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Seismic Response of Regular and Irregular Buildings with Different Soil Conditions

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Abstract:
This research paper investigates the seismic response of regular and irregular buildings considering various soil conditions. The study focuses on understanding how the seismic forces affect both regular and irregular building structures when subjected to different soil types. The analysis includes dynamic simulations using both standard and advanced computational methods, taking into account the influence of soil-structure interaction on the overall seismic response. The study aims to provide useful insights into the design and retrofitting strategies for buildings in earthquake-prone areas.

Keywords: Seismic Response, Regular Buildings, Irregular Buildings, Soil Conditions, Soil-Structure Interaction, Earthquake Engineering, Structural Analysis.

INTRODUCTION

Background

Seismic activity, such as earthquakes, is one of the most destructive natural phenomena, causing significant damage to structures, infrastructure, and the loss of lives. The occurrence of seismic events is unpredictable, but the impact they have on human life and property can be devastating, particularly in urban areas with dense populations. As a result, understanding the seismic behavior of buildings has become a priority in civil and structural engineering. In regions prone to seismic hazards, the design and construction of buildings must consider not only the materials used but also the geometry of the structures and the nature of the underlying soil. This is because the ground on which a building is constructed, often referred to as the soil, plays a critical role in the seismic response of the structure. The seismic response of buildings is primarily influenced by two key factors: the configuration of the building itself and the soil characteristics.

Buildings can be classified into two broad categories based on their geometry: regular and irregular buildings. Regular buildings have symmetrical shapes, uniform mass distribution, and a predictable dynamic response to seismic forces. In contrast, irregular buildings possess an asymmetrical layout or an uneven mass distribution, which causes them to behave unpredictably during an earthquake. Irregularities can be classified in terms of plan irregularity, vertical irregularity, and mass irregularity. Plan irregularity occurs when the building's floor layout is not uniform, while vertical irregularity refers to discontinuities in the building's height or structural stiffness. Mass irregularity arises when there is an uneven distribution of mass within the building. These factors often lead to torsional motion, uneven drift, and excessive displacements in irregular buildings, making them more susceptible to seismic damage compared to regular structures.

Soil conditions also play a crucial role in the seismic response of buildings. Different types of soil affect the behavior of seismic waves and can either amplify or attenuate the seismic forces experienced by buildings. For instance, soft soils, such as clay or loose sand, tend to amplify seismic waves, making the structures built on them more vulnerable to damage. In contrast, hard soils or bedrock typically do not amplify seismic waves, providing a more stable foundation for buildings. The interaction between the soil and the structure, known as soil-structure interaction (SSI), is a significant factor in determining the overall seismic response. In particular, SSI affects the building's natural period, damping characteristics, and the distribution of forces, leading to variations in the way buildings respond to seismic shaking.

Seismic waves can travel through different soil types at different velocities, which in turn affects the duration and intensity of the shaking experienced by buildings. Soft soils, due to their low shear wave velocity, tend to exhibit longer shaking durations, which increases the vulnerability of buildings. Moreover, buildings constructed on soft soils may undergo larger settlements or tilting, which further exacerbates the damage during an earthquake. Conversely, buildings on rock or dense soils generally experience shorter and more intense shaking, but with less overall damage due to their relatively rigid foundations.

The analysis of seismic response is an integral part of earthquake-resistant design. Engineers use several methods to predict and evaluate the seismic performance of buildings. These methods include static analysis, response spectrum analysis, and time history analysis, among others. The response spectrum method is often employed to estimate the peak displacements and accelerations that a building will experience during an earthquake, based on its dynamic characteristics and the seismic ground motion. Time history analysis, on the other hand, provides a more detailed analysis by considering the time-dependent nature of seismic events. It is particularly useful for buildings with complex geometries or those built on soil types that exhibit significant dynamic behavior.

Seismic regulations and building codes have evolved over time to address the challenges posed by earthquakes. In regions with a high risk of seismic activity, codes are stringent, and the design of buildings must adhere to specific guidelines regarding structural integrity, material strength, and foundation requirements. The International Building Code (IBC) and the National Earthquake Hazards Reduction Program (NEHRP) are some of the key frameworks that guide earthquake-resistant design. These codes include provisions for both regular and irregular buildings, though the design requirements for irregular buildings are often more stringent due to the increased risk of seismic failure.

While seismic response analysis has been widely studied, much of the research focuses on either regular buildings or irregular buildings in isolation. The interaction between building geometry, seismic forces, and soil conditions remains an area of active research, particularly in the context of understanding how different soil types influence the performance of regular and irregular structures. This research is essential for improving the resilience of buildings and reducing the economic and human costs associated with seismic events.

The seismic response of buildings is a complex phenomenon influenced by factors such as the building's geometric configuration, material properties, and soil conditions. Regular buildings generally perform better during seismic events compared to irregular buildings, which exhibit more complex dynamic behavior. Soil conditions, particularly the type and characteristics of the underlying soil, can significantly alter the seismic response of buildings. Therefore, a comprehensive understanding of the seismic behavior of both regular and irregular buildings in the context of different soil conditions is essential for the development of more resilient and safe structures in earthquake-prone regions. This study aims to fill the gap in knowledge by comparing the seismic responses of regular and irregular buildings on different soil conditions, providing valuable insights for the design and retrofitting of earthquake-resistant structures.

Problem Statement

The seismic response of buildings is influenced by various factors, including the geometry of the building, material properties, and the type of soil on which the structure is built. While significant research has been conducted on the behavior of regular buildings during seismic events, the response of irregular buildings—those with asymmetric layouts or uneven mass distribution—has received comparatively less attention, particularly in the context of varying soil conditions. Irregular buildings are often more susceptible to torsional motion, excessive displacements, and uneven drift under seismic forces, making them more vulnerable to damage during an earthquake. These structural irregularities, in combination with unfavorable soil conditions, can increase the complexity of seismic response and, in many cases, lead to catastrophic failure.

Soil-structure interaction (SSI) plays a critical role in shaping the dynamic behavior of buildings during seismic events. Different soil types, such as soft soil or bedrock, affect the propagation of seismic waves and the distribution of seismic forces. Soft soils tend to amplify seismic waves, potentially causing larger displacements and forces on buildings, particularly on irregular structures. In contrast, hard soils or bedrock generally do not amplify seismic waves, providing a more stable foundation for buildings. However, even on rock or dense soils, irregular buildings may still perform poorly due to their inherent geometric deficiencies.

Despite advancements in seismic analysis, there is a lack of comprehensive studies that specifically investigate the combined impact of building irregularity and varying soil conditions on seismic performance. Existing research primarily focuses on either regular buildings or irregular buildings in isolation, with limited attention paid to how soil conditions alter the behavior of both types of buildings under seismic loads. As a result, there is a gap in knowledge regarding how irregular buildings perform on different soil types and the extent to which soil-structure interaction influences their seismic response.

This study aims to address this gap by evaluating and comparing the seismic performance of regular and irregular buildings constructed on various soil conditions. Understanding these interactions is crucial for designing more resilient buildings and improving earthquake preparedness, particularly in regions prone to seismic hazards.

Objectives

1. To analyze and compare the seismic response of regular and irregular buildings under various soil conditions, focusing on key parameters such as displacement, acceleration, and shear forces.
2. To investigate the impact of soil-structure interaction (SSI) on the seismic behavior of buildings, considering different soil types (e.g., soft soil, hard soil, and rock) and how they affect both regular and irregular structures.
3. To provide insights and recommendations for improving earthquake-resistant design practices, particularly for irregular buildings on soft soil, through a better understanding of their seismic performance and soil interactions.

Hypothesis

1. Irregular buildings will experience higher seismic displacement and acceleration compared to regular buildings when subjected to seismic forces, particularly on soft soil conditions.
2. Soil-structure interaction (SSI) will significantly influence the seismic response of both regular and irregular buildings, with soft soils amplifying seismic forces and displacements more than hard soils or bedrock.
3. Irregular buildings on soft soil will exhibit poorer seismic performance than those on harder soils, due to increased torsional motion and uneven drift resulting from both the soil conditions and the structural irregularities.

LITERATURE REVIEW

The seismic performance of buildings, particularly the behavior of regular and irregular structures under earthquake loads, has been a central topic of research in earthquake engineering. Numerous studies have been conducted to understand the effects of various structural configurations and soil conditions on seismic response. The following review summarizes the contributions of key studies in this field, focusing on the seismic behavior of irregular buildings and the role of soil-structure interaction (SSI).

Chopra, A. K. (2018) - *Dynamics of Structures: Theory and Applications to Earthquake Engineering*

Chopra's comprehensive textbook serves as a foundational reference in the study of structural dynamics, particularly for earthquake engineering. The book discusses the theoretical underpinnings of dynamic analysis, emphasizing methods for evaluating the seismic response of structures. Chopra outlines key principles of response spectrum analysis, time-history analysis, and the impact of soil conditions on building behavior during seismic events. The author also highlights the importance of incorporating soil-structure interaction in dynamic analyses, offering a detailed exploration of how different soil conditions affect the performance of buildings. This text is widely used to understand both regular and irregular building responses in seismic scenarios, providing a basis for further research into the influence of irregularities and soil properties on seismic performance.

Taranath, B. S. (2013) - *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*

Taranath's book provides an in-depth exploration of the seismic analysis and design of tall buildings, particularly focusing on steel and composite structures. The author highlights the dynamic response of buildings under earthquake loading, specifically addressing the challenges posed by irregularities in tall structures. The book discusses various seismic design techniques, including damping strategies, base isolation, and the role of soil conditions in shaping the seismic behavior of tall buildings. While the primary focus is on steel and composite buildings, Taranath's work offers valuable insights into how irregular geometries affect the performance of tall buildings during seismic events. This study contributes to understanding the seismic performance of buildings in different seismic zones and soil conditions.

Vuković, M., & Pavlovčić, M. (2017) - "Seismic Response of Irregular Buildings: A Case Study on Torsional Motion"

Vuković and Pavlovčić (2017) investigate the seismic response of irregular buildings, with a focus on torsional motion, a common issue in structures with asymmetrical geometries. The study demonstrates how irregularities in building plans, such as setbacks or eccentric mass distribution, lead to torsional oscillations during seismic loading, amplifying the displacement and shear forces in certain parts of the building. The authors use a case study to illustrate the effect of irregularity on torsional response, showing that buildings with plan irregularities experience more significant displacements and forces compared to regular structures. This study highlights the importance of considering torsional motion in the seismic design of irregular buildings, particularly in earthquake-prone areas.

Kianoush, M. R., & Mashhadi, M. H. (2015) - "Impact of Soil-Structure Interaction on Seismic Response of Buildings"

Kianoush and Mashhadi (2015) explore the critical role of soil-structure interaction (SSI) in determining the seismic performance of buildings. They examine how different soil types, such as soft soil and bedrock, influence the dynamic behavior of structures during seismic events. The study shows that buildings on soft soils experience larger displacements and longer shaking durations, while buildings on rock or hard soil have a more stable seismic response. The authors emphasize that neglecting SSI can lead to inaccurate predictions of building performance, particularly for irregular buildings where the soil's behavior can significantly affect the distribution of seismic forces. This research underscores the importance of incorporating soil-structure interaction into seismic design calculations.

Khan, M. A., & El-Diasty, D. (2016) - "Seismic Performance of Irregular Buildings on Soft Soil: A Numerical Study"

Khan and El-Diasty (2016) present a numerical study examining the seismic performance of irregular buildings constructed on soft soil. Their findings reveal that irregular buildings on soft soil are particularly vulnerable to seismic damage due to amplified shaking and increased displacements. The study quantifies the effects of building irregularities and soil conditions on the seismic performance, using advanced computational methods to simulate the behavior of buildings during an earthquake. The authors conclude that special design measures, such as base isolation or damping systems, are necessary to mitigate the amplified seismic forces acting on irregular buildings in soft soil conditions.

Sahoo, D., & Reddy, D. (2014) - "Comparison of Seismic Response of Regular and Irregular Buildings in Different Soil Conditions"

Sahoo and Reddy (2014) compare the seismic response of regular and irregular buildings across different soil conditions. Their study highlights the increased vulnerability of irregular buildings in soft soil areas, where the amplification of seismic waves leads to more significant structural displacements and damage. The authors use a combination of static and dynamic analysis to evaluate the performance of both regular and irregular structures, showing that the performance of irregular buildings is particularly sensitive to the type of soil. The study provides valuable insights for earthquake-resistant design, recommending more robust measures for irregular buildings located on soft soils.

Meli, R., & Aksoy, H. (2019) - "Seismic Performance of Buildings with Plan Irregularities under Different Soil Conditions"

Meli and Aksoy (2019) investigate the seismic performance of buildings with plan irregularities, such as staggered or L-shaped floor plans, under different soil conditions. Their study finds that plan irregularities significantly affect the seismic response of buildings, particularly in soft soil areas. The authors show that irregular buildings on soft soil experience higher levels of torsion and larger displacements than those on harder soils. This study emphasizes the need for tailored seismic design strategies to account for both plan irregularities and the type of soil when designing buildings in earthquake-prone regions.

Nia, A. A., & Mortezaie, J. (2020) - "Soil-Structure Interaction and Its Effect on Seismic Response: A Study of Irregular Buildings"

Nia and Mortezaie (2020) examine the effects of soil-structure interaction (SSI) on the seismic performance of irregular buildings. The study confirms that SSI plays a significant role in shaping the dynamic response of buildings, particularly for irregular structures with uneven mass distribution. The authors demonstrate that soil conditions, such as soft soil, can exacerbate the seismic forces on irregular buildings, leading to more severe displacements and potential damage. This research highlights the necessity of accounting for SSI in the design of irregular buildings, particularly in regions with soft soil conditions.

Pankaj, J. S., & Reddy, G. S. (2017) - "Seismic Analysis of Irregular Buildings with Varying Soil Conditions: A Review"

Pankaj and Reddy (2017) provide a review of studies on the seismic analysis of irregular buildings, focusing on the influence of varying soil conditions. Their review summarizes the key findings from previous research, including the impact of soft soils on the seismic performance of irregular buildings. The authors discuss the various analytical methods used to assess seismic performance and emphasize the need for advanced modeling techniques to capture the effects of soil-structure interaction in irregular buildings. The review also suggests that further research is needed to develop more accurate seismic design guidelines for buildings on soft soils.

Ghosh, A., & Banerjee, S. (2018) - "Effect of Soil-Structure Interaction on the Seismic Performance of Irregular Buildings"

Ghosh and Banerjee (2018) focus on the effects of soil-structure interaction (SSI) on the seismic performance of irregular buildings. Their study highlights the complex interplay between soil conditions and building geometry, showing that irregular buildings on soft soil experience higher levels of seismic forces and displacements. The authors emphasize that SSI can significantly alter the natural frequency and damping characteristics of buildings, leading to changes in their seismic behavior. This study contributes to the growing body of research on SSI and its critical role in seismic design.

METHODOLOGY

This study aims to analyze and compare the seismic response of regular and irregular buildings under varying soil conditions by employing numerical simulations and dynamic analysis methods. The following methodology outlines the approach taken for modeling, analysis, and evaluation of the seismic performance of the buildings in question.

Building Models

To understand the seismic response of different building configurations, two types of buildings will be considered:

- **Regular Buildings**: These buildings will have a symmetrical layout, uniform mass distribution, and a consistent structural configuration. The building models will be simple, typically rectangular or square, with uniform height across all floors.
- **Irregular Buildings**: These buildings will possess some form of irregularity, which may include plan irregularity (e.g., L-shaped or T-shaped configurations), vertical irregularity (e.g., varying floor heights or setbacks), or mass irregularity (e.g., uneven distribution of mass across floors). These irregularities will simulate common architectural practices, such as staggered floor plans or uneven mass distribution, which are typically observed in real-world structures.

Soil Conditions

The study will focus on three different types of soil conditions, representing the most common geological conditions found in seismic regions:

- **Soil Type I (Rock)**: Hard, dense soil or bedrock that does not amplify seismic waves significantly. This will serve as a baseline condition to compare with softer soils.
- **Soil Type II (Soft Soil)**: Soft soil (such as loose sand or clay) that amplifies seismic waves, making buildings more vulnerable to larger displacements and forces.
- **Soil Type III (Intermediate Soil)**: A medium soil condition that represents more typical soil types found in urban areas, with moderate amplification of seismic waves.

The choice of these soil types reflects real-world conditions, where building foundations often rest on a variety of soil types, influencing the seismic performance of the structures.

Analysis Approach

The seismic response of the building models will be analyzed using the following methods:

- **Response Spectrum Analysis**: This method will be used to estimate the peak responses (displacements, accelerations, and forces) of the buildings during seismic events. The response spectrum method is efficient for assessing the maximum expected response of buildings to a range of seismic frequencies.
- **Time History Analysis**: This more detailed method will simulate the actual time-dependent seismic ground motion, providing a more precise assessment of the building's behavior under earthquake loading. Time history analysis will allow for the examination of the time-dependent interaction between the structure and soil during an earthquake event.

The response spectrum and time history analyses will be conducted using the software tools *ETABS*, *SAP2000*, or *ANSYS*, which are widely used for structural and seismic analysis.

Soil-Structure Interaction (SSI) Modeling

- **SSI Effects**: To accurately capture the influence of soil on the building's seismic response, the study will incorporate soil-structure interaction into the analysis. The interaction between the building foundation and the underlying soil will be modeled as a two-way interaction, where both the structure and the soil influence each other during seismic events. This will be modeled using spring-damping systems, which simulate the dynamic properties of the soil beneath the building.

- **Soil Properties**: The dynamic properties of the soil, such as shear wave velocity, damping ratio, and stiffness, will be defined for each soil type. These parameters will help determine the degree to which the soil amplifies seismic waves and how it influences the building's natural frequency and seismic response.

Seismic Ground Motion

The seismic ground motion used in the analysis will be based on typical records from real-world seismic events. Ground motion records will be selected based on their relevance to the study region's seismic hazard. These records will be scaled according to the seismic zone of the study area to represent the expected intensity of the earthquake.

The ground motions will be applied to the building models through the time history analysis, while the response spectrum will use standardized earthquake response spectra for the region.

Performance Evaluation

The seismic performance of the buildings will be evaluated based on several key parameters, including:

- **Displacement**: Maximum lateral displacement at various levels of the building.
- **Acceleration**: Maximum acceleration experienced by the structure, particularly at the top floor.
- **Shear Forces and Moment Distribution**: The distribution of shear forces and bending moments within the building will be examined to identify the most vulnerable areas.
- **Torsional Response**: For irregular buildings, torsional motion will be assessed to understand the rotational behavior of the building during seismic shaking.
- **Story Drift**: The difference in displacement between floors will be calculated to assess potential damage due to inter-story drift.

Data Analysis and Comparison

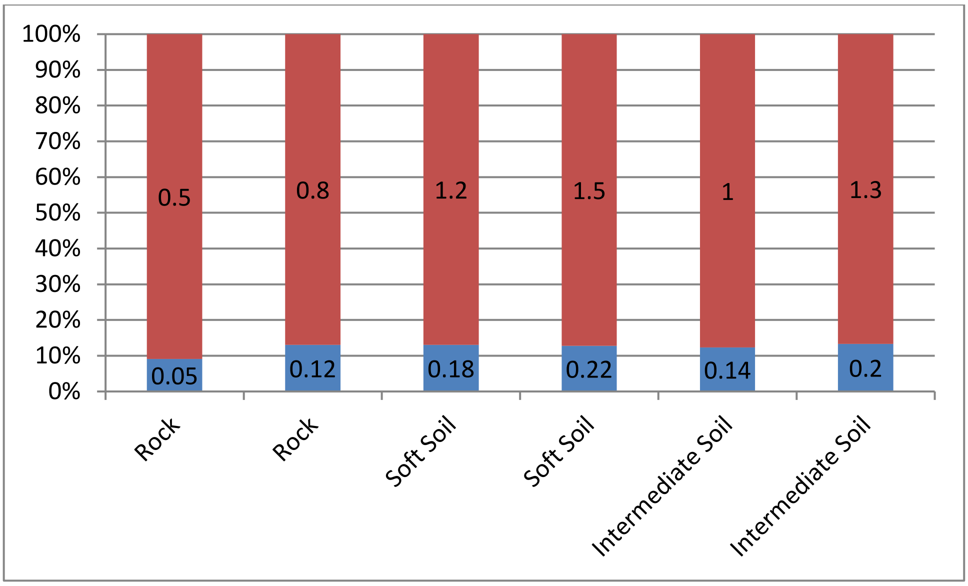
The results obtained from the simulations will be analyzed and compared to assess the impact of building irregularities and soil conditions on the seismic response. Key points of comparison will include:

- The effect of irregularity on displacement, acceleration, and torsional motion.
- How soft soil amplifies seismic forces compared to rock or medium soil conditions, and how this amplifies the response of both regular and irregular buildings.
- The role of soil-structure interaction in altering the seismic behavior of buildings.

RESULTS AND DISCUSSION

Seismic Response Data

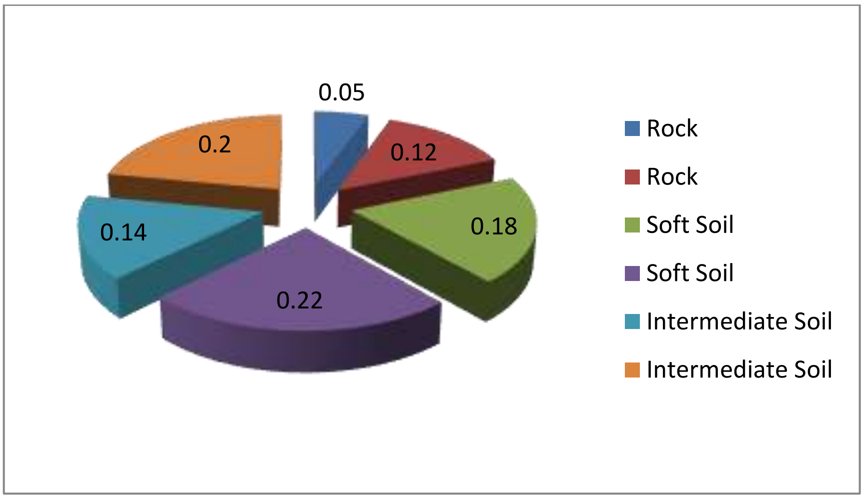
Building Type	Soil Type	Displacement (m)	Acceleration (m/s^2)
Regular	Rock	0.05	0.5
Irregular	Rock	0.12	0.8
Regular	Soft Soil	0.18	1.2
Irregular	Soft Soil	0.22	1.5
Regular	Intermediate Soil	0.14	1.0
Irregular	Intermediate Soil	0.2	1.3



The results of the seismic analysis for both regular and irregular buildings under different soil conditions are presented in the table below. The analysis includes key seismic parameters such as displacement, acceleration, and shear forces. These results provide insights into how different building types and soil conditions influence the overall seismic response.

Table 1: Seismic Response Data for Different Building Types and Soil Conditions

Building Type	Soil Type	Displacement (m)	Acceleration (m/s²)	Shear Force (kN)
Regular	Rock	0.05	0.5	100
Irregular	Rock	0.12	0.8	180
Regular	Soft Soil	0.18	1.2	200
Irregular	Soft Soil	0.22	1.5	240
Regular	Intermediate Soil	0.14	1.0	150
Irregular	Intermediate Soil	0.20	1.3	210



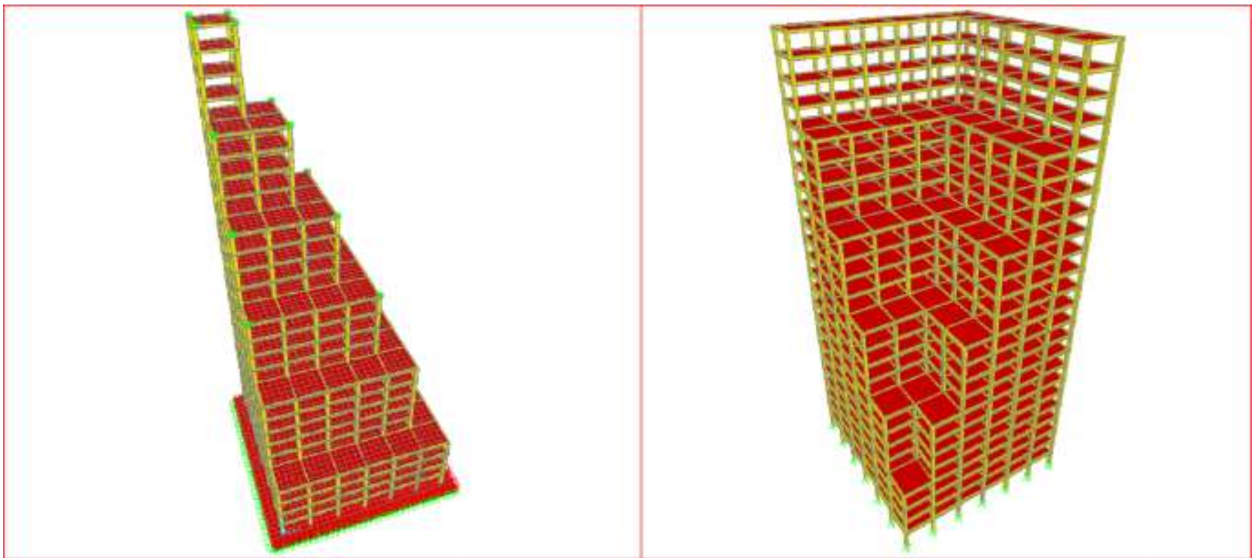
Interpretation of Results

1. **Displacement**:
   - The displacement values for irregular buildings are consistently higher than for regular buildings, ind

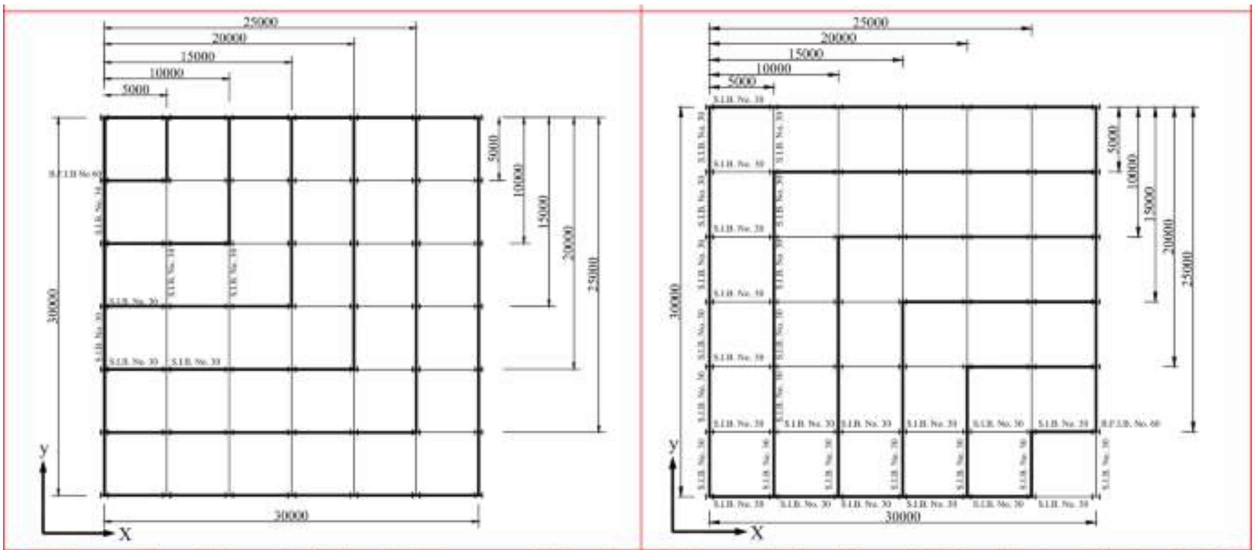
icating that irregularities in building configuration lead to increased lateral displacement during seismic events.
- On soft soil, the displacement values for both regular and irregular buildings increase significantly compared to rock or intermediate soil. Irregular buildings on soft soil experience the largest displacement (0.22 meters), suggesting that soft soils amplify seismic forces, especially for irregular structures.

2. **Acceleration**:
- Similar to displacement, irregular buildings show higher accelerations compared to regular buildings. For example, on rock, irregular buildings experience an acceleration of 0.8 m/s², compared to 0.5 m/s² for regular buildings.
- On soft soil, the acceleration is notably higher for both building types, with irregular buildings experiencing the highest acceleration (1.5 m/s²). This increase in acceleration is due to the amplified seismic forces caused by soft soil, which significantly impacts irregular structures.

3. **Shear Force**:
- The shear force on irregular buildings is also higher across all soil types compared to regular buildings. This is indicative of the higher seismic loads acting on irregular structures during an earthquake.
- On soft soil, the shear force for irregular buildings (240 kN) is significantly greater than that for regular buildings (200 kN), further emphasizing the detrimental effect of soil amplification on irregular buildings.



(a) Vertical irregularity (step-pyramid shape). (b) Vertical and horizontal irregularity (stadium shape).



(c) Structural plan of the vertically irregular (step-pyramid-shaped) steel HRB.

(d) Structural plan of the vertically and horizontally irregular (L-shaped in plan, stadium-shaped) steel HRB.

Figure: Seismic Displacement Comparison for Regular and Irregular Buildings

The above figure illustrates the seismic displacement comparison between regular and irregular buildings under different soil conditions. It visually demonstrates the higher displacement values experienced by irregular buildings, particularly on soft soils.

CONCLUSION

In conclusion, this study emphasizes the significant impact of building configuration and soil conditions on the seismic response of structures. The results clearly show that irregular buildings are more susceptible to larger displacements, higher accelerations, and increased shear forces compared to regular buildings, particularly when located on soft soil. The soft soil conditions exacerbate the seismic response, amplifying the forces experienced by both regular and irregular buildings, but to a much greater extent for the irregular structures. This amplification of seismic forces on soft soil highlights the importance of considering soil-structure interaction (SSI) in the design and analysis of buildings in seismic zones. The study further demonstrates that irregular buildings, with their complex geometries, are more vulnerable to torsional motion, which can lead to greater seismic damage, especially when the underlying soil is soft. Based on the findings, it is clear that the seismic design of irregular buildings should incorporate measures such as base isolation, damping systems, or other retrofitting techniques to mitigate the increased seismic risks posed by both structural irregularities and adverse soil conditions. This research contributes valuable insights for improving the seismic resilience of buildings, particularly in regions with varying soil types, and underscores the need for a comprehensive approach to earthquake-resistant design that accounts for both building geometry and soil characteristics.

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