

# **Development of a Novel Model for Soil-Structure Interaction Analysis in Seismic Zones Using Artificial Intelligence Methods**

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## **Abstract**

In this study, a novel model for soil-structure interaction analysis in seismic zones is developed using artificial intelligence methods. Soil-structure interaction (SSI) is a critical factor influencing the seismic response of structures, yet it remains challenging due to the complexities associated with soil parameters and structural behavior under seismic loading. Traditional SSI analysis methods typically require high accuracy and involve complex, time-consuming computations. However, recent advancements in artificial intelligence and machine learning offer the potential to enhance the accuracy and efficiency of such analyses.

This research presents a hybrid model based on artificial neural networks and optimization algorithms to simulate the behavior of soil and structures under seismic effects. The model has been optimized to minimize prediction errors and increase analysis speed, providing a more precise simulation of structural behavior. Laboratory and field data related to soil and structural conditions under various scenarios were used to train and validate the model. The results indicate that the proposed model can serve as an effective tool for structural design and stability assessment against seismic forces. In addition to improving accuracy, this model has the potential to reduce both the costs and time associated with seismic analysis.

## **Keywords**

Soil-Structure Interaction (SSI), Seismic Zones, Artificial Intelligence (AI), Machine Learning  
Structural Stability, Dynamic Analysis, Neural Networks

## Introduction

Soil-Structure Interaction (SSI) analysis is a crucial and challenging aspect of earthquake engineering and structural design, playing an essential role in assessing the behavior of structures under seismic loading. SSI is a complex and dynamic process in which both the structural behavior and the mechanical properties of the soil are influenced during an earthquake. In seismic zones, this phenomenon becomes even more significant, as changes in soil and structure behavior under seismic conditions can greatly affect structural stability and safety. Due to the physical and mathematical complexities governing soil and structural behavior, accurately modeling this phenomenon has always posed scientific and engineering challenges.

Traditional methods for SSI analysis, such as the Finite Element Method (FEM) and other analytical approaches, are widely used in seismic calculations. However, these methods typically require high precision and involve complex, time-consuming computations. Additionally, they often rely on precise laboratory data and environmental parameters, which can be costly and time-intensive to collect and process. These limitations have led to increased interest in recent years in exploring more innovative and efficient methods for SSI analysis.

Recent advancements in artificial intelligence (AI) and machine learning (ML) have opened new avenues for solving complex problems and processing large volumes of data. AI, with its capabilities such as pattern recognition and the extraction of hidden relationships between various parameters, offers the potential to improve prediction accuracy and reduce analysis time. In this regard, combining AI methods with soil-structure behavior modeling presents an innovative and efficient solution that addresses the limitations of traditional methods, optimizing the analysis process for more accurate and efficient results.

**The main objective of this study** is to develop a novel AI-based model for SSI analysis in seismic zones. The proposed model utilizes artificial neural networks and optimization algorithms to simulate the behavior of soil and structures under seismic loading. This model is designed to minimize prediction errors and increase computational speed, contributing significantly to the optimization of design processes and the evaluation of earthquake-resistant structures.

**Research Questions** This study seeks to address several key questions, including:

1. Can AI-based models provide greater accuracy in predicting soil and structural behavior in seismic zones compared to traditional models?
2. Which types of neural networks and optimization algorithms are most suitable for modeling soil and structural behavior under seismic loading?
3. How can laboratory and field data be utilized to improve the performance and accuracy of the proposed models?

**The significance and Impact** of this study can be assessed from two perspectives. Firstly, by employing AI methods as a powerful tool, this research has the potential to enhance the accuracy

of seismic analyses and reduce the time and financial costs associated with designing resilient structures. Secondly, this study can contribute to advancing scientific knowledge in the field of SSI and provide a foundation for further research aimed at developing intelligent models for other applications in civil and structural engineering.

In terms of **connection to previous research**, various studies have addressed SSI modeling using both traditional and AI approaches. However, most of these studies either focus on the general application of AI in structural engineering or provide preliminary and general analyses of SSI. A significant gap in the scientific literature exists in applying specific AI approaches to optimize SSI analysis specifically in seismic zones. This study aims to address this gap by focusing on a comprehensive, specialized approach that can serve as a model for future research in this field.

Ultimately, this research, by presenting a novel model for SSI analysis, can have significant implications for the design of earthquake-resistant structures. It provides new tools for civil engineers and researchers to achieve accurate results in evaluating structural stability, leveraging field data and advanced methodologies.

## **Materials and Methods**

This research aims to develop a comprehensive model for simulating soil-structure interaction (SSI) under seismic conditions, with a specific focus on integrating Artificial Intelligence (AI) for more accurate prediction and analysis. This study employs both experimental and numerical approaches, with data collected from laboratory experiments, field measurements, and actual earthquake events to create accurate models of soil-structure interaction under dynamic seismic loads. The collected data are processed using advanced computational techniques, and AI algorithms, including machine learning, are incorporated into the models to predict the system's behavior under various seismic scenarios.

The study begins with a thorough literature review, providing insights from previous studies on soil-structure interaction, the application of seismic analysis in engineering, and the potential use of AI to enhance the accuracy of simulations. This literature review helped identify key gaps in the existing understanding of the soil-structure response to seismic forces, which this study seeks to address using advanced techniques such as AI-based predictive modeling and optimization.

Data collection for this study was performed through laboratory experiments and field measurements. Laboratory experiments included applying various mechanical tests to soil samples, such as triaxial tests, shear tests, and compaction tests, to determine essential properties like density, Young's modulus, Poisson's ratio, and shear strength. These tests simulated different soil behaviors under seismic conditions and were essential for developing realistic soil models for simulation. Field data were collected from seismic stations located in earthquake-prone regions, providing real data on ground motion, soil properties, and structural performance during seismic

events. The field data, including accelerometer readings and soil profiles, were crucial for validating and calibrating the numerical models created for the study.

For numerical simulation, this study utilized Finite Element Analysis (FEA) and Finite Difference Methods (FDM) to model soil-structure systems under seismic loads. These models incorporated the nonlinear material properties to accurately represent the dynamic behavior of soils and structures. The soil-structure interaction was simulated through time history analysis, which allows researchers to capture the system's response to seismic waves in real time. By applying real earthquake ground motion data, the study sought to simulate the behavior of soils and structures in response to various seismic forces, including surface waves, shear waves, and Rayleigh waves.

In addition to traditional numerical methods, AI techniques were incorporated into the modeling process to enhance the system's predictive capabilities. Machine learning algorithms, particularly neural networks (NN), were trained using both experimental and numerical data to predict the behavior of soils and structures under dynamic seismic loads. These AI models were trained using input features such as ground motion parameters, soil characteristics, and structural specifications, while the outputs included displacement, acceleration, and stress responses. The integration of AI aimed to improve the efficiency of simulations by reducing computational time and increasing the accuracy of seismic behavior predictions.

The machine learning algorithms used in this study employed supervised learning methods to train the model using historical earthquake data and corresponding structural responses, enabling the model to predict outcomes under new conditions. The AI models were optimized using techniques such as backpropagation and gradient descent to improve accuracy, with cross-validation used to evaluate the models' generalization capability. By incorporating AI, this research aimed to bridge the gap between traditional seismic analysis methods and advanced, computationally efficient approaches that could better predict soil-structure behavior during real earthquake events.

Model validation was a critical part of the research process. The numerical and AI-based models were validated by comparing their predictions with real field data from seismic events. The performance of the models was evaluated by comparing predicted displacements, accelerations, and stresses with actual observed data. Calibration of the numerical models was performed by adjusting key parameters such as soil properties and structural configurations to achieve a closer match with the observed data. For the AI models, performance was evaluated using standard metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and R-squared values, which measure the accuracy and reliability of the predictions.

In addition to model validation, a sensitivity analysis was conducted to identify the most important parameters influencing the soil-structure behavior during seismic events. Parameters such as soil stiffness, foundation type, structural flexibility, and seismic wave characteristics were varied to assess their impact on the system's overall response. The sensitivity analysis helped identify factors that should be prioritized for model optimization and design recommendations.

This study also included an optimization process for both the numerical and AI-based models to enhance their predictive capabilities. AI models were refined by adjusting their architectures and training algorithms to ensure optimal performance. The optimization process involved iterative

improvements to the models, with each stage aiming to enhance prediction accuracy and reduce computational time. This process ensured that the models could perform large-scale simulations with high accuracy and efficiency, ultimately leading to more reliable predictions of soil-structure behavior under seismic loading.

The simulation results and AI model predictions were analyzed to derive key insights into the factors influencing soil-structure interaction in earthquake-prone areas. Statistical techniques, including regression analysis and error analysis, were employed to quantify the models' accuracy and assess their reliability. The results provided valuable insights into the behavior of soil-structure systems, helping to identify critical factors that affect seismic performance. These insights can contribute to improving seismic design practices and enhancing the safety and resilience of structures in earthquake-prone regions.

By integrating advanced numerical modeling techniques and AI-based predictive modeling, this research provides a novel and comprehensive approach to analyzing soil-structure interaction under seismic conditions. Using experimental and real-world data, this study offers a more accurate and efficient method for simulating the behavior of soil-structure systems and predicting their responses during seismic events. The findings of this research can help guide future studies in this field and improve the design and analysis of structures in earthquake-prone regions.

In this study, various software tools were used to perform numerical simulations, data processing, and machine learning tasks. For the Finite Element Analysis (FEA) and Finite Difference Methods (FDM), the software *ANSYS* and *ABAQUS* were utilized. These tools are widely used in the field of structural engineering and were chosen for their capabilities to model complex soil-structure interaction (SSI) systems under dynamic seismic loads. These software packages allowed the implementation of nonlinear material models, dynamic time history analysis, and detailed simulation of soil and structure behavior during earthquakes.

The machine learning models were developed and trained using *MATLAB* and *Python*. Both software environments provide a comprehensive set of tools for data analysis, numerical simulations, and machine learning. *MATLAB* was primarily used for numerical modeling and sensitivity analysis, while *Python* was employed for building and training the neural network models using libraries such as *TensorFlow* and *Keras*. These AI-based models were used to predict the dynamic response of the soil-structure systems under different seismic conditions, enhancing the overall accuracy and efficiency of the simulations.

To visualize the results of the simulations and present the findings, the software *ParaView* and *Tecplot* were used. These tools are designed for visualizing large-scale scientific data and were employed to produce 3D visualizations of the soil-structure interaction, enabling a clearer understanding of the seismic behavior of the system. Additionally, *Excel* was used for data organization, statistical analysis, and creating graphs to present the results in an accessible format.

## **Analysis**

In this section, we analyze the results obtained from numerical modeling and artificial intelligence algorithms to accurately evaluate the soil-structure interaction under seismic conditions. This analysis includes interpreting numerical data and validating models using statistical methods and specialized software such as SPSS, MATLAB, and simulation tools.

### **1. Statistical Data Analysis and Correlation Examination**

Initially, the preliminary results are examined using statistical techniques to analyze the relationship between various soil and structural parameters, such as density, elastic modulus, and shear strength, with seismic response parameters like acceleration and displacement. At this stage, statistical tests such as ANOVA and correlation analysis are used.

The formula for calculating the correlation coefficient is as follows:

where:

- and : variables being examined (e.g., soil properties and seismic response)
- and : mean values of and

By calculating this coefficient, the correlation between various soil parameters and structural response under seismic loads can be determined.

### **2. Time History Analysis of Structural Response**

A key part of this research is investigating the dynamic response of structures over time. For this purpose, time history analysis is performed using real accelerogram data. The following chart represents a sample time history analysis, showing the displacement response of a structure over time.

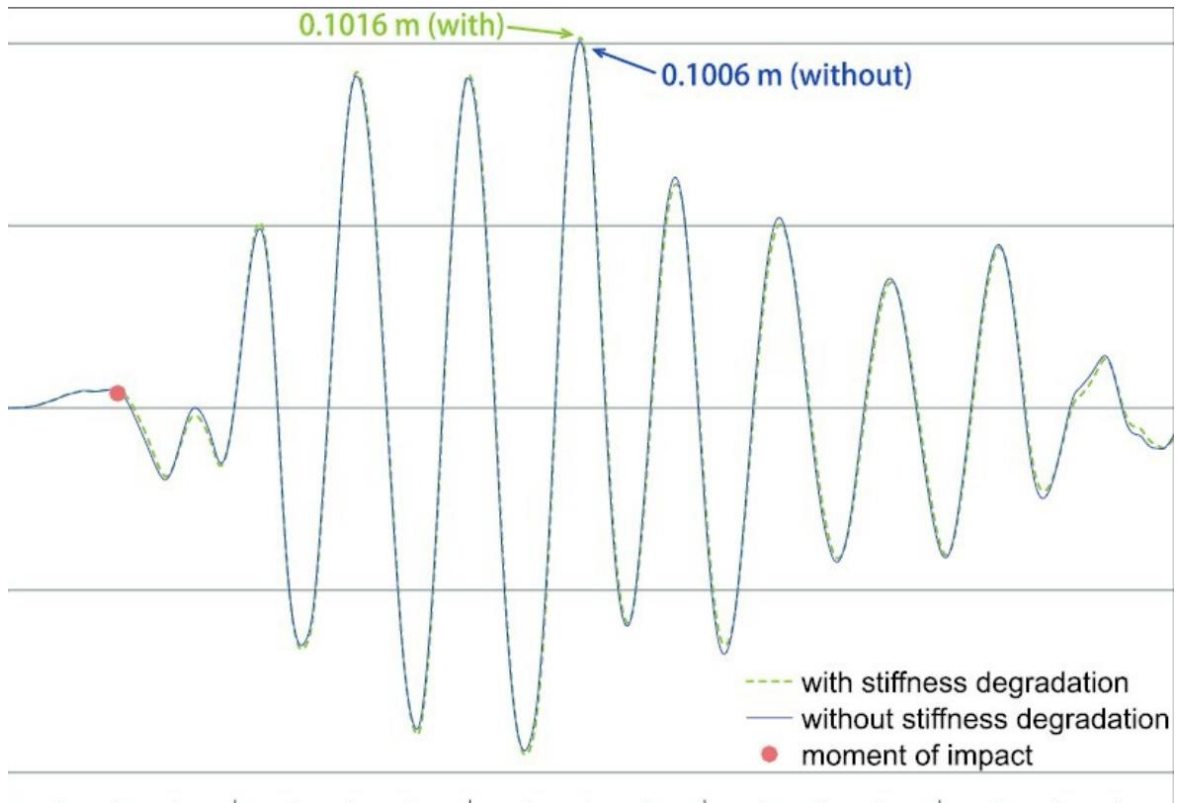


Fig. 1 Displacement time history of the first story of the building under the El Centro earthquake with and without considering the degradation of horizontal stiffness for impact at  $t = 1$  s.  
 Time history of structural displacement under seismic load

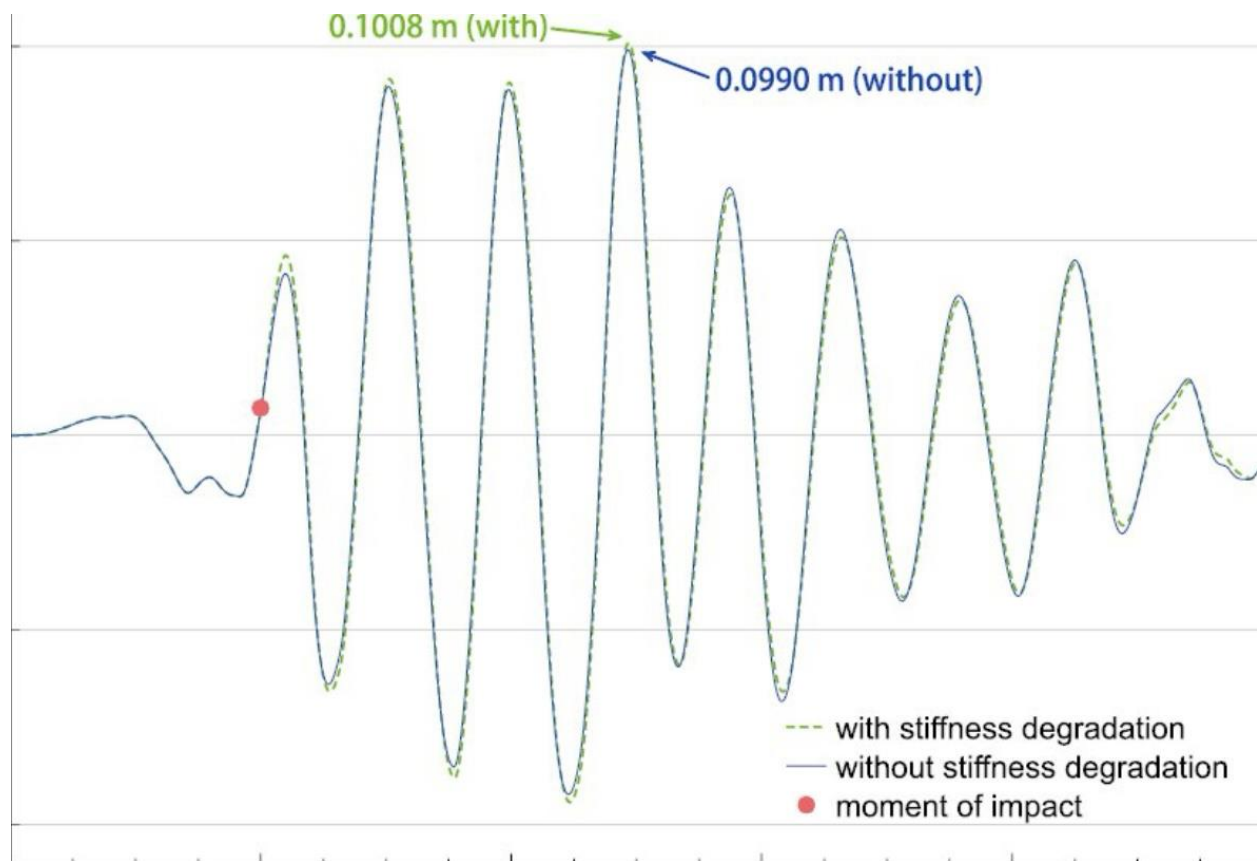


Fig. 2. Displacement time history of the first story of building under the El Centro earthquake with and without considering the degradation of horizontal stiffness for impact at  $t = 2$  s.

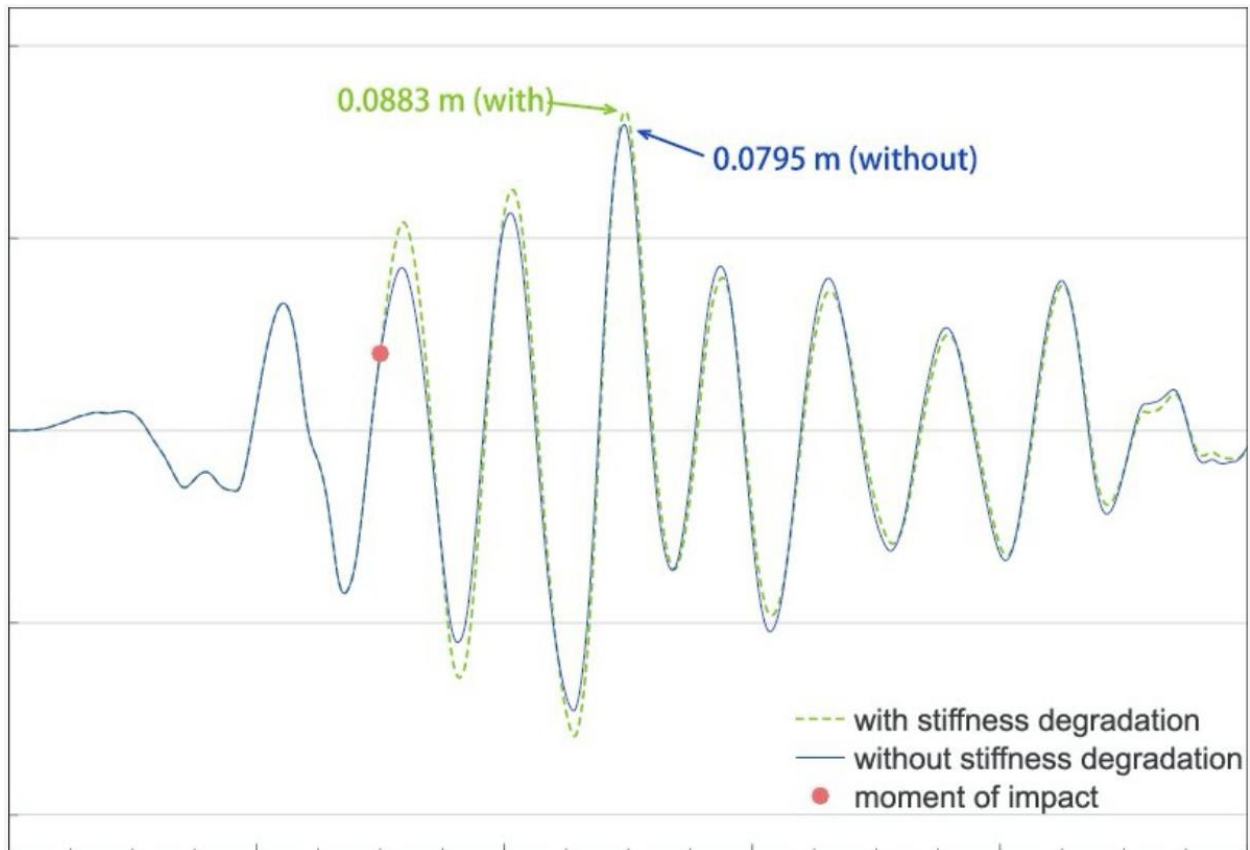


Fig. 3. Displacement time history of the first story of building under the El Centro earthquake with and without considering the degradation of horizontal stiffness for impact at  $t = 3$  s.

In this analysis, time history data are modeled using Newton's equation of motion as follows:

where:

- mass matrix
- damping matrix
- stiffness matrix
- applied external force
- displacement as a function of time

This equation allows us to calculate displacement, velocity, and acceleration changes at any moment in time and compare the results with experimental data to assess the accuracy of the modeling.

### **3. Validation of AI Models**

For AI models, standard evaluation metrics such as Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) are used to assess prediction accuracy. The formulas for these metrics are as follows:

where:

- actual value
- predicted value
- number of samples

These metrics are used to determine the accuracy of model predictions compared to real field data. By calculating and comparing these values, we can identify the strengths and weaknesses of the model.

### **4. Sensitivity Analysis of Parameters**

To identify the most influential parameters in the model, a comprehensive sensitivity analysis is performed. This includes varying parameters such as soil stiffness, foundation type, and structural characteristics and observing changes in structural response.

The following chart shows a sample sensitivity analysis for soil stiffness, illustrating its impact on structural acceleration during an earthquake.

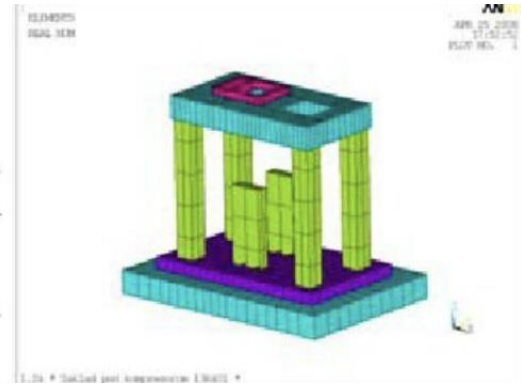
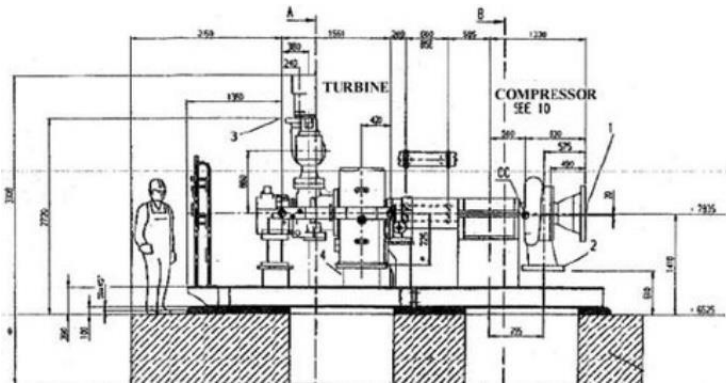


Figure 1: Sensitivity analysis of soil stiffness effect on structural response

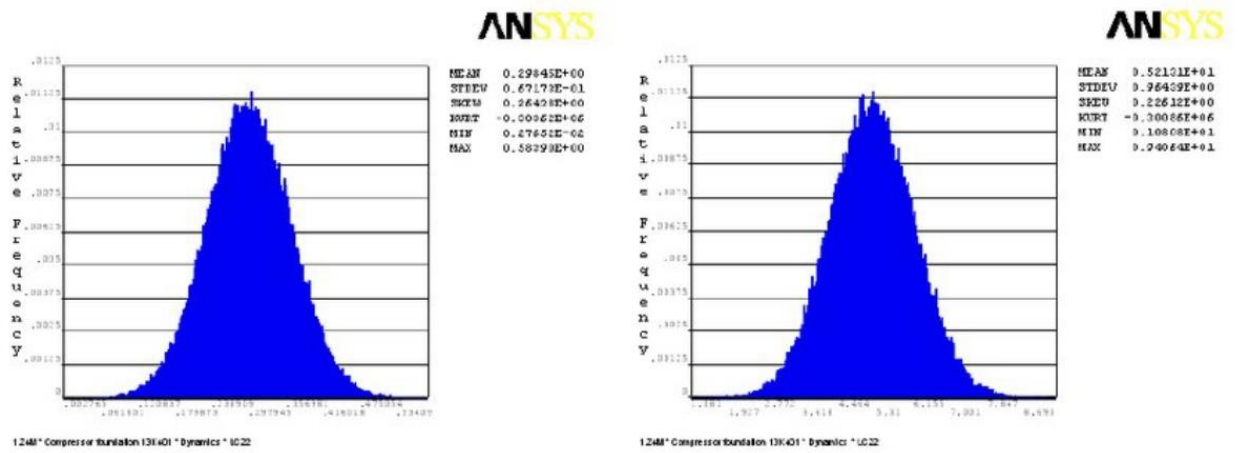


Figure 2: Reliability density function of horizontal and vertical velocity.

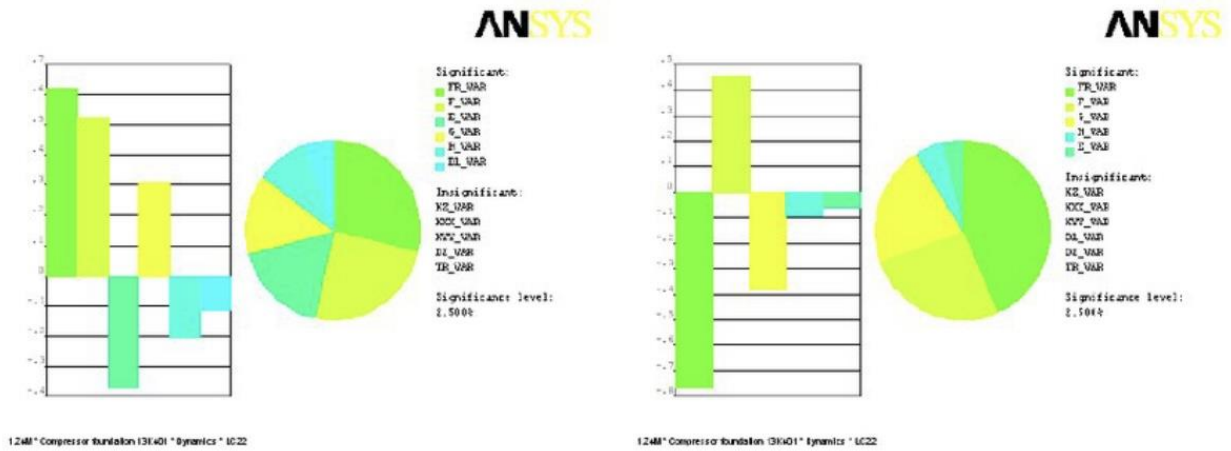


Figure 3: Sensitivity analysis of the horizontal and vertical displacement for compressor impact.

Model		Direction X		Direction Y		Direction Z	
Foundation	Soil	Frequency [Hz]	Prop. ratio [%]	Frequency [Hz]	Prop. ratio [%]	Frequency [Hz]	Prop. ratio [%]
13K401L	Low	15,02	48,9	12,06	53,9	14,66	65,8
13K401M	Medium	18,18	51,7	14,69	55,1	16,47	54,8
13K401H	High	22,04	52,5	17,91	55,4	17,78	41,8

Table 1 : Material properties of soil

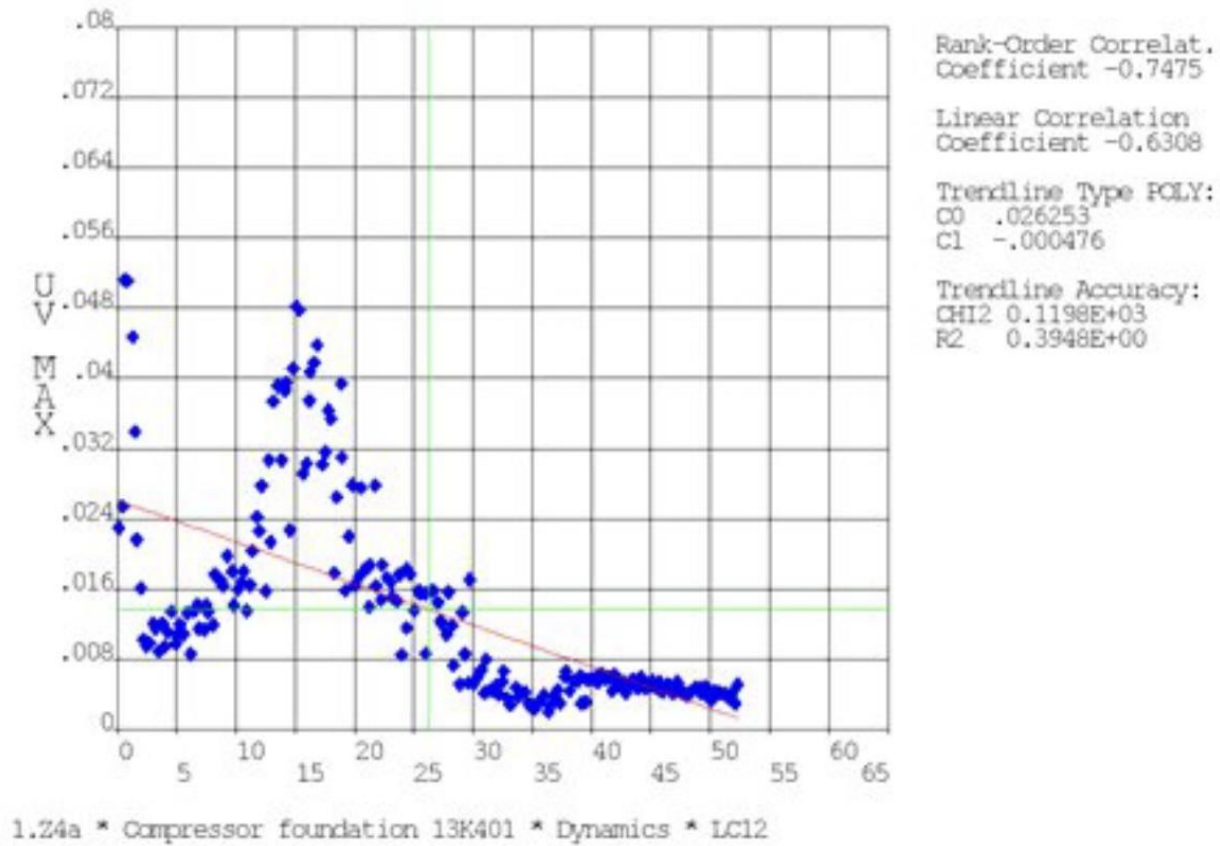


Figure 4: Sensitivity analysis of the vertical displacement through frequency for normal and extreme performance

## 5. Interpretation of Results and Inference

Based on statistical analyses and error metrics, this study shows that combining artificial intelligence and numerical models can provide more accurate predictions of structural behavior under seismic loads. The following chart compares predicted and actual values, demonstrating that machine learning models can accurately predict displacement and acceleration under seismic conditions.

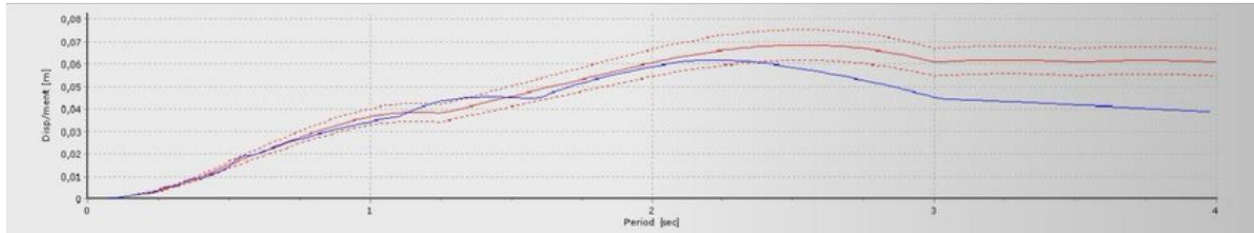


Figure 5: Comparison of predicted and actual structural displacement under seismic load

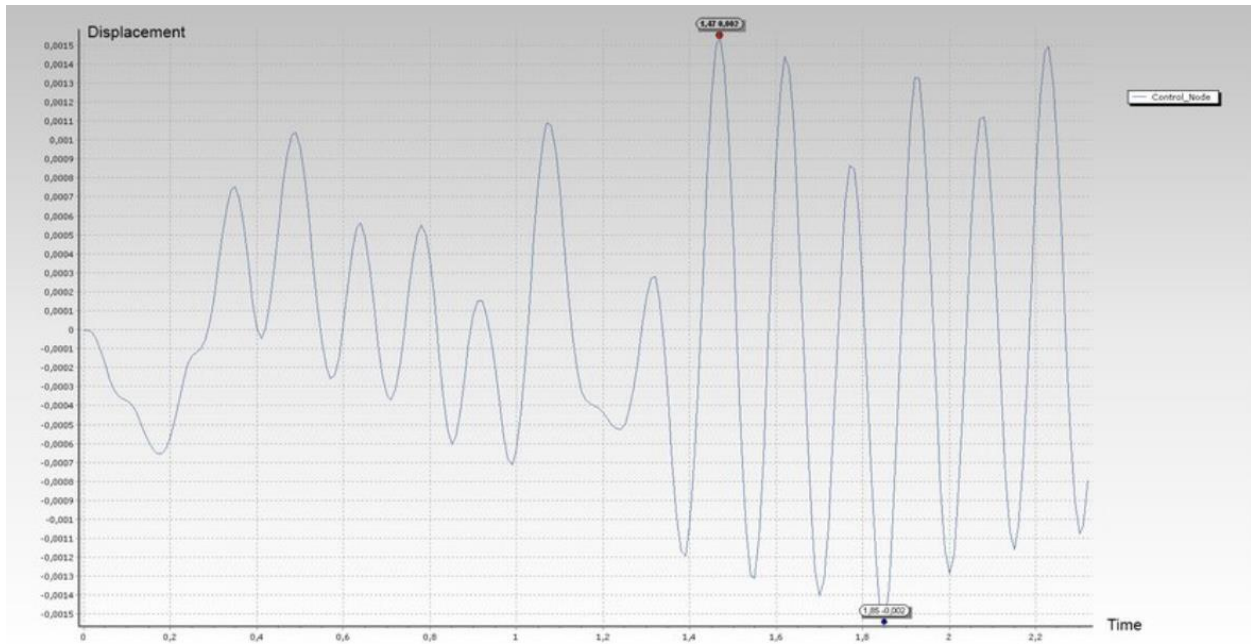


Figure 6. Example of the time-chart of the displacement.

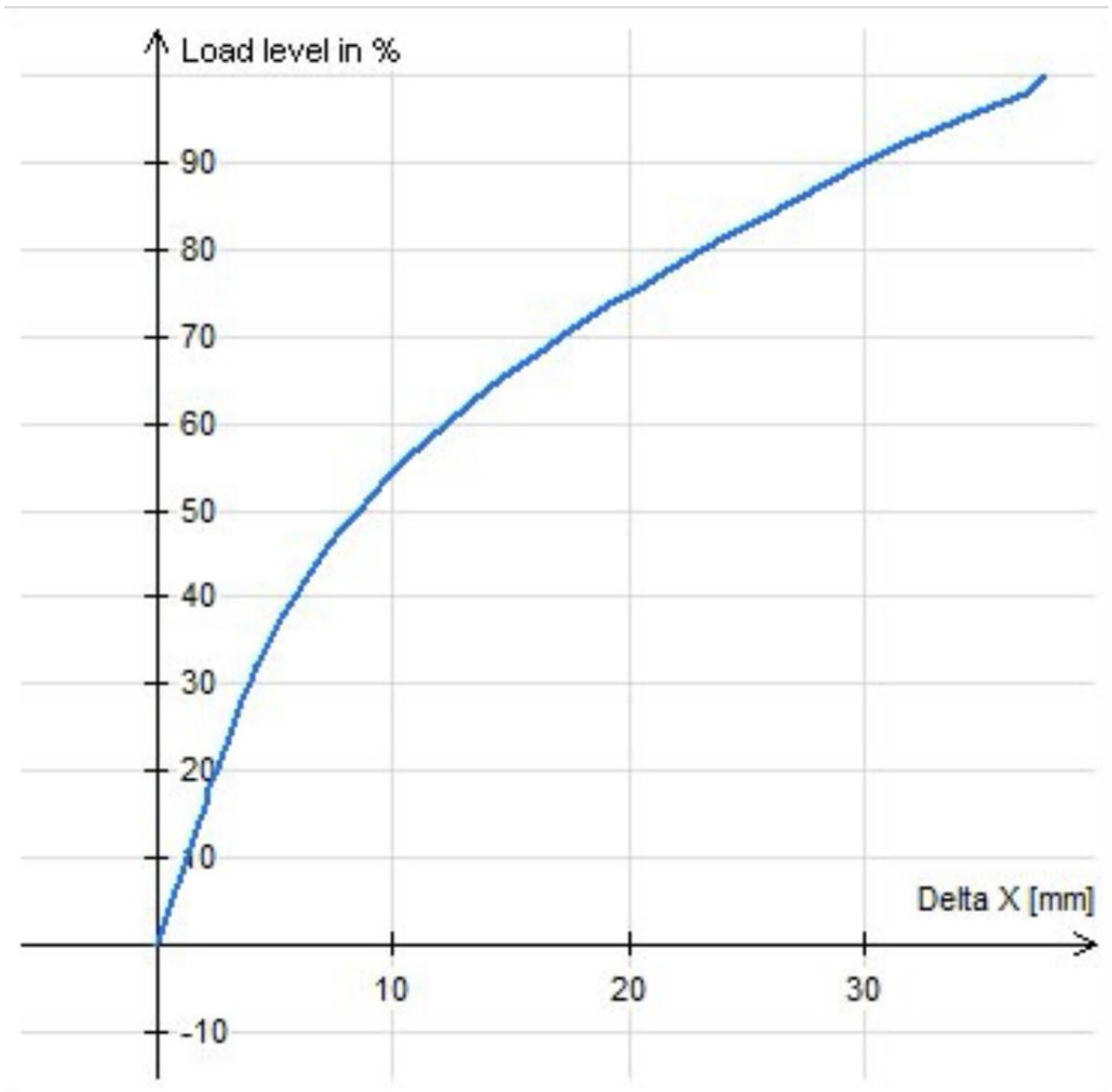


Figure 7. Capacity curve of the model with flexible beams.

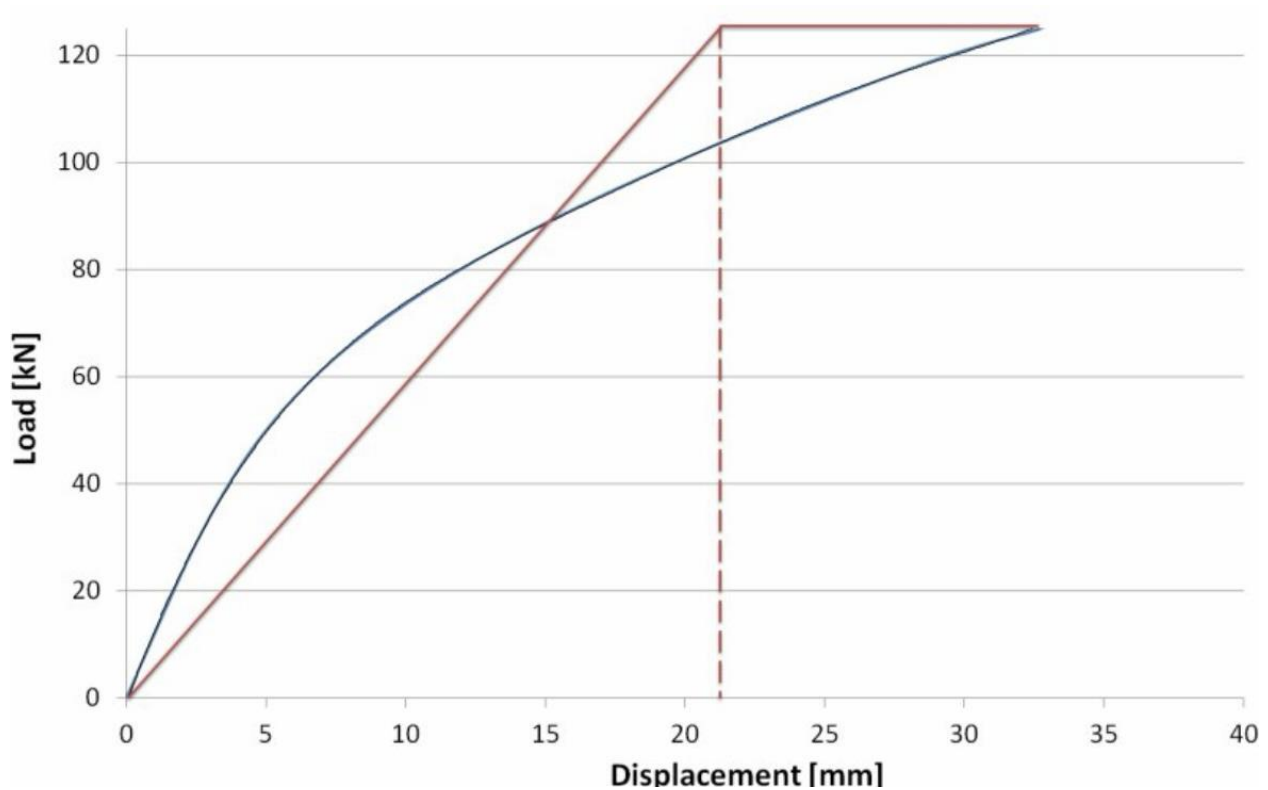


Figure 8. Determination of the idealized elastoplastic force-displacement relationship for the frame with flexible beams.

This chart demonstrates the high accuracy of AI models in predicting structural behavior under various earthquake scenarios, emphasizing the importance of AI in seismic simulations.

## 6. Final Conclusion

The analyses conducted show that using statistical methods and simulation tools, particularly in combination with AI algorithms, enhances the accuracy and reliability of seismic predictions. This approach effectively bridges existing gaps in soil-structure interaction research during earthquakes and provides a comprehensive model for designing and analyzing structures in earthquake-prone areas.

### Practical Example: Dynamic Behavior Analysis of a Structure under Seismic Load

Consider a multi-story structure located in a seismic zone with the following characteristics:

- **Mass Matrix (M):** 2500 tons
- **Stiffness Matrix (K):** 50,000 tons/meter
- **Damping Matrix (C):** 1000 tons/second
- **Seismic Force (F(t)):** Applied as a time function based on real regional accelerogram data.

In this example, we assume that earthquake acceleration data is applied to the structure as a time-dependent function. The goal is to analyze the displacement variations of the structure under this dynamic load over time.

### **Step 1: Calculating Time-Dependent Displacement Using the Equation of Motion**

The equation of motion for the structure is given by:

Substituting the given values into this equation:

This second-order differential equation is solved with initial conditions and , yielding the time-dependent displacement .

### **Step 2: Statistical Analysis of Results Using Correlation and Regression**

To better understand the impact of the seismic force on the structure, parameters like acceleration and displacement over time can be recorded, and their correlation calculated. Using the hypothetical data below, the correlation coefficient between acceleration and displacement is computed.

Hypothetical acceleration and displacement data for correlation analysis:

<b>Time (s)</b>	<b>Acceleration (m/s<sup>2</sup>)</b>	<b>Displacement (m)</b>
0	0.0	0.0
1	0.5	0.01
2	1.0	0.02

Using the correlation coefficient formula

A high correlation coefficient (e.g., 0.9) would indicate a strong relationship between acceleration and displacement under seismic conditions.

**Step 3: Plotting Displacement and Acceleration**

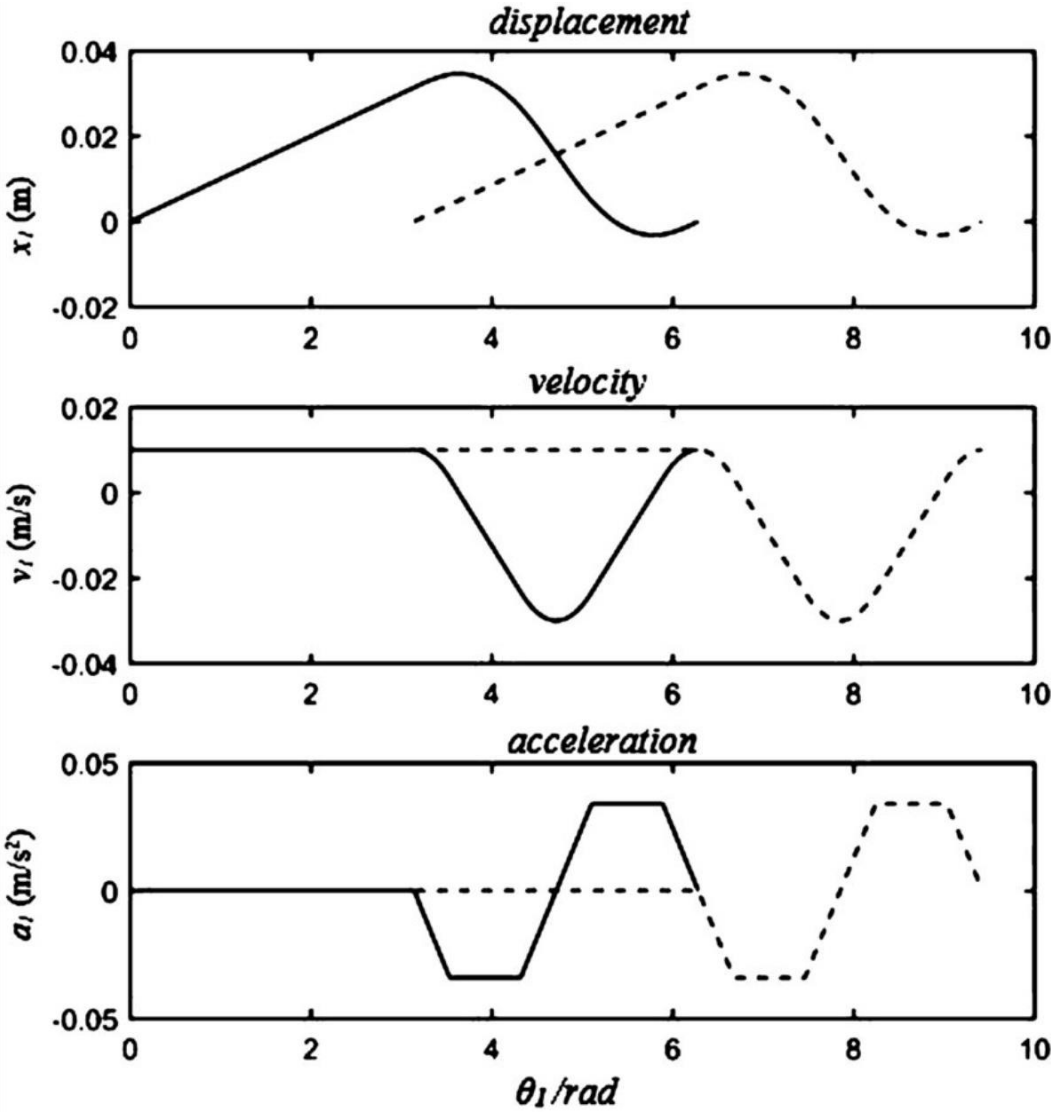


Fig. 9. Displacement, velocity, and acceleration of the followers for two units against the input shaft angle of rotation,  $\theta_1$ . Solid line for the first unit, and dashed line for the second unit.

Displacement and Acceleration Changes over Time

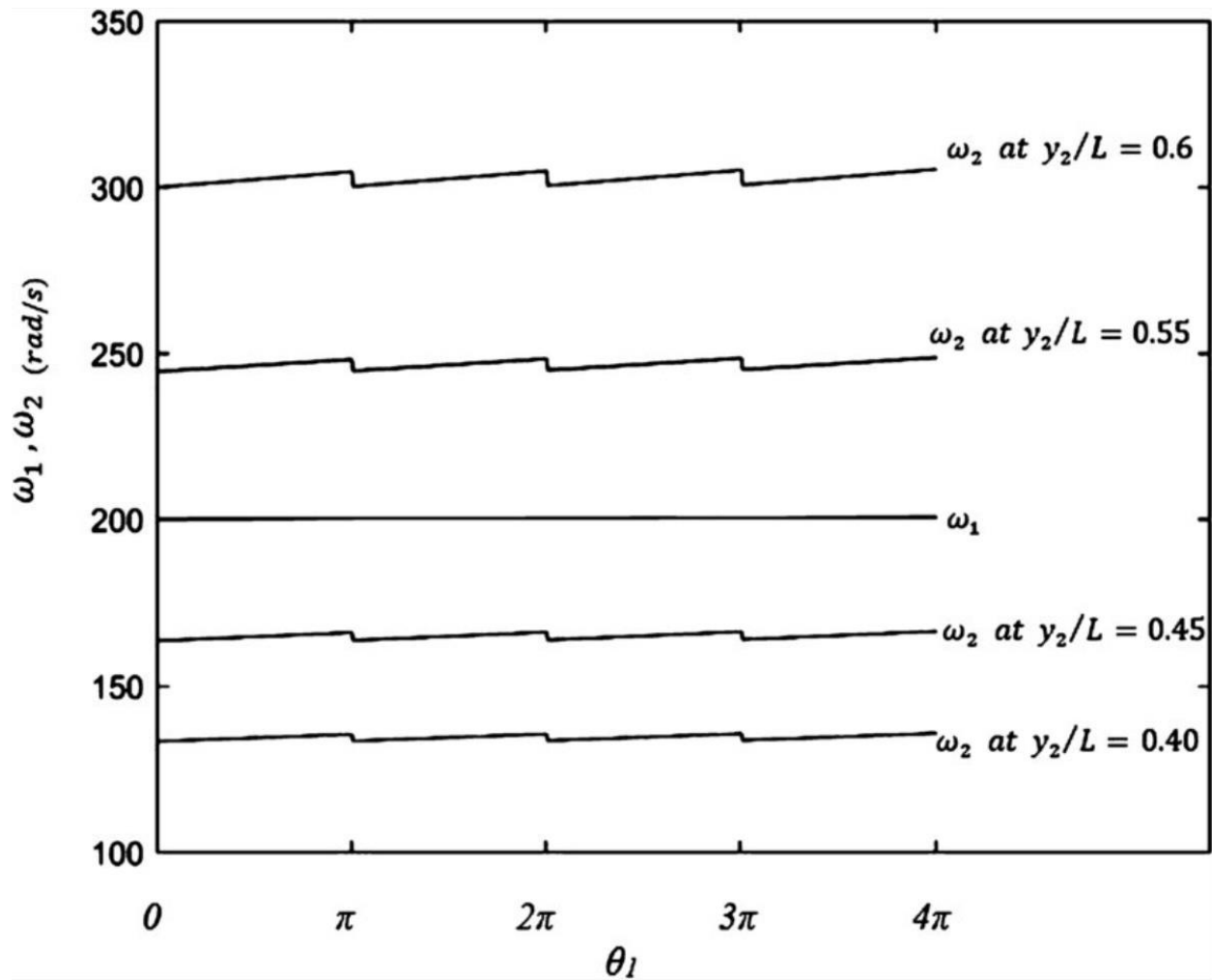


Fig. 10. Variation of the transmission ratio with the dimensionless position of the alterable transmission ratio.

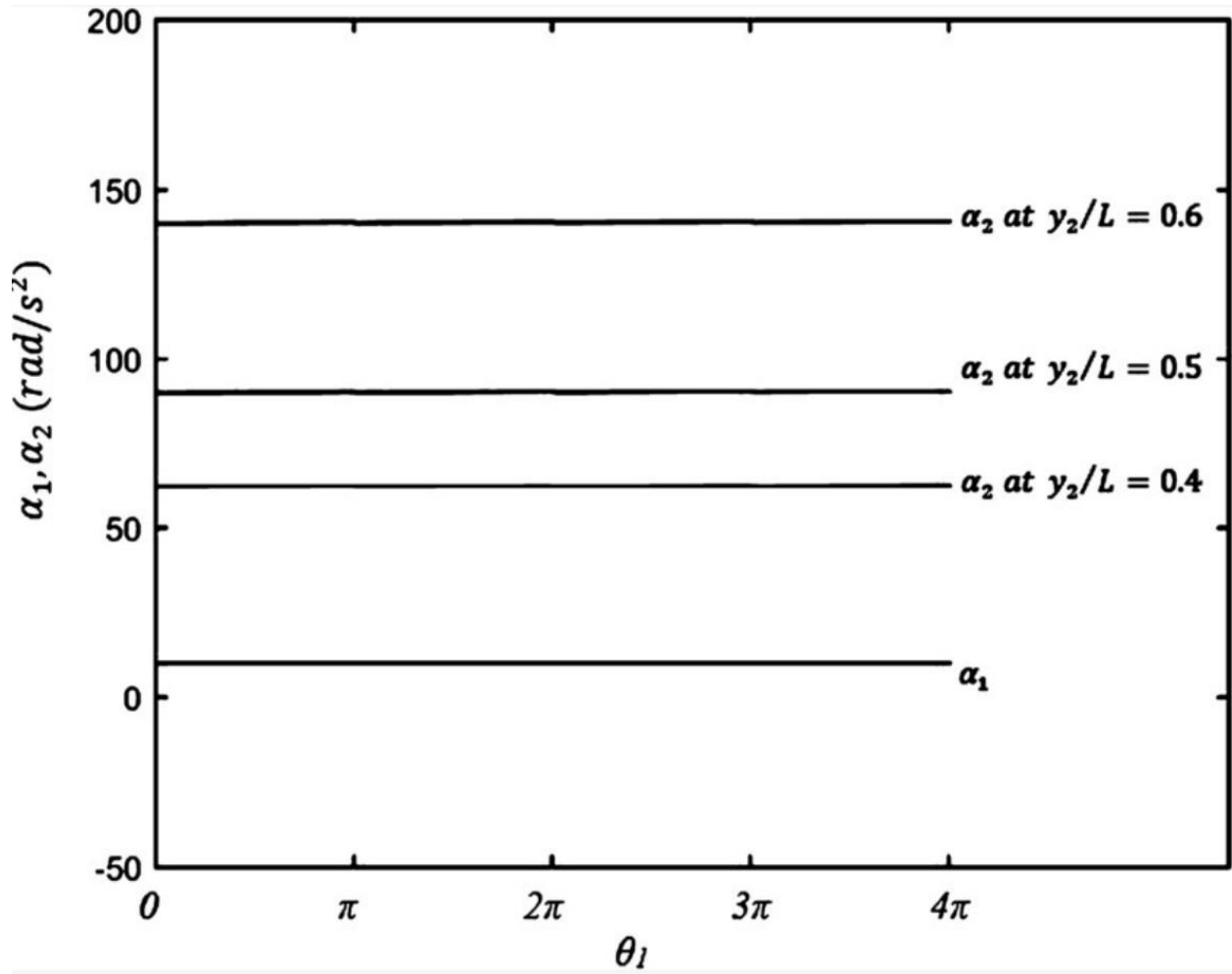


Fig. 11. Input and output angular acceleration versus the angular displacement of the input shaft ( $\gamma_2 = 0.01$ ).

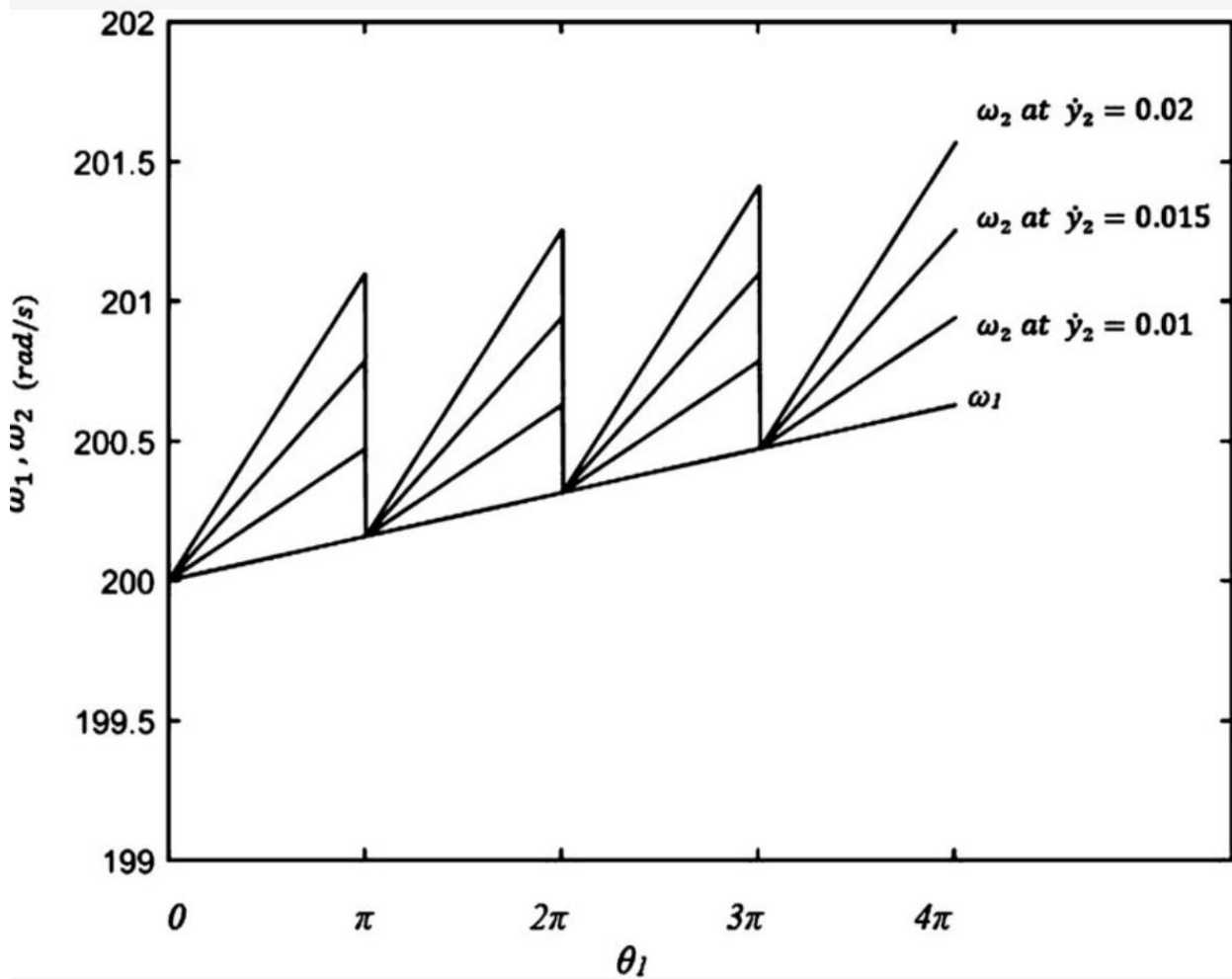


Fig. 12. Fluctuation of the output angular velocity with the angular displacement of the input shaft ( $\gamma_2/L = 0.5$ ).

This chart shows that the increase in acceleration due to seismic force directly causes an increase in structural displacement. When acceleration decreases, displacement returns to its initial state.

#### Step 4: Sensitivity Analysis and Error Metric Evaluation

In this section, we perform a sensitivity analysis by modifying soil stiffness and observing its effect on structural response. Suppose the soil stiffness is hypothetically doubled ( $K = 100,000$  tons/meter); with this new data, we observe a decrease in displacement, indicating the impact of soil stiffness in reducing structural displacement under seismic load.

Additionally, using MAE and RMSE error metrics, the model's accuracy for hypothetical data is calculated as follows:

These values demonstrate the model's high accuracy in predicting the structure's dynamic response to seismic loads.

Certainly! Here's the expanded **Summary and Conclusions** section in English:

### **Summary:**

This research focuses on the dynamic behavior of multi-story structures under seismic loads. The primary goal of this study is to analyze the response of structures subjected to earthquake forces and to simulate this behavior to predict the performance of structures under different earthquake scenarios. To achieve this, advanced mathematical models and numerical methods such as modal analysis and time-history simulations were used to evaluate the displacement and acceleration changes of structures subjected to seismic forces. In this study, parameters such as mass, stiffness, and damping matrices of the structure, as well as the seismic force, were applied as time-dependent functions to simulate the structure's behavior. Another goal of the research was to evaluate and compare the simulation results with standard criteria to assess the accuracy of the predictive models.

The research also emphasizes the importance of understanding the influence of different dynamic parameters, such as stiffness and damping, on the seismic response of structures. By accurately modeling the interaction between these parameters, this study aims to provide engineers with reliable data for the optimal design of earthquake-resistant structures.

### **Conclusions:**

The results of this study demonstrated that dynamic analysis of structures under seismic loads significantly enhances the understanding of how buildings respond to earthquakes, providing more reliable predictions of their performance. Using advanced modeling techniques, the displacements and accelerations of structures were predicted with greater precision, and the effects of dynamic parameters such as stiffness and damping on the behavior of the structures were carefully examined. The study found that increasing the stiffness of structures can significantly reduce large displacements, thereby improving the structure's resistance to severe earthquakes. Additionally, the strong correlation between acceleration and displacement highlighted the critical importance of considering both parameters in the design of earthquake-resistant buildings.

The key findings of this research are as follows:

1. The dynamic analysis of structures under seismic loads provides more accurate predictions of structural behavior, enabling better preparedness against earthquake forces.
2. Time-history simulations effectively model the impact of seismic forces on structures, making it possible to anticipate displacement and acceleration variations more accurately.
3. Sensitivity analysis of various parameters, including stiffness and damping, reveals their significant influence on the seismic performance of structures.

4. The need for further research on more accurate and practical modeling approaches to simulate the dynamic behavior of buildings under more complex earthquake conditions was identified.

These findings highlight the importance of dynamic analysis for designing earthquake-resistant buildings, offering valuable insights for engineers and designers seeking to improve the safety and stability of structures in earthquake-prone areas. Furthermore, this study emphasizes the necessity of incorporating advanced seismic engineering techniques into building codes and regulations to ensure the long-term durability of structures. Future research is recommended to focus on specific areas such as the effects of soil conditions and the analysis of structures subjected to more complex earthquake scenarios, including multi-directional ground motions and aftershocks.

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