iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 9 **Issue:** IX **Month of publication:** September 2021

DOI: https://doi.org/10.22214/ijraset.2021.37907

www.ijraset.com

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.429
Volume 9 Issue IX Sep 2021- Available at www.ijraset.com

Literature Review on Interaction Analysis of Building Resting on Sloping Ground

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Abstract: An increase in economic growth, as well as urbanization in the hilly areas, encourages the construction in the hilly region. Considering this fact the engineers should assure the safety of constructions in the slopy region. To understand the past attempts carried out on the constructions of the building on the slopy ground the systematic literature survey is done which includes the parameters like types of the building suitable for hilly regions, slope inclinations for safe superstructure in seismic events, types of safety measures recommended to assure the safety of superstructure and necessity of interaction analysis for the constructions in the hilly region. The survey so carried out in the paper gives a fair idea about the research gap and thus motivates researchers to carry out future research on the gap identified.
Keywords: soil-structure interaction; slopy ground; bracing system; literature survey; equivalent static analysis; hilly region constructions.

I. INTRODUCTION

A. Buildings on Sloping Ground

With the increase in economic growth as well as urbanization in the hilly areas of the world, the demand for the construction of buildings on the sloping ground has increased. Buildings on the sloping ground are vulnerable to earth pressures and seismic activities. Various places are categorized into various zones depending on the records of seismic activity such that any structure to be constructed in that zone must be capable of withstanding the expected seismic intensity. The topographical features of the earth also impact the seismic vulnerability of any structure built.

The occurrence of earthquakes is due to the movement of tectonic plates along the fault line. Generally, the areas having the rock types such as trap rock or basaltic rock are more vulnerable to earthquakes. Globally Japan, Nepal, India, Ecuador, Philippines, Pakistan, Mexico and some islands are more prone to earthquakes of severe intensity and magnitudes. In India, most of the north-eastern parts and Himalayan regions confirming seismic zones IV and V are vulnerable to great earthquakes of magnitude 8 and above due to the movement of the Indian plate towards the Eurasian plate at the rate of 50 mm per year. Guwahati, Srinagar, Delhi, Mumbai and Chennai ranks the top five most earthquake-prone areas in India (Ref Fig.1). With the unavailability of plain ground in the northeastern part of India, buildings are constructed on hills i.e., on the sloping grounds (Ref Fig. 2). According to some researches, hills and mountains can reduce the power of earthquakes but they direct the earthquakes to certain localized areas making the effects more powerful than that expected for certain earthquakes.

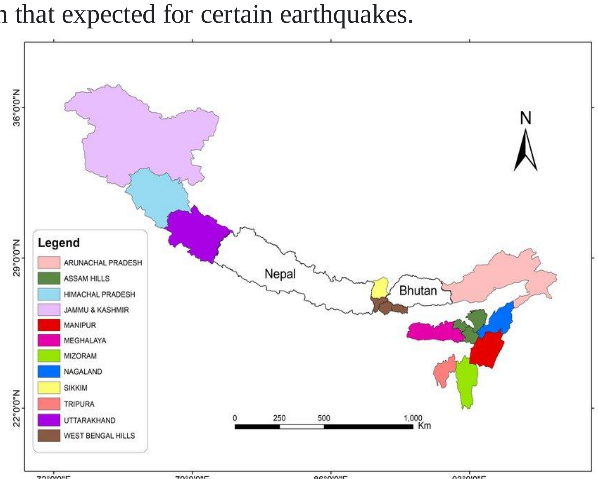

Fig. 1. Map Showing Indian States with Hilly Regions (Source: Survey of India).

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Fig. 2. Buildings on Sloping Ground in Sikkim (Web source)

Considering the above fact it is the need to analyses the structures built on the slopes more accurately to assure the safety of the superstructure during the seismic event. Several attempts have been made to study the behaviour of the buildings on a sloping ground of different configurations for seismic activities and analyze the responses. The seismic responses are analyzed by various numerical modelling techniques and by conducting static analyses such as Equivalent Static Analysis and Pushover analysis and dynamic analyses such as Response Spectrum Analysis and Time History Analysis as per the recommendations of IS 1893:2002. The fragility curves are drawn to study and estimate the vulnerability of the earthquakes in a certain region. The systematic literature review is carried out for the building constructed on the slopy ground considering the analysis types, types of building recommended for slopy ground, soil-structure interaction and availability of soils strata in the slopy region etc in the following subsections.

B. Seismic Analysis of Buildings on Sloping Ground

For the seismic analysis of any building of a certain configuration, the buildings are modelled and analyzed by various developed engineering analytical tools as per the recommendations of IS 1893:2002. The loads are considered as per the recommendations of IS 875. The RC design of buildings is as per the codal provisions suggested in IS 456: 2000. Several studies and researches have conducted experimental studies and analyzed the behaviour of buildings on sloping grounds and suggested certain mitigation methods to control the failure with minimal damage to earthquakes in certain prone areas. Considering the study the following are the recommended types of the building which shows better performance during a seismic event.

C. Types of Building Configurations Constructed on Sloping Ground

The main configurations of buildings constructed on sloping grounds are classified into 3 types. They are Set back buildings, Step back buildings and a combination of step back and set back (Stepback-Setback Building). Set back is the building with the side looking like having setbacks from one building to another building with some steps.

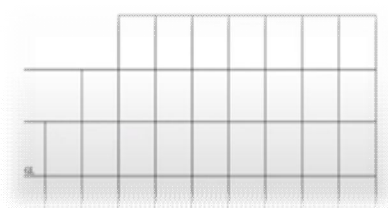

Fig. 3. Set Back Building

Step back buildings will have their columns on the ground floor. So the ground storey will be considered as a soft storey.

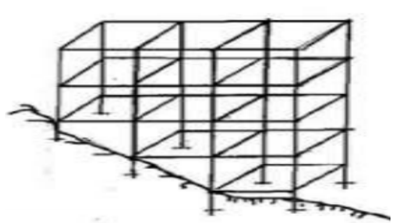

Fig. 4. Step Back Building

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In the combination of step back and set back building the design and architectural features are combined and constructed.

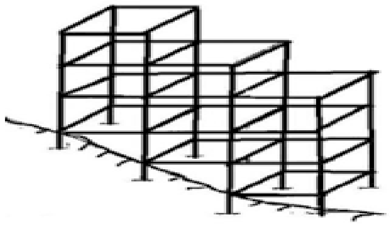

Fig. 5. Stepback-setback Building

As per the literature, of these three building configurations, the building with a stepback-set back configuration performs well. The addition of bracings to the stepback building configuration offered better performance than step back-set back building configuration.

D. Short Column Effect

Buildings constructed on the sloping ground are different from those in the plain ground. Buildings on the sloping ground are irregular and unsymmetrical. The buildings are constructed with different column heights. Thus, they tend to severe damage to the building when affected by earthquakes. As per the literature during the past earthquakes in ancient times, in the case of RC framed buildings have columns of different heights within a storey. The shorter columns suffered more damage compared to taller columns in the same storey of the building. Due to various site conditions, buildings are characterised by unequal column heights in a single story that leads to variation in the stiffness of columns. In an earthquake, a tall column and a short column of the same cross-section move horizontally by the same amount this leads to the poor performance of the short column even with considerable more stiffness than the long column attracts the large earthquake forces that lead to significant damage of short column in the form of X shaped cracking. This effect is called the short column effect. In 2015, the Uttarakhand earthquake in India has seen that buildings located near the edges have undergone severe damages due to the irregular heights of columns in a storey. Strength and stiffness are the important criteria to be considered during the design of buildings on slopes.

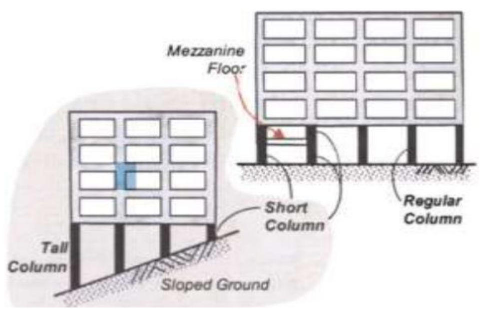

Fig. 6. Building Frame with Long and Short Columns (Parikh & Shaligram, 2019).

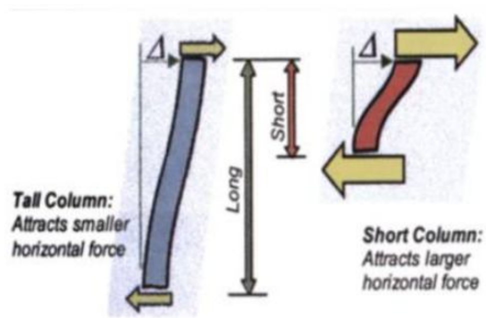

Fig. 7. Structural Behavior of Short Column under Lateral Load (Parikh & Shaligram, 2019).

The buildings with no slender columns can avoid the short column effect in the building resting on sloping ground. This can be done by adding ties to the long columns in the open ground storey.

E. Soil-structure Interaction

Generally, buildings are constructed on two types of slopes i.e., on hilly areas with hard rock strata confirming fixed base analysis and buildings on sloping ground with different types of soil (Φ, c-Φ and c) confirming to flexible base analysis or analysis considering the soil-structure interaction.

In fixed-base analysis, the type of soil does not affect the response and performance of the building whereas soil structure interaction affects the response and performance of the building. Consideration of soil-structure interaction is significant for the buildings constructed on the sloping ground with different soil types and stratified soils. Consideration of soil-structure interaction shows significant behaviour in the performance of the buildings on sloping ground. The structures without consideration of interaction system overestimate the forces acting on them and underestimate the responses from analyses. Thus by considering the interaction system responses of greater magnitude and considerably fewer forces acting on the structure are observed.

F. Techniques to Improve the Performance of Building on Sloping Ground

There are some mitigation techniques to minimize the damage and avoid the failure of the building for seismic loads. Certain methods are :

1) Shear walls at suitable positions in the building.
2) Addition of bracings in various configurations.
3) Replacing columns in Open Ground Storey with RCFSTC.
4) Incorporation of outriggers.
5) Addition of dampers at suitable positions.
6) Slope stabilization in case of loose soil on a geotechnical basis.

II. LITERATURE REVIEW

A. Review on Buildings Constructed on Sloping Ground

The Response Spectrum Analysis is carried out on 24 RC building models in three different configurations such as step back, set back, step back-set back buildings and their responses in terms of the fundamental time period, top storey displacement and the base shear are studied. They concluded that Step back-Set back buildings are found to be more suitable on the sloping ground (Biradar & Nalawale, 2004). In 2013, Ajay Kumar Sreerama and Pradeep Kumar Ramancharla had worked on Earthquake behaviour of reinforced concrete framed buildings on hill slopes. The study focused on the analysis of the five different cases of G+3 buildings on varying slopes ranging from 0^o to 45^o. The structural components are strictly designed as per as per IS 456 (2000 Rev). The seismic analysis was carried out by applying the N90E component of Northridge ground motion with a PGA of 0.565g of magnitude M6.7 in SAP2000 using lateral load analysis and incremental dynamic. The study inferred that with the increase in the slope, hinge mechanism forms and increases at the shorter columns and from the fragility curves, estimated that the damage of the structure increases with steep angle (Sreerama & Ramancheral, 2013).

Mohammed et., al., in 2014 performed A Performance study and seismic evaluation of RC frame buildings on sloping ground-based codes IS 1893, ATC-40 and FEMA-356. Here they had generated a 3D analytical model of eight storied buildings for symmetric as well as asymmetric buildings and analyzed for linear Static, linear Dynamic and evaluated by pushover analysis using structural analysis tool 'ETABs'. A parametric study had been carried out for the varying height of columns in the ground storey due to sloping ground and the effect of the shear wall at different positions during an earthquake in zone III. They observed that the performance of buildings on the sloping ground suggested an increased vulnerability of the structure with the formation of column hinges at the base level and beam hinges at each story level at the performance point. They concluded that the plastic hinges are more in buildings resting on the sloping ground compared to buildings resting on the plain ground (Mohammed et., al, 2014).

In 2014, Hemal et. al., performed a Seismic Time History Analysis of Building on Sloping Ground considering the Near/Far-Field Earthquake. In this work, the response of buildings had been studied by the response spectrum method and time history analysis against the Chamoli and Uttarkashi earthquake considering near and far-field with 5 and 10 storey buildings. The terrain condition is considered slopy with 23 degrees and 27 degrees in zone V with medium soil. The base shear and other parameters such as horizontal displacement were studied in the response spectrum analysis. In time history analysis time periods of various buildings are calculated and they found that the buildings with 23-degree slope are rigid and more vulnerable to earthquakes as its time period was found to be less than plain and 27-degree slope. The study concluded that time history analysis is one of the accurate methods that give an idea about the forces developed in buildings during an earthquake and the columns near the ground level were subjected to the short column effect. So proper care must be taken during the design to resist the earthquake forces (Hemal et. al., 2014).

Suresh and Arunakanthi (2014) carried out a 3D Seismic Analysis of Buildings Resting on Sloping Ground and Considering Bracing systems. The numerical analysis of the step back and step back-set back building resting on a slope is carried out in this study. The dynamic responses of the building were calculated by performing the dynamic analysis using the response spectrum analysis. Firstly it was observed that the step back-set back building performs well compared to the step back building. The study also focused on the bracing system associated with building to improve its performance and infers that the bracing system offered better performance than step back-set back building configuration (Suresh and Arunakanthi, 2014).

Halemani and Sreenivasa studied the influences of Bracing System in RC Structure on Sloping Ground under Wind Loads. The bracings selected for the buildings mainly includes the diagonal brace, X-brace, V-brace and inverted V-brace. The numerical seismic analysis has been carried out to understand the dynamic responses of the buildings such as displacement, storey drift, axial shear, shear force and bending moments etc. The study reveals that the X-bracing and inverted V-bracing were showing better performances (Halemani & Sreenivasa, 2015).

In 2016, Manjunath and Karthik carried out the seismic analysis of 12 storey RC Buildings on Sloping Grounds with Different Types of Bracing Systems where the parametric study is carried out for various types of eccentric steel bracings such as x-Bracing, Diagonal bracing, K- bracing, V-bracing and inverted V bracing for frame building resting on sloping ground with step back and setback-stepback type configurations in seismic zone V and medium soil condition. The Pushover analysis is performed and the performance of the structure has been evaluated. It was found that inverted V bracings perform well compared to other types of braces. The study concludes that the use of eccentric bracings is an effective and economical way for building safety (Manjunath & Karthik, 2016).

The seismic Analysis of 10 storey buildings resting on plain ground and slopy ground (20^0) Considering a Bi-Directional Earthquake is performed. The building types included in the study are Set back-step back building and Step back building subjected to Bhuj and Chamoli earthquakes and the response spectrum analysis and Time History analysis were carried out and the design parameters such as Base Shear, Axial force and moments are determined. The study observed that the columns near the ground attract higher moments, thus such columns must be properly designed to resist those higher moments (Paresh et, al, 2016). The parameters such as variation of the base shear, mode period, storey displacement and storey acceleration, concerning the variation of slope angle for different configurations of building frames, the attempt has been made to analyze G+10 RCC Multi-Storey Building Resting On Flat Ground and Sloping Ground in the seismic environment. The response spectrum analysis has been carried out and the analysis has been extended for comparative parameters such as different configurations of the building and study infers that the short column was affected more during an earthquake (Likhitharadhya et., al. 2016). The effect of positioning of RC Shear Walls of Different Shapes for the buildings resting on the slopy ground has been studied. To understand the effect the 3-D RCC building frames with different shear walls such as straight, L, T and Channel shaped at the edges are modelled and the seismic analysis is carried out to check the Seismic Performance of the Building Resting on Sloping Ground. The responses in terms of the base shear, fundamental time period, roof displacement and member forces are observed. The study concluded that to resist the lateral displacement with maximum base shear and reduced time period the straight type or rectangular shear walls proved to be the better configuration (Pawar, al, 2016) In 2017 Devarasetty et.al., investigated the Seismic Behaviour of RC Building Constructed with Different Configurations Of Shear Walls. They performed a seismic analysis of G +14 multi-storey building with core and edge shear walls and symmetrical plan under earthquake zones-III in accordance to IS 1893:2002. Various parameters such as lateral force, storey shear, storey displacement, story drift are determined and analyzed that the buildings with Core shear wall and Edge shear wall gave nearly equal storey shears in all the storeys along with the height of the building at all earthquake zones. It found that to minimize the earthquake effects core shear wall must be provided as storey drifts are very low compared to edge shear walls in earthquake zones - III.

As the vulnerability of the set back buildings on plain ground and sloping ground are high, considering this fact, the attempt was made to understand the mitigation of failure of such buildings under earthquake environment. The numerical analysis of the G+4 residential setback building located in zone V is carried out for the equivalent static force method, response spectrum method and time history method and compared the results for various response parameters. The columns of setback buildings at the higher slopes are subjected to higher bending moments so they adopted three mitigating techniques such as the OGS models modified using shear walls, magnifying the OGS columns to 2.5 times of storey forces and replacing the OGS columns with RCFSTC and found the use of RCFSTC in the place of ordinary RC column at OGS as the best way (Ghosh & Debbarma, 2017). The Analysis of setback step-back 10,15 & 20 storied buildings resting on sloping ground ranging from 0°, 10°, 15° and 20° for zone IV and medium soil is carried out. The study observed concluded that set back-step back buildings are better in performance in hilly regions (Pawar &. Sohani, 2017).

The study has extended for the flexible base and observed that the load participation ratio in the form of base shear, storey drift and peak storey shear was increasing for a fixed-width case and decreasing for fixed height case with an increase in the inclination (Ashok, 2017). The 3D Non-linear pushover analysis and Response Spectrum Analysis were performed for zone III with fixed base and flexible base condition using equivalent springs and their responses were recorded in terms of lateral displacement, base shear and shear forces. The building is considered to be founded on a sloping angle kept at 27º to horizontal. The study gave inference on the comparative response flexible and fixed base and stated that the from fixed base condition to the flexible base condition the shear forces were brought down but the displacements increased (Kavya et., al. 2018). The vulnerability to seismic attack and torsional moments developed in step back building are higher and stepback-setback building configuration is the optimum choice for the selection on the sloping ground (Sawant et.al., 2018). Also, the introduction of flat slab impacts the dynamic responses of the building rested on a slopy ground. The parameters like storey shear, storey drift, time period, lateral displacement were reduced with increased stiffness on the sloping ground (Neelesh et., al, 2019). The seismic collapse fragility curves are developed for assessing the relative vulnerability of buildings and evaluates the impact that affects the response of analytical nonlinear models of archetype reinforced concrete moment frame buildings on a slopy ground. These curves estimate the vulnerability factor which is the indication of the building failure rested on a slopy ground (Richa & Raghunandan, 2019). The seismic performance of building on the sloping ground can be improved significantly by providing shear walls with different configurations since lateral displacement and member forces reduce considerably in building due to the provision of shear walls (Dangi & Akhtar, 2019). Apart from shear wall positioning the outrigger techniques also proves to be performance improver for tall building rested on a slopy ground (Sundaresan & Suresh, 2019). The suitability of RCFST columns as a mitigation measure for plan irregular building resting on plain and sloping ground are investigated. It is found that the performance of a midrise building can be enhanced by this technique (Parikh & Shaligram, 2019). Buildings on the hilly terrain differ from those on the plain ground i.e., they are very irregular and unsymmetrical in horizontal and vertical planes, and torsionally coupled as compared to those on plain ground. The bracings contribute to minimizing displacement, maximum base shear and minimum time period for the structures found in a slopy ground (Swarup & Parekar, 2019). Shear Wall Thickness and Reinforcement Percentage play a major role in the performance criteria of the buildings rested on a slopy ground. For such buildings, the increase in the thickness of the shear wall the displacement and time period decreased and base shear increased (Arpitha & Mohan, 2019). The same study was extended for irregular and regular buildings and found that irregular set back buildings are more prone to disaster in the slopy ground (Deshmukh & Amankar, 2020).

B. Review on Buildings Constructed on Sloping Ground Considering Soil-Structure Interaction

From the design point of view of buildings constructed on sloping ground, the consideration of soil-structure interaction is essential. Pandey and Sharma (2011) studied the seismic responses of five different buildings including three-step back buildings and two-step backset back buildings with varying soil conditions and found that including interaction the building shows stable responses for 2 storey building height. For greater heights, the building shows unexpected responses which infer that draw constructions can be suitable in the slopy ground.

Clayton and Beer (2014) had carried out an investigation on the Interaction of geotechnical and structural engineering in the seismic assessment of existing buildings. The researcher studied the soil-foundation-structure interaction as one of the key parameters which deviate the responses than the fixed base system idealization. Thus needed to be considered in the response analysis of the building rested in a slopy ground.

The supporting soil and the building height are the important characters that control the response of the buildings. Also, soils experience greater stress during seismic events hence the type of building and the type of the soil need to co-relates in the combined responses in case of structure soil interactions.

The building with step back-set back configuration is the preferred recommendation for all soil types on the sloping ground considering the maximum ht of 30 m (Arun & Nishil, 2014). The high rise buildings show the trend of exponential increase in storey wise displacement with and without interactions (Sai Kumar et.al., 2016). Soil stiffness is one of the fewer parameters for controlling time period, displacement, moments, storey shear and storey drifts of the building. Stiffer the soil, better is the performance of the building and is applicable for all intensity of the earthquake (Raghavendra et.al., 2017),. In soil-structure interaction analysis for homogenous soil conditions, the performance of the building increases with an increase in soil stiffness (Achin & Patel., 2017). The interaction effect varies to the soil slope inclination. The structures without SSI consideration overestimate the forces and underestimate the responses for all inclination support (Ghosh & Debbarma, 2019). The seismic performance of the building with interaction effect is large as compare to inclination (Suryawanshi & Bogar, 2019).

C. Research on Buildings Constructed on Sloping Ground Considering Soil Strata

The topographic irregularities like hills, slopes and ridges could play an important role in modifying the ground motion characteristics like amplitude and frequency content. Mohammad et.al., (2011). carried out an experimental investigation on two hilly sites in Tehran and a numerical model is developed for the building rested on these 2 sites under consideration in a seismic environment. It is observed that the instrumentation of the site is important to understand the prefect of the site and meaningful assessment can be done to recommend the SSI consideration of the analysis. The geological, geomorphological and seismological features of the area are needed to be understood before the actual constructions as sometimes the residual soils play critical loads in response calculations. For such sites, the slope stability analyses and local seismic response analysis are needed to be conducted and the results of local seismic response and slope stability analyses made it possible to develop a 3-grade zonation map of the ground motion and landslide hazard of the area (Facciorusso et. al., 2012). Landslides that are triggered by earthquakes represent a major threat to the population and the built environment in most of the mountainous and hilly regions. The probabilistic treatment of uncertainties may be achieved by fragility (or vulnerability) curves, which provide relationships between some metric(s) of the landslide intensity and the probability of reaching or exceeding certain limits. Pitilakis (2013) aimed to provide analytical fragility curves for low rise RC frame buildings subjected to earthquakes. Six simplified yet realistic step like slope configurations is considered for this study, non-linear behaviour through non-linear static time history analysis of the building were performed to assess the response of the building to the differential ground deformation induced by the earthquake-induced landslide. The parametric analysis results in the construction of fragility curves as a function of PGA at the outcrop and PGD at the slope. Several portfolios of fragility curves for RC low-rise, frame structures both in terms of PGA and PGD have been proposed based on an extensive parametric investigation and sensitivity analysis of various slope configurations, soil properties and distances of the building concerning the slope's crown (Pitilakis, 2013). Few methods are suggested for the construction through the GIS where the buildings can be constructed in a seismic environment. The technique carries the operations like compiling, analyzing, and refining the information of an area where a building is likely to be located. The locational and topographical attributes of an area that is located in the hilly regions play a major role in safe site selection. Spatial safety aspects such as topography, slope, elevation, land use, open space, existing utilities, water supply system, sub-soil dispersion system, etc., must be identified to locate a building using GIS. The study concludes that the GIS-based analysis results, such as field value, scale value, and cell counts, provide a clear picture of which area is sufficient and safe for locating a particular type of building (Kumarn & Bansal, 2016). In few studies, it is recommended that the 15^0 slope is the maximum slope where the mid-rise buildings can be safely constructed with all types of soil conditions (Deependra et. al., 2002). In few attempts, the lifeline buildings are investigated which are situated in earthquake-prone areas like the Himalayan base. The study parameters include building typology, the number of stories, age of the building, roofing material, wall material, foundation type, foundation material, building location, soil type, ground slope, quality of construction, building condition, irregularities, re-entrant corner, pounding, overhang length, overhang length and engineering input etc. The study reveals that most of the design considerations fall short due to ignorance of the interaction effect in these scenarios, thus existence and consideration of soil is one of the very important aspects in the safe design of the structures in the slopy and earthquake intense zones (Joshi et. al., 2019). The designation of the core shear walls at the central portion in the mid-rise structure is more beneficial for regular buildings constructed on the sloping ground and for stepback-setback buildings and a shear wall along the short column was more beneficial for setback building (Mazher & Padmawar, 2019).

III.SCOPE OF STUDY

Several attempts were made so far to understand the salient responses of dwarf and mid-rise buildings located on the slopy ground including soil-structure interaction effect for several inclinations of the ground. However, the following gaps in the works of literature have been identified;

A. The soil-structure interaction analysis in the seismic scenario for high rise buildings supported on a deep foundation system.
B. The seismic soil-structure interaction analysis of mid-rise building with stratified soil conditions at the several inclinations and different stratified sequences of the residual soul at the hilly regions.
C. The development of the fragility curves for the different categories of buildings like the mid-rise and tall buildings for different soil conditions for the different inclinations including interaction effect for regular and irregular buildings.
D. The development of probable soil combination and slope characteristic correlation with the height of the building for a holly region construction scenarios.

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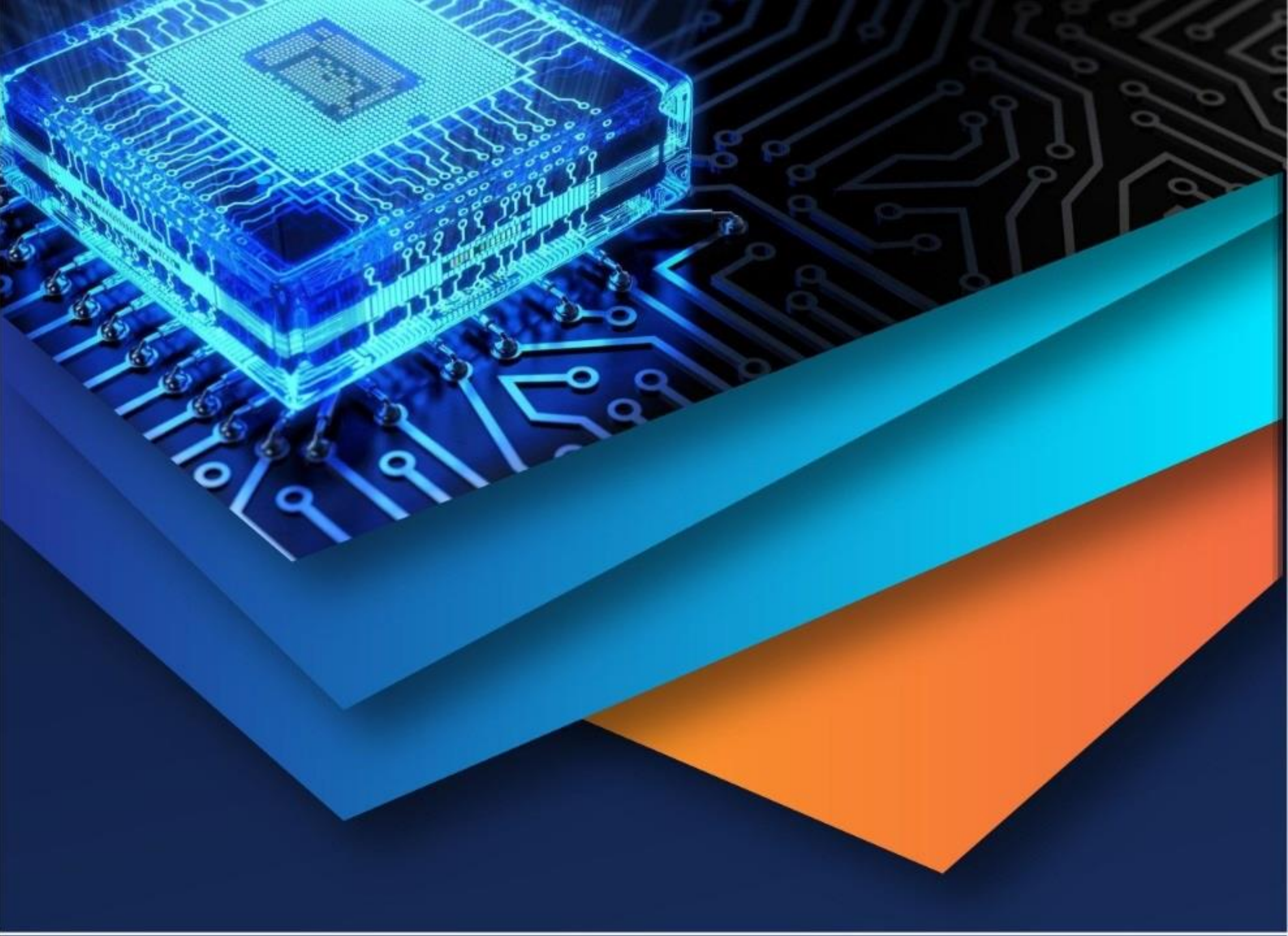

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