounts for SSI and operational variability simultaneously. Experimental validation via shake-table tests on scaled pipe rack–foundation–soil models

are urgently needed to calibrate and verify numerical predictions.

IX. CONCLUSIONS

This paper has presented a comprehensive and critical review of the seismic behavior of pipe rack structures with emphasis on soil–structure interaction and foundation aspects. The following principal conclusions are drawn:

1. SSI exerts a dual role in pipe rack–piping systems. It is beneficial for piping components by acting as a seismic isolation mechanism that reduces pipe stresses by 40–45% and increases the seismic intensity required to reach limit states. Conversely, SSI is generally detrimental to the structural rack, increasing interstorey drift, fragility, and the annual frequency of limit state exceedance.
2. Pipe boundary conditions represent the dominant source of modeling uncertainty in pipe rack–piping system fragility assessment, capable of changing the collapse limit state probability from 0% to 59%. This finding has profound implications for both engineering practice and code development.
3. Foundation stability comprising bearing, overturning, and sliding checks governs seismic design of isolated footings for tall multi-level pipe racks in moderate-to-high seismicity zones. Overturning is often the critical failure mode. SSI-beneficial base shear reductions are partly offset by amplified displacement demands that increase overturning moment arms.
4. Current seismic design codes both Eurocode 8 and ASCE 7 provide insufficient provisions for the integrated seismic design of pipe rack systems accounting for SSI, dynamic coupling, and performance-based design principles. The high overstrength reserves observed in code-compliant designs (mean annual frequency of SLLS exceedance 92% lower than code target) confirm systematic overconservatism in prescriptive approaches.
5. Research on related structural systems RC frames with uneven settlement, wind turbines with multiple foundation types, and masonry buildings with lumped parameter SFSI models provides valuable methodological insights transferable to pipe rack engineering. Staged-construction

approaches for differential settlement simulation and LPM calibration from frequency-domain impedance functions offer promising directions for future pipe rack studies.

6. Critical research gaps remain in the areas of combined SSI–uneven settlement effects for PRs, torsional behavior under SSI conditions, foundation type variability, experimental validation, and liquefaction potential. Addressing these gaps is essential for developing robust, risk-consistent seismic design frameworks for industrial pipe rack systems.

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