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Seismic Analysis of Structures on Sloped Ground Incorporating Angle Diagrid and Bracing Systems using ETABS- A Review

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Abstract: Rapid urbanization and scarcity of flat land have increased the construction of high-rise buildings on sloping terrain, especially in hilly and seismic-prone regions. Buildings constructed on slopes are more vulnerable to earthquake and wind forces due to irregular geometry, uneven stiffness distribution, and short column effects. To overcome these challenges, advanced structural systems such as diagrid systems, bracing systems, outrigger systems, and shear wall systems are increasingly being adopted in modern construction. This review paper presents a comprehensive review of previous research studies related to seismic analysis of structures on sloping ground using angle diagrid and bracing systems. The study highlights the influence of diagrid angle, soil–structure interaction, plan irregularity, and different bracing configurations on structural performance. Various analytical methods such as response spectrum analysis, nonlinear analysis, pushover analysis, and time-history analysis using ETABS, SAP2000, PLAXIS 3D, and OpenSees software are reviewed. The findings from previous studies indicate that diagrid and bracing systems significantly improve lateral stiffness, reduce displacement and storey drift, and enhance seismic resistance of buildings on sloping terrain. However, limited studies are available on the combined effect of angle diagrid systems and bracing systems on sloping ground considering soil–structure interaction and irregular configurations. Therefore, further research is required to develop optimized structural systems for safe and economical high-rise construction in seismic regions.

Keywords: Diagrid Structure, Sloping Ground, Seismic Analysis, Bracing System, ETABS, Soil–Structure Interaction, Storey Drift, High-Rise Building.

I. INTRODUCTION

The rapid growth of population and urbanization has led to an increased demand for high-rise buildings and infrastructure development in hilly and sloping regions. Due to scarcity of flat land in metropolitan and mountainous areas, construction on sloping terrain has become unavoidable. However, buildings constructed on slopes exhibit complex structural behavior during earthquakes because of irregular geometry, unequal column heights, torsional effects, and uneven distribution of stiffness and mass. These irregularities make such structures more vulnerable to seismic forces compared to buildings on flat ground. Conventional framed structures often fail to provide adequate lateral stiffness and stability for tall buildings subjected to earthquake and wind loads. Therefore, advanced lateral load resisting systems such as diagrid systems, bracing systems, outriggers, and shear walls are increasingly being used in modern structural engineering. Among these systems, the diagrid structural system has gained significant importance due to its high stiffness, reduced material consumption, architectural flexibility, and efficient load transfer mechanism. In diagrid systems, inclined diagonal members resist both gravity and lateral loads mainly through axial action, thereby reducing bending stresses and improving structural efficiency. Similarly, bracing systems play a vital role in improving the seismic performance of buildings by increasing lateral stiffness and reducing displacement and drift. The performance of these systems becomes more critical when structures are constructed on sloping terrain where additional torsional effects and short column effects are present.

Researchers have carried out various studies using ETABS, SAP2000, PLAXIS 3D, and OpenSees software to analyze the seismic behavior of buildings with different structural configurations, slope angles, and soil conditions. This review paper focuses on the seismic analysis of structures on sloped ground incorporating angle diagrid and bracing systems using ETABS software. The paper reviews previous research studies related to diagrid systems, bracing systems, soil–structure interaction, and sloping terrain behavior to identify the major findings and existing research gaps in this field.

II. LITERATURE REVIEW

(1) Geetha L et al. (2026) studied the effect of different diagrid inclination angles on high-rise buildings under wind and seismic loading. The analysis was carried out using ETABS software by comparing conventional and diagrid structural systems. The study found that optimized diagrid angles significantly improve lateral stiffness and structural stability. Storey displacement and storey drift were reduced effectively in diagrid buildings. The diagonal members provided efficient load transfer and better rigidity. The study concluded that diagrid systems are highly suitable for modern tall buildings.

(2) Dhimant Parmar et al. (2025) evaluated RC buildings on sloping terrain by considering soil–foundation–structure interaction. Different structural systems such as bare frame, bracing, and shear walls were analyzed using PLAXIS 3D software. The results showed that bare frame structures experienced maximum displacement and drift. Bracing and shear wall systems significantly improved seismic resistance. Lateral displacement and inter-storey drift were reduced considerably. The study concluded that soil–structure interaction must be considered for safe design in hilly regions.

(3) Juan Benito Crispin Ichpas et al. (2025) compared the seismic performance of diagrid and dual structural systems for important buildings. Parameters such as time period, displacement, and storey drift were analyzed under earthquake loading. The study found that the diagrid system performed better due to efficient axial load transfer. Significant reduction in displacement and vibration time period was observed. The diagrid structure provided higher stiffness and improved stability. The study concluded that diagrid systems are more effective for earthquake-resistant buildings.

(4) Md. Mahmudul Haque Ovi et al. (2025) analyzed high-rise buildings on sloping terrain with outrigger bracing systems under wind and seismic forces. Buildings with different slope angles and outrigger configurations were compared. The study found that outrigger systems greatly improved structural stiffness and stability. Sway displacement and storey drift were reduced significantly with multiple outriggers. Buildings on lower slopes performed better than those on steeper slopes. The study concluded that outrigger systems are effective for tall buildings on sloping ground.

(5) Aman Shah et al. (2025) reviewed the seismic behavior of buildings constructed on sloping terrain. Different structural configurations, slope angles, and soil conditions were considered in the study. The research found that sloping ground buildings show irregular seismic behavior due to uneven stiffness distribution. Shear walls and bracing systems effectively improved seismic resistance. Soil–structure interaction also influenced displacement and drift values. The study concluded that advanced analysis and proper structural configuration are essential for safe design.

(6) A. G. Hansora et al. (2025) compared diagrid systems with different inner core configurations such as shear wall, moment frame, and brace tube systems. ETABS software was used to analyze displacement, drift, and base shear. The results showed that the diagrid shear wall system provided maximum stiffness and best seismic performance. Proper optimization of diagonal angle improved load transfer efficiency. The brace tube system also showed balanced structural behavior. The study concluded that diagrid systems with suitable core arrangements enhance seismic safety.

(7) Sujal Panchal et al. (2024) reviewed the seismic behavior of irregular diagrid structures constructed on sloping terrain. The study highlighted the importance of considering plan irregularity and slope effects in structural analysis. Diagrid systems were found more efficient than conventional systems in resisting lateral loads. The triangulated configuration improved stiffness and load distribution. However, irregular plans caused torsional effects and uneven deformation. The study concluded that proper analysis is necessary for safe construction on sloping ground.

(8) Chengqing Liu et al. (2024) investigated the seismic performance of diagrid core-tube structures with replaceable steel coupling beams. Advanced pushover and seismic response analyses were carried out. The results showed

improved ductility and energy dissipation capacity in the structure. Inter-storey drift and seismic damage were reduced significantly. The replaceable beams absorbed seismic energy and protected main structural members. The study concluded that this system provides sustainable and efficient seismic resistance.

(9) Rohan Singh et al. (2024) compared conventional framed buildings and diagrid structures under seismic loading. ETABS software was used to analyze displacement, time period, and stiffness. The study found that diagrid systems provide better lateral load resistance and structural efficiency. Storey displacement and time period were reduced compared to conventional systems. Diagonal members transferred loads effectively through axial action. The study concluded that diagrid structures are more suitable for high-rise seismic-resistant buildings.

(10) Arturo Quiroz Ramírez et al. (2024) compared traditional and diagrid structural systems for buildings located in seismic zones. The study found that diagrid systems experienced less structural damage during earthquakes. The diagonal grid arrangement improved load transfer and reduced stress concentration. Significant reduction in greenhouse gas emissions was also observed due to lower material usage. The diagrid system provided both structural and environmental advantages. The study concluded that diagrid systems are suitable for sustainable high-rise construction.

(11) Gaurav S. Kewatkar et al. (2023) analyzed the seismic response of diagrid buildings considering soil–structure interaction. Different soil conditions such as hard, medium, and soft soil were evaluated. The study found that soil flexibility increases displacement and structural time period. Soft soil conditions produced higher drift and deformation values. However, diagrid systems still performed efficiently due to their triangulated configuration. The study concluded that SSI must be considered for realistic seismic analysis.

(12) Bush Rc et al. (2023) compared RC buildings on sloping terrain with regular buildings by considering URM infill walls. Nonlinear seismic analysis was carried out to evaluate displacement and drift. The study found that buildings on slopes are more vulnerable due to irregular geometry and short column effects. URM infill walls improved structural stiffness and reduced displacement. Buildings without infill walls experienced higher drift and instability. The study concluded that infill walls improve seismic safety in sloping terrain structures.

(13) M. Soumya et al. (2023) studied the seismic behavior of buildings on sloping terrain using ETABS software. Step-back buildings in seismic zones II and III were analyzed using response spectrum analysis. The results showed higher displacement and drift compared to buildings on flat ground. Bracing systems significantly improved lateral stiffness and reduced seismic vulnerability. Torsional effects increased due to variation in column heights. The study concluded that bracing systems improve safety of buildings on slopes.

(14) K. Veera Babu et al. (2023) compared seismic performance of buildings on sloping and flat terrain using ETABS software. Response spectrum analysis was carried out for displacement, drift, and bending moment evaluation. The study found that sloping ground buildings experience higher torsional effects and instability. Short columns on uphill sides were more vulnerable to damage. Buildings on flat ground showed more uniform structural behavior. The study concluded that special seismic design measures are necessary for buildings on slopes.

(15) Gaurav S. Kewatkar et al. (2023) reviewed the seismic response of diagrid systems and the effect of soil–structure interaction on conventional buildings. The study highlighted that fixed base assumptions may not provide realistic results. Soil flexibility changes seismic force distribution and displacement response. Diagrid systems showed lower drift and better lateral load resistance. The inclined members improved structural stiffness and reduced material usage. The study concluded that combining diagrid systems with SSI consideration improves seismic safety.

(16) Kajal G. Patel et al. (2022) evaluated buildings with plan irregularities on sloping terrain considering soil–structure interaction. Different building shapes and slope angles were analyzed using ETABS software. The results showed that irregular buildings experience higher torsional effects and uneven load distribution. Soil flexibility increased displacement and structural time period. Buildings on steeper slopes showed greater drift and deformation. The study concluded that slope angle and plan irregularity significantly affect seismic behavior.

(17) D. V. Mehtani et al. (2022) studied the seismic performance of concrete filled steel tube diagrid systems for high-rise buildings. Nonlinear static and dynamic analyses were carried out using OpenSees software. The results showed that CFST diagrid systems possess high stiffness, ductility, and strength. The structures also exhibited good energy

dissipation capacity during earthquakes. Response modification factors satisfied seismic safety requirements. The study concluded that CFST diagrid systems are highly suitable for seismic-resistant construction.

(18) Shravani A. Bhale et al. (2022) compared diagrid structures with conventional RCC framed buildings under seismic loading. ETABS software and response spectrum analysis were used for evaluation. The study found that diagrid systems reduce time period, displacement, and storey drift. Inclined diagonal members improved stiffness and load transfer efficiency. Conventional RCC buildings showed comparatively higher deformation. The study concluded that diagrid systems are more efficient for high-rise buildings in seismic zones.

(19) Pratik Jadhav (2021) evaluated diagrid structures using the concept of performance-based design. Nonlinear analysis methods such as pushover analysis were used for seismic assessment. The study found that diagrid systems efficiently resist lateral loads through axial action of diagonal members. Performance-based design provided realistic evaluation of structural behavior. The system improved stability, safety, and overall structural efficiency. The study concluded that combining PBD with diagrid systems results in safer earthquake-resistant buildings.

(20) Nourin N et al. (2021) reviewed the seismic performance of steel diagrid structures for high-rise buildings. The study found that diagrid systems efficiently resist gravity and lateral loads through inclined steel members. Compared to conventional systems, diagrid buildings reduced material consumption and improved stiffness. The systems also minimized shear lag effects and enhanced structural efficiency. Architectural flexibility and sustainability were additional advantages observed. The study concluded that steel diagrid systems are highly suitable for seismic-resistant tall buildings.

(21) Mohammed Hassain B et al. (2020) analyzed the seismic performance of high-rise steel buildings with diagrid systems using ETABS software. Different diagrid angles were evaluated under wind and earthquake loading. The study found that angles between 60° and 74° provide optimum stiffness and structural performance. Top storey displacement and storey drift were reduced effectively. Diagonal members carried most lateral loads through axial action. The study concluded that proper angle selection improves seismic efficiency of diagrid buildings.

(22) Ali Seyedkazemi et al. (2019) evaluated advanced double-layer steel diagrid systems for high-rise buildings. Internal and external diagonal members were used to improve structural behavior. The results showed higher stiffness, ductility, and energy dissipation compared to conventional single-layer systems. The additional diagonal layer improved seismic resistance significantly. Proper angle optimization reduced storey drift and deformation. The study concluded that double-layer diagrid systems are highly efficient in seismic regions.

(23) Harshada A. Naik et al. (2018) compared diagrid and conventional concrete buildings under earthquake loading using STAAD-PRO software. Buildings of different heights were analyzed in seismic zone III. The study found that diagrid systems reduce lateral displacement and storey drift effectively. Inclined members improved stiffness and load transfer efficiency. Material usage was also reduced due to elimination of closely spaced columns. The study concluded that diagrid systems effectively reduce earthquake forces in high-rise buildings.

(24) Jinkoo Kim et al. (2012) evaluated seismic performance of diagrid systems with different brace angles using nonlinear analysis methods. The study compared conventional diagrid systems with tubular and buckling restrained brace systems. Results showed that brace angle significantly affects stiffness and lateral strength. Buckling restrained braces improved ductility and energy dissipation capacity. Diagrid systems exhibited higher overstrength compared to tubular structures. The study concluded that optimized brace configuration is essential for efficient seismic-resistant design.

III. RESEARCH GAP

From the detailed review of previous research studies, it is observed that many researchers have investigated the seismic behavior of diagrid structures, bracing systems, and buildings constructed on sloping terrain. Most studies concluded that diagrid systems provide better stiffness, reduced displacement, and improved seismic resistance compared to conventional framed structures. Similarly, bracing systems and shear walls significantly improve the lateral load resistance of buildings on slopes. However, several important research gaps still exist in this area.

Most of the previous studies focused either on diagrid systems or bracing systems separately, while very limited research has been carried out on the combined behavior of angle diagrid systems with different bracing configurations on sloping ground. In addition, many studies considered only regular plan buildings, whereas irregular plan structures on sloping terrain require further investigation due to their complex seismic behavior and torsional effects. Another major limitation observed in previous studies is that soil–structure interaction was often neglected, even though it significantly influences displacement, drift, and seismic response. Very few researchers studied the combined effect of slope angle, diagrid angle optimization, and bracing systems together under different soil conditions. Moreover, limited studies are available on comparative seismic performance of various bracing arrangements such as X-bracing, V-bracing, inverted V-bracing, and K-bracing combined with diagrid systems. Most of the available research mainly focused on high-rise steel buildings, while comparatively fewer studies have been conducted on reinforced concrete diagrid structures on sloping terrain. In addition, nonlinear seismic analysis and performance-based design approaches for sloping ground diagrid buildings are still limited. The effect of varying slope angles, irregular configurations, and wind–earthquake combined loading conditions also requires further investigation. Therefore, there is a need for detailed seismic analysis of structures on sloped ground incorporating optimized angle diagrid and bracing systems using ETABS software. The present study aims to fill these research gaps by evaluating the structural behavior of buildings on sloping terrain under seismic loading with different diagrid angles and bracing configurations.

CONCLUSION

From the review of previous research studies, it can be concluded that buildings constructed on sloping terrain are more vulnerable to seismic forces due to irregular geometry, uneven stiffness distribution, torsional effects, and short column behavior. Conventional framed systems are often inadequate for resisting lateral loads in such conditions, especially for high-rise structures. The literature review clearly indicates that diagrid structural systems provide superior seismic performance compared to conventional systems due to efficient axial load transfer through inclined diagonal members. Diagrid systems significantly reduce displacement, storey drift, and structural time period while improving stiffness and stability. Similarly, bracing systems, shear walls, and outrigger systems enhance lateral load resistance and reduce seismic vulnerability of structures on sloping terrain. Previous studies also highlighted that soil–structure interaction, slope angle, plan irregularity, and diagrid angle optimization play an important role in determining seismic performance. Proper selection of structural configuration and advanced analysis methods such as response spectrum analysis, pushover analysis, and nonlinear dynamic analysis are necessary for safe and economical design. However, limited research is available on the combined effect of angle diagrid systems and bracing systems on buildings constructed on sloping terrain considering soil–structure interaction and irregular configurations. Therefore, further detailed investigation is required in this field using ETABS software to develop optimized structural solutions for high-rise buildings in seismic-prone hilly regions.

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