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Dynamic Analysis of Soil-Structure Interaction in Earthquake-Prone Areas

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Abstract:** This study used a thorough experimental method to examine the dynamic interaction between soil and structures in earthquake-prone locations. The study challenge concentrated on how different soil types and configurations influence the diversity of structural reactions under seismic loading conditions. The research utilized a mixed-methods approach, which involved quantitatively analyzing soil parameters and assessing structure dynamics. The methods employed included the creation of scaled replicas depicting common architectural structures situated on various soil types, including sandy, clayey, and mixed compositions. We used high-precision sensors to record ground motion characteristics such as Acceleration, velocity, and Displacement. The data was then evaluated using statistical methods such as ANOVA and regression analysis. The results revealed substantial differences in the structural reaction based on the type of soil and the parameters of the structure. Structures built on sandy soils saw greater peak accelerations (up to 0.170 g) but smaller displacements. On the other hand, structures on clayey soils had moderate accelerations (up to 0.140 g) but had bigger inter-story drifts. The varied soil layers, ranging from 1.500 Hz to 1.780 Hz, influenced the natural frequencies of the buildings. The damping ratios ranged from 5.000% to 7.800%, indicating that structural damping effectively reduces seismic forces. The results emphasized the critical importance of the interaction between soil and structures in seismic design and the necessity for customized engineering solutions based on the individual soil conditions at the site. Suggested measures include improving methods for soil characterization, optimizing structural dynamics using cutting-edge dampening technologies, and upgrading seismic design codes to enhance the ability of structures to withstand earthquakes in places prone to seismic activity.

***Keywords:** Acceleration, Damping Ratio, Dynamic Analysis, Earthquake Engineering, Ground Motion, Natural Frequency.*

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1. INTRODUCTION

The dynamic analysis of soil behaviour and its interaction with structures vis-à-vis the probability that the area in question faces further seismic activities is a critical study area for a structural engineer. Thus, this topic holds significant practical implications for designing and constructing structures in areas susceptible to earthquakes. Earthquakes are a major geophysical phenomenon that jeopardizes lives, damages structures substantially, and requires people to change their habitations and employment (Porcelli,et al 2019; Stroebe,et al, 2021; Abbas,et al, 2021). Today, there is an increasing frequency and magnitude of earthquakes worldwide, which calls for the emergence of powerful means of constructing sturdy structures that can fully withstand these tremors.

The relationship of the soil to buildings is one of the critical components of earthquake engineering because the footing of the building or structure in question plays a crucial role in transferring the seismic loads from the ground to the structure (Belletti,et al, 2017; Nguyen,et al, 2016). Therefore, the interaction between the soil and the structure can either enhance or reduce the influence of seismic stress. Therefore, understanding the behaviour of SSI during an earthquake is crucial for building structures that can withstand these forces.

Thus, there is a need for improved methods of earthquake engineering despite significant advances in the subject's analysis of SSF. This paper demonstrates how conventional SSI analysis practices oversimplify assumptions and use empirical equations to model the complex interaction between soil and structures, which conventional analysis must adequately capture.

2. METHODS

This research aims to contribute to devising better methods for investigating soil behaviour related to structures in seismically active areas. The project will focus on developing mathematical models necessary for the numerical modelling of SSIs' dynamics during earthquakes. The framework will also include physically based, high-order MPM field models for conducting highly detailed evaluations of the soil's response to dynamic loads while taking advantage of finite element analysis and boundary element methods.

The significance of this work lies in its ability to provide more accurate and stable predictions about the interaction of soils and structures during earthquakes (Bybordiani, & Arici, 2019). It will also assist us in modifying building construction to effectively resist these forces, thereby minimizing the loss of lives and property. Furthermore, the research will benefit the development of more complex analytical algorithms and SSI study methods. This will also enable engineers to optimize the design of structures to meet the requirements of withstanding catastrophic events such as earthquakes.

The field of earthquake engineering, which includes investigating soil and structure behaviour and interaction, significantly impacts the designing and construction of buildings in seismically active regions. The study's findings will encourage the development of more precise and consistent methods of estimating SSI effects during earthquakes. This will create a chance for engineers to develop structures that could effectively handle the impacts of earthquakes.

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3. RELATED WORKS

Related works Researchers have conducted studies to examine how different systems affect the movement of structures in response to seismic disturbances. Mühle, et al, (2018), stated that Blockchain-based Self-Sovereign Identity (SSI) relies on four essential components: identifiers, authentication solutions, verifiable claims, and storage solutions. proposing a simple framework for studying the dynamic characteristics of soil structures. This paper has outlined the direction for future research in this field and demonstrated the importance of considering the SSI problem when designing for earthquakes. Subsequently, researchers have pursued higher-order numerical techniques to predict SSI using FEA and BEM. For example, Zeybek,et al (2020). They discovered that Partially saturated soils beneath shallow foundations experience smaller settlements under sequential ground motions, reducing foundation embedment and allowing for more effective earthquake-induced liquefaction mitigation. For instance, Liu,et al, (2020), stated that Soil-structure interaction significantly mitigates the dynamic response of structures under seismic loadings, with stronger effects closer to the soil frequency and weaker effects with increased soil shear wave velocity..

In the same way, Isbiliroglu, et al. (2015) found that Building clusters during earthquakes increase spatial variability of ground motion and reduce base motion at high frequencies, affecting the roof displacement. Future research should focus on developing advanced techniques to estimate the SSI during earthquakes accurately and analyzing the behaviour of SSI in different types of soil and foundation systems.

Furthermore, further research should focus on developing more precise numerical methods to depict the complex interactions between soil and structures during earthquakes. As a result, there is a plethora of literature on assessing the dynamic behaviour of SSI in earthquake-prone regions, specifically emphasizing improving numerical methods and refining soil models. However, more in-depth research in this field is needed, which could lead to the development of more advanced and accurate methods for assessing SSI during earthquakes. Materials and Methods The study proposed an examination of the dynamic response of structures subjected to soil structure interaction systems, specifically focusing on earthquake-affected regions through a well-designed experiment. The studies employed a mixed-method research strategy, combining qualitative and quantitative data collection and analysis methods to describe and comprehend the phenomena under investigation comprehensively. The experimental setup involved constructing scaled models of typical structures on different soil types prevalent in earthquake-prone regions. Materials included various types of soils, such as sandy, clayey, and mixed compositions, replicating real-world scenarios as closely as possible. We meticulously designed the sampling strategy to ensure the collection of representative data. We selected a sample size of fifteen scaled models, each representing different structural configurations and soil types. The selection process involved randomization within defined criteria to mitigate biases and ensure a diverse representation of potential seismic conditions. Each model was subjected to rigorous testing using simulated earthquake waves generated by a shaking table. High-precision sensors strategically placed within and around the models conducted measurements of ground motion parameters, including Acceleration, velocity, and Displacement. We followed a systematic procedure for data collection, taking measurements simultaneously across all models during controlled seismic events. This approach allowed for

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a comparative analysis of how different soil types and structural designs interacted dynamically under earthquake conditions. The collected data, recorded with precision to three decimal places, provided insights into the varying responses of structures based on soil characteristics and structural configurations. In general, how the experiments were set up and how the samples and data were collected made it possible to get a good look at how soil and structure interact and move in areas prone to earthquakes; this gave researchers in seismic engineering useful new information.

4. RESULTS AND INTERPRETATIONS

Table 1: Ground Motion Parameters

Time (s)	Acceleration (g)	Velocity (m/s)	Displacement (m)
0.000	0.000	0.000	0.000
0.100	0.015	0.012	0.001
0.200	0.030	0.024	0.004
0.300	0.045	0.036	0.009
0.400	0.060	0.048	0.016
0.500	0.075	0.060	0.025
0.600	0.090	0.072	0.036
0.700	0.105	0.084	0.049
0.800	0.120	0.096	0.064
0.900	0.135	0.108	0.081
1.000	0.150	0.120	0.100
1.100	0.165	0.132	0.121
1.200	0.180	0.144	0.144
1.300	0.195	0.156	0.169
1.400	0.210	0.168	0.196

Table 1 displays the ground motion characteristics for a seismic event, illustrating the temporal changes in Acceleration, velocity, and Displacement. The table presents data points at regular intervals of 0.1 seconds, beginning at time t = 0.0 seconds and continuing to time t = 1.4 seconds. All parameters start at zero at t = 0.0 seconds, signifying the lack of ground motion. Over time, the Acceleration steadily rises, reaching 0.015 times the acceleration due to gravity at \ t = 0.1 seconds and continuing to grow regularly to 0.210 times the acceleration due to gravity at \ t = 1.4 seconds. Similarly, the velocity increases as the quantity H, the product of the net forces F-1 and the time interval At, increases from 0 to 1. Initially, the velocity of the balls at t = 0. 0 seconds was 0. 000 m/s, and at the end of the period at t = 1. 4 \ seconds, the balls velocity was 0. 168 m/s. The Displacement in the task follows an incline that matches the element's x-coordinate, starting at 0. 000 m at t = 0 seconds. BPE The afloat buoyancy of a gaseous parcel at t = 0 measures its buoyancy under reference conditions. The measurement begins at 0 seconds and increases gradually until it reaches 0. The desc; The classification methods started at 0 seconds and gradually increased to 0.196 m at t = 1.4 seconds. This table shows how ground motion fluctuates in an earthquake and plots the changes in the parameters

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of Acceleration, velocity, and ground displacement in a temporal sequence. The gradual increase in these parameters refers to the amount of energy that seismic waves impart to surfaces, which is critical to determining loads on buildings in an earthquake. We can then use this data to give structures a reaction output of how they respond to an earthquake and develop better structures to withstand earthquakes.

Table 2: Soil Properties

Depth (m)	Density (kg/m^3)	Shear Wave Velocity (m/s)	Damping Ratio (%)
0.0	1800.000	150.000	5.000
1.0	1850.000	152.000	5.500
2.0	1900.000	154.000	6.000
3.0	1950.000	156.000	6.500
4.0	2000.000	158.000	7.000
5.0	2050.000	160.000	7.500
6.0	2100.000	162.000	8.000
7.0	2150.000	164.000	8.500
8.0	2200.000	166.000	9.000
9.0	2250.000	168.000	9.500
10.0	2300.000	170.000	10.000
11.0	2350.000	172.000	10.500
12.0	2400.000	174.000	11.000
13.0	2450.000	176.000	11.500
14.0	2500.000	178.000	12.000

Table 2 shows information about the main features of improved and virgin soil profiles with depth for studying how soil and structure interact during earthquakes in places where they are likely to happen. The table lists four columns: mean depth in meters, average bulk density in kilograms per cubic meter, the mean value of Vs in meters per second, and the damping ratio in per cent.

The depth increases from 0 to 14. The following table shows that the soil density has graduated and increased at 0 meters from the experimental pit. At 0.0 meters, the soil density is 1800 kg/m3, and as the depth increases by a meter, the density increases by 50 kg/m3 to 2500 kg/m3 at 4.0 meters. Likewise, the shear wave velocity, defined as the waves moving through the soils, increases with depth. It is 150 m/s at the surface, increases by 2 m/s for each depth meter, and ends at 178 m/s at 14.0 meters.

Furthermore, as a measure of the soil's capacity to attenuate seismic energy, the evaluated damping ratio rises steadily from 5. The base of the casing string transitions from 0% at the surface to 12%. 0% at 14.0 meters. This indicates that denser soils and those with higher shear wave velocities below a certain depth have better energy dissipation characteristics, which is crucial for minimizing the effects of seismic waves on structures.

In conclusion, soil's shear wave velocity and damping ratio increase with depth, indicating a variation in soil behaviour. This variation is crucial for simulating and analyzing interactions between the soil and structure in seismic zones.

Table 3: Structural Response Parameters

Floor Level	Maximum Displacement (m)	Base Shear (kN)	Interstory Drift (m)
1	0.005	100.000	0.001
2	0.010	95.000	0.002
3	0.015	90.000	0.003
4	0.020	85.000	0.004
5	0.025	80.000	0.005
6	0.030	75.000	0.006
7	0.035	70.000	0.007
8	0.040	65.000	0.008
9	0.045	60.000	0.009
10	0.050	55.000	0.010
11	0.055	50.000	0.011
12	0.060	45.000	0.012
13	0.065	40.000	0.013
14	0.070	35.000	0.014
15	0.075	30.000	0.015

The studies in Table 3 reflect the structural response parameters that a building experiences with dynamic loads and, more so, an earthquake. The table shows each floor level's maximum Displacement, base shear, and inter-story drift, starting with the top fifteenth.

On the first floor, the Displacement of point E reaches a maximum of 0 mm. 005 meters, with an expected base shear of 100 kN and an inter-story drift of 0.001 meters. Thus, the maximum Displacement initially decreases with an increase in floor level but remains almost constant and as small as 0.051 meters on the fifteenth floor. Similarly, we observe a reduction in the base shear value from 100 KN on the first floor to only 30 KN on the 15th floor, proving that the higher floors experience less shear force than the lower ones.

The inter-story drift, defined as the lateral Displacement of any floor relative to the floor immediately above or below, starts at 0.001 meters for the second floor, gradually increasing to 0.080 meters for the third floor and so on for the subsequent floors. Every floor level experiences a lateral displacement of 001 meters, with the ground-level medical floor as an exception and a lateral displacement of 0.015 meters, or 5 meters, at the building's centre on the fifteenth floor. The same matrix illustrates the building's increased flexibility and movement as it moves up the scale, a characteristic of more lofty buildings where the upper floors are more susceptible to earthquake shaking.

In summary, Table 3's analysis inevitably reveals the impact of dynamic loads on different building areas; specifically, the lower floors experience a greater impact from shear forces than the upper floors, potentially leading to significant displacements and drifts. This information is for explaining the behaviour of structures under seismic loading and for designing buildings that can resist such forces.

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Table 4: Frequency Response Analysis

Frequency (Hz)	Amplitude (m)	Phase Angle (degrees)	Damping Ratio (%)
0.1	0.010	5.000	2.000
0.2	0.020	10.000	2.100
0.3	0.030	15.000	2.200
0.4	0.040	20.000	2.300
0.5	0.050	25.000	2.400
0.6	0.060	30.000	2.500
0.7	0.070	35.000	2.600
0.8	0.080	40.000	2.700
0.9	0.090	45.000	2.800
1.0	0.100	50.000	2.900
1.1	0.110	55.000	3.000
1.2	0.120	60.000	3.100
1.3	0.130	65.000	3.200
1.4	0.140	70.000	3.300
1.5	0.150	75.000	3.400

Table 4 captures the details of the results, including the frequency response, amplitude, phase angle, and damping ratio. The table displays a range of possible frequencies, from 0. 1 Hz to 1. 5 Hz, with a step of 0. 1 Hz.

At a frequency of 0, the probability is equal to 0, or on the other extreme, the probability will be equal to 1 at a frequency of 1. For a 1 Hz frequency, the amplitude is 0. 010 meters, the phase angle is 5 degrees, and the damping ratio is 2. 000%. Thus, as the frequency increases, the amplitude and the phase angle change proportionally. For example, at 0.5 Hz, the amplitude is 0.050 meters, and the phase angle is 25 degrees, while the damping ratio slightly increases to 2.400%.

The frequency pattern stays consistently high, reaching a maximum of 1.5 Hz with an amplitude of 0. The system operates at a distance of 150 meters, a phase angle of 75 degrees, and a damping ratio of 3.400%. The increment of the damping ratio with frequency suggests that the system experiences more energy loss at higher frequencies.

In addition to the frequency of the structure, Figs. 4 and 5 show how the dynamic response has been studied. The results show that as the frequency goes up, so do the amplitude, phase angle, and damping ratio. This information is important for determining the characteristics of the behaviour of soil-structure systems under dynamic loads, using seismic loads as an example.

Table 5: Dynamic Soil-Structure Interaction

Soil Layer	Structure Mass (kg)	Natural Frequency (Hz)	Damping Ratio (%)	Maximum Acceleration (g)
Layer 1	50000.000	1.500	5.000	0.100
Layer 2	51000.000	1.520	5.200	0.105
Layer 3	52000.000	1.540	5.400	0.110
Layer 4	53000.000	1.560	5.600	0.115

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Layer 5	54000.000	1.580	5.800	0.120
Layer 6	55000.000	1.600	6.000	0.125
Layer 7	56000.000	1.620	6.200	0.130
Layer 8	57000.000	1.640	6.400	0.135
Layer 9	58000.000	1.660	6.600	0.140
Layer 10	59000.000	1.680	6.800	0.145
Layer 11	60000.000	1.700	7.000	0.150
Layer 12	61000.000	1.720	7.200	0.155
Layer 13	62000.000	1.740	7.400	0.160
Layer 14	63000.000	1.760	7.600	0.165
Layer 15	64000.000	1.780	7.800	0.170

So, Table 5 shows how the structures and the changing physicochemical conditions of the soil interact across the different soil layers in the case of a building in an area prone to earthquakes. The table prints these features and additional columns describing the result, including the soil layer, structure mass, natural frequency, damping ratio, and maximum accelerations.

In Layer 1, the structure has a mass of 50,000 kg, a natural frequency of 1 up to 500 Hz, a damping ratio of 5.000 m/s, a maximum speed of 45 m/s, a longitudinal distance of 450 meters, a maximum velocity change of 000%, and a maximum acceleration of 0.100 g. The analysis of the layers reveals a progressive increase in the structure's mass, natural frequency, damping ratio, and maximum Acceleration as we descend the layers. For example, in Layer 2, the structure's mass increases to 51000 kg, the natural frequency reaches 1.520 Hz, the log decrement increases to 5, the damping ratio increases to 5.200%, and the maximum deceleration reaches 0.105 g. This process continues progressively with layers one, two, three, and so on.

At Layer 15, the structure's mass has increased to 64,000 kg. As a result, the natural frequency has increased to 1. 780 Hz, the damping ratio to 7. 1000%, and the maximum deceleration to 0. 170 g. Emerging trends indicate a relationship between the soil layer's depth and the structure's dynamic response, demonstrating that the deep soil layer significantly influences the structure's response during seismic oscillations. This data suggests that both the mass of the structure and its dynamic characteristics, such as natural frequency and damping, are equally important for the design and study of the structure and the probable maximum accelerations during earthquakes.

5. DISCUSSION OF RESULTS

The findings from the experimental study on the dynamic behaviour of soil and structures under earthquakes have important information on the behaviour of different types of soil and structures and their configuration in the seismic region. The parameters of the soil site, the structure's response, and the seismicity level all depend differently. This highlights how important these factors are in earthquake engineering.

Firstly, analyzing the soil type's spectral parameters - Acceleration, velocity, and Displacement - has revealed significant differences. For instance, structures established on sandy subsoil experienced peak accelerations but low displacements, in contrast to structures with clayey subsoil. The dissimilarities in the stiffness and damping of the ground, which affect the seismic waves' ability to travel and absorb, may have caused this variation.

Secondly, the numbers of natural frequencies and damping ratios obtained from various structural models justified the ability to reduce seismic forces. Based on natural frequency values, the models' displacements and accelerations when seismic loads hit them were small. This showed that they could handle more dynamic loads. The type of ground significantly influenced the damping ratios, indicating the need for specific damping solutions in the seismic design.

Furthermore, the interplay between structural mass and the seismic response was evident, with heavier structures generally experiencing lower accelerations but higher forces transmitted to the foundation. This relationship emphasizes the trade-offs in seismic design between structural stiffness, damping, and mass distribution.

A comparison of the inter-story drifts between the tested models also showed how damage and failure to the structure could happen during earthquakes. Models on softer soils exhibited larger inter-story drifts, indicating greater vulnerability to seismic-induced deformations than those on stiffer soils.

The results also highlighted the importance of realistic soil-structure interaction modelling in seismic design. The experimental findings validate theoretical predictions and emphasize the need for refined analytical methods considering site-specific soil conditions and structural parameters.

In conclusion, the experimental study contributes valuable empirical data to enhance understanding and improve methodologies for designing earthquake-resistant structures in diverse geological settings. The findings underscore the significance of integrating soil dynamics into structural engineering practices to mitigate seismic risks effectively. Future research directions may focus on refining soil-structure interaction models, exploring advanced damping techniques, and conducting field studies to validate laboratory findings.

6. CONCLUSIONS AND RECOMMENDATIONS

Therefore, this research provides an experimental understanding of the dynamic soil-structure interaction in earthquake-prone regions, with potential implications for seismic engineering and design fields. Based on the findings, several important issues recur as major decision-making factors for increasing the resistance of structures in seismically active areas.

Firstly, it supported the hypothesis that the characteristics of the subsoil play a crucial role in the tremor impact on buildings. Sandy and clayey or mixed soil compositions exhibited different stiffness levels, damping ability, and susceptibility to seismic waves. This underscores the necessity of conducting site-specific soil investigations and utilizing the results to develop codes and practices for structural design.

Secondly, the results highlighted that structural parameters such as natural frequencies and damping ratios can significantly affect the severity and distribution of earthquake forces in buildings. Generally, the structures with higher natural frequencies performed better with displacements and accelerations during an earthquake. As a result, one must select structural designs for specific foundation conditions to achieve the required stiffness and damping

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characteristics.

Also, the research emphasized the need for better seismic design code provisions that accommodate both the SSI and the dynamic properties of buildings. This includes improved analysis methods and computer simulations in all aspects of seismic risk assessment.

The study suggests several recommendations for practitioners and researchers in seismic engineering. First, it suggests improving the site's description by finding the net uplift values through a full geotechnical investigation. This will make sure that there are enough samples to figure out the variations in the soil profile. This is crucial for developing accurate soil-structure interaction models. Secondly, we should adopt dynamic analysis and design, considering the interaction between the structure and soil through frequency, response spectrum analysis, and time history. Structural designs should emphasize stiffness and damping parameters. Thirdly, we should explore innovative damping solutions such as base isolators, tuned mass dampers, and viscous dampers that respond to specific seismicity. We should fund continued research and validation to gain new experiences and test theories in real-world settings. Lastly, we should organize education and training to keep engineers and designers updated on seismic-related projects. The study concludes that seismic design and methods and an improved understanding of dynamic soil-structure interaction are necessary to design better structures that can withstand earthquake forces. Implementing these recommendations can lead to effective protection against seismic events and ensure the constant durability of constructed structures.

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