Industrial Engineering Journal
ISSN: 0970-2555
Volume : 53, Issue 1, January : 2024

SEISMIC ANALYSIS OF SLOPED BUILDING WITH VARIED PLANS AND SOIL-STRUCTURE INTERACTION

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ABSTRACT: Structures with setbacks face heightened vulnerability during earthquakes due to their vertical design and irregular mass distribution. The risk is further amplified when these structures exhibit stiffness irregularities in elevation, and it becomes even more precarious if they are situated on sloping terrain. This study aims to assess the seismic performance of setback constructions, both on flat ground and on hillsides, with varying plan configurations. The research employs three distinct methods: the equivalent static force method, the response spectrum method, and the time history method, to comprehensively analyze the buildings' seismic behavior. All structures were developed in accordance with IS 875:1987 part 1, part 2, and IS 1893:2016 (equivalent to dead, live, and seismic loads) and in accordance with IS 456:2000 and IS13920 (1993, Reaffirmed 2008). Details of the reactions obtained from the various buildings under various seismic excitations were provided. Max top story displacement, max story drift, and max base shear are the characteristics employed in the comparison of analysis of all configurations. Buildings situated on sloped terrain exhibit higher susceptibility compared to those on flat ground, and this vulnerability escalates with an increase in the slope angle. When subjected to directional force on a sloping surface, noticeable movement occurs within the structure. These sloped constructions demonstrate disparate movement on each side, with the taller side moving more significantly in the force's direction than the shorter side. This observation indicates a concentration of stiffness on the structure's shorter side, particularly on steeper slopes. Due to the asymmetry in their floor plans, the C and L-shaped models experience higher base shear in comparison to the regular and +-shaped models..

Keywords: *Soil-structure interaction, variation in plan configuration, Sloping ground, Linear Time history analysis, ETABS software.*

I.INTRODUCTION

Frequent occurrences of powerful earthquakes pose a significant threat worldwide, causing widespread destruction to various structures and claiming lives. While all constructions are susceptible to seismic forces, those with irregularities are particularly vulnerable. The necessity of building on hill slopes arises from the scarcity of flat land in hilly regions. Creating level surfaces for construction by excavating terrain is both prohibitively expensive and time-consuming, not to mention the detrimental impact on the natural beauty of landscapes.

Hillside buildings constructed with mortar made from mud and unreinforced masonry stone mortar perform badly during earthquakes, resulting in fatalities, property damage, and a negative impact on the country's economy. Figure 1-1 depicts some of the traditional constructions that have crumbled in prior earthquakes. In prior earthquakes, reinforced concrete (RC) buildings performed better than mud, stone, and brick-and-mortar constructions. Despite its high cost, R.C. construction is becoming more popular due to tough weather conditions, the longevity of concrete, and the great performance of R.C. structures compared to traditional brick, mud, stone, and brick-mortar buildings.

Figure 1-1: Brick Masonry Failures in Buildings

Buildings on inclines differ significantly from those on flat surfaces, displaying high levels of complexity and asymmetry in both horizontal and vertical planes. The mass and stiffness of such structures vary along both axes, causing the centre of mass and rigidity to be non-coincident on different levels and resulting in structural torsion. Given these conditions, it becomes crucial to investigate the responses of such structures to ensure their earthquake resistance and prevent potential collapse, thereby safeguarding lives and property. The unpredictable nature of hilly slopes necessitates a thorough examination of the impact of slope variations on buildings when subjected to earthquake forces. Contrary to the common assumption of fixed bases for structures, often treated as indefinitely stiff, this concept proves inaccurate due to the flexibility of the soil beneath the structure. Therefore, it is essential to incorporate Soil-Structure Interaction (SSI) considerations to obtain a realistic response from the structure under seismic conditions.

Figure 1-2&3: Hill Buildings Failure in Sichuan and Haiti Earthquake

1.1 Structural Irregularities in Buildings

This irregularity turns into a weak point during an earthquake as a result of the construction process's loss of size, strength, and rigidity. This weakness contributes to additional structural deterioration and eventual structural collapse. Distinct irregularities are a significant factor contributing to structural failures during earthquakes. For instance, the most major structures to collapse were soft-shelled buildings. Therefore, it's crucial to consider how direct variations affect structures' seismic activity. These structures have strong characteristics that set them apart from traditional structures due to differences in durability and size. Below is a complete list of structural flaws and code restrictions. The structural flaws can be generically categorized as vertical irregularities and plan irregularities.

1.2 Overview of Soil-Structure Interaction

Traditionally, the impact of interaction of the soil structure has been disregarded in the past. But since its impact is more pronounced for large structures supported by comparatively softer soils. If we take the impacts of soil structure interaction into account, we may create a more flexible structural design. This aids in lengthening the structure's natural lifespan. Compared to a comparable rigid construction, this offers a better structure. There are four different ways of analysis that may be used to determine how soil and structure interact.

1.2.1 Spring Models

This approach analyses the soil and the structure as a whole. A continuum is used to describe the soil system beneath the building. The entire system includes the foundations, the four borders between the soil and the building, the structural components, and the foundation-soil interface elements.

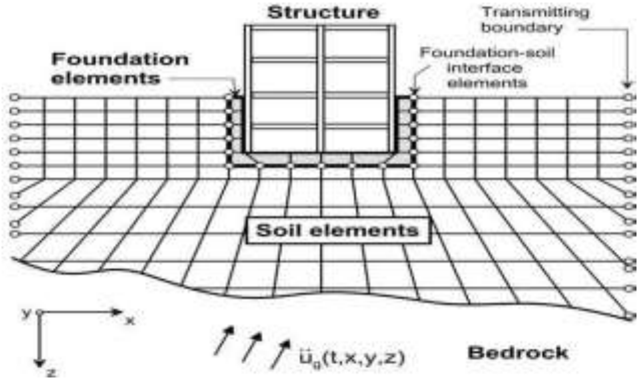

Figure 1.10: Figure Demonstrating the Direct Analysis of Soil-Structure Interaction Utilizing Finite Elements.

1.2.2 Lumped Mass Model

In this model, vertically interconnected lumped masses are employed to simulate the ground. Each lumped mass corresponds to one ground layer and is associated with its spring constant and damping coefficient. The model assumes complete stiffness in the surrounding soil.

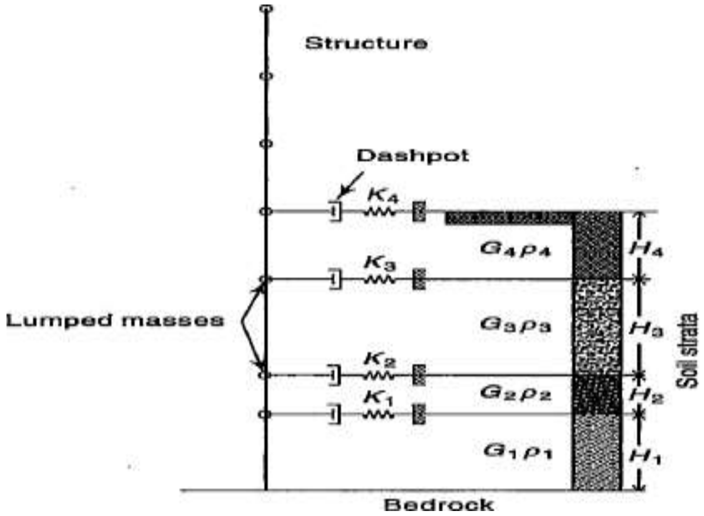

Figure 1.11: Analytical model of soil-structure comprising of vertical lumped parameter system of springs and dashpots

II.LITERATURE REVIEW

(Ghosh and Debbarma, 2017) Efforts were undertaken to assess the seismic performance of setback structures located on both conventional flat ground and a 45° sloping ground featuring an open ground story. A G+4 building model was constructed in ETABS, employing three distinct analytical methods: the equivalent static force technique, response spectrum analysis, and time history analysis. To mitigate the associated effects and extreme responses, three mitigation strategies were implemented: infilling the open ground story with core panels featuring shear walls, designing open ground story columns with 2.5 times the base story moment and shear force, and replacing open ground story columns with RCFSTC. The findings indicated that structures with open ground stories employing these three approaches exhibited commendable performance under seismic loads, surpassing the fully infilled model.

(Ghosh and Debbarma, 2019) Explored the seismic influence of varying slope angles on structures situated on sloping terrain, considering both scenarios with and without soil-structure interactions. The study focused on a G+4 building with slope angles ranging from 0° to 45°, utilizing the equivalent static method (ESM), response spectrum method (RSM), and time history method (THM) within ETABS for analysis. Structures that neglect soil-structure interactions tend to overestimate forces (base shear and bending moment), underestimate impacts on sloping ground, emphasizing the need for caution when designing columns on higher slopes. Additionally, other investigations highlighted the efficacy of shear walls in structures erected on sloping land. These findings indicated that shear walls reduce stresses on shorter columns while effectively resisting seismic forces.

(Bhavikatti and Cholekar, 2017) Explored the impact of soil-structure interactions in the seismic analysis of a building situated on sloping terrain with slope angles of 16°, 20°, and 24°. The study revealed an inverse relationship between the base shear and the slope angle, indicating that the influence of soil-structure interactions diminishes the base shear. **(Manjunath and Holebsgilu, 2016)** Examined 10-story structures with slope angles varying from 0° to 30° through response spectrum analysis in ETABS. In this study, three soil types (hard, medium, and soft) were considered. The findings indicated that soil characteristics significantly impact the seismic performance of the structures. Earthquake-induced stresses contribute to increased soil stiffness, thereby enhancing the overall performance of the buildings.

(Ceroni, F., S. Sica, Mr Pecce.2012) The consideration of soil-structure interaction becomes pertinent, although often overlooked, when investigating the dynamic behavior of structures in terms of frequencies and vibration modes. Despite being a well-explored concept, practical applications of soil-structure interaction are still evolving. After reviewing the current state of understanding regarding soil-structure interaction phenomena, numerical parametric analyses are employed on various reinforced concrete (RC) and masonry structures representing diverse structural typologies to quantify the impact of SSI. In line with previous observations, the interaction between the soil and the structure results in: (1) an increase in the building's fundamental period compared to a fixed-base solution; and (2) enhanced damping of the system, attributed to the energy dissipation through the foundation soil (radiation damping).

(H.Matinmanesha, 2011) Various soil types enhance bedrock mobility at the soil-structure interface to varying extents. The degree of enhancement is influenced by factors such as soil qualities, seismic frequency content, and the characteristics of the structure above. Bedrock motion is most noticeably heightened when conditions result in lower effective damping, influenced by soil conditions, structural models, and seismic excitations.

For instance, packed sand exhibits a shorter period compared to loose sand, and taller structures generally have longer periods than low-rise buildings. The combination of these factors plays a crucial role in magnifying earthquake effects. In congested urban areas, five-story structures constructed over shorter time periods exhibited the highest amplification during earthquakes and the lowest maximum acceleration at the soil-structure contact.

On the other hand, the longest period soil-structure system, represented by a 20-story building on loose sand, experienced the greatest amplification in low-intensity earthquakes and the least in high-intensity earthquakes. Across all models, the soil-foundation contact consistently experienced the highest primary stress under the columns, while the core of the foundation encountered the lowest stress.

(Jammula and Konda, 2021) Explored strategies to mitigate torsional and stiffness irregularities in structures situated on uphill terrain, considering two key parameters: step-back construction and building on steep slopes. The study focused on a G+9 storey structure positioned on a 36-degree slope, identified as a step-back building (H1), and a conventional building (H2) with 4 stories above road level, featuring a straight setback at the sixth floor only (H3). SAP 2000 was utilized to analyse the model's responses subjected to seismic forces.

Observations indicated increased forces on the corner columns of the building due to torsional and stiffness inconsistencies. Consequently, shear walls were strategically placed in corners experiencing higher forces. The study concluded that altering the positioning of columns and the height of columns at ground level, coupled with the placement of shear walls, can effectively modify the behaviour of building structures, resulting in decreased damage.

(Ashok, 2017) Examined a step-back structure on sloped ground with three varying inclinations (10°, 30°, and 45°). The study focused on a 3-story step-back building with two phases. In the first phase, three different inclinations were achieved by maintaining the building's height constant, while in the second phase, the structure's width was kept constant. Using the STAAD Pro software and employing the response spectrum approach, the investigation revealed that in any inclination of the ground storey, the smaller column in the middle of the structure bears a higher load compared to the longer-length column. Elevating the angle with a fixed height led to diminished column forces and reduced structure stiffness, but this effect was reversed for structures with fixed width.

(Gem Thomas and **Dheekshith K 2018)** Examined the seismic behavior of G+12 storied step-back buildings across three different slopes (0°, 27°, and 40°) with variations in frames, including bare frame, bare frame with core wall, and bare frame with core wall and infill wall. The study encompassed diverse soil conditions—soft, medium, and hard soil—resulting in a total of 27 models.

Utilizing ETABS, a Finite Element Method (FEM)-based program, the research assessed the behavior of these models by analyzing top storey displacement, base shear, time period, storey displacement, and storey drift.

The findings indicated a consistent increase in the base shear of buildings for hard, medium, and soft soil, with structures in soft soil experiencing a 23% greater displacement compared to those in medium soil. The overall response was noted to be more favorable for structures on hard soil compared to medium and soft soils. Additionally, the bare frame with core wall construction exhibited superior performance, particularly with a zero-degree slope inclination.

(B G Naresh Kumar et al., 2018) Conducting a comparative study on buildings subjected to seismic loads, the research employed pushover analysis to investigate the differences between mass regular and irregular structures. ETABS 2015 was utilized to model a G+5 box-shaped building, applying standard loads based on IS regulations. The study concluded that mass irregular buildings exhibit greater lateral displacement compared to their mass regular counterparts

Objective of Work

The primary goal of this study is to conduct seismic analyses on structures constructed on hill slopes.

- ➢ Examine the impact of varying slope angles on buildings with different plan configurations on fixed bases under seismic loads.

- ➢ Investigate the influence of soil-structure interaction under seismic loads in step-back structures with various plan configurations.Steps for achieving aims

III.METHODOLOGY

3.1 Methods of Analysis

A building is a system that responds to various forms of stresses by causing disturbance in the form of rotation and displacement. These displacements and forces must be studied in order to anticipate the building's reaction. There are several building analysis methodologies, the three most common of which are described below:

3.1.1 Linear Static Analysis or Equivalent Static Analysis

In this method, it is assumed that the horizontal lateral force is equivalent to the dynamic loading. The estimation of base shear is derived from the structure's mass, fundamental period of vibration, and its corresponding shape. As per regulations, the base shear is then distributed along the height of the building.

This approach is fundamentally built on the presumption that a building is a rigid structure with complete fixity between the foundation and its supports. Equal accelerations are felt at each point of the structure. The horizontal forces of the earthquake are thought to be the primary influence. This approach approximates the horizontal force or base shear on the structure.

IV.MODELING AND ANALYSIS

4.1 Computational Modelling of Building

Building modelling involves converting the real scale model of the building in the practical field to a scaled mathematical model in some sort of software through which all the calculations can be done and the required response can be calculated that matches the response in the real field.

4.1.1 Building Configuration

For this study, a total of 24 building models were chosen, the types, slopes, plan irregularity conditions, base conditions, and related notations of which are listed below and will be used in the following pages of the thesis.

Table 4.1: Modelled Building Notations

Serial No.	slope of structure	shape of structure	Type of base/soil	Notation
1	0°	Regular	Fixed	RF0
2	15°			RF15
3	30°			RF30
4	45°			RF45
5	0°		Medium	RS0
6	15°			RS15
7	30°			RS30
8	45°			RS45
9	0°	+ shaped	Fixed	+F15
10	15°			+F15
11	30°			+F30
12	45°			+F45
13	0°		Medium	+S0
14	15°			+S15
15	30°	+ shaped	medium	+S30
16	45°			+S45
17	0°	L-shaped	Fixed	LF0
18	15°			LF15
19	30°			LF30
20	45°			LF45
21	0°		Medium	LS0
22	15°			LS15
23	30°			LS30
24	45°			LS45

4.1.2 Specifications of The Modelled Building

- Type of building : Commercial cum Residential building
- Seismic Zone : V
- Soil Type : Medium
- Importance factor : 1.5
- Response reduction factor : 5
- Damping ratio : 5%
- Type of structure : Special Moment Resisting Frame

Table 4.2: Specifications of the Modelled Building

Plan dimension	18m X 18m
Story height	3m
Bay width in X and Y-direction	3m X 3m
No. of story's	Ground Floor +10

4.2.1 Geometry of Model 1-8

The regular buildings with slope angle variation 3D models view with and without SSI is shown in the figures below

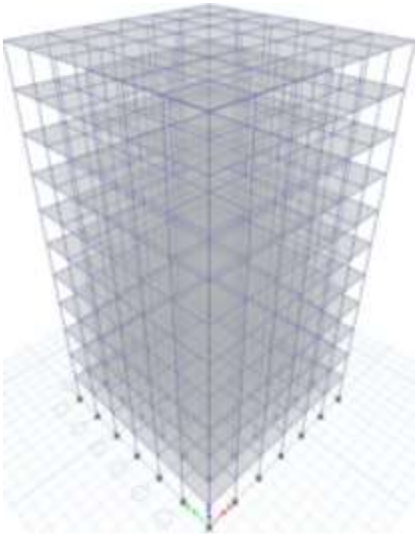

Figure 4.1 RF0

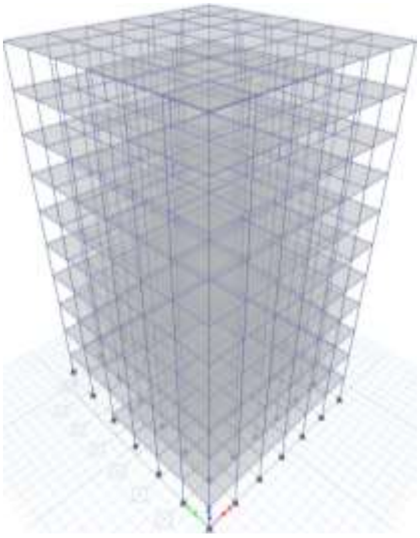

Figure 4.2 RF15

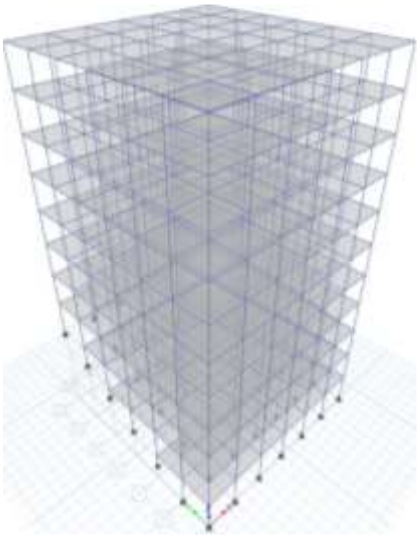

Figure 4.3 RF30

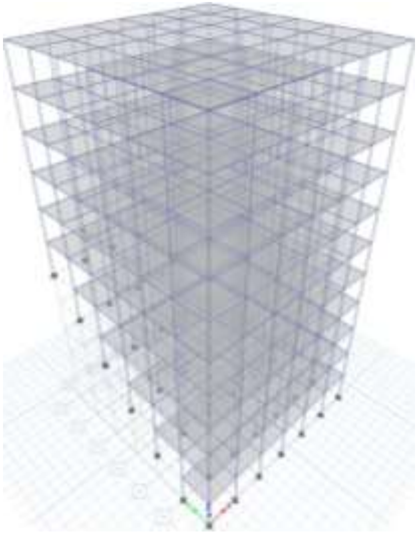

Figure 4.4 RF45

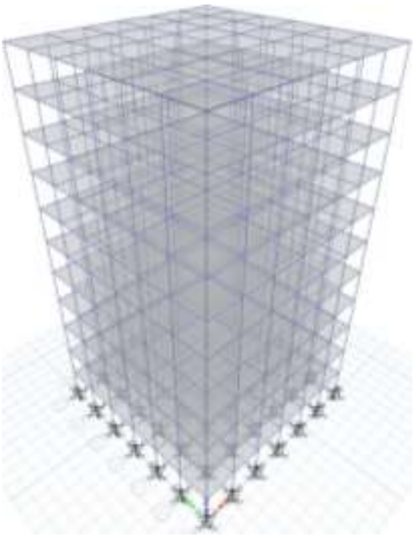

Figure 4.5 RS0

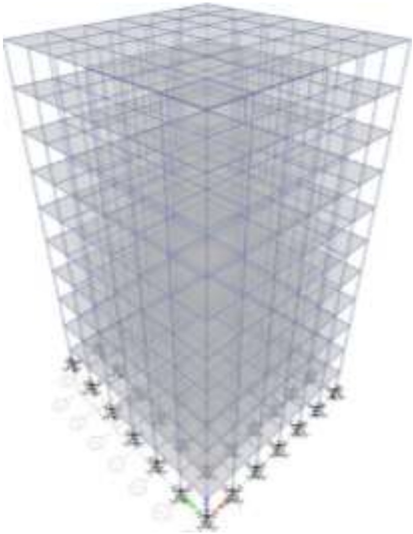

Figure 4.6 RS15

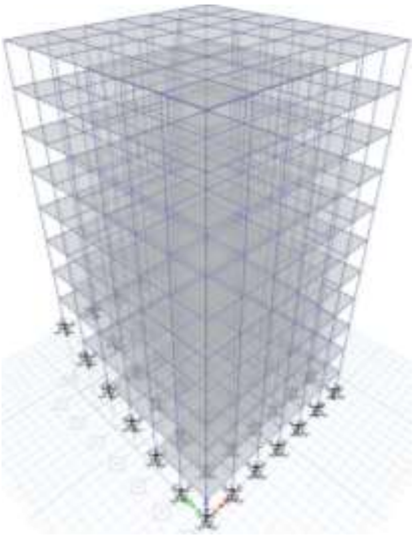

Figure 4.7RS30

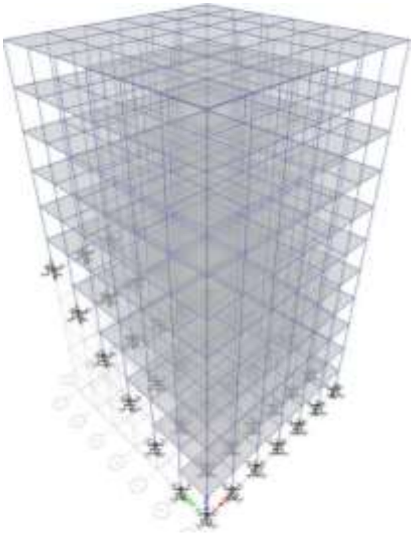

Figure 4.8 RS45

4.2.2 Geometry of Model 8-16

The + shaped buildings with slope angle variation 3D models view with and without SSI is shown in the figures below

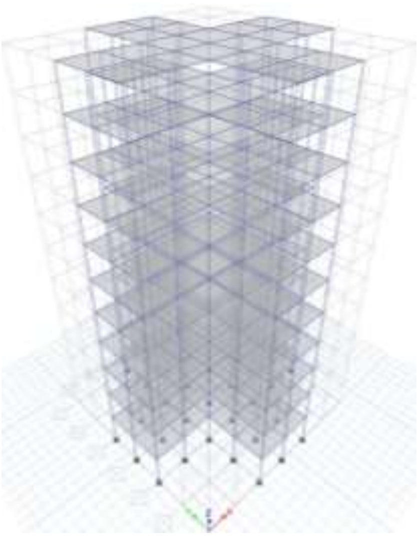

Figure 4.9 +F0

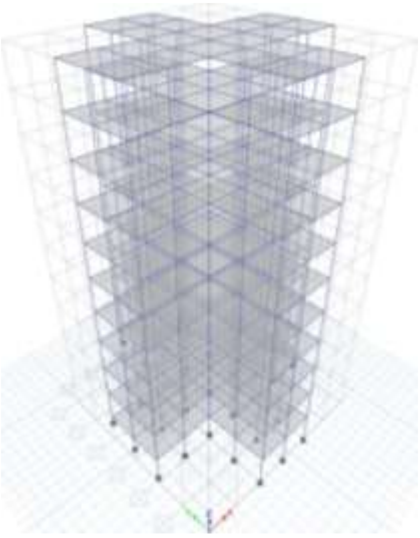

Figure 4.10 +F15

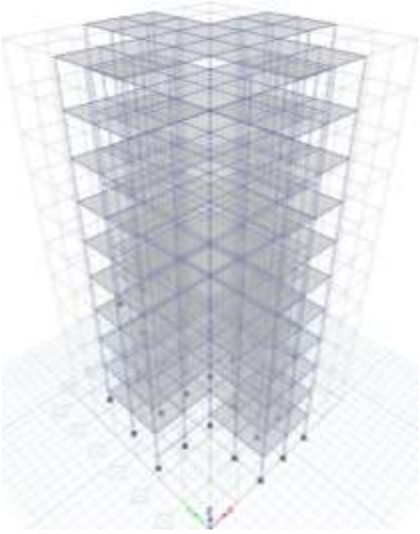

Figure 4.11 +F30

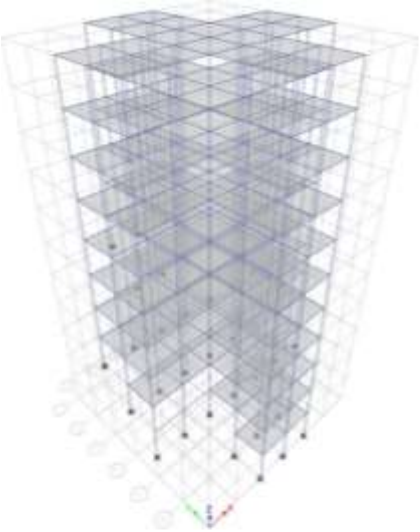

Figure 4.12 +F45

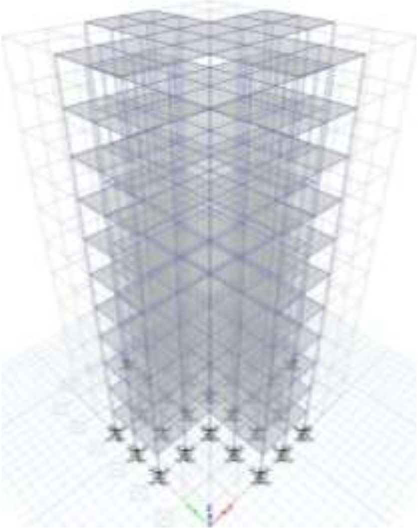

Figure 4.13 +S0

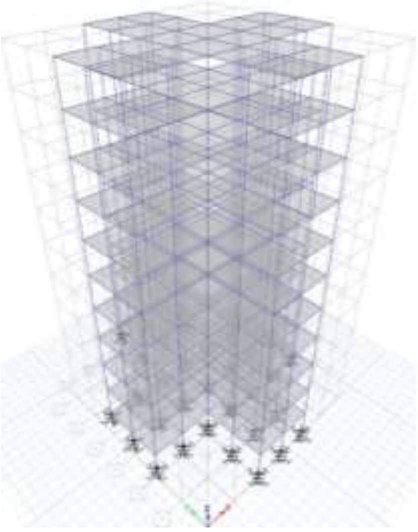

Figure 4.14 +S15

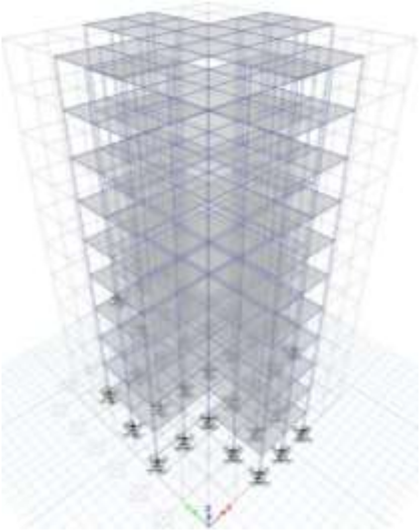

Figure 4.15 +S30

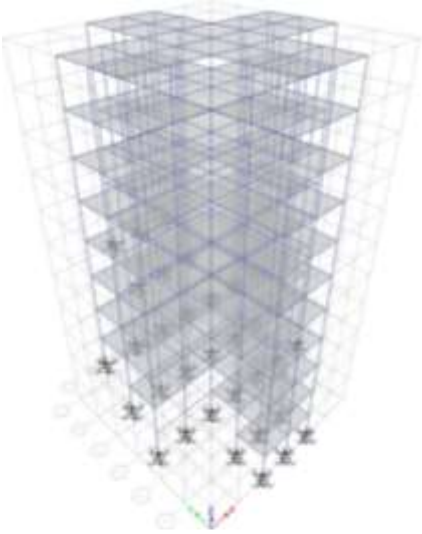

Figure 4.16 +S45

4.2.3 Geometry of Model 16-24

The L shaped buildings with slope angle variation 3D models view with and without SSI is shown in the figures below

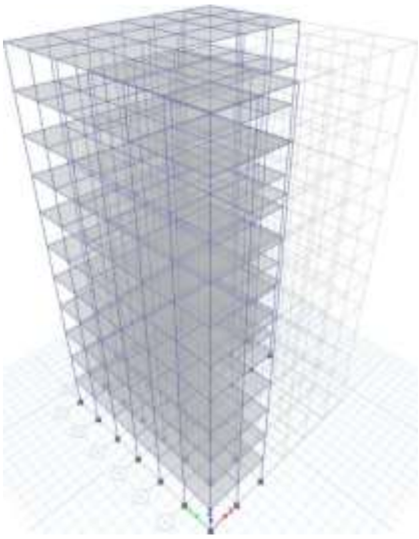

Figure 4.17 LF0

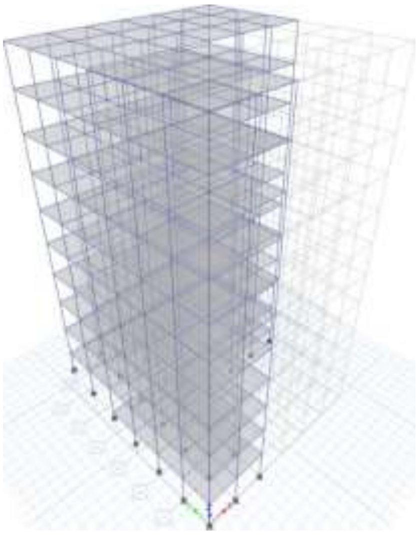

Figure 4.18 LF15

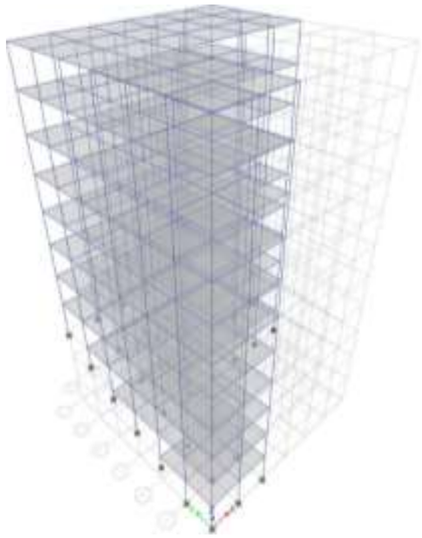

Figure 4.19 LF30

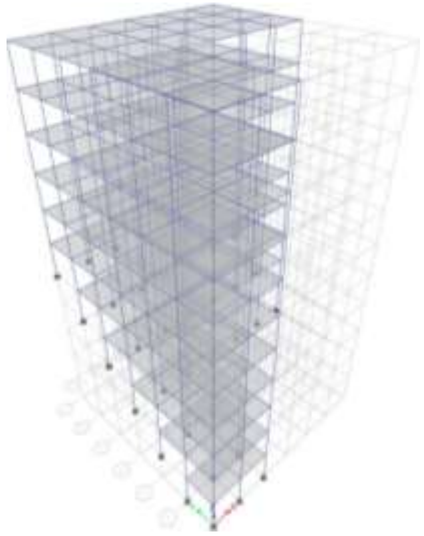

Figure 4.20 LF45

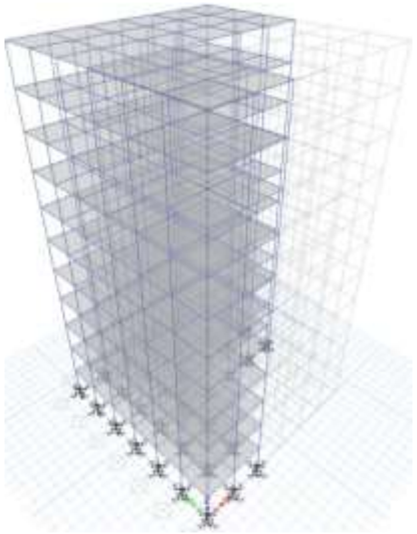

Figure 4.21 LS0

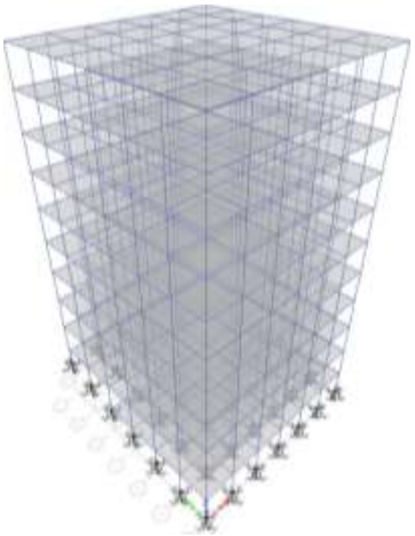

Figure 4.22 LS15

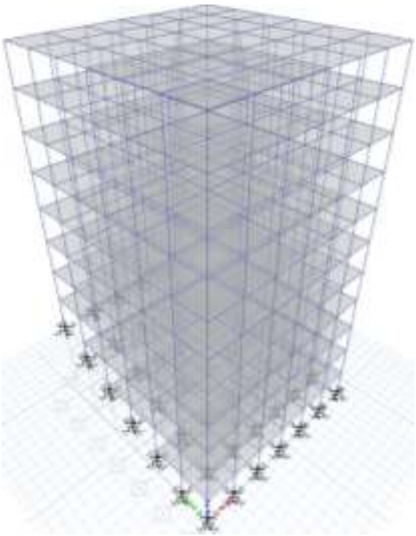

Figure 4.23 LS30

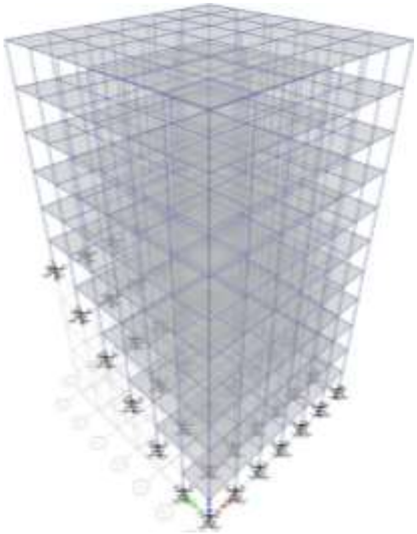

Figure 4.24 LS45

V.RESULTS AND DISCUSSIONS

The outcomes of ESM for several models, taking various factors into consideration, are first compared, and the impact of slope angle change along with SSI and various plan configurations is investigated. The outcomes of the linear time history analysis were then provided.

The **time period** for models on a 45° slope is slightly longer than that for models on a 30° slope.

For models with slopes of 15° and 30°, intermediate column lengths (ranging between 0 and 3 m) at various storey levels hinder the free vibration of storeys collectively. In contrast, models on a 45° slope feature a complete storey on each level, contributing to a minor increase in flexibility and time period. These intermediate columns provide additional rigidity, resulting in a shortened time period for the models. When considering Soil-Structure Interaction (SSI), all models exhibit longer periods compared to the fixed base model due to increased flexibility at the base of the structure. Intriguingly, the rate of time span increase due to SSI implementation also intensifies with decreasing slope angle.

The **base shear** of models (RF15, RF30, and RF45) is increased compared to RF0. And the models (RS15, RS30, and RS45) base shear reduces compared to RSO. With the implementation of SSI in the models (RS0, RS15, RS30, and RS45), the base shear gets Decreased as compared to the models (RF0, RF15, RF30, and RF45). The base shear of models (+F0 & LFO) decreases as compared to the RFO. The base shear of models (+S0 & LSO) decreases compared to the RSO. With the exception of the model at a 45° angle, elevating slope angles result in heightened spectral acceleration and diminished time period, leading to an increase in base shear. The 45° angle model experiences a minor rise in flexibility and time period but demonstrates the most significant reduction in floor space and mass, consequently lacking floor shears. Introducing Soil-Structure Interaction (SSI) at the base enhances the structure's flexibility, thereby reducing the base shear.

The **displacement** in the force direction (X direction) exhibited an increase with rising floor height and a decrease with an increasing slope. Recorded displacements in the X direction against a force in the same direction were observed for a model positioned on a slope, revealing an increment in displacement values with an increasing slope. It is noted that the displacement on the taller side of the model surpasses that on the shorter side. This indicates that, at low incline levels, the tall side is more flexible than the short side at high incline levels. In comparison, the model with Soil-Structure Interaction (SSI) demonstrated relatively larger displacement values in both directions compared to the model with a fixed base.

VI.CONCLUSIONS

1. In this research, both static and dynamic methods are employed to conduct seismic analyses of structures situated on different slope angles, considering scenarios with and without the incorporation of Soil-Structure Interaction (SSI).
2. Structures located on sloped terrain are observed to be at a higher risk compared to those situated on flat ground, and the degree of vulnerability increases as the slope angle becomes steeper
3. When situated on an inclined surface, the structure has been noted to experience displacement when subjected to a directional force. Such inclined buildings display varying movement on each side, with the taller side ascending more than the shorter side in the direction of the applied force. This phenomenon suggests that stiffness is concentrated on the shorter side of the structure when positioned on steeper slopes.
4. Due to the asymmetrical in plan the L-shaped models got high base shear compare to the regular and +-shaped model
5. The L- shaped model got high Time period to compare the other models in both cases fixed and flexible.in flexible base i.e. 1.075sec and fixed base 1.605sec.
6. The L- shaped model got high displacement to compare the other models in both cases fixed and flexible.in flexible base i.e. 39.937mm and fixed base 57.146mm.
7. The + - shaped model got low base shear to compare the other models in both cases fixed and flexible.in flexible base i.e. 2266kN and fixed base 3362Kn.
8. In this context, the importance of Soil-Structure Interaction (SSI) is underscored, as structures that neglect SSI tend to overestimate forces, such as base shear, and underestimate responses, including time period and displacement.

9. This incorrect force and response estimation can have severe negative effects on the structure. As a result, the current research highlights the negative effects of increasing the slope angle on structures sitting on sloping terrain and suggests that extra attention be taken when designing columns for sloped structures that are on a higher level.

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