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Soil Structure Interaction Effect Accounted for Seismic Design of RC Structure

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ABSTRACT

Seismic design of reinforced concrete (RC) structures is a critical aspect of ensuring structural safety and resilience in earthquake-prone regions. Soil-structure interaction (SSI) may have significant effects on free vibration characteristics and seismic response of some structures. These effects result from the soil inability to fully restrain the movements of structure foundation in addition to soil's large energy dissipation capacities. The seismic response of structure is greatly influenced by soil structure interaction. This work aims to address the importance of considering soil- structure interaction (SSI) effects in the seismic design process for RC structures Taking a multistory reinforced concrete frame structure as an example the modal analysis of whole structure carried out by using SAP 2000 software. The 8, 10, 12 story structure is modeled. The current research on 8, 10, 12 storey structure is analyzed in SAP 2000 with and without soil structure interaction. The result shows that as number of storey increases the joint displacement also increases and as the story height increases the base reaction is decreases. The study shows that by introducing soil structure interaction the joint displacement and base reaction are increases as compared to structure without soil interaction.

KEY WORDS: Soil structure interaction, SAP 2000, Seismic analysis, Joint Displacement, Joint Reaction

I. INTRODUCTION

Soil-structure interaction (SSI) is a critical factor in the seismic design of reinforced concrete (RC) structures. This phenomenon refers to the interplay between the structural system and the underlying soil or foundation during seismic events, and it can have a substantial impact on the structural response to earthquakes. Soil-structure interaction (SSI) is a critical consideration in the seismic design of reinforced concrete (RC) structures. In seismic design practices, SSI is addressed through various means, often guided by specific design codes and standards such as the International Building Code or Eurocode. These codes typically require structural engineers to account for SSI effects during the analysis and design phase. The properties of the foundation, particularly soil stiffness and damping, play a crucial role in SSI, as they affect how the structure responds to ground motion.

To consider SSI effects, engineers employ advanced analytical methods like finite element analysis to model the interaction between the structure and the underlying soil. The results of these analyses help in assessing the structure's response to seismic loads. Additionally, engineers may incorporate SSI mitigation measures into their designs, such as base isolators or deep foundations, to reduce the impact of SSI on the structure's performance during an earthquake.

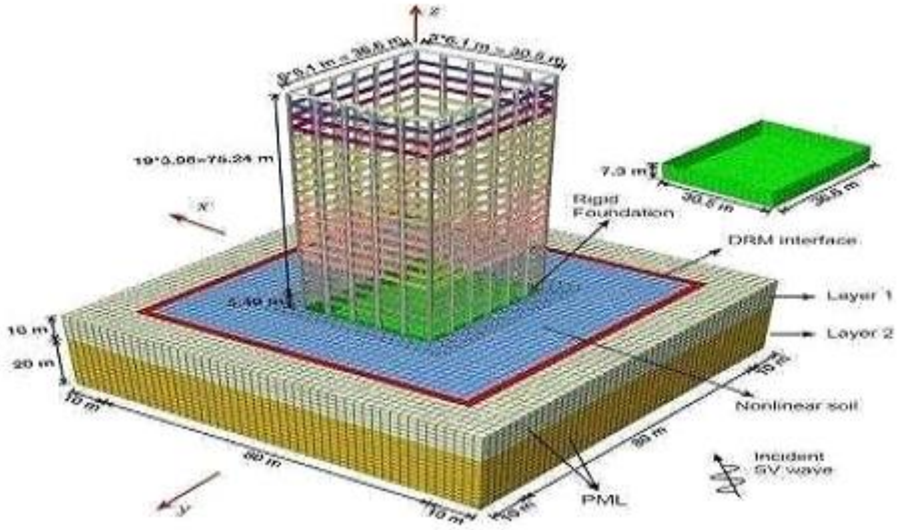

Fig1: Dynamic soil structure interaction

The fig 1. shows that Dynamic Soil-Structure Interaction (DSSI) is a complex field of study in structural engineering and geotechnics. It examines how the interaction between a building or structure and the underlying soil affects the structure's response to dynamic loads, such as earthquakes or vibrations. In DSSI, the behavior of both the structure and the soil is considered simultaneously, as opposed to traditional static analysis. During dynamic events, the stiffness and damping properties of the soil can change, impacting the structure's natural frequencies, displacements, and stresses. Engineers use advanced computational methods, including finite element analysis, to model this interaction accurately. Understanding DSSI is crucial for designing resilient structures, ensuring they can withstand seismic forces or other dynamic loads.

Needs of Soil structure Interaction:

Studying soil-structure interaction (SSI) is essential for:

- Dynamic Response:

During an earthquake, the ground motion induces dynamic forces on structures. SSI affects how these forces are transmitted from the ground to the structure, impacting its dynamic response. Neglecting SSI can lead to inaccurate predictions of a structure's behavior

- Amplification and Damping:

SSI can lead to amplification or reduction of ground motion at the foundation level. Understanding these effects helps engineers design foundations and structural systems to withstand the seismic loads effectively.

- Deformation Compatibility:

SSI accounts for the relative deformations between the soil and the structure. Ignoring this interaction can result in excessive stress concentrations, leading to structural damage or failure.

- Lateral Soil Resistance:

The lateral resistance provided by the surrounding soil affects the lateral stability of a structure during an earthquake. SSI analysis helps ensure that the structure remains stable under seismic loads.

Techniques for soil structure interaction:

- Dynamic Analysis:

Dynamic analysis methods such as time history analysis and response spectrum analysis are frequently used to analyze response patterns in seismic scenarios. SSI can be integrated into these analyzes by taking into account the different stiffness and damping properties of the soil

- Equivalent Static Analysis:

This simple approach involves converting the power supply into a static equation that includes SSI effects. The concept of dynamic time is used to represent the dynamic behavior of the system. This method is used when dealing with earthquake or wind energy. Instead of considering the time history of dynamic loads, engineers calculate a series of static loads that will create something like maximum response.

- Site-Specific Response Spectra:

Determining site-specific response spectra that consider local soil conditions is essential. These spectra can be used to account for amplification or de amplification of ground motion due to the soil's characteristics. These spectra are custom-generated for specific locations based on the local geological and geotechnical conditions. Site-specific response spectra provide a graphical representation of ground motion, showing the acceleration response of a site to different frequencies and amplitudes of seismic waves.

- Nonlinear Analysis:

Nonlinear analysis methods can capture more complex SSI effects, such as soil yielding or foundation rocking. This is particularly important for structures on soft soils. This analysis considers the nonlinear response of materials under various loading conditions, allowing for a more accurate representation of real-world structural behavior. Nonlinear analysis is crucial when dealing with complex problems, such as large deformations, material yielding, and post- elastic behavior, which cannot be adequately addressed through linear analysis methods.

- Pushover Analysis:

Pushover analysis helps assess the seismic performance of a structure by applying lateral forces incrementally. This approach can incorporate SSI effects by considering soil behavior and foundation flexibility. This method involves applying a gradually increasing lateral load to a structure and studying its response in a nonlinear manner.

Problem Description:

Soil-structure interaction (SSI) is a crucial consideration in the assessment of the dynamic behavior and seismic response of reinforced concrete structures. It represents the complex interplay between the building's foundation, the underlying soil, and the structure itself. In seismic-prone regions, understanding and accounting for SSI is paramount for designing resilient and safe buildings.

During an earthquake, the ground motion can cause the foundation to move relative to the soil, leading to dynamic forces that impact the structure's stability. Neglecting SSI can result in inaccurate predictions of a building's behavior during a seismic event. By considering SSI, engineers can optimize the design and reinforcement of structures to withstand the forces generated by an earthquake.

Effective SSI analysis involves modeling the interaction between the building and the soil, considering factors such as soil stiffness, damping, and the building's mass and flexibility. This comprehensive approach ensures that the structure can dissipate seismic energy and remain structurally sound, protecting occupants and preserving property.

II. LITERATURE REVIEW

- **Tomeoa, et al. (2017),** investigated how soil-structure interaction (SSI) affects the seismic performance of reinforced concrete buildings. Researchers varied soil properties, SSI modeling techniques, and seismic design levels. Results showed that the modeling approached significantly impacts seismic demanded estimates. A detailed finite element model (fem) could reduce seismic demands by up to 50%, while a simplified beamed on nonlinear Winkler foundation (BNWF) model had smaller effects, primarily in 8-story buildings on soft soils. The key difference lied in damping characteristics, with the BNWF model underestimating energy dissipation due to SSI.
- **Shehata, et al. (2014),** studied analyzed impact of soil-structure interaction (SSI) on multi-story buildings with raft foundations. They used three analysis methods and found that the fundamental period of vibration was influenced by SSI and may been underestimated by empirical expressions. SSI, especially with soft soil, increased story displacement and shear responses. The studied showed that SSI significantly affects base forces and roof displacement. For mid-rise moment- resisting buildings on soft soil, considering SSI in seismic design was crucial for structural safety during earthquakes. neglecting SSI may lead to unreliable safety assessments.
- **Ibrahim, et al. (2020),** investigated the impact of soil-structure interaction on 40 existing buildings constructed before and after the implementation of turkey's modern seismic design code in 1998. They used non-linear time history analyses with four different soil conditions. The findings revealed that soil-structure interaction doesn't increase displacement capacity but could shifted it. Weak soil conditions increased rotations at the base, affecting elastic drift ratios. Soft soil conditions had the most significant impact, particularly on low-story buildings. The first stories were most affected, and the number of collapsed buildings increased under soft soil conditions, with old and low-story buildings being more vulnerable.
- **M. Requena Cruz, et al. (2022),** focused on assessing the effects of Soil- Structure Interaction (SSI) in seismic vulnerability analyses of reinforced concrete buildings in Lisbon. It presents a methodology for including and quantifying SSI effects. The key conclusions include:Soil Characterization: A method is proposed to define soil parameters based on laboratory and in situ tests, with a focus on clayey soil common in Lisbon. Superstructure Modeling: The chosen mid- rise building is susceptible to p-Δ effects and is affected by SSI according to EC8. Foundation Analysis: Properly modeling footings is crucial for accurate results, and the study highlights the importance of considering the ultimate soil capacities3D Soil Modeling: Coarse mesh and linear soil models result in rigid behavior and unreliable outcomes. Improved modeling considers flexible soil properties and interactions with footings, leading to more accurate results.
- **P. N. Thakur, et.al (2022),** the researched paper concludes that "Soil Structures Interaction of Multi-Storey Buildings on Raft Foundations under Dynamic Loads" highlights the importance of dynamic soil-structure interaction in mitigating the impact of seismic events on high-rose buildings. The studied emphasizes the used of shear walls supported by piled mats to reduced damaged caused by seismic impacts. Through a 3D numerical approached, the researched assesses the effects of soil-structure interaction on the seismic performance and earthquake- induced losses in tall buildings. The studied also investigates the influenced of size and load- bearing mechanisms of piles on the seismic performance of buildings considered soil-pile- structure interaction. Overall, the research underscores

the significance of understood and optimizing soil-structure interaction to enhance the resilience of multi-storey buildings under dynamic loaded.

III.METHODOLOGY

- **General**

The methodology entails outlining a step by step procedure to be followed for the completion of project.

- **Introduction to SAP 2000:**

SAP2000 is the most powerful Windows version of the SAP series. It is the most integrated and effective 3D static and structural analysis software. SAP 2000 integrates all calculations and analysis of load calculation, dynamic seismic analysis, linear and non-linear analysis, steady-state and functional spectral density analysis and static pushover analysis, and provides fast, reasonable and reliable as true linear, non- linear, static and dynamic analysis. SAP has been widely used in the field of structural engineering analysis since its birth.

The general steps of structure analysis and design with SAP2000 are as follows:

Create and modify models to define the material, geometry, load, and analysis parameters of the structure; Model analysis

View analysis results

View and optimize structural design

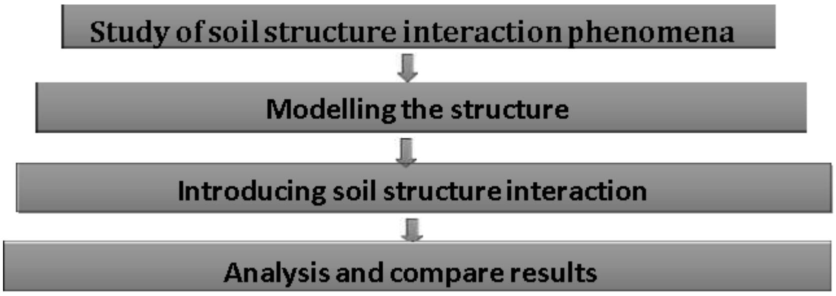

Fig 2. Methodology Flow chart

- **Study of soil structure interaction phenomena:**

To understand the phenomenon of soil structure interaction the research papers are incorporated.

- **Modelling the structure:**

The structural model was created in SAP 2000 software. The 8, 10, 12 stories RC building is currently being created. Cross-sectional properties are being assigned to each element such as beam, column, slab. It includes the step of applying loads to structure such as dead load, other load, live load, seismic load using Indian standards and also checking the structural model is safe or not. For the seismic zone the zone 5 is considered as per IS1893:2016

Here are the data we considered for modelling of each structure as follows:

Table 1. Data for structure modelling

Story height	3m
No of bays in 'X'	5
Bay width in 'X'	3m
No of bays in 'Y'	7
Bay width in 'Y'	3m

Beam size	400X500 mm
Column size	500X500 mm
Grade of concrete	M25
Slab thickness	125 mm
Seismic zone	5
Importance factor	1
Response spectrum	5

- **Introducing soil structure interaction:**

It includes introducing Soil structure interaction. Firstly, it is assuming mat foundation in all models then it including the soil properties.

- **Analysis and comparing results:**

First of all, the extracting the results between models with soil structure interaction and without soil structure interaction and then comparing the results.

Following factors are being considered for comparison.

a. Joint Displacement

b. Base Reaction

IV. RESULTS

- **General**

In this project for the first objective the structural model was created in SAP2000 software. For that8,10,12 story structure was created. For that modeling firstly input the section properties like beam and column to each element. The loads like dead load, live load, other loads. EQx, EQy are applied. For seismic design zone 5 is considered as per IS 1893:2016. For the zone 5 the importance factor as 1 and response spectrum is 5 considered.

- **Modelling 8 story structure in SAP 2000:**

The fig 3 is representing model of 8 story structure modelled in SAP 2000 software. In which the sectional properties are inserted like beam, column, slab. This model is 3D viewed.

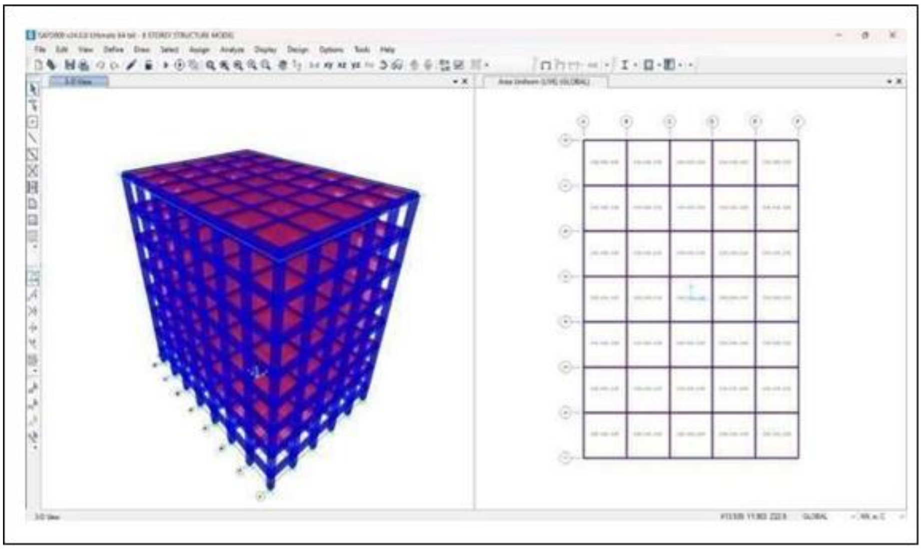

Fig 3. Modelling of 8 story

- **Modeling of 10 story structure in SAP 2000**

The fig 4 represents the structure of 10 story structure modelling. In which the sectional properties are inserted like beam, column, slab. This model is 3D viewed.

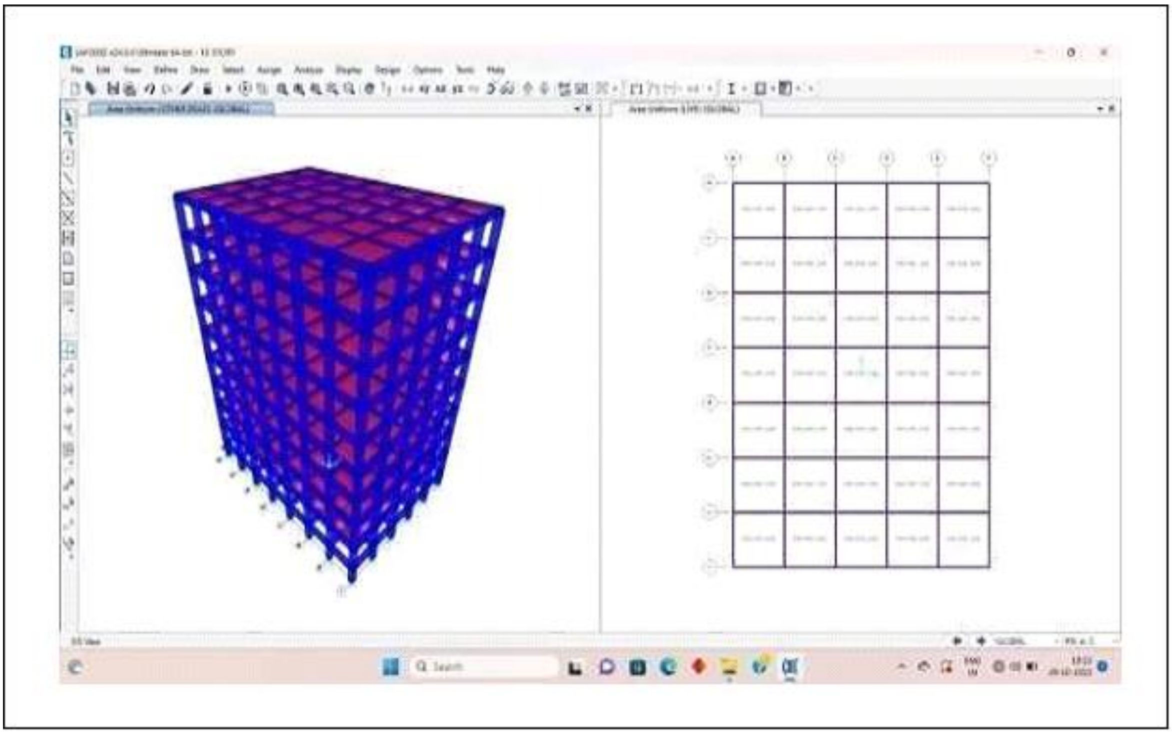

Fig 4. Modeling of 10 story structure

➢ **Modeling of 12 story structure in SAP 2000 software:**

The fig 5. shows about 3D model of 12 story structure

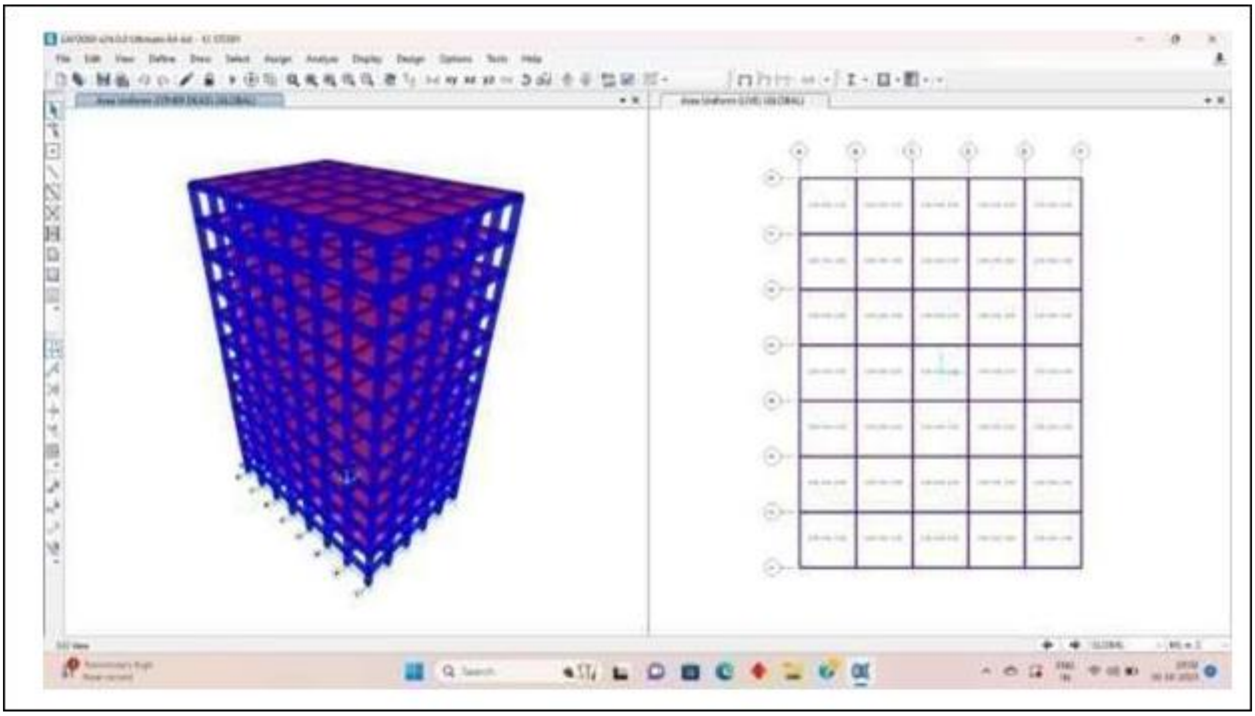

Fig 5. Modelling of 12 story structure

Here are the results of joint displacement and base reaction of 8,10,12 storey structure without considering soil interaction:

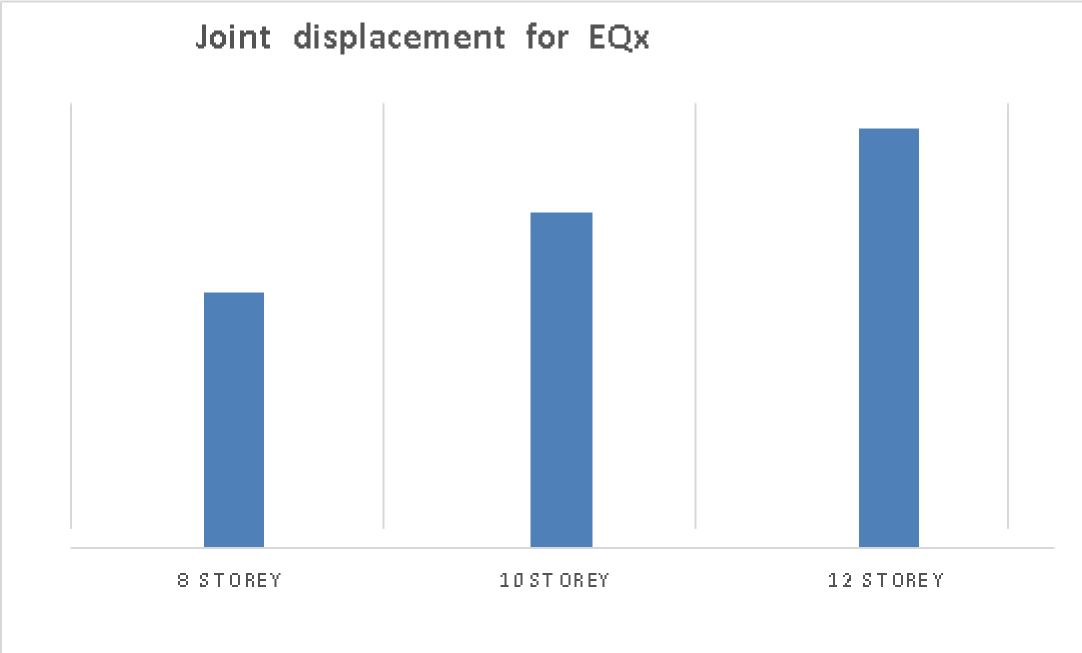

Fig 6 Results of Joint Displacement in EQx

Above fig 6. shows about the joint displacement in EQx. The joint displacement of 8, 10, 12 story are 17.21 mm, 22.60 mm, 28.32 mm respectively. It seems that as the story height increases the joint displacement increases.

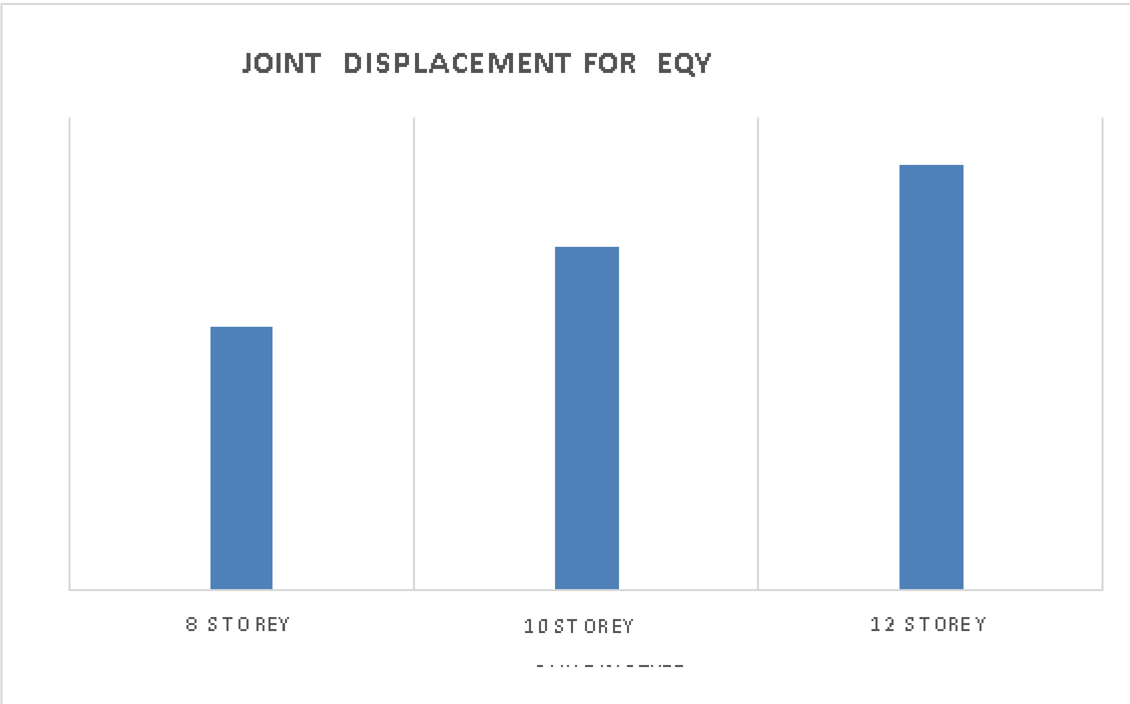

Fig 7. Results of Joint Displacement of EQy

Above fig 4.5 shows about the joint displacement in EQy. The joint displacement of 8, 10, 12 story are

16.67 mm, 21.71 mm, 26.95mm respectively. It seems that as the story height increases the joint displacement increases.

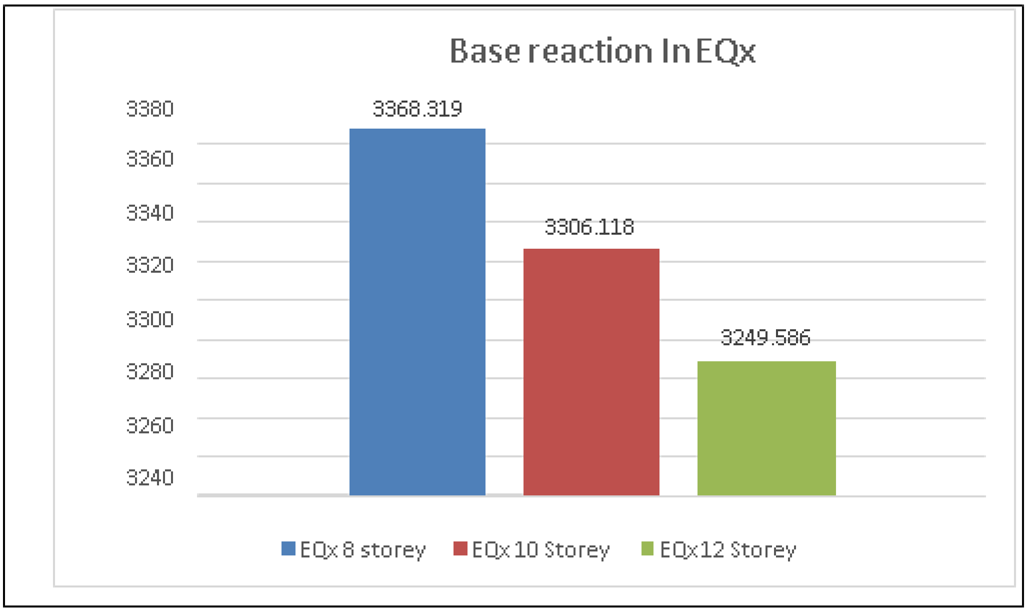

Fig.8 Base Reaction in EQx

The base reaction is addition of lateral force. Above fig 4.6 shows about the base reaction in EQx. The base reaction of 8, 10, 12 story are 3368.319KN, 3306.118KN,3249.586 respectively. It seems that as the story height increases the base reaction decreases.

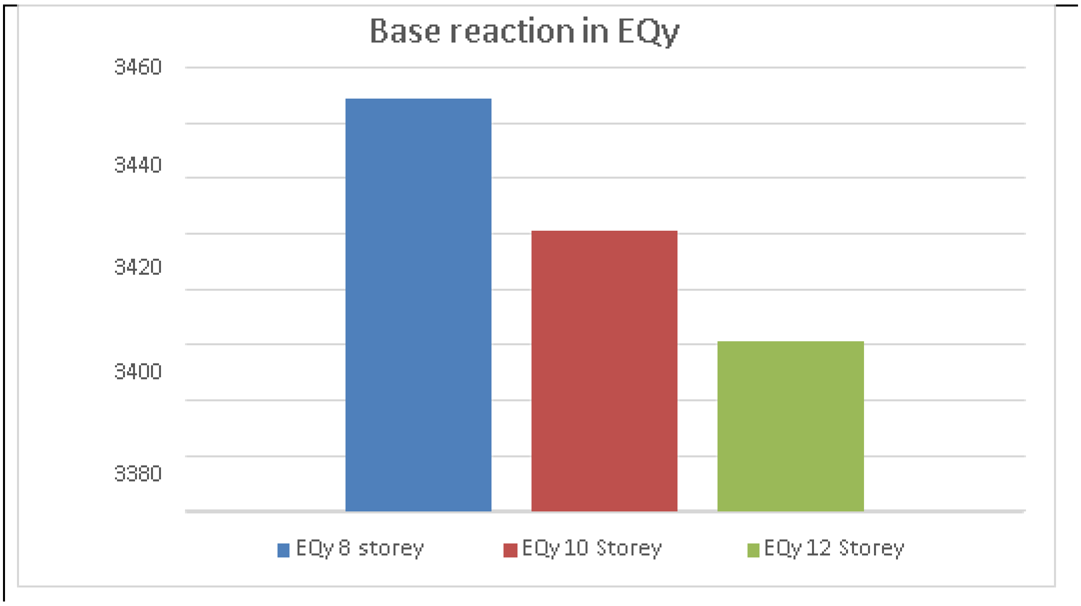

Fig.9 Base Reaction EQy

Above fig 9 shows about the base reaction in EQy. The base reaction of 8, 10, 12 story are 3448.706 KN, 3401.303KN 3361.564 KN respectively. It seems that as the story height increases the base reaction decreases.

By the results it concludes that the joint displacement increases with story height. It seems that here is 31% increase in joint due to increasing 2 stories. There is no large difference between joint displacement in EQx and EQy because the structures are regular.

Also, the base reaction is decreases as the story height increase.

Here are the structures considering soil structure interaction:

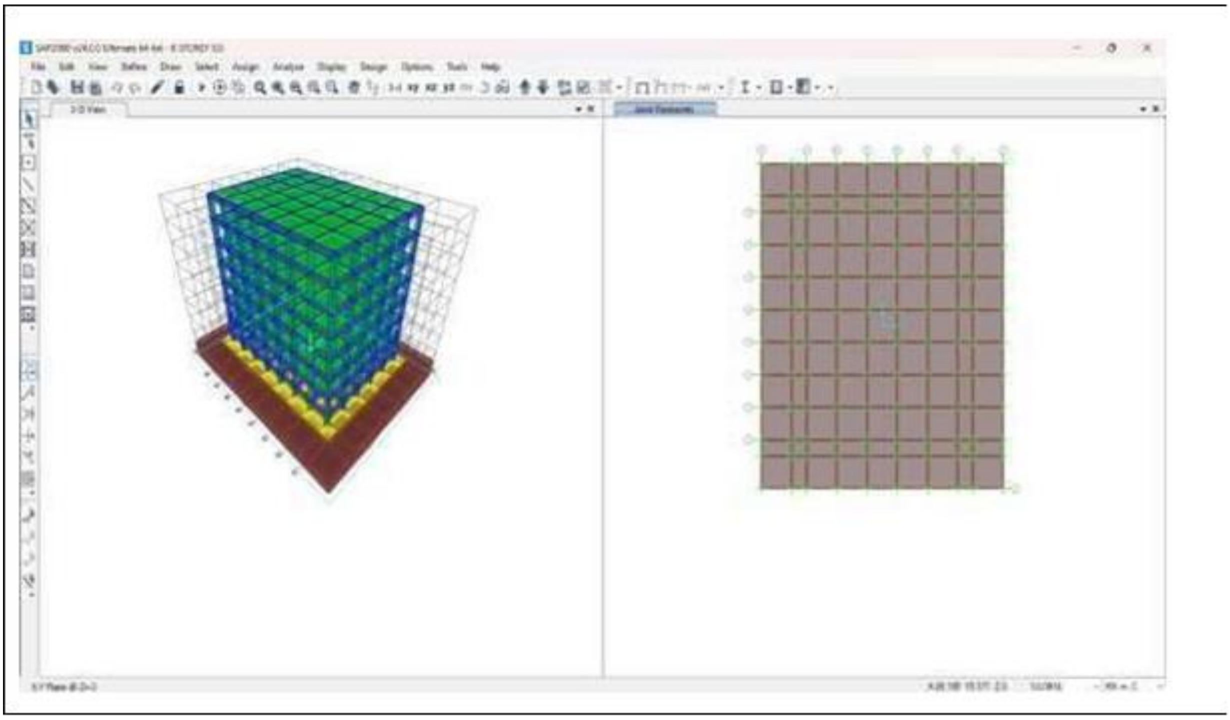

Fig 10 : 8 storey structure considering soil structure interaction

The above fig 10 shows that the soil structure interaction is introduced in 8 strorey structure using SAP2000 software. Similarly, 10 and 12 storey structure is created by introducing soil interaction. The structure are given below in fig 11 and 12

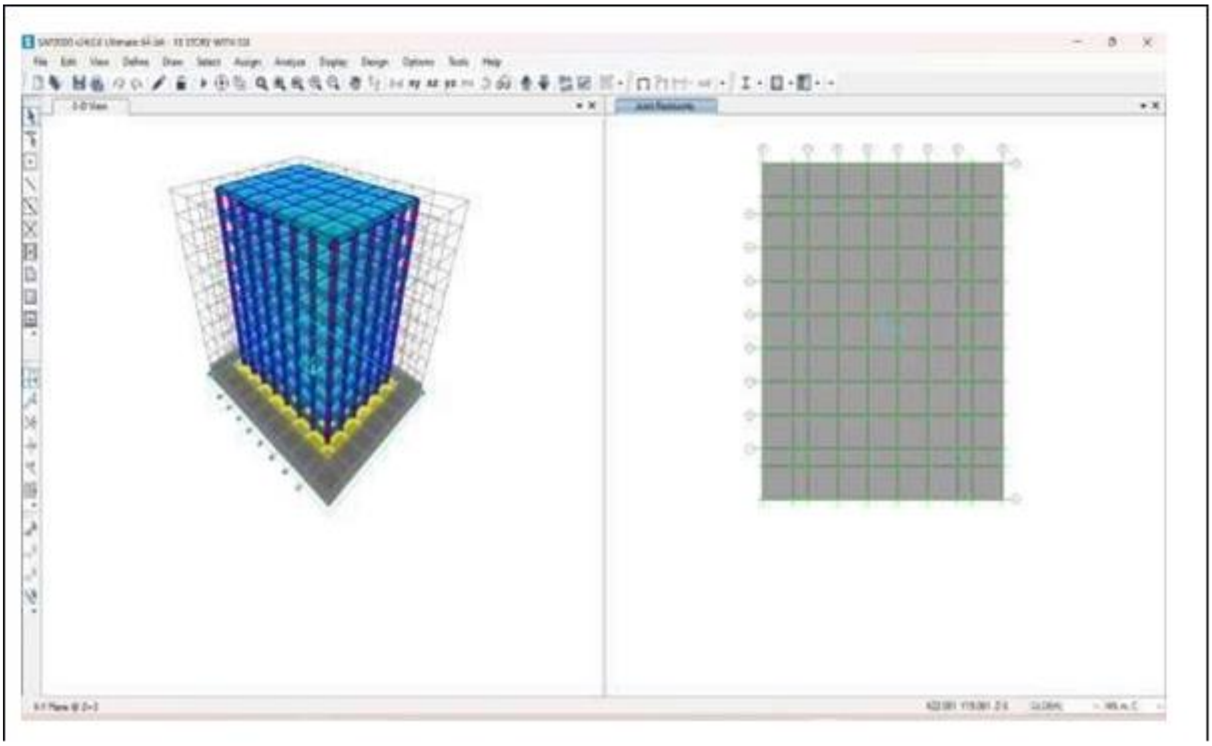

Fig 11: 10 storey structure considering soil interaction

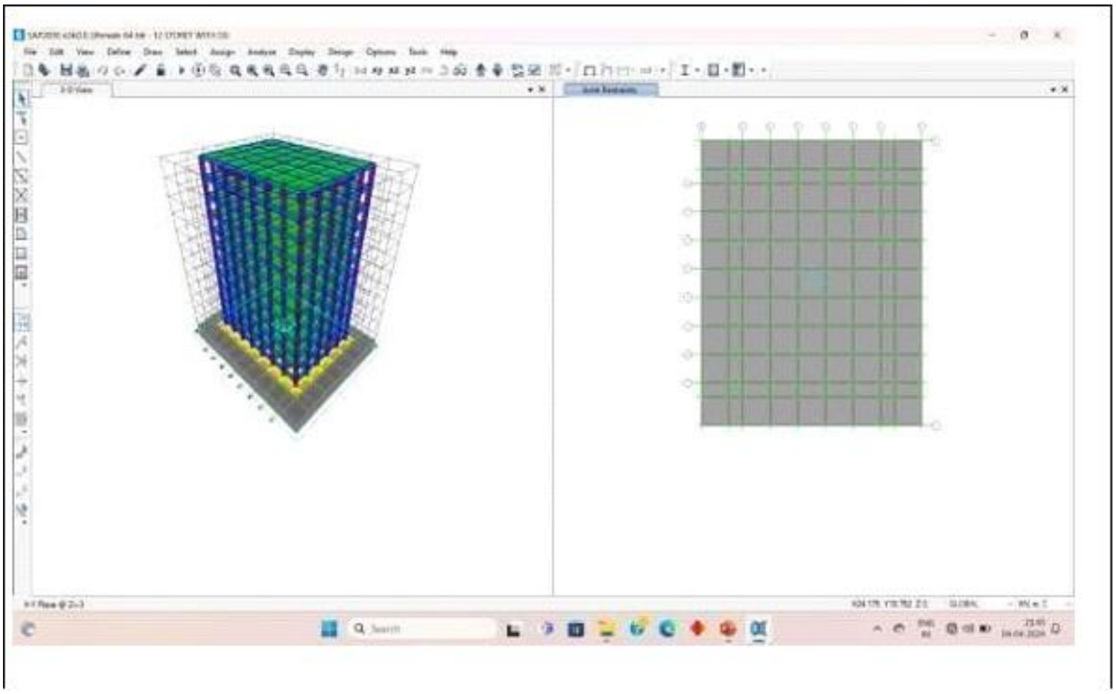

Fig 12: 12 storey structure considering soil interaction

Here are the results of joint displacement of 8,10,12 storey structure considering soil interaction in EQx and EQy:

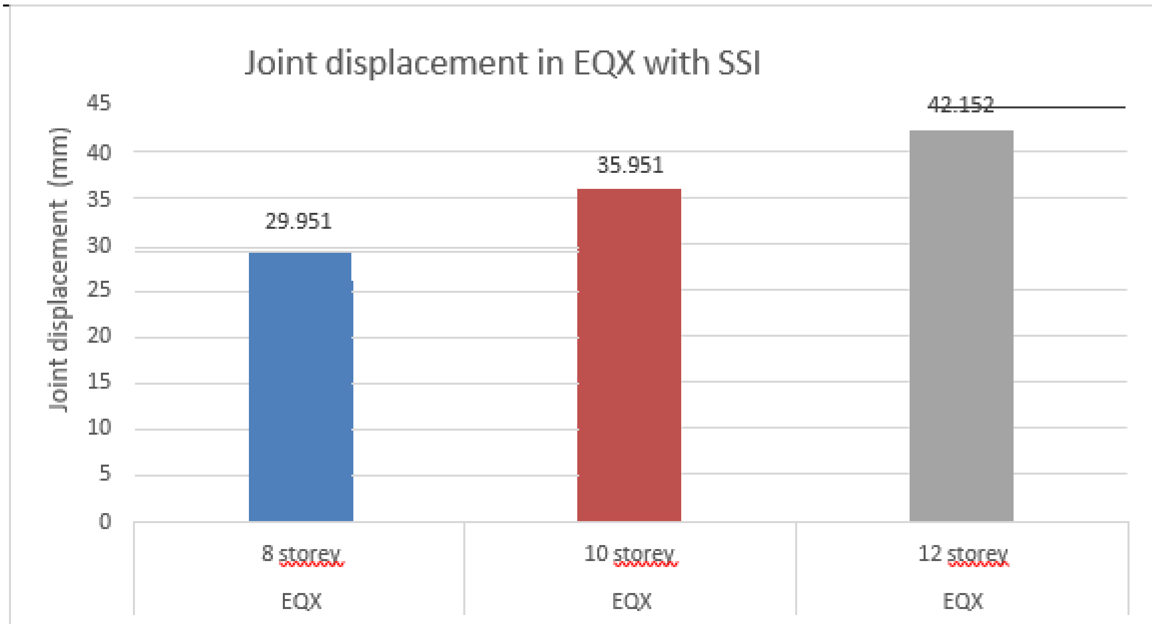

Fig 13 Joint displacement of 8,10,12 storey in EQx considering soil structure interaction

The above fig 13 shows the result of joint displacement of 8,10,12 storey considering soil structure interaction in EQx. The joint displacements are 29.951mm, 35.951mm, 42.152mm of 8,10,12 storey respectively.

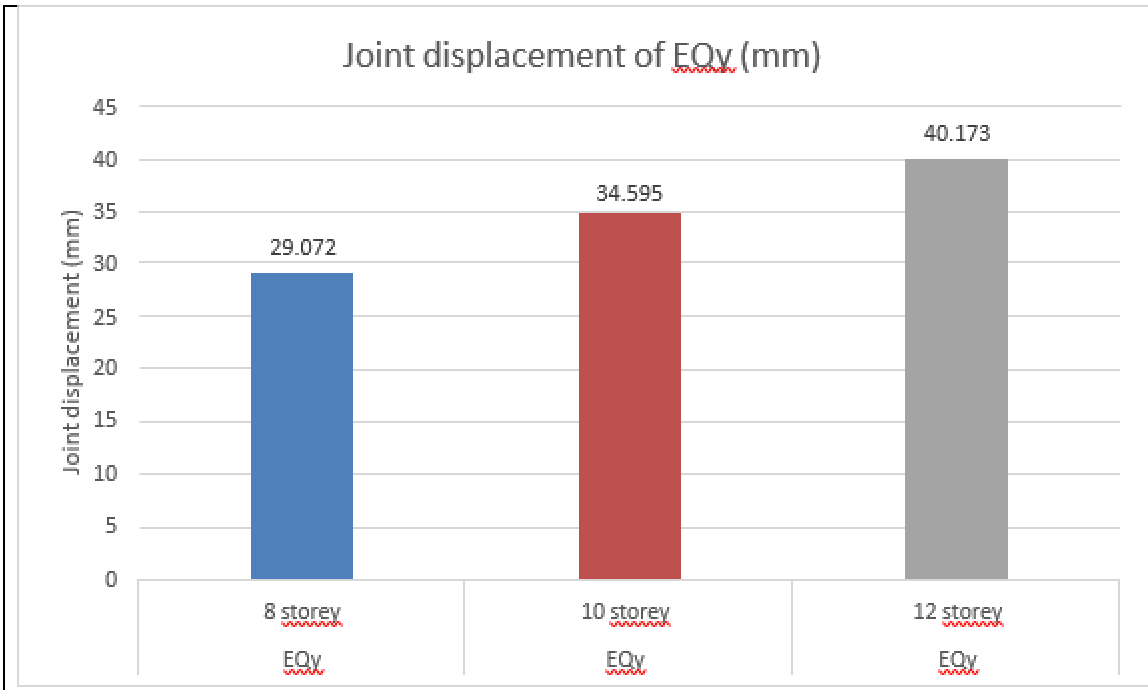

Fig 14 Joint displacement of 8,10,12 storey in EQy considering soil structure interaction

The above fig 14 shows the result of joint displacement of 8,10,12 storey considering soil structure interaction in EQy. The joint displacements are 29.072mm, 34.595mm, 40.173mm of 8,10,12 storey respectively.

Here are the results of base reaction of 8,10,12 storey structure considering soil interaction in EQx and EQy:

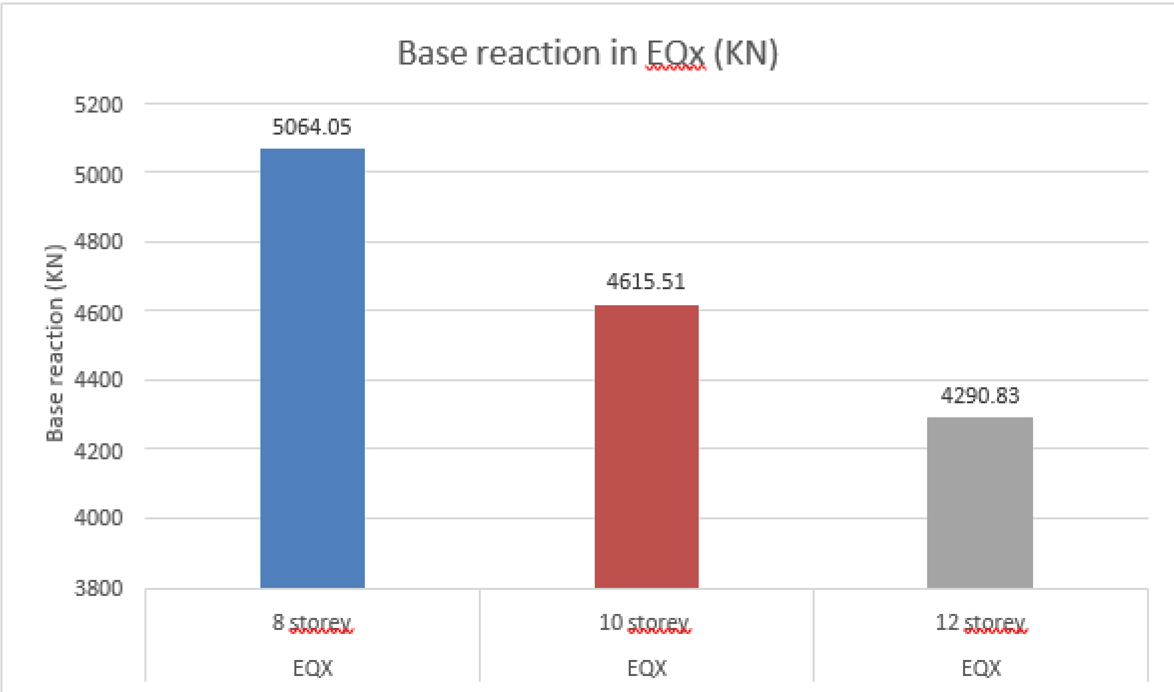

Fig 15 base reaction of 8,10,12 storey in EQx considering soil structure interaction

The above 15 shows the result of base reaction of 8,10,12 storey considering soil structure interaction in EQx. The base reactions are, 5064.05KN, 4615.51KN, 4290.83KN of 8, 10, 12 storey respectively.

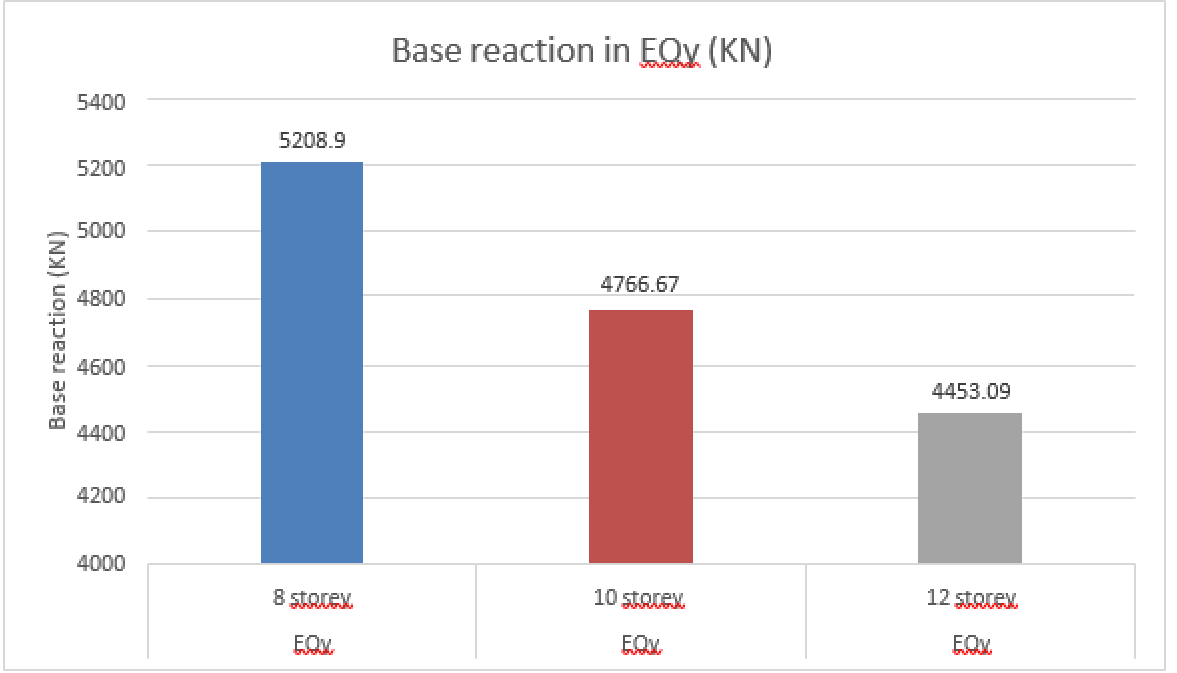

Fig 16 base reaction of 8,10,12 storey in EQy considering soil structure interaction

The above fig 16 shows the result of base reaction of 8, 10, 12 storey considering soil structure interaction in EQy. The base reaction are, 5208.9KN, 4766.67KN, 4453.09KN of 8,10,12 storey respectively.

Here are the combine graph of joint displacement of 8 storey structure with soil structure interaction and without soil structure interaction:

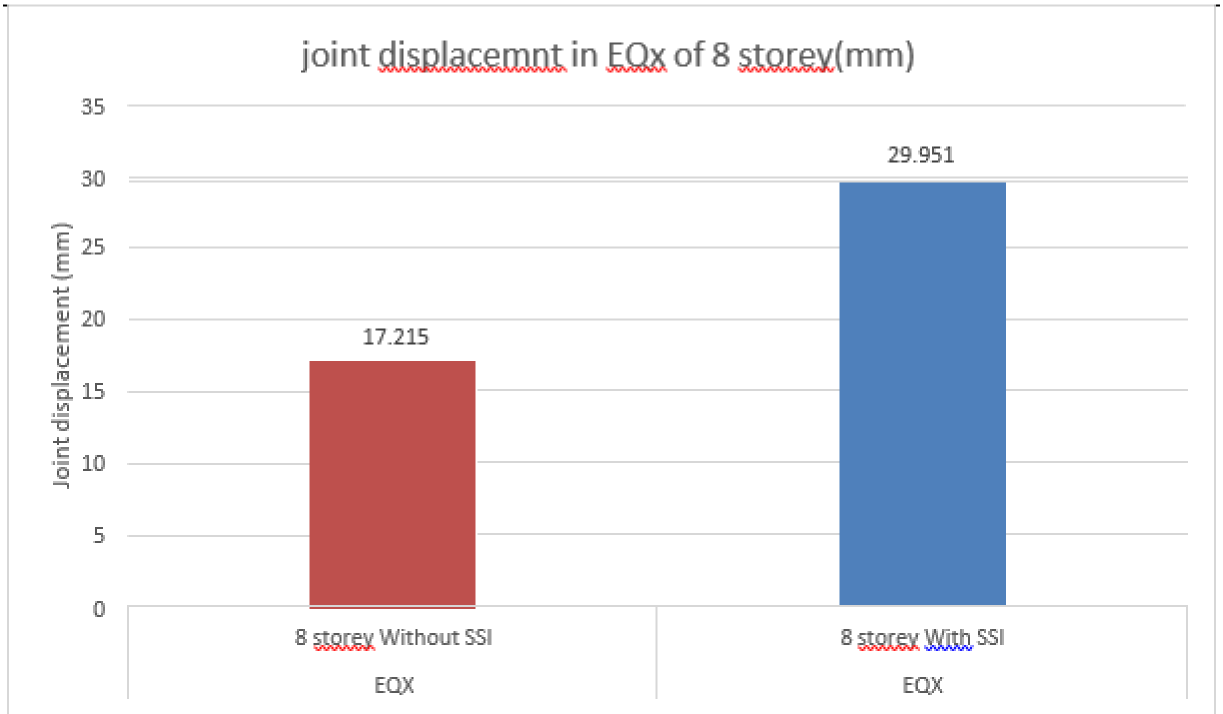

Fig 17: Joint displacement result of 8 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 17 shows the combine result of joint displacement of 8 storey structure with soil interaction and without soil interaction in EQx. The joint displacement of 8 storey without soil structure interaction is

17.215mm and with soil structure interaction is 29.951mm. It seems that the joint displacement is increases by introducing soil structure interaction. This because it considers the foundation flexibility, soil amplification and dynamic effects which can lead in higher deformation.

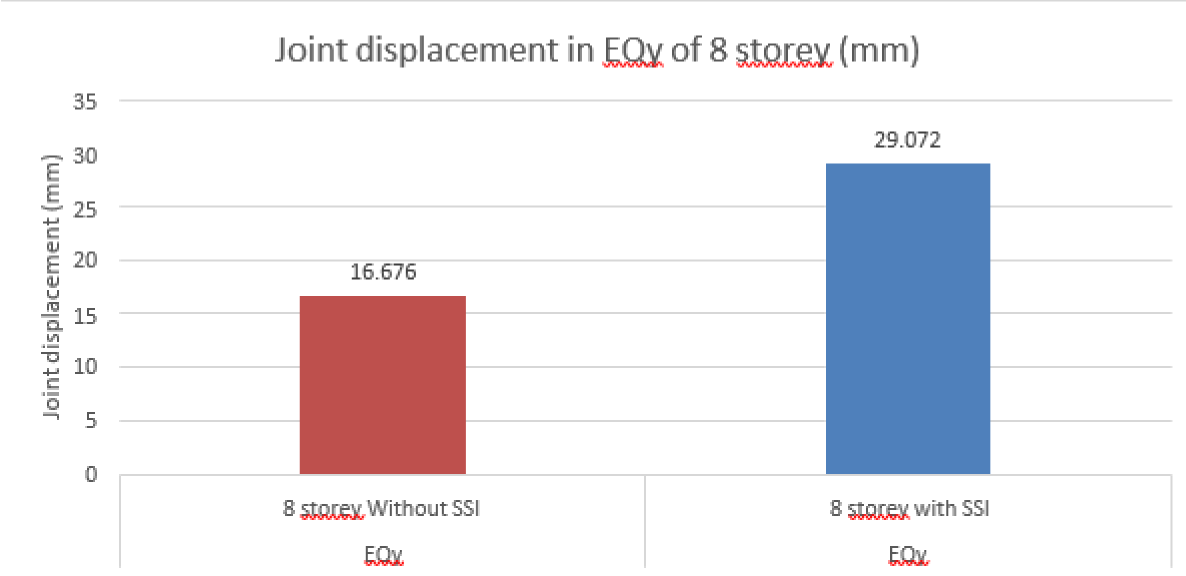

Fig 18: Joint displacement result of 8 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 18 shows the combine result of joint displacement of 8 storey structure with soil interaction and without soil interaction in EQy. The joint displacement of 8 storey without soil structure interaction is 16.676mm and with soil structure interaction is 29.072mm.

Here is the combine graph of joint displacement of 10 storey structure with soil structure interaction and without soil structure interaction:

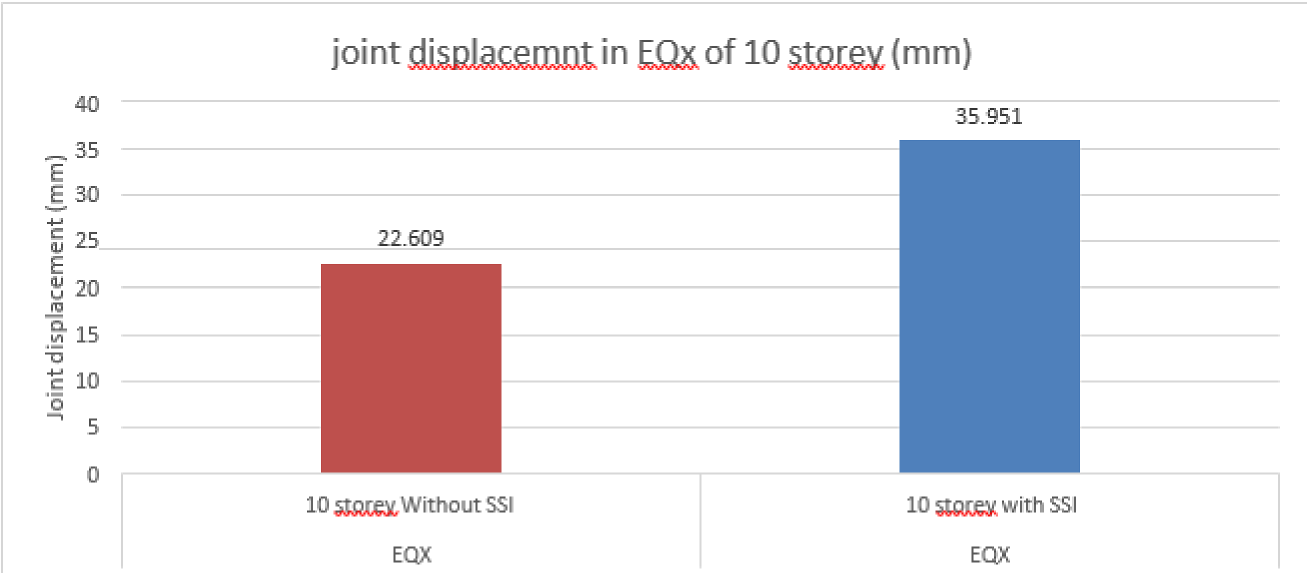

Fig 19: Joint displacement result of 10 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 19 shows the combine result of joint displacement of 10 storey structure with soil interaction and without soil interaction in EQx. The joint displacement of 10 storey without soil structure interaction is 22.609mm and with soil structure interaction is35951mm. It seems that the joint displacement is increases by introducing soil structure interaction.

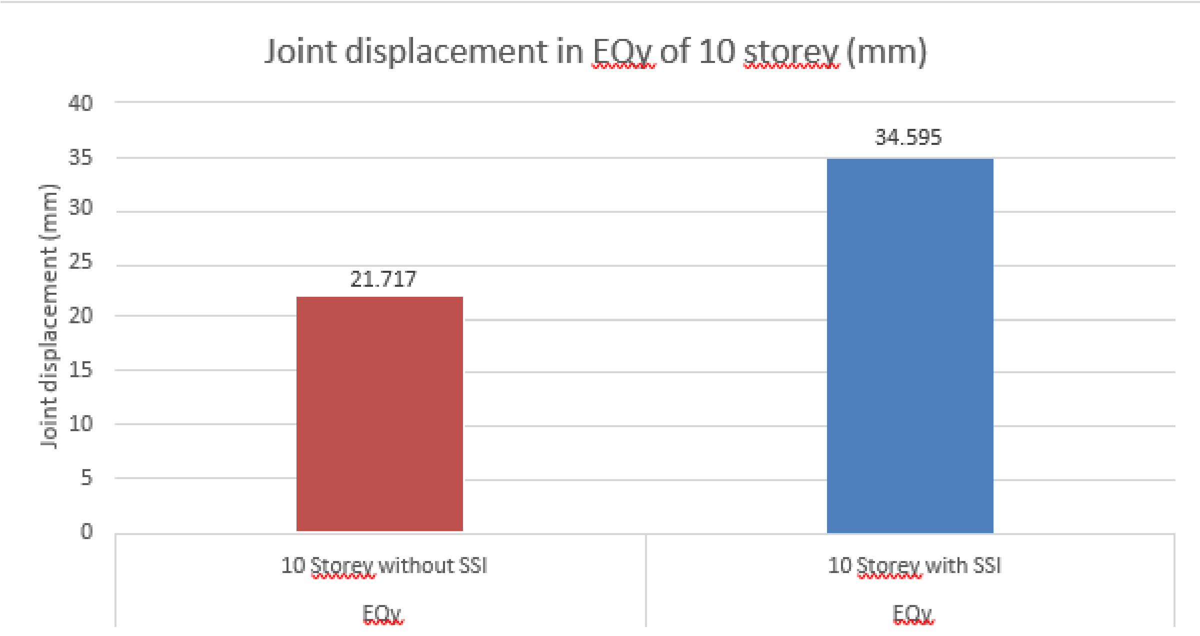

Fig 20: Joint displacement result of 10 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 20 shows the combine result of joint displacement of 10 storey structure with soil interaction and without soil interaction in EQy. The joint displacement of 10 storey without soil structure interaction is 21.717mm and with soil structure interaction is 34.595mm.

Here is the combine graph of joint displacement of 12 storey structure with soil structure interaction and without soil structure interaction:

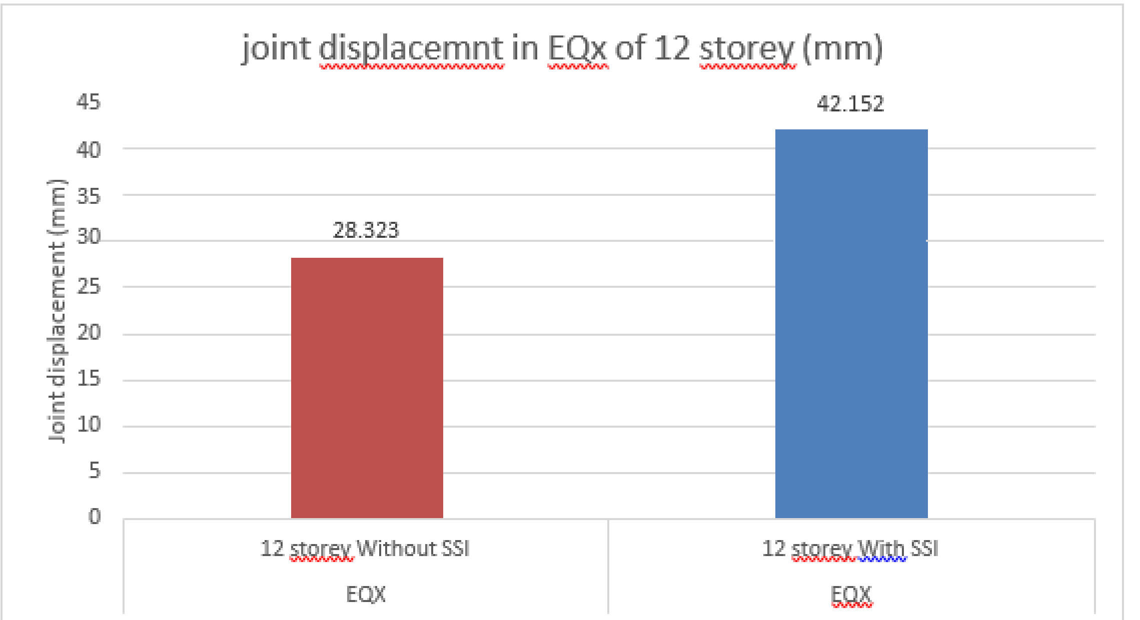

Fig 21: Joint displacement result of 12 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 21 shows the combine result of joint displacement of12 storey structure with soil interaction and without soil interaction in EQx. The joint displacement of 12 storey without soil structure interaction is 28.323mm and with soil structure interaction is 42.152mm. It seems that the joint displacement is increases by introducing soil structure interaction.

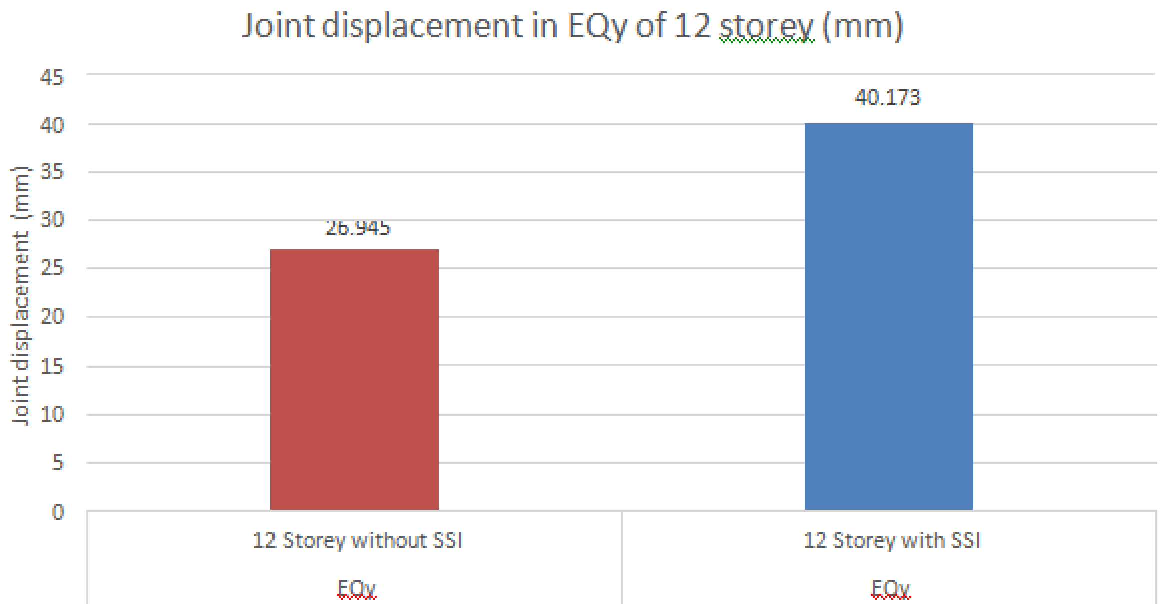

Fig 22: Joint displacement result of 12 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 22 shows the combine result of joint displacement of 12 storey structure with soil interaction and without soil interaction in EQy. The joint displacement of 12 storey without soil structure interaction is 26.945mm and with soil structure interaction is 40.173mm.

Here is the combine graph of base reaction of 8 storey structure with soil structure interaction and without soil structure interaction:

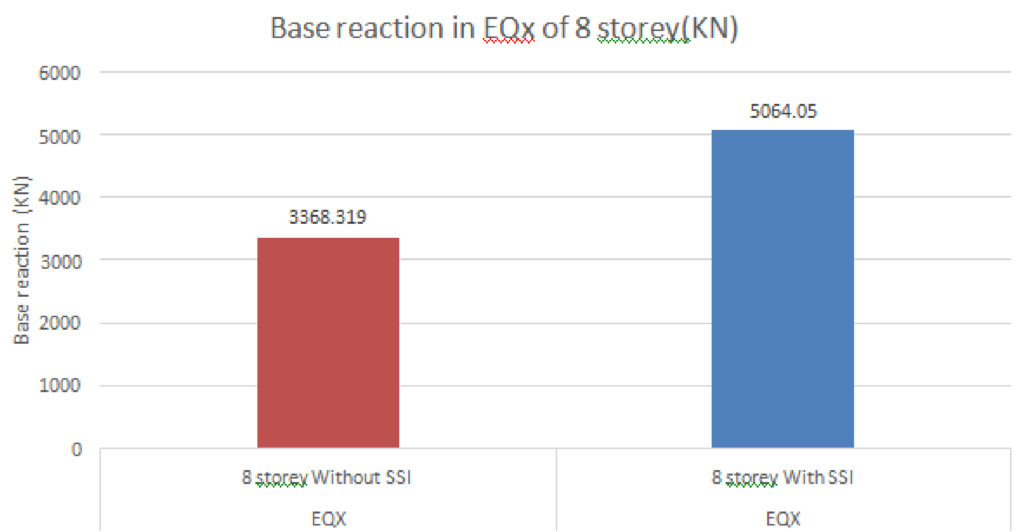

Fig 23: Base reaction result of 8 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 23 shows the combine result of base reaction of 8 storey structure with soil interaction and without soil interaction in EQx. The base reaction of 8 storey without soil structure interaction is 3368.31KN and with soil structure interaction is 5064.05KN. It seems that the base reaction is increases by introducing soil structure interaction. This because by introducing soil structure interaction it can lead higher load transmission to foundation as compared to analysis without soul structure interaction.

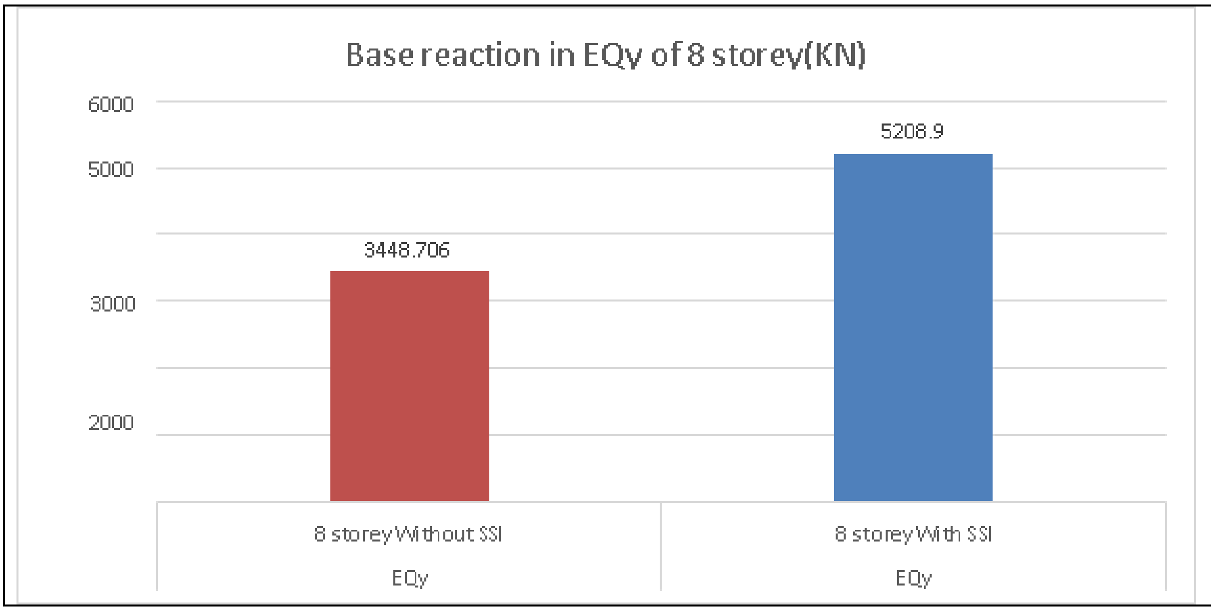

Fig 24: Base reaction result of 8 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 24 shows the combine result of base reaction of 8 storey structure with soil interaction and without soil interaction in EQy. The base reaction of 8 storey without soil structure interaction is 3448.70KN and with soil structure interaction is 5208.9KN.

Here is the combine graph of base reaction of 10 storey structure with soil structure interaction and without soil structure interaction:

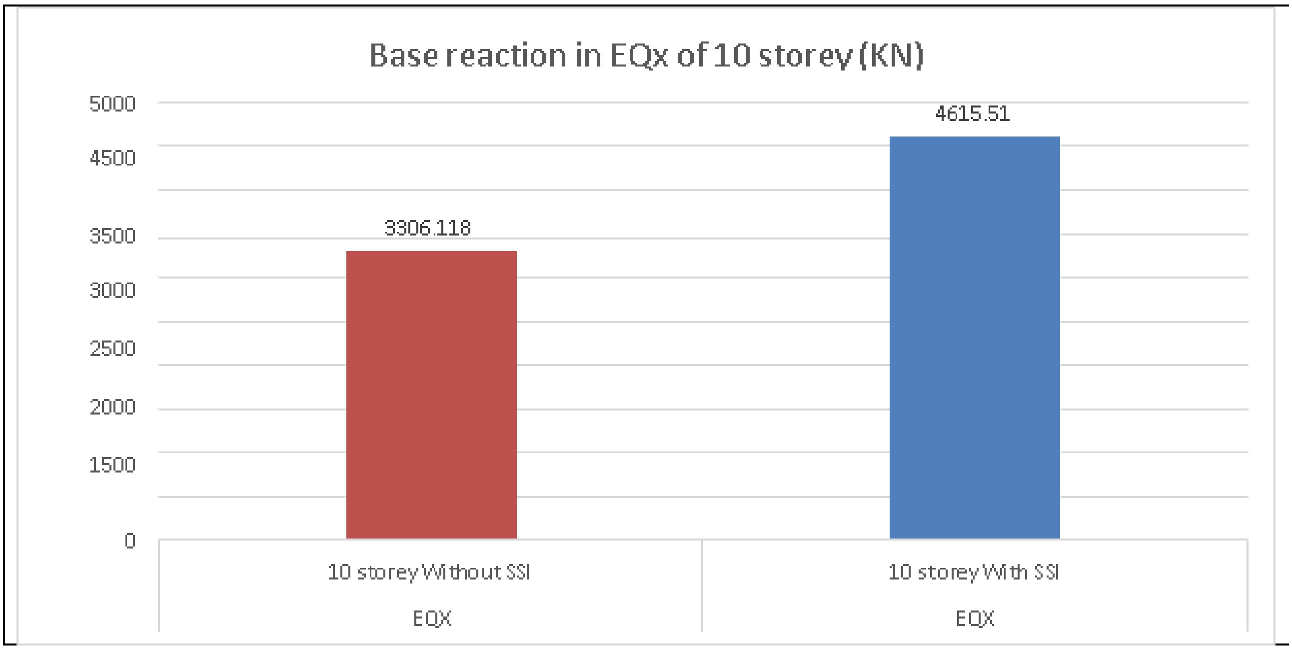

Fig 25: Base reaction result of 10 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 25 shows the combine result of base reaction of 10 storey structure with soil interaction and without soil interaction in EQx. The base reaction of 10 storey without soil structure interaction is 3306.118KN and with soil structure interaction is 4615.51KN.

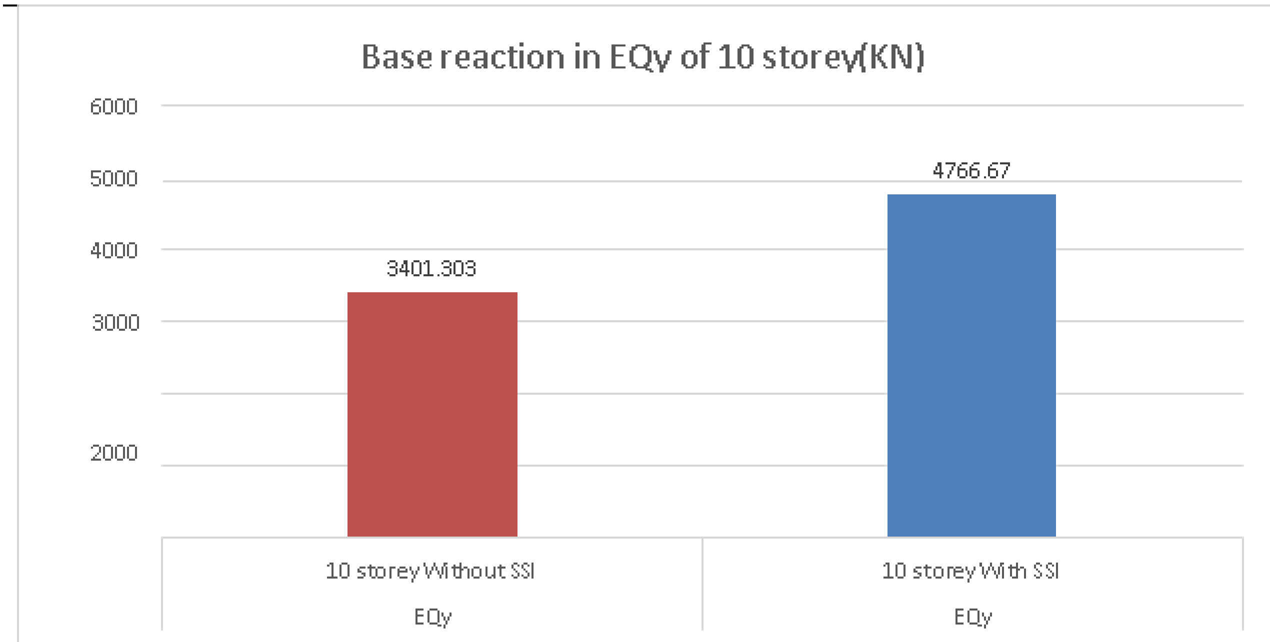

Fig 26: Base reaction result of 10 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 26 shows the combine result of base reaction of 10 storey structure with soil interaction and without soil interaction in EQy. The base reaction of 10 storey without soil structure interaction is 3401.3KN and with soil structure interaction is 4766.67KN.

Here is the combine graph of base reaction of 12 storey structure with soil structure interaction and without soil structure interaction:

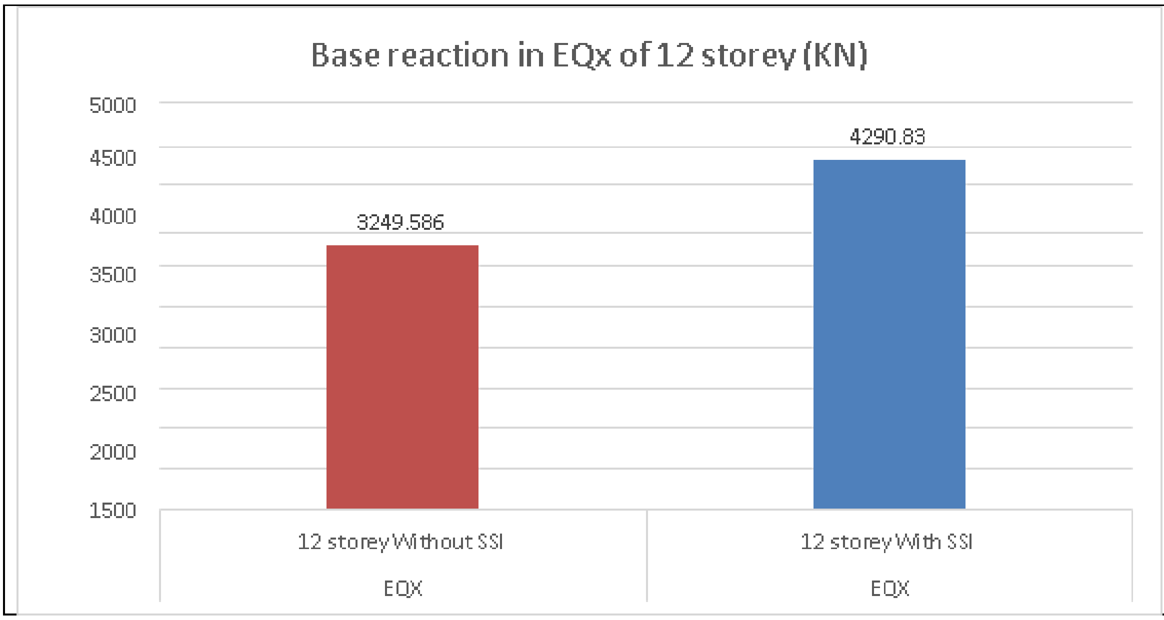

Fig 27: Base reaction result of 12 storey structure with soil structure interaction and without soil structure interaction in EQx

The above fig 27 shows the combine result of base reaction of 12 storey structure with soil interaction and without soil interaction in EQx. The base reaction of 12 storey without soil structure interaction is 3249.58KN and with soil structure interaction is 4290.83KN.

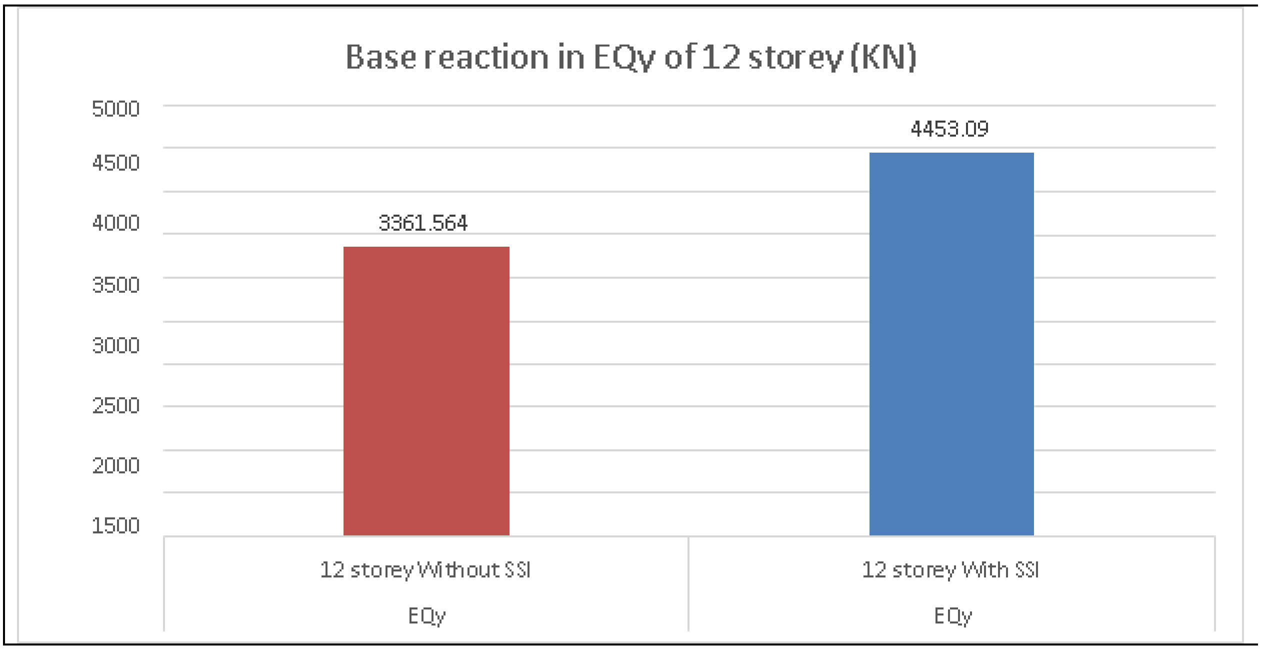

Fig 28: Base reaction result of 12 storey structure with soil structure interaction and without soil structure interaction in EQy

The above fig 28 shows the combine result of base reaction of 12 storey structure with soil interaction and without soil interaction in EQy. The base reaction of 12 storey without soil structure interaction is 3361.56KN and with soil structure interaction is 4453.09KN.

The combine graph of joint displacement of 8, 10, 12 storey shows that the joint displacement is increases by introducing soil structure interaction. Joint displacement and base reaction can be significantly influenced by soil structure interaction effect. For building with soil structure interaction, joint displacement is higher due to the flexible base and it is lower for buildings without soil structure interaction.

The combine graph of base reaction of 8, 10, 12 storey shows that the joint displacement is increases by introducing soil structure interaction. This is because by introducing soil structure interaction the load transmission to foundation is higher as compared to analysis without soil structure interaction.

V. CONCLUSION

It observed that as story height increases the joint displacement also increases. It seems that increasing story height by 2 storey there will be 31%increase in joint displacement. Also, by increasing 4 storey there will be 64%increase in joint displacement. The study represents that as the story height increases the base reaction is decreases. This is due to in a tall structure, the load is distributed over a larger area as you move up the building. This means that the lower levels of the structure bear a greater portion of the load, resulting in higher base reactions. Joint displacement and base reaction can be significantly influenced by soil structure interaction effect. For building with soil structure interaction, joint displacement is higher due to the flexible base and it is lower for buildings without soil structure interaction. The base reaction is increase by introducing soil structure interaction because it can lead higher load transmission to foundation as compared to analysis without soil structure interaction. Soil-structure interaction (SSI) significantly influences seismic design for reinforced concrete (RC) structures. Proper consideration and mitigation strategies are essential to ensure the safety and performance of RC structures in earthquake-prone areas.

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