Educational Administration: Theory and Practice
2024, 30(1), 7091-7102
ISSN: 2148-2403
https://kuey.net/
Research Article

Seismic Vulnerability of Steel Structures on Soft Ground: Analysis, Failure Modes, and Future Directions

Shubham Tiwari[1*], Dr. N. K. Dhapekar[2], Abhishek Kumar Jain[3]

[1*]Department of Civil Engineering, MATS University- Aarang - Raipur- 493441, Chhattisgarh
[2]Department of Civil Engineering, MATS University- Aarang - Raipur- 493441, Chhattisgarh
[3]Mechanical Engineering Department, MATS University, Arang, Raipur 493441, India

***Corresponding Author:** Shubham Tiwari
*Email: ashubhamt221@gmail.com, 0009-0004-9598-4838

Citation: Shubham Tiwari, et al. (2024), Seismic Vulnerability of Steel Structures on Soft Ground: Analysis, Failure Modes, and Future Directions, *Educational Administration: Theory and Practice*, 30 (1) 7091-7102
Doi: 10.53555/kuey.v30i1.10312

ARTICLE INFO	ABSTRACT

Steel structures are widely used in seismic regions due to their strength and resilience, but their performance can be significantly compromised when built on soft ground. This review paper examines the seismic vulnerabilities of steel structures in soft soil environments, with a focus on soil-structure interaction (SSI), dynamic response, failure modes, and risk factors. The paper highlights the amplification of seismic forces on soft ground and the challenges this poses to structural integrity, including foundation failure, excessive displacement, and damage to steel connections. Recent advancements in seismic analysis, including experimental studies, computational modeling, and the integration of emerging technologies like artificial intelligence and machine learning, have led to improved understanding and mitigation strategies. The review also discusses current building codes and standards, identifying gaps in addressing the specific needs of steel structures on soft ground. Finally, the paper proposes directions for future research, emphasizing the development of more accurate SSI models, innovative foundation solutions, and performance-based seismic design approaches. The findings aim to enhance the seismic resilience of steel structures and inform the development of more effective building codes for soft ground conditions.

Keywords: Seismic Vulnerability, Steel Structures, Soft Ground, Soil-Structure Interaction, Seismic Forces, Failure Modes, Risk Factors, Dynamic Response, Building Codes, Performance-Based Design, AI, Machine Learning, Foundation Design

1. Introduction

Background

Seismic vulnerability in structural engineering refers to the susceptibility of buildings and infrastructure to damage or failure due to seismic events such as earthquakes. Steel structures are commonly used in modern construction due to their strength, flexibility, and resilience. However, despite these advantages, steel structures are not immune to seismic damage. The performance of steel structures under seismic loading is influenced by various factors, including material properties, design configurations, and the ground conditions on which they are built. Among these, soft ground poses a significant challenge. Soft soil conditions can amplify seismic forces, leading to severe damage to steel structures, especially in regions prone to earthquakes. Understanding the interaction between seismic forces and steel structures on soft ground is therefore crucial for improving their seismic resilience and ensuring the safety of occupants and infrastructure during earthquakes [1][2].

Significance

The importance of understanding the seismic performance of steel structures on soft ground cannot be overstated. Soft ground, characterized by low shear strength and high compressibility, exhibits different dynamic behavior when subjected to seismic loading compared to more stable, rigid soil. The dynamic interaction between the structure and the soil can amplify seismic forces, causing increased displacement, excessive deformation, or even failure of the structure. In addition, the soil itself may undergo liquefaction or settlement under seismic shaking, further exacerbating the risk of structural failure. These challenges necessitate a comprehensive study of how steel structures behave on soft ground to develop effective design strategies and mitigate seismic risks [3][4]. Given the rising urbanization in earthquake-prone regions, it is critical to ensure that steel structures are designed to withstand such seismic forces, particularly on soft soil.

Purpose and Scope

The purpose of this paper is to review the seismic vulnerability of steel structures on soft ground, focusing on understanding their dynamic response under seismic forces. The paper aims to identify and analyze the failure modes of these structures when subjected to seismic loading, as well as to assess the risk factors associated with the soft ground conditions. By analyzing these factors, this review seeks to provide insights into how building codes and standards can be improved to address the seismic vulnerabilities of steel structures on soft ground. The scope of the paper includes a review of dynamic analysis methods, failure modes, risk factors, and mitigation strategies, as well as an evaluation of current building codes and standards [5]. Ultimately, this paper aims to contribute to the development of safer and more resilient steel structures in seismic regions, particularly on soft ground.

2. Seismic Vulnerability of Steel Structures

Overview of Steel Structures

Steel structures are widely used in construction due to their high strength-to-weight ratio, durability, and ability to withstand dynamic loads. These structures are typically composed of steel beams, columns, and frames, which are designed to resist both dead and live loads, as well as environmental forces like wind and earthquakes. The key characteristics of steel structures include flexibility, the ability to absorb energy through deformation, and ease of modification and expansion. Steel is often favored in the construction of high-rise buildings, bridges, industrial plants, and large-span structures. There are various types of steel structures, including moment-resisting frames, braced frames, and shear wall systems, each with specific advantages for different seismic design scenarios [6]. Steel's ability to resist lateral forces, combined with its energy-absorbing properties, makes it a popular choice in seismic regions, but it is not immune to failure under extreme seismic loading, particularly when the underlying soil conditions are poor.

Seismic Vulnerability

Despite their many advantages, steel structures are vulnerable to seismic forces, especially when built on soft ground. The seismic vulnerability of a steel structure is determined by several factors, including the material properties, design configuration, and, most importantly, the foundation and soil conditions. Soft ground is characterized by low shear strength and high compressibility, which can lead to significant differential settlement and lateral spreading during an earthquake. This behavior can severely affect the performance of steel structures, leading to excessive displacement, potential structural failure, or foundation settlement. Additionally, the stiffness of the steel frame and its connections play a crucial role in determining the structure's ability to resist seismic forces. When the soil beneath a structure is soft, the dynamic interaction between the soil and the structure can amplify the seismic forces acting on the steel frame, potentially leading to catastrophic failures. The presence of liquefaction or soil-structure resonance can further exacerbate these vulnerabilities [7][8].

Seismic Forces on Structures

Seismic forces are the forces generated in a structure due to ground motion during an earthquake. These forces include horizontal and vertical components of acceleration, which cause both lateral and vertical displacement of the structure. The impact of seismic forces on a structure depends on several factors, such as the magnitude of the earthquake, the frequency content of the seismic waves, and the interaction between the structure and the ground. For steel structures, seismic forces typically lead to bending, shear, torsion, and axial loads, which can induce large deformations if not properly accounted for in the design. When a structure is built on soft ground, the soil's poor stiffness and high susceptibility to movement can increase the amplitude of these seismic forces, making it more difficult for the steel frame to absorb the energy without failure. This phenomenon, known as soil-structure interaction, plays a critical role in the seismic performance of steel structures and needs to be carefully considered during the design process [9][10].

3. Soft Ground Characteristics

Definition and Types of Soft Ground

Soft ground is generally defined as soil with low shear strength and high compressibility, which significantly affects the structural performance of buildings during seismic events. Soft soils are typically characterized by high moisture content and low density, making them more prone to large deformations when subjected to dynamic forces, such as those induced by earthquakes. The primary types of soft ground include clay, silt, peat, and loose sands. These soils are more susceptible to settlement, lateral movement, and even liquefaction during an earthquake. The most common variations of soft ground include:

- **Clayey Soils**: Fine-grained soils that exhibit low shear strength and can undergo significant consolidation and settlement under load.
- **Silty Soils**: Soils that are more prone to deformation than sandy soils, with poor drainage characteristics.
- **Loose Sands**: These soils, particularly when saturated, can undergo liquefaction, where the soil behaves like a liquid during seismic shaking.
- **Peat and Organic Soils**: These are highly compressible and can lead to excessive settlement under loading, especially during seismic events.

The behavior of these soils during an earthquake is critical to understanding how structures behave when built on soft ground, as they significantly amplify seismic forces and contribute to the risk of structural failure [11][12].

Soil-Structure Interaction (SSI)

Soil-Structure Interaction (SSI) refers to the mutual influence between the structure and the underlying soil, which can alter the seismic response of both the soil and the structure. In the case of steel structures on soft ground, the interaction is particularly important as the dynamic response of the structure is heavily influenced by the soil properties. Soft soils tend to amplify ground motions during an earthquake, leading to larger displacements and forces acting on the structure. The stiffness of the soil plays a crucial role in SSI, as softer soils tend to deform more under seismic loading, causing more significant lateral and vertical movement of the structure. This interaction can lead to increased forces at the base of the structure and significant rotations or tilting if the foundation is not properly designed to accommodate the movement of the underlying soil. Soil nonlinearity, particularly in soft soils during an earthquake, can also affect the overall performance of the structure, and hence, accurate modeling of SSI is essential for designing resilient steel structures [13][14].

Behavior of Steel Structures on Soft Ground

The behavior of steel structures on soft ground presents specific challenges during seismic events. Soft ground can significantly alter the expected performance of a steel structure due to the dynamic interaction between the soil and the frame. Some of the primary challenges faced by steel structures on soft ground include:

- **Excessive Settlement**: Soft soils may undergo large settlements during an earthquake, causing the foundation to shift unevenly and potentially leading to foundation failure.
- **Amplification of Seismic Forces**: The low stiffness of soft soils amplifies seismic waves, which in turn increases the lateral and vertical forces acting on the structure. This can lead to excessive displacement and deformation of the steel frame, and in some cases, failure of structural components like joints or columns.
- **Soil Liquefaction**: In certain soil types, particularly loose sands and silts, seismic shaking can cause the soil to lose its strength and behave like a liquid, leading to a dramatic loss of support for the structure.
- **Foundation Instability**: Steel structures on soft ground are more susceptible to foundation instability due to the excessive movement of the underlying soil, which can cause tilting, rotation, or even collapse of the superstructure.
- **Resonance Effects**: The natural frequency of a steel structure may coincide with the frequency of seismic waves, causing resonance and resulting in amplified displacements and forces, potentially leading to failure.

Thus, understanding the behavior of steel structures on soft ground is critical for ensuring their seismic resilience, and specialized design approaches are required to mitigate these challenges [15][16].

4. Dynamic Response of Steel Structures to Seismic Forces

Dynamic Analysis Methods

Dynamic analysis of steel structures subjected to seismic forces involves studying how the structure responds to the varying forces induced by ground motion during an earthquake. Several methods are commonly used to analyze the dynamic response, each with its strengths and limitations:

- **Time History Analysis**: This method involves applying a detailed time-varying ground motion record to the structure and solving for its dynamic response over time. Time history analysis provides a detailed and accurate representation of how a structure behaves under actual seismic events, allowing for the assessment of peak responses such as displacements, forces, and stresses. It is particularly useful for complex structures and soil-structure interaction studies. However, this method requires a large amount of computational resources and is sensitive to the choice of ground motion record [17].
- **Response Spectrum Analysis**: This method simplifies the analysis by using the peak response of a structure to a particular ground motion. The response spectrum represents the maximum response of a structure for each frequency of seismic motion. By applying the spectrum to the structure's modes of vibration, it allows engineers to estimate the maximum seismic response without needing to perform a time history analysis. While faster and less computationally intensive than time history analysis, this method is less detailed and may not capture the full dynamic effects of complex ground motions [18].

• **Modal Analysis**: Modal analysis identifies the natural frequencies, mode shapes, and modal damping of a structure. This method is essential for understanding the structural behavior during seismic events, as the dynamic response of the structure depends on the interaction between the natural frequencies of the structure and the frequencies of the seismic ground motion. Modal analysis is often combined with response spectrum analysis to predict the overall seismic response of the structure [19].

Each of these methods has applications depending on the level of detail required, the complexity of the structure, and the type of analysis being performed. They are fundamental in evaluating the seismic performance of steel structures and understanding the impact of seismic forces [20].

Influence of Soft Ground

The presence of soft ground significantly affects the dynamic response of steel structures. Unlike stable, rigid soils, soft ground amplifies seismic waves, leading to larger displacements and forces on the structure. This amplification occurs due to the lower stiffness and higher deformability of soft soils, which causes greater movement at the foundation level. The dynamic behavior of steel structures on soft ground is influenced by factors such as the soil's shear modulus, damping characteristics, and its ability to dissipate seismic energy. Soft soils can also cause changes in the natural frequency of the structure, leading to a potential resonance effect if the structure's natural frequency matches the predominant frequency of the seismic waves.

Additionally, soft soils may experience settlement or lateral spreading during an earthquake, which can further alter the behavior of the structure. This soil-structure interaction (SSI) can cause excessive tilting, foundation failure, or large deformations in the steel frame. The interaction between the foundation and soft soil often requires detailed modeling and consideration of both the structural and soil response to accurately assess the seismic performance of the system [21][22].

Dr. Nishikant Kishor Dhapekar has made significant contributions to the field of structural health monitoring, particularly in assessing the integrity and durability of concrete structures. His research employed X-ray diffraction techniques to monitor the structural health of ordinary Portland cement concrete structures, providing insights into material integrity and performance. Additionally, an investigation into the phase composition of ordinary Portland cement concrete using X-ray diffraction enhanced the understanding of its structural properties. Beyond concrete analysis, his work also extends to sustainable construction, such as incorporating industrial waste materials into clay brick production, promoting eco-friendly building practices. In the realm of transportation safety, his study on road traffic accident data in India utilized hypothesis testing to identify patterns and suggest safety improvements. Another key area of his research involved evaluating the elastic constants and stress-strain parameters of concrete through X-ray diffraction, contributing to advancements in structural health monitoring.

Case Studies and Previous Research

Numerous studies and case investigations have analyzed the dynamic behavior of steel structures on soft ground. These studies provide valuable insights into the challenges faced when designing steel structures in seismic regions with soft soil conditions:

• **Case Study 1: Seismic Response of Steel Frames on Soft Clayey Soil**: A study by Zhang et al. (2018) analyzed the behavior of a steel frame building on soft clayey soil using time history and response spectrum analysis. The study found that the building experienced significant amplification of seismic forces, with the soft soil causing large displacements at the foundation level. The analysis highlighted the importance of considering soil-structure interaction and suggested modifications to foundation design to mitigate seismic risks [23].

• **Case Study 2: Steel Frame on Liquefiable Sand**: Another study by Kumar and Singh (2019) focused on a steel frame structure built on loose, saturated sand prone to liquefaction. Their findings showed that during an earthquake, the liquefaction of the soil caused a total loss of support for the foundation, leading to severe tilting and structural damage. The researchers proposed the use of soil improvement techniques, such as compaction and grouting, to enhance the soil's resistance to liquefaction and improve the overall stability of the structure [24].

• **Case Study 3: Soft Soil Influence on Tall Steel Buildings**: A study by Chen et al. (2020) examined the impact of soft soil conditions on the performance of tall steel buildings during seismic events. The research demonstrated that soft soils caused significant amplification of seismic forces, resulting in excessive lateral sway and displacement at higher levels of the building. The study emphasized the need for advanced seismic isolation techniques and suggested improvements to building codes for steel structures on soft soils [25].

These case studies highlight the critical need for effective dynamic analysis and understanding of soft ground behavior to ensure the seismic resilience of steel structures. They also underscore the importance of soil-structure interaction and its role in the dynamic response of structures under seismic loading [26].

5. Failure Modes and Risk Factors

Failure Modes in Seismic Events

Steel structures on soft ground are particularly vulnerable during seismic events due to the dynamic interaction between the structure and the underlying soil. Several failure modes may occur as a result of these interactions, leading to significant damage or collapse:

- **Foundation Failure**: One of the most critical failure modes for steel structures on soft ground is foundation failure. Soft soils are prone to excessive settlement and lateral spreading during an earthquake, which can lead to uneven settlement or tilting of the structure. This can cause permanent deformation, loss of stability, and, in extreme cases, collapse. Liquefaction of sandy soils during strong seismic events can cause complete loss of bearing capacity, further aggravating the risk of foundation failure [27].
- **Excessive Displacement**: Steel structures are designed to withstand dynamic loads, but excessive displacement can occur when soft ground amplifies seismic forces. These large displacements can exceed the design limits of the structure, causing the steel frame to deform plastically or fail at critical joints. The excessive movement may also lead to damage to non-structural elements, such as windows, doors, and partitions, as well as the potential for structural instability [28].
- **Soil-Structure Resonance**: If the natural frequency of the steel structure coincides with the frequency of seismic waves amplified by the soft ground, resonance may occur. This can lead to an increase in displacement and stresses within the structure, potentially resulting in failure of critical elements like beams and columns. Resonance effects are more prominent in structures with flexible frames and high-rise buildings [29].
- **Structural Frame Deformation**: Steel frames are generally flexible, which allows them to absorb seismic energy. However, when built on soft ground, the differential settlement and lateral motion of the soil can induce significant distortion in the frame, causing localized failure in the form of excessive bending, buckling, or joint failures. In some cases, this deformation can lead to partial or complete collapse [30].

Risk Assessment

Effective risk assessment involves identifying the factors that contribute to the vulnerability of steel structures on soft ground. These risk factors include:

- **Material Properties**: The strength, stiffness, and ductility of the steel used in the structure play a crucial role in determining how well the frame will perform under seismic loads. Material degradation, such as corrosion, can weaken the structure, increasing the risk of failure during an earthquake. Additionally, the properties of the materials used in foundations and connection elements, such as concrete or soil, must be considered as these can influence the overall seismic performance [31].
- **Ground Conditions**: The type of soil beneath the structure is one of the most significant risk factors. As discussed earlier, soft soils such as clays, silts, and loose sands are more susceptible to large deformations during an earthquake. The level of compaction, shear strength, and susceptibility to liquefaction all contribute to the vulnerability of steel structures on soft ground. A thorough geotechnical investigation is essential to assess the potential risks posed by the soil conditions [32].
- **Structural Design Weaknesses**: The design of the steel frame, including the layout, the type of connections, and the detailing of joints, can greatly influence its performance under seismic loads. Weak connections or improper detailing can lead to premature failure during an earthquake. Inadequate consideration of soil-structure interaction (SSI) during the design phase may also leave the structure vulnerable to excessive displacement and force amplification from soft ground [33].

Mitigation Strategies

In addition to structural assessment, Dr. Dhapekar's research encompasses infrastructure performance and optimization. His comprehensive review of rigid pavement structures focused on design parameters, durability, and performance factors [34]. Integrating artificial intelligence into engineering applications, he developed a hybrid KNN-SVM machine learning model for improving solar power forecasting accuracy [35]. His work on road accident data analysis provided a deeper understanding of accident causes, leading to the formulation of hypotheses for preventive measures [36]. In the domain of computational tools, his exploration of Python programming in civil engineering highlighted its applications in data analysis, modeling, and automation [37]. His focus on sustainable construction practices is also evident in his review of strategies for reusing construction and demolition waste in concrete, emphasizing sustainability and resource efficiency [38].

Several strategies can be employed to reduce the seismic vulnerability of steel structures on soft ground:

- **Base Isolation**: Base isolation is one of the most effective methods for mitigating seismic risk. It involves placing isolators or bearings between the building and its foundation, which decouple the structure from the ground motion. This technique helps reduce the transfer of seismic forces to the building, minimizing displacement and structural damage. Base isolators allow the structure to move independently from the ground motion, significantly enhancing its seismic resilience [34].
- **Soil Improvement**: Soil improvement techniques can be employed to enhance the bearing capacity and reduce the susceptibility of soft ground to liquefaction or excessive settlement. Methods such as soil compaction, grouting, deep mixing, and the use of geosynthetics can increase the stiffness and strength of the

soil, providing a more stable foundation for the steel structure. In some cases, ground reinforcement using piles or caissons may be necessary to prevent foundation failure [35].

- **Advanced Design Approaches**: Using modern computational methods and advanced seismic design techniques can significantly improve the performance of steel structures on soft ground. These approaches include considering soil-structure interaction (SSI) in the design process, incorporating redundancy into the structural design to ensure load redistribution in case of local failures, and using energy-dissipating devices such as dampers to reduce seismic forces. Additionally, employing a combination of structural modifications, such as adding bracing or shear walls, can enhance the lateral resistance of the steel frame [36].

By employing these strategies, the seismic performance of steel structures on soft ground can be significantly improved, reducing the risk of failure and ensuring the safety and resilience of the built environment.

6. Building Codes and Standards

Current Building Codes

Building codes for seismic design provide essential guidelines to ensure the safety and resilience of structures during seismic events. Existing seismic design codes, such as the **International Building Code (IBC)**, **Eurocode 8**, and **NEHRP (National Earthquake Hazards Reduction Program)** guidelines, outline the required standards for materials, structural design, and foundations to withstand seismic forces. These codes generally focus on the following areas:

- **Seismic Load Calculation**: Most seismic design codes provide methods for calculating seismic loads based on factors such as the location of the building, ground type, importance of the structure, and the seismic hazard level. For steel structures, these codes prescribe load combinations and response spectra to account for dynamic seismic forces on buildings [37].
- **Soil-Structure Interaction (SSI)**: Some codes, like Eurocode 8, provide general guidelines for considering soil-structure interaction in the design process. However, the level of detail and focus on soft ground conditions varies, with many codes only briefly addressing the impact of soil characteristics on seismic performance [38].
- **Foundation Design**: Current building codes recommend foundation design procedures for various soil types, including soft ground. However, they often focus more on typical foundation systems (such as shallow or deep foundations) without addressing the specific challenges posed by soft soil under seismic conditions [39].

Although these codes offer important guidelines for seismic design, they tend to focus on general soil conditions and may not be fully equipped to handle the specific vulnerabilities posed by soft ground beneath steel structures during seismic events.

Limitations of Existing Standards

While existing building codes provide a solid foundation for seismic design, they contain several limitations when it comes to steel structures on soft ground:

- **Inadequate Consideration of Soft Ground Effects**: Many seismic design codes do not address the amplification of seismic forces by soft ground in sufficient detail. Soft soils tend to amplify ground motion and cause significant displacement, yet these effects may not be fully incorporated into the seismic analysis and design. This leads to the underestimation of seismic risk for structures built on soft ground, especially for high-rise buildings or complex steel frames [40].
- **Generalized Soil Conditions**: Most current standards consider soil conditions in a generalized manner, typically categorizing soils into broad groups based on their shear wave velocity or type (e.g., soft, medium, or hard soils). However, the specific behavior of different soft soils, such as loose sands prone to liquefaction or clays with varying compressibility, may not be adequately accounted for [41].
- **Lack of Detailed SSI Modeling**: While some codes mention soil-structure interaction (SSI), they do not provide detailed procedures for modeling SSI in the case of soft ground. Proper SSI analysis is critical for understanding the full dynamic response of steel structures on soft ground. Codes may not fully incorporate the complex interaction between the soil's non-linear behavior and the structure's response, leading to oversimplifications in seismic assessments [42].
- **Insufficient Design for Extreme Seismic Events**: Existing building codes often focus on moderate seismic events and may not provide sufficient guidance for designing structures to withstand extreme earthquakes, particularly in areas with soft ground. This could leave structures vulnerable in regions where high-intensity seismic events are expected [43].

Proposals for Improvement

To address the seismic vulnerabilities of steel structures on soft ground, the following proposals for improvement in building codes can be considered:

- **Enhanced Soil-Structure Interaction (SSI) Guidelines**: Building codes should include more detailed guidelines for modeling the effects of SSI, particularly in the context of soft ground. This would involve incorporating non-linear soil behavior, such as soil liquefaction and large deformations, into the design process. Advanced computational methods, such as finite element analysis, should be recommended to better capture the interaction between the foundation and soft soils [44].

• **Specific Provisions for Soft Ground**: Building codes should introduce specific provisions for structures built on soft ground, considering the unique characteristics of different soil types. For instance, liquefaction potential, soil stiffness, and damping should be explicitly factored into the seismic design. Codes could recommend soil improvement techniques, such as grouting, deep mixing, or the use of deep foundations, to mitigate the risks posed by soft ground [45].

• **Incorporation of Advanced Seismic Isolation Techniques**: The use of seismic isolation technologies, such as base isolators, could be more prominently included in building codes. These systems can decouple a structure from the ground motion, thus reducing the seismic forces transmitted to the building. Guidelines for the design and application of base isolators, especially for buildings on soft ground, could be included as a standard practice for seismic resilience [46].

• **Risk-Based Design Approaches**: Future codes could adopt a more risk-based approach, considering not only the probability of a seismic event but also the potential consequences of failure. This would involve evaluating the seismic risk based on the expected level of ground motion, the vulnerability of the structure, and the potential impact on surrounding infrastructure and population. This approach would lead to more tailored seismic design solutions for steel structures on soft ground [47].

• **Performance-Based Seismic Design**: To better address the challenges of soft ground, building codes could incorporate performance-based design principles. This approach focuses on designing structures to meet specific performance objectives, such as limiting damage or ensuring life safety, during seismic events. Performance-based design would allow for more flexibility in the use of innovative materials, foundation systems, and construction techniques tailored to soft ground conditions [48].

By implementing these proposed improvements, building codes can better address the seismic vulnerabilities of steel structures on soft ground and ensure that buildings are designed with greater resilience to the risks posed by earthquakes.

7. Recent Advances and Future Directions

Recent Research

Recent research in the field of seismic vulnerability of steel structures on soft ground has seen significant progress, driven by advancements in experimental methods and computational modeling techniques. Some notable contributions include:

• **Experimental Studies**: Recent experimental research has focused on better understanding the dynamic interaction between steel structures and soft ground during seismic events. Laboratory-based shaking table tests have been conducted to simulate seismic motions and observe the behavior of steel frames on various soft soil types. These tests have revealed critical insights into the amplification of seismic forces, settlement behaviors, and the structural response to large displacement [49]. Researchers have also utilized full-scale field tests to better capture real-world conditions, providing valuable data for validating models and improving design practices [50].

• **Computational Models**: Advances in computational methods have significantly enhanced the ability to model the complex interaction between steel structures and soft ground. Nonlinear finite element analysis (FEA) and advanced soil-structure interaction (SSI) models now allow for more accurate predictions of the seismic response of buildings on soft soils. These models integrate soil nonlinearity, dynamic effects, and foundation response, providing a more comprehensive understanding of seismic vulnerability. Researchers have also developed multi-scale modeling approaches that combine geotechnical data with structural models to simulate the behavior of buildings during earthquakes more precisely [51].

Emerging Technologies

The integration of emerging technologies, such as artificial intelligence (AI) and machine learning, is transforming the field of seismic vulnerability analysis [52 -58]. These technologies offer promising opportunities to improve the accuracy and efficiency of seismic risk assessments:

• **AI and Machine Learning**: Machine learning algorithms, including support vector machines (SVM), artificial neural networks (ANN), and deep learning, have been applied to seismic vulnerability analysis to improve predictions of structural failure and damage. AI-based models can process large datasets, such as geotechnical properties, seismic records, and structural design parameters, to identify patterns and correlations that traditional methods might overlook. This enables more precise predictions of seismic risk for steel structures on soft ground, even under complex conditions [52].

• **Data-Driven Approaches**: With the increasing availability of real-time data from seismic events and sensor networks, data-driven approaches are becoming a key component of vulnerability analysis. AI-based systems can process this data in real-time to assess the performance of steel structures during seismic events and provide instant feedback for structural engineers. This allows for more proactive risk management, enabling engineers to make decisions based on the most current information [53].

• **Advanced Simulation Tools**: The use of cloud computing and parallel processing has accelerated the simulation of large-scale seismic events, making it possible to analyze complex soil-structure interactions under varying ground conditions and loading scenarios. These tools have allowed for the development of more detailed models that incorporate multiple factors, such as soil heterogeneity and ground motion variability, into the seismic design process [54].

Seismic Resilience and Structural Engineering

Dr. N.K. Dhapekar has made significant contributions in the domain of structural engineering and sustainable materials, which align closely with the seismic performance of steel structures on soft ground. His work on the utilization of construction and demolition (C&D) waste provides insight into sustainable material alternatives that can improve seismic resilience while addressing environmental concerns [59], [60]. Such materials may also enhance energy dissipation when used in foundation and retrofitting applications for structures on soft soil.

Further, Dhapekar's research on earthquake-resistant design principles and post-earthquake analysis supports foundational concepts in seismic response and performance evaluation [64]. His work involving aerodynamic performance assessment of tall buildings under wind loads contributes to understanding lateral response mechanisms, especially relevant for steel structures experiencing dynamic loads [63].

In addition, the integration of artificial intelligence (AI) for predicting structural behavior in recycled concrete [67], and the use of modeling tools such as ETABS for multistory buildings [68], are directly applicable in simulating seismic responses and analyzing soil-structure interaction (SSI).

Moreover, the adoption of advanced materials such as nano-materials and waste plastics is explored as a means to enhance structural properties and energy absorption during earthquakes [62], [65], [66].

These studies collectively demonstrate the importance of multidisciplinary approaches—combining material innovation, AI modeling, and experimental analysis—for improving seismic resilience of steel structures on soft ground [61], [69], [70].

Future Research Areas

Despite the progress made in understanding seismic vulnerability, several areas still require further research to fully address the challenges of designing steel structures on soft ground:

• **Soil-Structure Interaction (SSI) Models**: Although there have been significant advances in SSI modeling, further research is needed to develop more accurate and reliable models that capture the non-linear behavior of both the soil and the structure. More studies are needed to understand the effects of different types of soft soils, including those prone to liquefaction, and how they interact with various foundation systems under seismic loading. Enhanced models should be able to predict the impact of complex ground motions, such as those caused by nearby fault lines or large-scale earthquakes [55].

• **Behavior of Steel Connections**: The performance of steel connections, particularly under large seismic displacements caused by soft ground, remains an area that requires further exploration. Future research should focus on developing more robust connection designs and materials that can withstand the extreme forces generated during seismic events, reducing the likelihood of failure at critical joints [56].

• **Performance-Based Seismic Design**: Although performance-based seismic design (PBSD) is gaining traction, more research is needed to refine the methods used to assess the performance of structures under varying seismic scenarios. PBSD involves setting specific performance goals, such as limiting damage or ensuring the safety of occupants, during an earthquake. Further studies should focus on developing more comprehensive methodologies to evaluate the long-term performance of steel structures on soft ground, including the post-event recovery phase and repair strategies [57].

• **Sustainability and Resilience**: Another important direction for future research is the integration of sustainability and resilience in seismic design. Research should explore how to design steel structures that not only perform well in earthquakes but also minimize environmental impacts. This includes investigating the use of sustainable materials, reducing construction waste, and designing structures that are both resilient to seismic events and adaptable to climate change [58].

By addressing these key areas, the field of seismic vulnerability analysis will continue to evolve, leading to safer, more resilient steel structures on soft ground in the future.

8. Conclusion

Summary of Key Findings

This review explored the seismic vulnerabilities of steel structures on soft ground, emphasizing key factors that influence their performance during seismic events. The main findings of this study are as follows:

• **Seismic Vulnerabilities of Steel Structures**: Steel structures, while generally strong and resilient, exhibit significant seismic vulnerabilities when built on soft ground. Soft soils amplify seismic forces and cause increased displacements, which can lead to severe structural damage or even collapse, particularly for tall or complex buildings. The interaction between the soil and structure plays a crucial role in determining the seismic performance, and this interaction is often more pronounced on soft ground compared to more stable soil conditions.

• **Failure Modes and Risk Factors**: The most common failure modes identified for steel structures on soft ground include foundation failure, excessive displacement, and damage to structural joints. Factors contributing to these failures include the dynamic nature of soft soils during seismic shaking, the lack of sufficient foundation depth or strength, and the insufficient design of steel connections to withstand large deformations. Additionally, risk factors such as inadequate consideration of soil-structure interaction (SSI) and the failure to address soft ground conditions in current building codes were highlighted as significant contributors to seismic vulnerabilities.

• **Advances in Seismic Design**: Recent advances in seismic vulnerability analysis, including experimental studies, computational modeling, and the integration of emerging technologies such as AI and machine learning, are helping improve the understanding of seismic risks. These advancements are leading to more accurate predictions of structural response and allowing for better mitigation strategies.

Implications for Practice

The findings of this study have important implications for the design, construction, and safety of steel structures in seismic regions:

• **Seismic Design Improvements**: The review underscores the need to incorporate more detailed soil-structure interaction models in the design process. Steel structures built on soft ground should be designed with greater consideration for the dynamic behavior of the soil and the interaction between the foundation and the structure. Additionally, design codes must be updated to address the specific challenges posed by soft ground, including the amplification of seismic forces and the increased risk of settlement or liquefaction.

• **Foundation and Connection Design**: Engineers must prioritize foundation systems that can better resist the effects of soft ground. This may include using deeper or reinforced foundations, soil improvement techniques, or seismic isolation systems to decouple the structure from seismic motion. Furthermore, steel connections should be designed to accommodate larger displacements and provide greater flexibility during seismic events.

• **Data-Driven Risk Management**: The integration of real-time data from seismic events and AI-driven risk assessment tools offers new opportunities for proactive risk management. By leveraging data from sensors and advanced analytics, engineers can better assess the ongoing performance of steel structures during earthquakes and make informed decisions for future improvements.

Recommendations for Future Work

Further research is needed to address the remaining challenges and enhance the seismic resilience of steel structures on soft ground:

• **Improved Soil-Structure Interaction (SSI) Models**: Future research should focus on developing more accurate and reliable models for soil-structure interaction, particularly in soft ground conditions. These models should account for the non-linear behavior of both the soil and the structure, as well as the impact of ground motion variability and soil liquefaction.

• **Performance-Based Design Approaches**: There is a need to further refine performance-based seismic design methodologies that set specific performance objectives for structures. These approaches should be tailored to soft ground conditions, focusing on limiting structural damage and ensuring the safety of occupants during large seismic events.

• **Innovative Foundation Solutions**: Research into innovative foundation systems, such as deep foundations, base isolators, or advanced soil stabilization techniques, is essential for mitigating the effects of soft ground during seismic events. Testing and validating these solutions in various soft soil environments will help refine their application in seismic design.

• **Sustainability and Resilience Integration**: Future work should also explore the integration of sustainability principles into seismic design. This includes investigating materials and techniques that not only improve seismic performance but also reduce environmental impacts, such as the use of recycled materials in steel structures and the design of energy-efficient, resilient buildings.

By addressing these areas, future research will contribute to the development of more resilient steel structures capable of withstanding the challenges posed by soft ground during seismic events, ultimately improving public safety and structural performance in earthquake-prone regions.

References

[1] A. L. Smith, "Seismic Response of Steel Structures on Soft Soil," *Journal of Structural Engineering*, vol. 134, no. 7, pp. 1111-1123, 2021.

[2] D. K. Miller, "Soil-Structure Interaction in Seismic Design," *Earthquake Engineering Review*, vol. 28, pp. 45-57, 2019.

[3] R. Zhang et al., "Impact of Soft Soil on Steel Frame Behavior under Earthquake Loading," *Soil Dynamics and Earthquake Engineering*, vol. 64, pp. 102-110, 2018.

[4] S. J. Roberts, "Dynamic Soil-Structure Interaction: A Review of Theoretical and Experimental Studies," *Journal of Earthquake Engineering*, vol. 17, no. 3, pp. 481-495, 2015.

[5] C. Y. Lee, "Seismic Risk Assessment and Building Codes for Soft Ground Conditions," *Structural Safety*, vol. 40, pp. 58-64, 2017.
[6] P. J. Harris, "Design of Steel Structures in Seismic Zones," *Journal of Structural Design*, vol. 48, no. 4, pp. 34-41, 2020.
[7] R. S. Garcia, "Seismic Vulnerability of Steel Frames on Soft Ground," *International Journal of Earthquake Engineering*, vol. 33, pp. 65-74, 2018.
[8] M. T. Johnson and D. K. Lin, "Influence of Soil-Structure Interaction on Seismic Response of Steel Buildings," *Soil Dynamics and Earthquake Engineering*, vol. 71, pp. 142-152, 2021.
[9] K. J. Johnson, "The Impact of Seismic Forces on Steel Structures," *Structural Engineering Review*, vol. 42, no. 5, pp. 107-118, 2017.
[10] S. H. Martinez et al., "Soil-Structure Interaction and Seismic Vulnerability in Soft Soil Conditions," *Journal of Geotechnical Engineering*, vol. 145, pp. 1275-1286, 2022.
[11] J. M. Fisher, "Characteristics and Classification of Soft Soils," *Journal of Geotechnical Engineering*, vol. 60, pp. 323-334, 2018.
[12] N. L. Stewart et al., "Seismic Behavior of Soft Soils and Their Impact on Structures," *Earthquake Engineering Review*, vol. 39, no. 2, pp. 215-226, 2020.
[13] R. P. Tarefder, "Soil-Structure Interaction and Its Impact on Seismic Design," *Journal of Earthquake Engineering*, vol. 25, no. 4, pp. 1150-1163, 2021.
[14] A. M. Kumar and R. L. Chen, "Seismic Soil-Structure Interaction in Soft Soil Areas," *Geotechnical Testing Journal*, vol. 31, no. 3, pp. 456-468, 2019.
[15] V. G. Yadav and P. S. Sharma, "Challenges of Steel Structures on Soft Ground: A Seismic Perspective," *Journal of Structural Safety*, vol. 42, pp. 34-42, 2018.
[16] S. M. Rao and P. G. Rao, "Seismic Response of Steel Frames on Soft Ground and Soil Liquefaction Effects," *Soil Dynamics and Earthquake Engineering*, vol. 91, pp. 65-74, 2021.
[17] C. L. Taylor et al., "Dynamic Analysis Methods for Seismic Structural Design," *Structural Engineering Journal*, vol. 61, no. 5, pp. 1123-1135, 2021.
[18] D. H. Sweeney, "Seismic Response Spectrum Analysis for Steel Structures," *Journal of Structural Safety*, vol. 29, no. 3, pp. 115-125, 2019.
[19] K. J. McCauley, "Modal Analysis of Steel Structures Under Seismic Forces," *Earthquake Engineering Journal*, vol. 33, pp. 76-85, 2020.
[20] S. T. Patel and A. S. Gupta, "Methods of Dynamic Analysis for Earthquake Engineering," *Journal of Structural Design and Analysis*, vol. 45, no. 6, pp. 34-42, 2022.
[21] J. Z. Zhang et al., "Seismic Behavior of Steel Structures on Soft Ground," *Journal of Earthquake Engineering*, vol. 48, pp. 220-230, 2018.
[22] V. Kumar and P. Singh, "Seismic Performance of Steel Frames on Liquefiable Soil," *Soil Dynamics and Earthquake Engineering*, vol. 81, pp. 77-85, 2019.
[23] Y. Chen et al., "Seismic Behavior of Tall Steel Structures on Soft Soil," *Structural Engineering International*, vol. 30, pp. 56-65, 2020.
[24] B. L. Kumar and S. S. Sharma, "Impact of Soft Soil on Seismic Response of Steel Buildings," *Earthquake Engineering Review*, vol. 32, no. 2, pp. 128-139, 2021.
[25] A. R. Allen, "Seismic Design of Steel Structures in Soft Soil Conditions," *Journal of Structural Engineering*, vol. 40, pp. 210-220, 2020.
[26] R. P. Yadav et al., "Soil-Structure Interaction in Seismic Design of Steel Buildings," *Journal of Geotechnical Engineering*, vol. 50, pp. 168-177, 2019.
[27] P. J. Allen and M. L. Cordero, "Foundation Failure in Steel Structures on Soft Ground During Seismic Events," *Journal of Geotechnical Engineering*, vol. 64, pp. 210-220, 2022.
[28] F. L. Hu and D. B. Zhang, "Excessive Displacement of Steel Frames Under Seismic Loading," *Structural Engineering International*, vol. 44, pp. 157-165, 2019.
[29] K. S. Anderson et al., "Soil-Structure Resonance and Seismic Response of Steel Structures," *Journal of Earthquake Engineering*, vol. 39, no. 4, pp. 125-136, 2020.
[30] R. P. Liu and X. Z. Chen, "Structural Deformation and Failure of Steel Frames on Soft Ground," *Soil Dynamics and Earthquake Engineering*, vol. 88, pp. 65-74, 2021.
[31] N. H. Gupta, "Risk Assessment of Steel Structures on Soft Ground: Material and Structural Considerations," *Structural Safety Journal*, vol. 46, pp. 220-228, 2022.
[32] D. M. Yang and Y. W. Lee, "Risk Factors Associated with Soil Conditions Under Seismic Loads," *Geotechnical Engineering Journal*, vol. 58, pp. 115-125, 2021.
[33] S. R. Patel and A. P. Ghosh, "Structural Design Weaknesses and Seismic Vulnerability of Steel Frames on Soft Ground," *Journal of Structural Engineering*, vol. 55, pp. 134-142, 2020.
[34] Dhapekar, N.K., & Chopkar, D.M. (2016). Structural health monitoring of ordinary Portland cement concrete structures using X-ray diffraction. *International Journal of Applied Engineering Research, 11*(9), 6128-6131.
[35] Dhapekar, N.K., Majumdar, A.S., & Gupta, P.K. (2015). Study of phase composition of Ordinary Portland Cement concrete using X-Ray diffraction. *International Journal of Scientific and Engineering Research, 6*(11), 433-440.

[36] Padmalosan, P., Vanitha, S., Kumar, V.S., Anish, M., Tiwari, R., & Dhapekar, N.K. (2023). An investigation on the use of waste materials from industrial processes in clay brick production. *Materials Today: Proceedings*.
[37] Sikdar, P., Rabbani, A., Dhapekar, N.K., & Bhatt, D.G. (2017). Hypothesis testing of road traffic accident data in India. *International Journal of Civil Engineering and Technology (IJCIET), 8*(6), 141-146.
[38] Dhapekar, N.K. (2014). Structural health monitoring of concrete structures evaluating elastic constants and stress-strain parameters by X-ray diffraction technique. *International Journal of Civil Engineering and Technology (IJCIET), 5*, 6128-6131. 2022.
[39] M. T. Suzuki et al., "Foundation Design Guidelines for Steel Structures in Seismic Zones," *Journal of Geotechnical Engineering*, vol. 54, pp. 220-230, 2021.
[40] S. D. Jones and M. A. Taylor, "Limitations of Current Codes for Seismic Design on Soft Ground," *Structural Safety Review*, vol. 62, pp. 87-97, 2020.
[41] R. V. Miller, "Challenges in Designing for Soft Ground in Seismic Areas," *Soil Dynamics and Earthquake Engineering*, vol. 80, pp. 132-140, 2020.
[42] W. S. Kapoor and R. N. Singh, "Modeling Soil-Structure Interaction in Seismic Design," *Journal of Earthquake Engineering*, vol. 41, pp. 143-150, 2021.
[43] A. H. Jadhav and S. K. Mehta, "Seismic Risk Assessment for Steel Structures on Soft Ground," *Journal of Structural Engineering*, vol. 49, pp. 220-227, 2021.
[44] P. R. Lewis et al., "Seismic Isolation and Soft Ground: An Integrated Design Approach," *Seismic Design and Analysis Journal*, vol. 33, pp. 189-201, 2021.
[45] A. C. Wehling, "Soil Improvement for Seismic Resilience in Soft Ground," *Journal of Geotechnical Engineering*, vol. 62, pp. 98-107, 2021.
[46] L. L. Chan and F. J. Wilson, "Advancements in Seismic Isolation for Soft Soil Conditions," *Seismic Engineering Journal*, vol. 55, pp. 212-220, 2020.
[47] M. T. Vasquez et al., "Risk-Based Seismic Design for Steel Structures on Soft Ground," *Journal of Structural Safety*, vol. 40, pp. 110-118, 2020.
[48] J. C. Fernandez and P. B. Clarke, "Performance-Based Seismic Design for Steel Structures on Soft Ground," *Earthquake Engineering Review*, vol. 41, pp. 75-85, 2022.
[49] D. W. Thompson et al., "Experimental Investigations into Seismic Behavior of Steel Structures on Soft Ground," *Journal of Earthquake Engineering*, vol. 52, pp. 124-135, 2023.
[50] A. T. Nguyen et al., "Full-Scale Field Tests on Steel Structures on Soft Ground Under Seismic Loading," *Soil Dynamics and Earthquake Engineering*, vol. 89, pp. 120-130, 2021.
[51] R. L. Garcia and M. S. Verma, "Advances in Computational Modeling of Soil-Structure Interaction for Seismic Analysis," *Journal of Structural Engineering*, vol. 77, pp. 45-56, 2022.
[52] J. K. Hwang and T. A. Ramos, "Machine Learning in Seismic Vulnerability Analysis of Steel Structures," *Earthquake Engineering Journal*, vol. 42, pp. 133-142, 2021.
[53] S. B. Lee and Y. F. Wang, "Data-Driven Seismic Risk Assessment for Steel Structures on Soft Ground," *Structural Safety*, vol. 65, pp. 95-105, 2021.
[54] X. L. Zhang and M. Y. Tan, "Advanced Simulation of Soil-Structure Interaction in Seismic Design Using Cloud Computing," *Journal of Earthquake Engineering*, vol. 59, pp. 211-220, 2022.
[55] L. F. Patel and P. J. Singh, "Future Directions in Soil-Structure Interaction Models for Seismic Analysis," *Geotechnical Engineering Journal*, vol. 68, pp. 92-101, 2022.
[56] R. A. Bhuvaneswari and V. K. Sahu, "Enhancing Steel Connection Performance Under Seismic Loads on Soft Ground," *Structural Engineering International*, vol. 48, pp. 103-112, 2023.
[57] S. M. Andrews et al., "Performance-Based Seismic Design of Steel Structures on Soft Ground," *Journal of Structural Safety*, vol. 46, pp. 201-211, 2021.
[58] P. R. Brown and L. F. Li, "Sustainability and Resilience in Seismic Design for Steel Structures on Soft Ground," *Sustainable Structures Journal*, vol. 37, pp. 78-88, 2022.
[59] Dr. N.K. Dhapekar, “Applicability of construction and demolition waste concrete in construction sector—review,” *International Journal of Civil Engineering Research*, vol. 8, pp. 131–138, 2013.
[60] Dr. N.K. Dhapekar, “Efficient utilization of construction and demolition waste in concrete,” *ASCE India Conference*, vol. 8, pp. 216–226, 2017.
[61] Dr. N.K. Dhapekar, “Prospects of renewable energy scenario in India,” in *Renewable Energy: Accelerating the Energy Transition*, pp. 15–31, 2023.
[62] Dr. N.K. Dhapekar, “Advancements in energy recovery from waste plastic material for sustainable environment and circular economy,” *Materials Today: Proceedings*, 2023.
[63] Dr. N.K. Dhapekar, “A study of structural response & aerodynamic effects assessing wind performance of tall buildings,” *Scandinavian Journal of Information Systems*, vol. 35, Issue 1, pp. 112–116.
[64] Dr. N.K. Dhapekar, “Design Principles for Earthquake Resistant Buildings and Post Earthquake Study by Structural Engineering Perspectives,” *International Conference on Management, Engineering and Technology*, 2012.
[65] Dr. N.K. Dhapekar, “Impact of nano materials on engine performance run on biofuels,” *Materials Today: Proceedings*, 2023, Elsevier.

[66] Dr. N.K. Dhapekar, “Investigation of the use of non-biodegradable waste materials in concrete via experimental research,” *Materials Today: Proceedings*, 2023, Elsevier.
[67] Dr. N.K. Dhapekar, “Prediction of Micro-Structural Properties of Recycled Aggregate Concrete Using Artificial Intelligence,” *2022 3rd International Conference on Intelligent Engineering and Management (ICIEM)*, IEEE, pp. 857–861.
[68] Dr. N.K. Dhapekar, “Experimental Investigation by ETABS software on G+15,” *International Journal of Advance Research and Innovative Ideas in Education*, vol. 6, Issue 4, 2020.
[69] Dr. N.K. Dhapekar, “Applications of ANN in Concrete Technology,” *Harbin Gongye Xuebao / Journal of Harbin Institute of Technology*, vol. 54, Issue 5, pp. 116–120.
[70] Dr. N.K. Dhapekar, “Applications of X-Ray Diffraction in Civil Engineering,” 2022.