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NONLINEAR STATIC ANALYSIS OF RCC SPACE FRAME ON SLOPING GROUNDS INCORPORATING SSI

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SUMMARY

This paper presents a comprehensive investigation into the seismic performance of a G+5 reinforced concrete spaceframe subjected to pushover analysis. The analysis incorporates the critical influence of soil-structure interaction on varying slope inclinations. A nonlinear static pushover method is utilized to examine the lateral loading strength and deformation response of the spaceframe under various slope scenarios. Instead of the usual spring-type models, a more complex Monkey Tail model is used to describe the behaviour of the soil. This model incorporates the inherent nonlinearities and hysteretic properties of soil subjected to seismic excitation. These sample results are carefully contrasted with a fixed-base analysis to quantify the actual effect of soil-structure interaction on the response of the spaceframe. Thus, the objective of this study is to clarify this issue by investigating the effects of slope variations on capacity curve, key failure mechanisms and displacement demands on the structure. Engineers can benefit greatly from the knowledge gained from this study when building spaceframes in seismically active areas with sloping terrain. Engineers can improve structural safety and performance assessments by using the Monkey Tail model to reflect soil-structure interaction more realistically.

Key words: *soil structure interaction, consecutive pushover analysis, sloping ground.*

INTRODUCTION

As our cities grow at an ever-increasing pace, the need for land is greater than it has ever been, and this makes it vital to explore new building methods and find smart ways to use our space [1]. Building in the mountains presents a unique set of challenges, especially since flat land is often scarce [12]. Yet, these areas offer vast potential for development, calling for safe and efficient construction methods suited to the sloping terrain [3].

Roughly 17% of India is made up of mountains, and most of these regions are prone to strong earthquakes. The Himalayas and the Western Ghats form a large part of India's varied landscape, highlighting the need for specific building techniques in these zones. To create strong and durable structures in the mountains, we need to fully grasp how the soil and buildings interact, how earthquakes impact structures, and so on [2].

Building on a slope is a whole different ball game compared to flat land. The slanted ground and bumpy landscape make site prep, getting around, and moving materials and gear a real pain, and even a bit risky [11]. You really got to pay attention to the dirt and ground, cause hillsides can easily wash away, have landslides, and the soil can be all over the place [13]. This means you need to really study the land and build the right kind of foundation. When it comes to the actual building, you need to make sure it can handle the extra sideways pressure from gravity, wind, and earthquakes, and that it won't tip or sink unevenly [14]. Dealing with water is also a big deal – you need good systems to manage rainwater, stop erosion, and keep the building dry [6], [19]. At the end of the day, we really need to think about how we can reduce our impact on the environment when we're building in these delicate areas. Using sustainable building methods and making sure we don't mess up the natural beauty around us should be top priorities [7].

When we're figuring out how well a building will hold up in an earthquake, especially if it's on a slope, we absolutely have to consider how the soil and the building will interact [5]. The soil on these kinds of ground can be really uneven, and there's more sideways force during a quake. These things have a big impact on how the building moves and reacts [15]. If we don't take this interaction into account, we might not realize how much the building could shift, tilt, or stress, and that could put the whole thing at risk. Therefore, accurately modelling soil-structure interaction is essential for a realistic and reliable seismic assessment of structures on sloping sites [8].

Soil Structure Interaction

Soil-structure interaction plays an important role in predicting the seismic response of structures, particularly for structures constructed on slopes. Whereas soil-structure interaction provides a dynamic relationship between the soil and the structure, the base is traditionally assumed to be fixed during earthquakes [4], [16]. Since SSI usually causes a lengthening of the natural period of the system in relation to a fixed-base structure, it behaves like a structure that oscillates more slowly. In addition to that, SSI increases the damping ratio that works to dissipate energy due to radiation as well as soil's material damping [9], [10].

Accurately accounting for SSI is essential for a realistic seismic assessment. Neglecting SSI can lead to an underestimation of seismic demands, potentially compromising the safety and stability of the structure. While rigorous methods for analysing SSI exist, they can be computationally expensive and time-consuming [18]. Therefore, simplified models, such as the Cone Model, are often employed in practice to efficiently capture the essential aspects of SSI. These models provide a balance between accuracy and practicality, allowing engineers to incorporate SSI considerations in their designs without excessive computational burden [12].

In this study, the effects of soil-structure interaction are incorporated through the Cone model and site effects analysis [17]. While finite element and boundary element methods offer enhanced accuracy, their complexity and computational demands render them less suitable for parametric studies [23].

Previously, in various versions of pushover analysis method, the influence of SSI and the secondary ground motion component is often overlooked [22]. To address these limitations, the study made use of the extended consecutive modal pushover procedure for analysing, mid- and high-rise moment-resisting frame buildings subjected to seismic ground motion and considering SSI [20]. The ECMP procedure enhances the traditional consecutive modal pushover method by overcoming limitations related to the number of modes considered and the approach for incorporating each mode in the multi-stage analysis. Additionally, a modification factor is introduced to account for the torsional effects arising from the secondary ground motion component when estimating engineering demand parameters [19].

Extended Consecutive Modal Pushover Analysis

Extended Consecutive Modal Pushover Analysis (ECMPA) is a performance-based design approach that builds upon traditional pushover analysis, making it more sophisticated. Unlike the traditional method, ECMPA considers the influence of higher modes and captures the sequence in which different structural components yield. This makes it especially well-suited for structures where higher mode effects play a significant role, such as tall buildings with asymmetrical designs [21].

What's more, ECMPA can be adapted to account for Soil-Structure Interaction (SSI), a critical factor that's often neglected in conventional methods. By incorporating SSI, ECMPA enables a more accurate evaluation of seismic forces, particularly for buildings situated on diverse soil types. This is because ECMPA can precisely model the dynamic interplay between the structure and the underlying soil, as highlighted in reference [12].

Advantages of ECMPA

1. Better Handling of Higher Modes: ECMPA builds on traditional pushover analysis by taking into account the impact of higher modes. This is especially important for accurately predicting how structures like tall, asymmetrical buildings will react.
2. Accounting for Soil-Structure Interaction: This research adapts ECMPA to include the effects of soil-structure interaction (SSI), something often missed in conventional methods. This leads to a more realistic evaluation of seismic demands, especially for buildings on diverse soil types.
3. More Accurate Seismic Demand Estimates: ECMPA brings together results from multiple modal pushover analyses, resulting in a completer and more precise picture of a structure's overall seismic demands compared to standard pushover analysis.

Disadvantages of ECMPA

The ECMPA approach, while advantageous in many ways, does have some limitations to consider:

1. Higher Computing Demands: ECMPA asks for numerous pushover analyses for each mode shape, which makes it a heavier lift, computationally speaking, than the standard pushover analysis.

2. Reliance on Expert Knowledge: Picking the right mix of modes and making sense of ECMPA's results often calls for a good deal of seasoned engineering know-how.

Even with these hurdles, ECMPA remains a powerful method for engineers, delivering more realistic and reliable seismic demand estimates, especially in cases where higher mode impacts and soil-structure interaction play a major role.

Past research has looked into how structures behave during earthquakes when built on sloped ground, often using a method called Extended Consecutive Modal Pushover Analysis. However, how different slope angles really affect a building's earthquake demands, especially when the interaction between the soil and the building is considered, is still mostly a mystery. This study dives deep into this issue, examining how various slope angles change the earthquake response of a 6-story reinforced concrete building. It uses the ECMPA method within a software called OpenSees and includes a simplified model to account for the soil-structure interaction. By doing this, the researchers can closely analyze how the slope angle alters crucial engineering factors like the base shear force, the building's target displacement, the forces in the columns, the bending moments, and the settlement of the building. This gives us extremely useful information for designing earthquake-resistant buildings on sloped land.

METHODOLOGY

Here's how we'll tackle the analysis of a six-story reinforced concrete building when it's subjected to an earthquake, while also factoring in how the building interacts with the soil it's built on at different slope angles. We'll use a technique called the Extended Consecutive Modal Pushover Analysis, all within the OpenSees software.

Details of Model

Structural Details of the RCC frame

The 6-storey Reinforced Concrete building (Figure 1 and Figure 2) analysed in this study has the following geometry, as outlined in the tables below. The building features columns of varying sizes, with larger dimensions at the lower storeys and smaller dimensions at the upper storeys. Beam sizes and slab thicknesses are also provided. The geometrical and structural members' properties of the building model is mentioned in the table 1 and table 2 respectively.

Table 1. Building geometry

Number of storeys	6
Storey Height	3.1 m
Bays	
X direction	4
Y direction	3
Span	
X direction	6.5 m
Y direction	6 m

Table 2. Members' properties

Column Size	
From PL to 3rd Storey	500mm × 500mm
from 4th to 6th Storey	400mm × 400mm
Beam Size	300mm × 500mm
Slab Thickness	200mm
Shear Wall thickness	200mm
Height of plinth above GL	0.6m
Depth of foundation below GL	1.5m
Footing size below Column	3m × 3m × 0.5m
Footing size below Shear wall	3m × 9m × 0.5m
Grade of Concrete	M25
Steel	Fe415

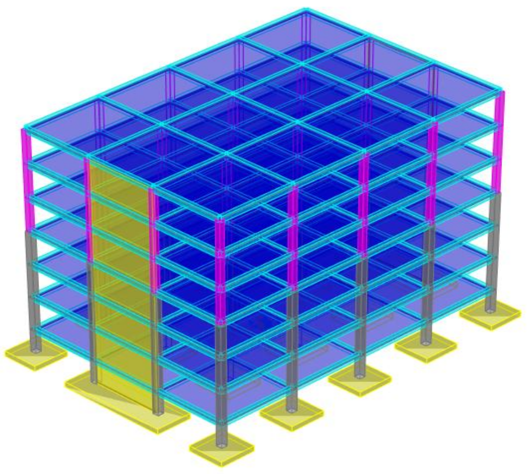

Figure 1. 3D view of the model

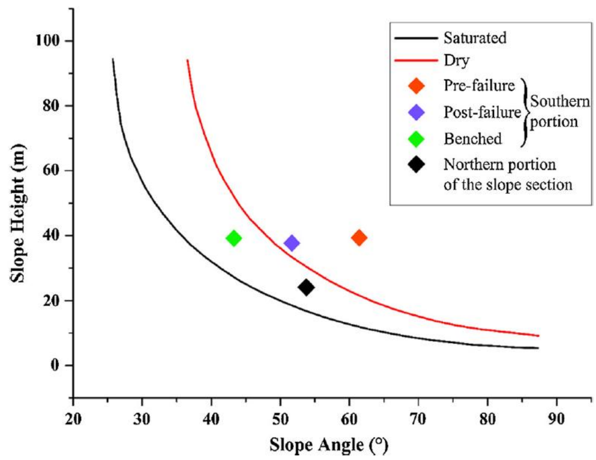

Figure 2. Critical slope height versus slope angle relation for soil slope geometry (after hoek and bray (1981)

Soil Model

Slope Geometry

This study considers soil profiles with varying slope angles to assess their impact on the seismic response of the structure. The soil profiles were modelled with slope angles ranging from 0 degrees (flat terrain) to 50 degrees, in increments of 10 degrees (Assumed on the basis of Hoek and Bray, fig. 2). This parametric approach allows for a systematic investigation of how the slope angle influences key engineering demand parameters, such as base shear, target displacement, column forces, and settlement. The engineering properties of the soil was assumed as given in the table 3.

Table 3. Soil properties

E_{Soil}	14.80 N/mm^2
μ_{Soil}	0.35

Soil-Structure Interaction

In this study, a simplified physical model is used for modelling soil-structure interaction. While modelling based on the finite element method or boundary elements is more accurate, they are not suitable for parametric studies due to the complexity and time-consuming nature of the modelling process. Here, the kinematic interaction and foundation input motions are ignored, and the Cone model is used to represent the inertial interaction [13].

The Cone model provides a computationally efficient way to incorporate soil-structure interaction effects in the analysis. By representing the soil as a diverging cone, the model can capture the essential soil behaviour without the need for complex finite element or boundary element formulations. The spring and dashpot coefficients are derived from beam theory, and the cone's opening angle is calibrated to match the three-dimensional soil response.

While the rocking stiffness and damping of the soil-foundation system are frequency-dependent, requiring a convolution integral, the Cone model employs simplified methods using an internal degree of freedom. This approach avoids the complexity of the convolution integral, yet still provides comparable accuracy to more sophisticated models. In this study, the "monkey tail" method is used to implement the Cone model, which has been shown to offer reliable results for soil-structure interaction analyses.

The soil properties detailed in table 4 are used to determine the Cone model parameters. This parametric approach enables the investigation of how variations in soil characteristics influence the seismic response of the structure on sloping grounds (Figure. 3).

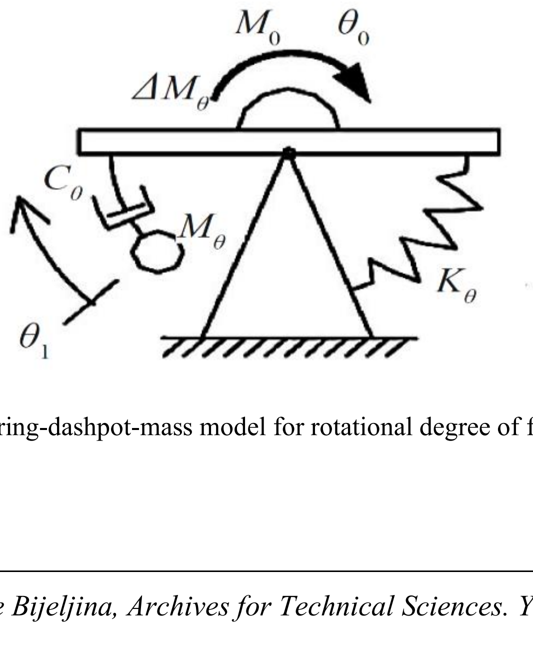

Figure 3. Spring-dashpot-mass model for rotational degree of freedom [13]

Table 4. Calculation for cone model parameters

Motion	Horizontal	Rocking		Torsional
Equivalent Radius $\boldsymbol{r_0}$	$\sqrt{A_o/\pi}$	$\sqrt[4]{4I/\pi}$		$\sqrt[4]{2I_o/\pi}$
Aspect Ratio, $\boldsymbol{z_o/r_o}$	$\frac{\pi}{8}(2-\nu)$	$\frac{9\pi}{32}(1-\nu)(c/c_s)^2$		$9\pi/32$
Poisson's Ratio $\boldsymbol{\nu}$	all ν	$\nu \leq 1/3$	$1/3 \leq \nu \leq 1/2$	all ν
Wave Velocity $\boldsymbol{c}$	c_s	c_p	$2c_s$	c_s
Trapped Mass ΔMor ΔM_θ	0	0	$1.2(\nu - 1/3)\rho I_o r_0$	0
Lumped parameter Model	$K = \rho {c_s}^2 \frac{A_o}{z_o}$ $C = \rho c_s A_o$	$K = 3\rho c^2 \frac{I}{z_o}$ $C = \rho c I; M_\theta = \rho I_o z_o$		$K = \rho {c_s}^2 \frac{I_o}{z_o}$ $C = \rho c_s I_o$

Extended Consecutive Modal Pushover Analysis

The procedure for conducting Extended Consecutive Modal Pushover Analysis is as follows:

1. Modal Analysis: Determine the natural frequencies (ω_n) and mode shapes (ϕ_n) of the structure, normalizing the lateral component of the roof displacement in the dominant direction to unity ($\phi_{nr} = 1$).

2. Lateral Force Distribution: Calculate the n^th mode lateral force distribution (${S_n}^*$)

3. Target Displacements and Increments: Compute target displacements (δt_x, δt_y) in both x and y directions. Determine the number of stages (N_s) and calculate displacement increment coefficients (β_r) for each stage.

4. Single-Stage Analysis: Apply gravity loads, followed by pushover analyses in x and y directions individually. For target displacement ratios ($T_R = \delta t \ / \ building\ height$) less than 2%, use uniform and fundamental mode load patterns, resulting in responses r_{s1} and r_{s2}, respectively. For $T_R \geq 2\%$, use the Equivalent Lateral Force distribution, yielding response r_s. Combine directional responses are calculated.

5. Multi-Stage Analysis: Apply gravity loads, then sequentially apply modal load distributions (${S_1}^*$, ${S_2}^*$,...), incrementing the control node displacement by $u_{s1} = \beta_r \delta_t$ for each mode r until the target displacement (δt) is reached. Repeat for both x and y directions. Combine directional responses and to obtain response r_{MS}.

6. Response Combination: Determine the ECMP response as the envelope of single-stage and multi-stage analyses. For $T_R < 2\%$, this involves two single-stage and one multi-stage analysis; for $T_R \geq 2\%$, one single-stage and one multi-stage analysis are used.

$$r = \begin{cases} \max\{r_{s1}, r_{s2}, r_{MS}\} & , \quad T_r < 2\% \\ \max\{r_s, , r_{MS}\} & , \quad T_r \geq 2\% \end{cases}$$

RESULTS AND DISCUSSIONS

This study examined a 6-storey Reinforced Concrete frame structure using Extended Consecutive Modal Pushover Analysis to evaluate the impact of varying soil slopes on seismic performance. By simulating a range of Slope conditions, the analysis revealed how slope angle influences the displacement in the structure. These findings underscore the importance of integrating Soil-Structure Interaction effects, especially for structures on sloping terrain, to achieve a more precise and dependable seismic assessment.

Modal Analysis of the Modelled RC Structure

The modal analysis was conducted to find various modes and their respective participation in the ECMPA. (table 5).

Table 5. Time period and participation factor in the X direction

MODE	Time Period (s)	UX	Sum UX
1	1.150189	0.74533	0.74533
2	1.13009	0	0.74533
3	1.101874	1.827E-20	0.74533
4	0.406898	0.1157	0.86104
5	0.401118	4.033E-18	0.86104
6	0.388268	1.439E-19	0.86104
7	0.23104	0.03528	0.89631
8	0.228078	9.629E-17	0.89631
9	0.219715	2.725E-16	0.89631
10	0.161211	0.02799	0.9243
11	0.159721	7.069E-16	0.9243
12	0.15302	1.601E-15	0.9243

- **Target displacements and base shear in pushover analysis**

It was observed that the target displacement (table 6) shows a declining trend of average 12.77% with increase in the slope by 10 degree which shows that the capacity of the structure to withstand the lateral load has reduced (Figure 4 and Figure 5).

Table 6. Target Displacement in the X direction

SLOPE	TARGET DISPLACEMENT (mm.)
FLAT	327.32
10° slope	304.66
20° slope	291.85
30° slope	276.3
40° slope	223.68
50° slope	183.55

- **Displacement Over Structure Height at Centre of Mass**

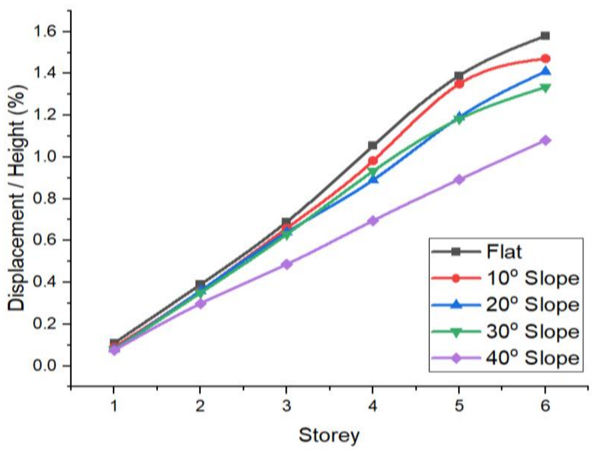

Figure 4. Displacement/height (%) without SSI

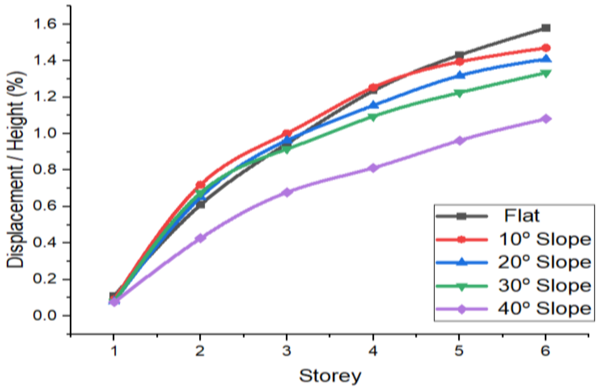

Figure 5. Displacement/height (%) with SSI

CONCLUSIONS

This study investigated the seismic response of a structure on varying slopes, revealing a significant relationship between slope angle and seismic demands. A 10-degree slope increase resulted in an average 4.25% increase in base shear and a 5.5% decrease in target displacement, highlighting the reduced seismic capacity on steeper slopes. Pushover analyses, while consistent with capacity spectrum method results, showed a 40% higher maximum settlement due to differing loading patterns. Furthermore, a 10-degree slope increase led to an average increase of 7.54% (without SSI) and 8.07% (with SSI) in column axial force, and 7.16% (without SSI) and 7.81% (with SSI) in column bending moment. Settlement also increased by 15.11% per 10-degree slope increment. These findings underscore the critical need to account for slope effects in seismic design to ensure structural safety and resilience on sloping terrain.

The study found that accounting for soil-structure interaction increased the column axial forces by an average of 9.12% and the column bending moments by 10.7%.

Based on this study, several promising research directions emerge to improve understanding of seismic performance in structures on sloping terrain. These include investigating advanced soil models, expanding the analysis to 3D to capture torsional effects and soil variations, validating the findings through experiments, assessing different foundation designs, developing seismic retrofitting solutions for existing buildings on slopes, and contributing to performance-based design guidelines for structures in challenging slope environments. Exploring these directions can help enhance the seismic resilience of buildings in slope-prone regions.

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