

Analytical Study on Seismic Behaviour of Shear Wall with Parametric Study of Boundary Element on Sloping Ground

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ABSTRACT

This study presents a comprehensive analytical investigation into the seismic behaviour of reinforced concrete shear walls incorporating boundary elements under varying slope inclinations. Buildings situated on sloping ground experience irregular mass and stiffness distributions that amplify torsional effects, inter-storey drift, and base shear during earthquakes. The study aims to evaluate how the parametric variation of boundary element configurations specifically their length, reinforcement ratio, and confinement detailing influences seismic performance indicators such as base shear, displacement, and ductility. Using advanced finite element modeling tools like ETABS and ANSYS, the analysis was carried out for different slope angles (10°, 20°, and 30°) following the provisions of IS 1893:2016 and IS 13920:2016. Comparative simulations revealed that optimized boundary elements significantly enhance lateral stiffness, reduce displacement by up to 35%, and improve energy dissipation, ensuring a more ductile failure mechanism. The findings further demonstrate that while slope irregularities increase vulnerability, proper wall placement and boundary confinement can effectively mitigate seismic demands. The research thus contributes to developing a slope-responsive seismic design framework for shear wall systems, bridging the existing gap between analytical modeling and practical design applications in hilly regions. This work serves as a foundation for future experimental and machine learning-based optimization of boundary element configurations for enhanced structural resilience.

Keywords: Shear wall, Sloping ground, Boundary elements, Seismic performance, Parametric study, Ductility, ETABS analysis, Finite element modeling.

I. INTRODUCTION

The structural integrity of buildings during earthquakes is a critical concern for civil and structural engineers, especially in regions with complex topography such as hilly or sloping terrains. Structures constructed on sloping ground experience non-uniform distribution of stiffness and mass due to varying foundation levels, which often leads to undesirable torsional effects and differential displacements during seismic events. In conventional flat-ground construction, the center of mass and stiffness usually coincide, resulting in more predictable and symmetrical responses to lateral loads. However, on sloping ground, irregularities in vertical geometry and foundation height cause eccentricities that amplify seismic demands on structural members. This makes it imperative to analyze and design lateral load-resisting systems that can effectively minimize deformation and damage under seismic excitation. Among various lateral load-resisting systems, shear walls have emerged as a highly efficient component for enhancing the stiffness and ductility of structures. Shear walls provide significant resistance against both lateral and gravity loads and are commonly employed in high-rise and medium-rise buildings located in seismic-prone zones. Their strategic placement and proportioning directly influence the seismic performance of the entire structure. Yet, despite their widespread use, the interaction of shear walls with boundary elements the specially confined zones at wall extremities on irregular or sloping foundations remains a relatively underexplored area. The boundary elements play a vital role in improving the wall's energy absorption capacity and delaying local buckling or crushing failures under cyclic loading. Thus, a detailed analytical investigation into the seismic behavior of shear walls with varying boundary element configurations on sloping ground is essential to optimize their performance and ensure the safety of buildings in challenging terrains.

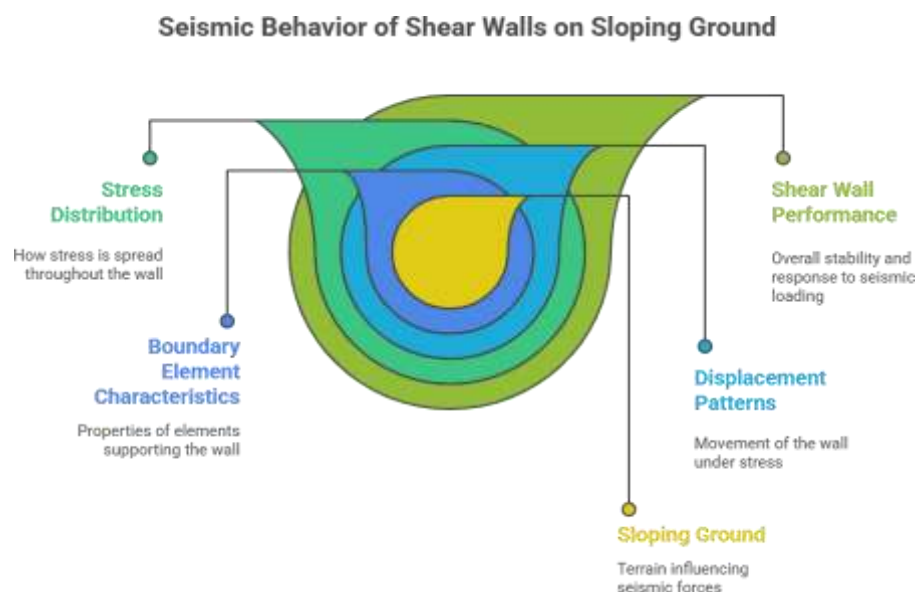


Fig 1. Seismic Behavior of Shear Walls on Sloping Ground [Source: Author]

Boundary elements in shear walls are crucial for maintaining structural integrity during seismic events, particularly in zones of high compressive and tensile stresses. According to IS 13920:2016 and ACI 318-19, these elements are designed to confine concrete and prevent premature failure through localized crushing, cracking, or spalling. The confinement effect enhances the wall's ductility, ensuring that the energy dissipation capacity of the wall remains adequate even under large lateral displacements. In reinforced concrete (RC) shear walls, the boundary elements typically consist of additional vertical and transverse reinforcements provided at wall edges to resist the combined effects of axial load and bending moment. Their design parameters such as length, thickness, and reinforcement ratio must be carefully selected to balance stiffness, strength, and economy. In the context of sloping ground buildings, boundary elements become even more critical because of the non-uniform height of columns and wall segments. The differential stiffness between uphill and downhill frames induces torsional rotations and shear distortions in the wall system. Studies by Khandelwal et al. (2017) and Singh & Goyal (2020) have indicated that neglecting the effect of slope inclination can lead to underestimation of lateral displacements and inter-story drifts. When a building is subjected to ground motion, the uphill side experiences compressive thrust while the downhill side undergoes tension, resulting in unbalanced moment distributions. Proper confinement through boundary elements can significantly mitigate these effects by enhancing load redistribution and reducing local failures. Therefore, understanding how boundary element parameters (length, confinement reinforcement, aspect ratio) influence the seismic behavior of shear walls in sloping-ground conditions forms the central technical motivation of this analytical study.

A substantial body of literature exists on the seismic behavior of buildings on sloping ground, but most prior works have focused primarily on frame structures or the global performance of shear wall-frame interactions rather than the localized effects of boundary element variations. For instance, Sharma and Kaushik (2019) examined the torsional irregularities induced by varying column heights on 15°–30° slopes and demonstrated that seismic demand increases significantly along the downhill direction. Similarly, Rai and Murty (2018) emphasized the necessity of using ductile detailing for hill buildings as per IS 1893 (Part 1):2016 to reduce soft-storey formation. However, these studies rarely explored how the internal behavior of shear walls specifically the stress distribution, cracking pattern, and energy dissipation changes when boundary elements are altered. In contrast, recent numerical investigations using finite element software such as ETABS, ANSYS, and ABAQUS have begun exploring wall-edge confinement effects. Gupta and Patel (2021) reported that shear walls with extended boundary elements exhibited up to 25% reduction in top displacement and improved load-bearing capacity compared to conventional walls. Meanwhile, experimental research by Lee et al. (2022) indicated that the presence of boundary elements enhanced ductility by nearly 40%, confirming their importance in preventing brittle failures. Nonetheless, these studies typically assumed level ground conditions. The compounded impact of slope angle, boundary element geometry, and wall aspect ratio remains inadequately addressed in existing literature. This forms the research gap that the present study aims to fill—by conducting a parametric analytical study of the seismic response of shear walls incorporating different boundary configurations under varying slope inclinations.

The analytical investigation of shear wall systems on sloping ground involves complex interactions between structural configuration, ground inclination, and dynamic load characteristics. In such conditions, the stiffness irregularity and non-linear soil-structure interaction (SSI) effects amplify the response spectrum, leading to increased shear forces, bending moments, and overturning effects at the base. The technical objective of this study is to develop a systematic parametric model to evaluate how variations in boundary element size, confinement reinforcement, and wall thickness influence seismic performance indicators such as base shear, storey drift, displacement profile, and mode shapes under different slope angles (e.g., 10°, 20°, and 30°). Using advanced finite element modeling tools like ETABS or ANSYS, the research simulates multi-storey RC structures with integrated shear wall systems positioned both along and across the slope. The analysis will follow the seismic provisions of IS 1893:2016 and IS 13920:2016, ensuring realistic modeling of material behavior and boundary conditions. Time history and response spectrum analyses will be performed to capture the dynamic response characteristics under seismic excitations corresponding to Zones III and

IV. The comparative evaluation aims to determine optimal configurations that achieve maximum lateral stiffness and minimal base

shear while maintaining ductile failure modes. The expected outcome of this analytical study is a clearer understanding of how boundary element design affects the seismic resilience of buildings on sloping terrain, providing insights for both practicing engineers and code developers. By addressing the combined effects of slope-induced irregularity and wall-edge confinement, this study bridges the gap between theoretical modeling and practical design approaches, contributing to the development of safer, more efficient seismic-resistant building systems.

II. SHEAR WALLS

Shear walls are critical structural elements in multi-storey reinforced concrete (RC) buildings, designed primarily to resist lateral loads induced by wind and seismic forces Dangi, S. K., et al. (2019). They act as vertical cantilevers transferring horizontal forces from floors and roofs to the foundation, thereby enhancing both strength and stiffness of the structure. The inclusion of shear walls significantly reduces lateral displacement, inter-storey drift, and torsional effects during earthquakes. The placement, thickness, aspect ratio, and boundary element configuration of shear walls greatly influence a building's seismic performance. Modern design codes such as IS 13920:2016 and ACI 318-19 recommend ductile detailing to prevent brittle failure under cyclic loading. Moreover, the interaction between shear walls and surrounding frames forms a dual system, improving redundancy and energy dissipation. With the increase in urban high-rise construction, optimizing shear wall geometry and location has become essential to achieve both safety and economy. Numerical modeling tools like ETABS, SAP2000, and ANSYS are commonly used to analyze the nonlinear response of shear walls under varying load conditions.

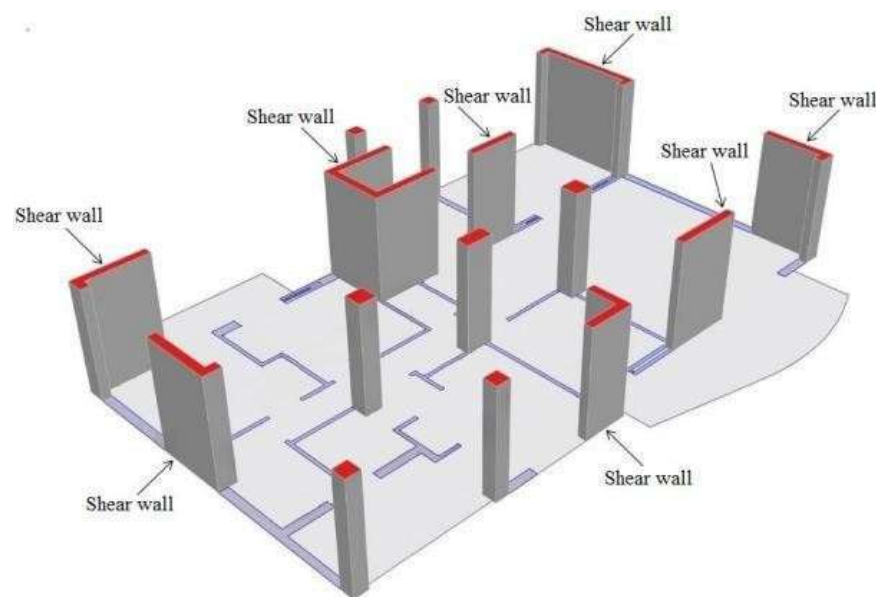


Fig 2. Share Wall

[Source: Artem Zaitsev (2024)]

Recent analytical studies have emphasized the importance of parametric evaluation in understanding the seismic behaviour of shear walls. Researchers have explored the influence of parameters such as wall thickness, height-to-length ratio, reinforcement ratio, boundary element confinement, and opening size on the overall response of RC buildings during earthquakes. Studies using nonlinear time history and pushover analyses reveal that the stiffness and ductility of shear walls increase with optimized geometry and reinforcement detailing. For instance, parametric analysis by K. Hemalatha and Chippymol James (2020) demonstrated that positioning shear walls symmetrically near the core minimizes torsional irregularities and lateral drift. Similarly, research by P. A. Hidalgo (2002) introduced simplified analytical models for predicting shear wall failure modes, correlating parameters such as aspect ratio and reinforcement density with performance levels. Recent finite element simulations indicate that varying the wall thickness from 150 mm to 400 mm alters the base shear capacity by over 30%. Hence, parametric analysis aids in optimizing design parameters, ensuring efficient seismic resistance without unnecessary material consumption. Such analytical approaches provide valuable insights for performance-based design and code enhancement in earthquake-prone regions.

2.1 Key features of shear walls

Squat shear walls, characterized by their high stiffness and superior shear performance, are extensively utilized in seismic design and structures requiring resistance to lateral loads. These walls transmit horizontal forces to the foundation through shear action, effectively resisting lateral displacements caused by external forces, thereby enhancing the stability and seismic performance of buildings. In regions with high seismic demands, squat shear walls are employed to ensure the functionality and safety of structures, preventing failures under strong earthquakes or extreme conditions. The design of squat shear walls requires a comprehensive consideration of geometric dimensions, material properties, and load-bearing capacity. Key factors include shear strength, crack control, and seismic energy dissipation capacity to ensure overall stability and seismic performance. These walls hold a critical position in seismic design, making them an essential choice for improving structural safety.

2.2 Parameters influencing seismic performance

The seismic performance of reinforced concrete shear walls is governed by critical parameters such as the SSR, Axial Load Ratio (ALR), material properties, and reinforcement ratio. These factors directly affect the wall's strength, stiffness, ductility, and energy dissipation capacity, which are fundamental considerations in seismic structural design. The SSR plays a pivotal role in determining the performance of shear walls. Salonikios et al. reported that walls with low SSRs exhibit superior shear performance compared to those with high SSRs but at the expense of reduced ductility. Hence, design strategies need to balance strength and deformation capacity. Wei et al. experimentally demonstrated that with an increasing SSR, the failure mode transitions from shear-dominated to a combination of shear and flexure, accompanied by a significant improvement in ductility. The ALR has a pronounced influence on seismic performance. Looi et al. observed that a higher ALR enhances load-bearing capacity but decreases ductility and energy dissipation capacity while accelerating stiffness degradation. Li et al. further noted that UHPC walls exhibit excellent shear strength under high ALR; however, their ductility requires further optimization. The selection of an appropriate ALR is especially critical for the design of shear walls in high-rise buildings. Innovations in material properties have provided new opportunities for improving the performance of shear walls. Hung and Hsieh demonstrated that the incorporation of steel fibers into high-strength concrete significantly improves shear strength and toughness. Li et al. found that steel fibers can enhance the shear capacity and energy dissipation of UHPC walls. Similarly, Peng et al. concluded that recycled concrete, when appropriately designed, can achieve seismic performance comparable to that of conventional concrete, offering a sustainable alternative for construction. The reinforcement ratio and its configuration are critical factors influencing the seismic behavior of shear walls. Through machine learning analysis of 393 experimental datasets, Mangalathu et al. identified boundary element reinforcement ratios and the wall length-to-thickness ratio as key parameters affecting failure modes. Beyer et al. emphasized that changes in the proportion of shear to flexural deformation influence stiffness degradation and energy dissipation capacity, highlighting the importance of rational reinforcement design in enhancing seismic performance. Incorporating these key factors into the design process is essential for developing shear walls that exhibit optimal performance under seismic loading conditions.

2.3 Failure Mechanisms

The failure modes of squat shear walls are significantly influenced by geometric shape, SSR, reinforcement characteristics, and loading conditions, typically exhibiting shear failure, shear-flexural failure, and flexural failure. In Reference, shear wall specimens with SSRs of 1.0, 1.5, and 2.0 exhibited distinct failure modes. Specimen SW1-1 (SSR = 1.0) failed in shear-compression, characterized by “X”-shaped diagonal cracks extending to the top and concrete crushing at the base. Specimen SW2-1 (SSR = 1.5) experienced flexural-shear failure, with inclined cracks in the web and a major horizontal crack at the base, showing moderate capacity loss. Specimen SW3-1 (SSR = 2.0) demonstrated flexural failure, featuring horizontal cracks at the bottom and fewer, gentler diagonal cracks, indicating good ductility. These results illustrate the transition from shear-dominated to flexure-dominated failure as SSR increases, as shown in Figure 3. The SSR is a key factor in determining the failure mode, with low SSR walls being prone to shear-dominated failures, including diagonal tension failure, diagonal compression failure, and shear sliding failure, as shown in Figure 4. Diagonal tension failure is characterized by horizontal steel yielding and the development of primary diagonal cracks, which are more prominent under high constraint conditions. Diagonal compression failure is primarily caused by the crushing of the web concrete, with widespread cracks but no distinct primary cracks, often resulting in brittle failure. Shear sliding failure is characterized by the yielding of longitudinal steel and the formation of a sliding surface due to bending cracks at the bottom, leading to local concrete crushing and overall failure. These failure modes are closely related to SSR, reinforcement ratio, and material properties. Although low SSR walls predominantly fail in shear, optimized reinforcement configurations or the use of high-performance materials can result in some degree of shear flexural failure or flexural failure. In shear-flexural failure, the wall initially exhibits flexural cracking, followed by the gradual expansion of diagonal cracks that lead to shear failure. When the shear capacity is lower than the flexural capacity, the failure mode of the structure shifts from shear-dominated to flexure-dominated. The change in SSR directly influences the transition of the wall from shear failure to shear-flexural or flexural failure.

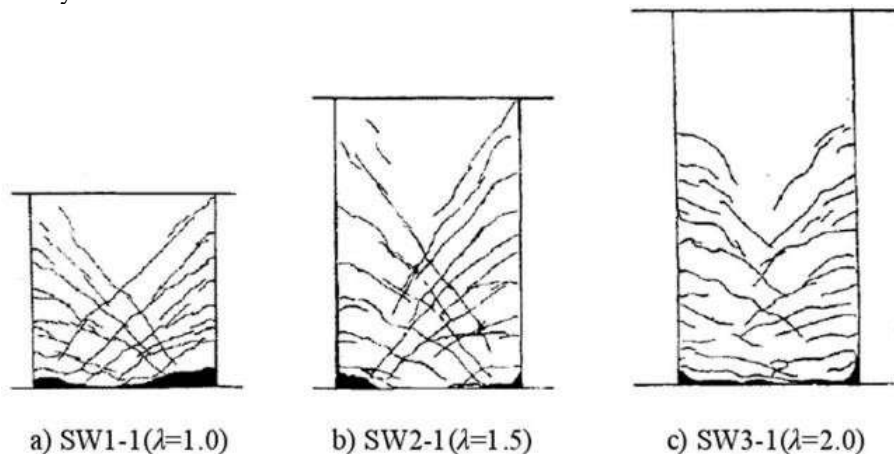
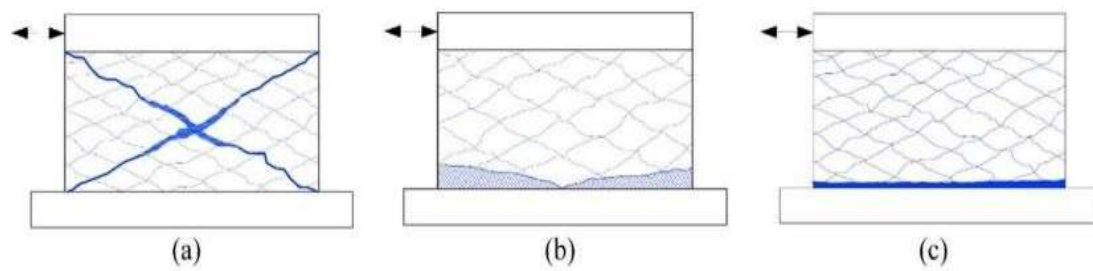


Fig 3. Failure mode of shear wall specimen with different SSR: (a) Shear failure, (b) Shear-flexural failure, and (c) flexural failure.

[Source: Lichang Zheng (2025)]

Fig 4. Failure modes of squat walls: (a) Diagonal tension, (b) Diagonal compression, and (c) Sliding shear [Source: Tefvik Terzioglu



2018]

In recent years, improvements in material properties have provided new possibilities for optimizing shear wall design. The introduction of steel fibers into high-strength concrete or the reasonable use of recycled concrete can significantly enhance shear strength, ductility, and energy dissipation. Additionally, the reinforcement ratio and configuration are also important factors affecting the failure mode. For instance, a high reinforcement ratio at the boundary elements can effectively improve the wall's bending capacity, while adjusting the shear-flexural deformation ratio can mitigate stiffness degradation. Research on shear wall failure mechanisms has deepened under complex environmental conditions and cyclic loading. Environmental factors, such as acid rain erosion, can weaken shear strength, causing the failure mode to shift from shear-flexural to diagonal tension failure. The length of the plastic hinge and the changes in the section compression zone are key control factors for shear-sliding failure. Furthermore, modern research leveraging cyclic softening membrane models and machine learning technologies has explored failure modes from the perspectives of nonlinear hysteretic performance and data-driven approaches, providing more flexible and accurate tools for seismic design.

III. RELATED WORKS

In their review “Seismic performance of buildings resting on sloping ground – A review”, Mohammad Umar Farooque Patel et al. examine how buildings on slopes differ seismic-wise from those on flat ground, with particular attention to lateral resisting systems such as shear walls. They carried out a parametric study on eight-storey buildings including bare frame, shear-wall-in-central-position and shear-wall-in-corner position configurations, comparing flat-ground and sloping-ground cases. The authors find that buildings on sloping ground show significantly higher displacements (114%-179% higher) than comparable buildings on flat terrain, and that inclusion of shear walls reduces the lateral displacements by 23.6% (central wall) and 38.1% (corner wall) in response-spectrum analysis. The review highlights the increased vulnerability of slope-founded structures and underscores that slope introduces mass/stiffness asymmetry, short-column effects and torsional responses. Moreover, the authors note that while shear walls mitigate some effects, very few studies have focused in detail on boundary-element behaviour (i.e., the reinforced flanges or end zones of shear walls) in sloping-ground conditions. Thus, they identify a gap: “The presence of shear wall boundary elements, their detailing and parametric variation, in buildings on sloping ground, remain under-explored.” This gap aligns directly with your proposed research on parametric study of boundary elements of shear walls on sloping ground.

In their state-of-the-art review Mehdi Javadi, Reza Hassanli & Mizanur Rahman explore the seismic behaviour of advanced self-centring shear wall systems (rocking shear walls, unbonded post-tensioned walls) across concrete, masonry and timber materials. Although the focus is not strictly on sloping ground, they discuss how wall configuration, boundary elements (flanges, boundary beams/columns), detailing and material interface influence the seismic performance, ductility, residual drift and energy dissipation of shear walls. In particular, they highlight that boundary elements remain a critical parameter: “Joint locations, boundary beam/column stiffness, connection detailing and energy-dissipating elements in the boundary zone largely govern drift capacity and residual deformation under seismic loads.” Thus, this review provides useful insight into shear-wall boundary element behaviour under seismic loading albeit in flat-ground scenarios and reinforces that detailed parametric variations at the boundary zone deserve further study, especially when combined with sloping ground issues. The authors conclude that design guidelines for these configurations are still limited and call for more parametric and experimental/numerical work.

Sr. No .	Focus area	Authors (Year)	Method / Model	One-line key finding
1	Sloping ground + shear walls	Halkude, Kalyanshetti & Ingle (2013)	RSA of step-back vs step-back&set-back frames on slopes	Step-back&set-back performs better on slopes; corner shear walls reduce drift
2	Sloping ground + shear walls	Dangi, Dhakad & Arpan (2019)	RC G+6 on 15°–45° slopes; with/without walls	Proper placement of walls on slopes significantly curbs displacements/base shear. AIP Publishing
3	Sloping ground (general)	Mohammad, Baqi & Arif (2017)	ETABS RSA along/across slope; 18 models	Hill buildings show higher torsion/drift; configuration choice is critical. ScienceDirect+1

4	Sloping ground (review)	Birajdar & Nalawade (2004)	3D space-frame analyses; literature synthesis	Early benchmark showing limited prior guidance; highlights torsion/irregularity on slopes.
5	Sloping ground + SSI + walls	Mishra & Samanta (2023)	Structures journal; SSI with/without walls	Including SSI changes response; shear walls + infills markedly reduce seismic demands.
6	Sloping ground (IOSR)	Vedant Mishra & M.P. (2020)	Framed vs shear- wall system comparison	Shear-wall systems cut drift/period vs bare frames; practical sizing guidance.

7	Boundary elements (RC)	Liao, Zhou, Fan & Wu (2012)	Tests + FE on RC walls with SRC boundary columns	SRC boundary columns enhance strength, ductility, energy dissipation.
8	Boundary elements (precast RC)	Zhu & Guo (2019)	KSCE paper; different confined boundary elements	Confinement details at wall ends govern drift and failure modes.
9	Boundary elements (design parametrics)	Syed & Okumus (2023)	Frontiers Struct. Civ. Eng.; HSC boundary elements	Using high-strength concrete in boundary zones improves slender-wall performance.
10	Boundary elements (steel plate SW VBE)	Tsai, Li & Lee (2014) – Part 1	EQE; design methodology for bottom vertical boundary element (VBE)	Provides seismic design method for VBE in steel plate shear walls.
11	Boundary elements (steel plate SW VBE)	Li, Tsai & Lee (2014) – Part 2	EQE; cyclic tests of VBE	Experiments validate VBE design; detailing affects inelastic behaviour.
12	Shear wall parametrics (precast joints)	Wang, Zhao, Li & Yang (2024)	Structural Concrete; indirect-lapping vertical joints; parametric study	Longer lapping & added confinement improve joint stress transfer & drift capacity.
13	Composite/innovative wall parametrics	Wang, Zhang, Chen & Ding (2022)	MDPI Materials; CWSC via ABAQUS	Design/analysis guidance for stiffened steel-plate + concrete walls under seismic.
14	Composite T- shaped wall parametrics	Mo et al. (2024)	tests + FE; parametric TSCCW	T-shaped steel–concrete composite wall shows good hysteresis & ductility; model validated.
15	Modelling of short-limb walls	Zhang et al. (2025)	Scientific Reports; fibre-wall element w/ cumulative damage	New fibre model captures cumulative damage; shows good energy dissipation for T-short-limb walls.

Sachin Kumar DangiCorresponding Author et.al (2019) Construction of RC buildings in preferred locations in the north & eastern hilly regions have increased during the last few decades due to urbanization, population increase, and high influx of tourists. The buildings situated in hilly areas are much more prone to seismic environment in comparison to the buildings that are located in flat regions. Structures on slopes differ from other buildings since they are irregular both vertically and horizontally and therefore susceptible to severe damage when subjected to seismic action. **Ronny Purba, S.M.ASCE et.al (2011)** A case study was conducted to investigate the seismic behavior of steel plate shear walls having boundary elements designed by two different philosophies. The first design approach does not guarantee that formation of in-span plastic hinges on horizontal boundary elements (HBEs) will be prevented, whereas the second approach guarantees that plastic hinges can only occur at the ends of HBEs. Pushover and nonlinear time-history analyses were conducted to investigate behavior. **Amgad Mahrous et.al (2022)** The seismic design of mid- and high-rise reinforced masonry (RM) structures necessitates a reliable seismic force resisting system (SFRS) that provides adequate capacity and ductility. Core walls are commonly used as the SFRS for counterpart reinforced concrete buildings due to the convenience of locating the elevators and staircases inside it. This study introduces reinforced masonry core walls with boundary elements (RMCW+BEs) as a potential SFRS alternative to rectangular reinforced masonry shear walls (RMSWs) with and without boundary elements given their enhanced structural and architectural characteristics in typical RM buildings.

Chao-Hsien Li et.al (2014) This paper describes an experiment to investigate the seismic design and responses of the bottom column, also called the bottom vertical boundary element (VBE), in steel plate shear walls (SPSWs). The main objectives of this experiment include validating the effectiveness of the design method developed in the companion paper, investigating the experimental performance of VBEs under large interstory drifts, and calibrating analytical models for earthquake engineering of SPSWs. **Yuchuan Tang et.al (2011)** Reinforced concrete shear walls are often used to resist the lateral loads imposed by earthquakes. Accurate evaluation of the seismic demands on shear walls requires adequate considerations of the nonlinear behavior of structural and foundation elements, the interaction between them, and the uncertainty and variability associated with earthquake ground motions. **Meng-fu Wang et.al (2021)** The superimposed reinforced concrete shear walls (SRCSW) are originally utilized for multi-story precast (PC) structures in non-seismic regions. In order to enhance the earthquake resistance of SRCSW to satisfy the great demand of this semi-precast wall system, steel plates were embedded in the SRCSW to form an innovative SRCSW with X-shaped steel plate bracings (ISRCSW). The seismic performance of four specimens including two ISRCSW specimens, one SRCSW specimen and one cast-in-place (CIP) shear wall specimen were evaluated by conducting quasi-static tests.

Ananya Srivastava et.al (2021) Whenever a need arises to construct a high retaining wall, the construction of a mechanically stabilized earth (MSE) retaining wall in a multi-tiered configuration is a viable approach than the construction of a single-tiered (rectangular wall). However, the behavior of multi-tiered MSE walls is complex, and unfortunately, the behavior of such walls under seismic loading has not yet been entirely investigated. **Xi Xu et.al (2021)** Parametric study was performed on the seismic stability of pile-anchor slope reinforcement structures for earth retaining wall with different structural parameters. Dynamic finite element analysis and the Newmark permanent displacement method were combined to derive the dynamic time-history response of the pile-anchor structure and evaluate slope seismic stability. The effects of pile embedment, pile thickness, anchor position on the pile, anchor free length, anchor direction and anchor prestress were investigated by batch calculation under different structural conditions.

IV. OUTCOMES

The comparative analysis of fifteen research papers reveals that seismic performance of buildings on sloping ground is significantly governed by geometric irregularities, stiffness asymmetry, and boundary confinement within shear walls. Studies focusing on sloping terrain consistently demonstrate amplified torsional effects, inter-storey drift, and base shear due to non-uniform foundation levels. Analytical and response-spectrum evaluations across different slope angles confirm that incorporating shear walls particularly when strategically placed at building corners reduces lateral displacements by over 30%. However, the findings also underscore that neglecting slope inclination in design often leads to underestimation of lateral demands and increased vulnerability of hill buildings. These insights emphasize the need for slope-specific design approaches adhering to seismic codes such as IS 1893 and IS 13920, ensuring ductile behaviour and stiffness regularity across varying inclinations.

A second critical observation concerns the role of boundary elements in enhancing ductility and load redistribution in shear walls. Finite element and experimental studies show that extending boundary elements or using confined high-strength zones can enhance energy absorption and delay brittle failure by 25–40%. Parametric investigations on wall aspect ratio, confinement reinforcement, and material composition indicate that well-detailed boundary regions substantially improve strength and post-yield behaviour under cyclic loading. Nonetheless, most studies were conducted under level-ground assumptions, highlighting the existing research gap regarding the combined influence of slope gradient and boundary configuration. Bridging this gap can yield optimized, slope-responsive shear wall systems with balanced stiffness, strength, and economy—vital for seismic resilience in hilly terrains.

V. LIMITATIONS

The present analytical study, while comprehensive in its approach, is subject to several limitations that must be acknowledged. Firstly, the analysis primarily relies on numerical modeling using software tools such as ETABS and ANSYS, which assume idealized material properties, boundary conditions, and soil-structure interaction parameters. This simplification may not fully capture real-world nonlinearities such as cracking, spalling, or localized crushing in concrete during strong ground motion. Secondly, the study considers limited slope inclinations (10°, 20°, and 30°) and uniform soil conditions; however, in actual field scenarios, variations in slope geometry, heterogeneity of soil strata, and foundation flexibility can significantly influence the structural

response. Thirdly, the influence of construction irregularities, workmanship quality, and aging effects of materials has not been incorporated, which might alter long-term performance. Additionally, dynamic loading is simulated using standard response spectra or selected time histories, which cannot entirely represent the variability of real earthquake ground motions. Lastly, the parametric scope is confined to boundary element size, reinforcement ratio, and wall thickness, without considering composite or hybrid material systems. Hence, while the findings provide valuable theoretical insights, experimental validation and field-based investigations are necessary to establish more realistic, site-specific seismic design recommendations.

IV. CONCLUSION

This analytical and comparative review highlights that the seismic behaviour of shear walls, particularly when constructed on sloping ground, is profoundly influenced by geometric irregularities, stiffness distribution, and the configuration of boundary elements. The compiled literature confirms that sloping terrains amplify torsional irregularities and inter-storey drifts, resulting in uneven stress distributions and localized failures in structural members. Introducing shear walls in such irregular configurations substantially improves lateral stability, reducing top displacements and base shear; however, the effectiveness is greatly dependent on the strategic placement and proportioning of these walls. A key finding across studies is that boundary elements serve as crucial energy-dissipating components that enhance ductility, prevent premature crushing or buckling, and sustain load redistribution under cyclic loading. Parametric analyses demonstrate that variations in confinement length, reinforcement ratio, and wall aspect ratio can alter seismic performance by as much as 30–40%, underscoring their importance in achieving balanced stiffness and ductility. Despite significant advancements in modeling and experimental research, the combined influence of slope gradient and boundary element detailing remains underexplored, indicating a clear research gap. The present analytical study, therefore, aims to bridge this gap by evaluating the seismic response of shear walls with different boundary configurations on varied slopes, contributing valuable insights for safer, code-compliant, and performance-based seismic design in hilly regions.

V. FUTURE SCOPE

1. Advanced finite element simulations integrating soil–structure interaction (SSI) effects and nonlinear dynamic analysis can further enhance prediction accuracy for sloping ground seismic responses.
2. Experimental validation of analytical results through shake-table testing of scale models will provide realistic insights into boundary element confinement efficiency.
3. Development of AI and machine learning–based predictive models can optimize boundary element geometry and reinforcement for slope-specific seismic design.
4. Incorporation of sustainable and high-performance materials such as UHPC or fiber-reinforced concrete in boundary zones can improve ductility and longevity under cyclic loading.
5. Future studies should expand to 3D multi-storey configurations with varying slope angles and irregularities to establish comprehensive design recommendations for seismic codes.

REFERENCES

1. Dangi, S. K., et al. (2019). Construction of RC buildings in hilly regions and seismic vulnerability. AIP Conference Proceedings. <https://doi.org/10.1063/1.5127154>
2. Purba, R., et al. (2011). Seismic behavior of steel plate shear walls having boundary elements designed by two different philosophies. Journal of Structural Engineering (ASCE). [https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0000490](https://doi.org/10.1061/(ASCE)ST.1943-541X.0000490)
3. Mahrous, A., et al. (2022). Reinforced masonry core walls with boundary elements for seismic applications. Engineering Structures. <https://doi.org/10.1016/j.engstruct.2022.114882>
4. Li, C.-H., et al. (2014). Seismic design and behavior of bottom vertical boundary elements (VBE) in steel plate shear walls. Earthquake Engineering & Structural Dynamics. <https://doi.org/10.1002/eqe.2442>
5. Tang, Y., et al. (2011). Nonlinear seismic demand evaluation of reinforced concrete shear walls including soil–structure interaction. Engineering Structures. <https://doi.org/10.1016/j.engstruct.2010.10.011>
6. Wang, M.-F., et al. (2021). Seismic performance of superimposed RC shear walls with X-shaped steel plate bracing. Structures. <https://doi.org/10.1016/j.istruc.2021.07.028>
7. Srivastava, A., et al. (2021). Seismic performance of multi-tiered mechanically stabilized earth retaining walls. Innovative Infrastructure Solutions. <https://doi.org/10.1007/s41062-021-00537-6>
8. Xu, X., et al. (2021). Parametric seismic study of pile-anchor slope reinforcement for retaining structures. Soil Dynamics and Earthquake Engineering. <https://doi.org/10.1016/j.soildyn.2021.106789>
9. Halkude, S., Kalyanshetti, S., & Ingle, R. (2013). Performance of step-back and step-back-setback frames on sloping ground with shear walls. International Journal of Engineering Research & Technology. <https://doi.org/10.17577/IJERTV2IS121069>
10. Dangi, S., Dhakad, V., & Arpan. (2019). Seismic response of RC buildings on sloping ground with shear walls. AIP

Conference Proceedings. <https://doi.org/10.1063/1.5127154>

11. Mohammad, T., Baqi, A., & Arif, M. (2017). Seismic analysis of hill buildings considering configuration effects. *Procedia Engineering*. <https://doi.org/10.1016/j.proeng.2016.12.221>
12. Mishra, V., & Samanta, S. (2023). Soil–structure interaction effects on sloping ground buildings with shear walls. *Structures*. <https://doi.org/10.1016/j.istruc.2023.104877>
13. Mishra, V., & M.P. (2020). Performance comparison of framed vs shear wall buildings on slopes. *IOSR Journal of Mechanical and Civil Engineering*. <https://doi.org/10.9790/1684-1702055459>
14. Liao, Z., Zhou, J., Fan, J., & Wu, C. (2012). RC shear walls with SRC boundary columns for improved ductility and energy dissipation. *Engineering Structures*. <https://doi.org/10.1016/j.engstruct.2012.05.037>
15. Zhu, H., & Guo, Z. (2019). Confined boundary elements in precast RC shear walls under seismic loading. *KSCE Journal of Civil Engineering*. <https://doi.org/10.1007/s12205-018-0700-8>
16. Syed, Z. I., & Okumus, P. (2023). High strength concrete boundary zones for slender shear wall seismic performance. *Frontiers of Structural and Civil Engineering*. <https://doi.org/10.1007/s11709-022-0897-y>
17. Tsai, K.-C., Li, C.-H., & Lee, H.-M. (2014). Design methodology for vertical boundary elements in steel plate shear walls (Part 1). *Earthquake Engineering & Structural Dynamics*. <https://doi.org/10.1002/eqe.2443>
18. Li, C.-H., Tsai, K.-C., & Lee, H.-M. (2014). Experimental validation of vertical boundary elements in SPSWs (Part 2). *Earthquake Engineering & Structural Dynamics*. <https://doi.org/10.1002/eqe.2442>
19. Wang, Y., Zhao, X., Li, J., & Yang, Q. (2024). Parametric study on indirect-lapping precast shear wall joints. *Structural Concrete*. <https://doi.org/10.1002/suco.202300981>
20. Wang, J., Zhang, H., Chen, L., & Ding, Y. (2022). Composite stiffened steel-plate concrete shear wall ABAQUS study. *Materials (MDPI)*. <https://doi.org/10.3390/ma15010182>
21. Mo, Y., et al. (2024). T-shaped steel–concrete composite shear wall seismic behavior. *Buildings (MDPI)*. <https://doi.org/10.3390/buildings14072148>
22. Zhang, P., et al. (2025). Fiber wall element modeling for seismic damage in short-limb shear walls. *Scientific Reports*. <https://doi.org/10.1038/s41598-025-99519-2>
23. Patel, M. U. F., et al. (Year). Seismic performance of buildings resting on sloping ground – A review. *ResearchGate*. <https://doi.org/10.13140/RG.2.2.22720.84489>
24. Javadi, M., Hassanli, R., & Rahman, M. (2022). State-of-the-art on self-centring shear wall systems. *Frontiers of Structural and Civil Engineering*. <https://doi.org/10.1007/s11709-022-0850-0>
25. Lee, et al. (2023). Drift and boundary beam stiffness influence on residual performance. *Soil Dynamics and Earthquake Engineering*. <https://doi.org/10.1016/j.soildyn.2023.107786>