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Original Article

Evaluating the Effectiveness of Shear Keys on Stability and Design Efficiency of Cantilever Retaining Walls

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Abstract - *Retaining walls are critical geotechnical structures designed to resist lateral earth pressures, with sliding and overturning identified as primary failure modes. Although shear keys are commonly used to enhance sliding resistance, limited quantitative research has compared stability performance and design efficiency across varying wall heights. This study investigated the effect of shear keys on the stability and material use of cantilever retaining walls subjected to static lateral earth pressures by evaluating walls with and without shear keys at different heights. Stability analyses were conducted using Rankine's active earth pressure theory, followed by iterative optimization of the wall base dimensions to achieve a target safety of 1.5 for both sliding and overturning. The results demonstrate that shear keys significantly improve sliding stability and reduce the required base width, especially at lower wall heights. However, their effectiveness diminishes as the wall height increases, and sliding governs the design at higher heights. Additionally, the presence of a shear key yields only marginal reductions in concrete volume, indicating limited material savings. These findings provide practical insights for engineers in selecting and optimizing key shear designs, highlighting that their primary benefit lies in stability enhancement rather than material efficiency.*

Keywords - *Cantilever retaining wall, Shear Key, Sliding stability, Overturning stability, Design optimization.*

1. Introduction

A retaining wall is a structural system designed to resist the lateral pressure exerted by soil or water, thereby maintaining differences in the ground elevation [1-3]. Typically, a retaining wall comprises a vertical component known as the stem and a base slab that provides stability. A shear key is often incorporated at the base of cantilever retaining walls to enhance the sliding resistance by mobilizing additional passive soil pressure. Despite the widespread use of shear keys, field observations have shown that retaining walls can still experience considerable lateral deformation under significant earth pressure [3-5].

In practical applications, shear keys are most commonly installed directly beneath the stem of a wall, primarily for ease of construction [6-8]. Although the Federal Highway Administration (FHWA) [9] recommends the use of shear keys to improve sliding stability, it does not provide specific guidance regarding optimal placement.

According to Caltrans Bridge Specifications [10], the shear key should be positioned at the heel of the retaining wall, and the potential slip plane should be considered as an inclined surface extending from the tip of the shear key toward the toe of the wall. In contrast, the NAVFAC design guidelines [11] recommend placing the shear key directly beneath the stem and assuming a horizontal failure plane parallel to the base of the wall extending toward the toe.

Previous studies looked at how shear keys are used in retaining wall designs through experimental and numerical methods. Experimental work has shown that retaining walls with shear keys tend to have larger rotational movements compared to translational sliding. This indicates that shear keys help resist sliding but also unintentionally increase wall rotations under lateral loads [4].

Sichani and Bargi [7] found that cantilever retaining walls with a shear key under the wall stem displayed more noticeable rotational shifts than walls with flat bases. This emphasizes the difficulty of predicting wall behaviour when shear keys are involved. These findings highlight the need for stronger design procedures that specifically consider the possible rotational movements of cantilever retaining walls with shear keys, especially during seismic events. Kalemci et al. [12] created a design tool using the Grey Wolf optimization algorithm to tackle optimization challenges. This tool determines the best setup for cantilever retaining walls with shear keys to improve their horizontal load capacity. Their research looked at walls with 3 m and 4.5 m stem heights, designed to hold back embankments made of cohesive and non-cohesive soils.

The optimization process included 30 independent runs, each with 1000 iterations. The results showed strong agreement with previous optimization studies that used different algorithms.

In addition, Öztürk et al. [13] used Teaching-Learning-Based Optimization (TLBO) and Jaya algorithms to reduce the construction cost of a 10-m-high counterfort retaining wall with a shear key placed in cohesive soil. Their results showed that the TLBO algorithm performed better than the Jaya algorithm in creating cost-effective designs.

Despite the recognized role of shear keys in improving the sliding stability of cantilever retaining walls, most past studies have either examined isolated cases or focused on design optimization. The impact of wall height on material use and stability was not taken into account. Although shear keys are generally recommended in current design guidelines, quantitative comparisons of retaining walls with and without shear keys under various geometric conditions are not provided.

Prior research has optimized retaining wall designs involving shear keys using metaheuristic techniques. However, they have not evaluated the performance of shear key inclusion across different design scenarios; instead, they focus on cost effectiveness or single wall heights. In a similar vein, previous experimental research has examined rotational displacement behaviour without taking into account the overall trade-off between material use and stability.

This leaves a critical gap in understanding how shear keys affect structural behaviour and design optimization for different wall heights. To fill this gap, this study examined the effects of shear keys on the stability and design efficiency of cantilever retaining walls under lateral earth pressure. It evaluates the sliding and overturning safety factors for walls with and without shear keys at three different heights.

This study then performs iterative optimization to achieve the defined safety targets. The innovation of this study comes from its combined approach, which merges traditional stability analysis with geometric optimization. This allows for assessing both safety performance and material efficiency. The findings provide useful insights to support engineering decisions on shear key use, balancing structural performance and material efficiency.

2. Methodology

This study focused on evaluating retaining walls of different heights that faced static lateral earth pressure. It looked at safety factors against sliding and overturning and aimed to improve wall shapes to meet a target safety factor of 1.5 for both types of failure. This study compared different cases to measure the impact of shear keys on stability and determined the necessary concrete volumes for each improved design. This offered a way to assess the structural and economic effects of adding shear keys.

The geometric layout of the cantilever retaining wall examined in this study is shown in Figure 1. The wall has a vertical stem that is 0.3 m thick and a base slab that includes a 0.2 m toe and a 1.0 m heel, resulting in a total base width of 1.5 m. The height of the wall (H) was tested in three cases: 1 m, 2 m, and 3 m.

This was done to assess how the wall height affects stability performance and design efficiency. For cases including a shear key, the key was modelled with a constant thickness of 0.3 m and depth of 0.5 m positioned beneath the heel of the wall base. The shear key is intended to mobilize additional passive resistance to improve sliding stability.

The soil properties for both the original ground and backfill were assumed to be identical and characterized as cohesionless materials with zero cohesion (c = 0) and an internal friction angle of 25°, representing typical granular soil behaviour. The unit weight of the soil was assumed to be constant throughout the analysis.

In addition to the self-weight of the retaining wall and the weight of the retained soil, a uniform external surcharge load of 10 kN/m^2 was applied at the surface of the backfill along the entire horizontal extent of the retained zone. This surcharge simulates typical live loads such as traffic or pedestrian use, which may act on the retained area in practical applications.

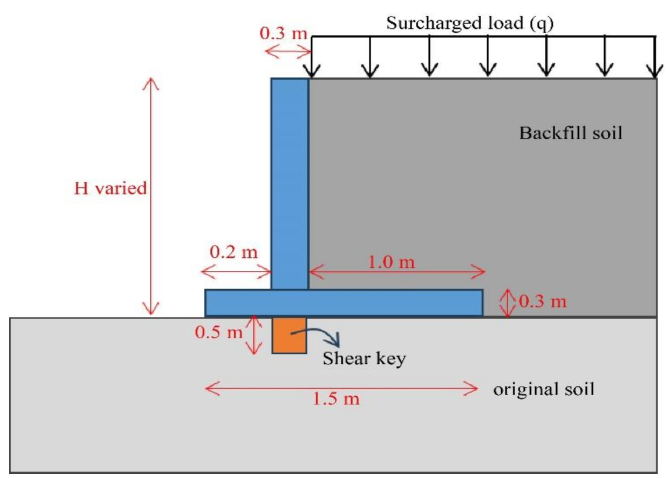


Fig. 1 Retaining wall configuration used in this study

Stability analyses were performed to evaluate the Factors of Safety (*FS*) against both Sliding (*SL*) and Overturning (*OT*) for each wall configuration. The analyses considered the active lateral earth pressure calculated according to Rankine's active pressure theory [14], assuming dry backfill and zero wall-backfill interface friction. The horizontal earth thrust P_a acting at a height of *H/3* above the base of the wall is determined as follows:

$$P_a = \frac{1}{2} K_a \gamma H^2 + K_a q H \tag{1}$$

Where K_a denotes the Rankine active earth pressure coefficient, γ denotes the unit weight of the backfill soil, q denotes the uniform surcharge load, and H denotes the wall height. The active earth pressure coefficient K_a was calculated as follows:

$$K_a = tan^2\left(45° - \frac{\varphi}{2}\right) \tag{2}$$

Where, ϕ denotes the internal soil-friction angle.

The sliding stability was assessed by comparing the total available resisting force, primarily from the base friction, against the driving horizontal thrust from the lateral earth pressure. The factor of safety for sliding was calculated as

$$FS_{SL} = \frac{\mu \sum W}{P_a} \tag{3}$$

Where μ is the base friction coefficient and $\sum W$ is the total vertical load acting on the base of the wall, including the self-weight of the wall and the weight of the soil over the heel.

For overturning stability, the overturning moment M_{OT} was calculated from the horizontal earth thrust and surcharge components, as follows

$$M_{OT} = P_a \frac{H}{3} \tag{4}$$

The resisting moment, $M_{R,}$ is computed as the sum of the moments produced by the vertical loads acting on the toe of the wall.

$$M_R = W_c x_c + W_b x_b + (qB) x_q \tag{5}$$

Where W_c, W_b, and qB are the vertical forces from the wall weight, backfill weight over the heel, and surcharge load, respectively, and x_c, x_b, and x_q are the lever arms corresponding to the toe. The factor of safety against overturning was determined as the ratio of resisting to overturning moments

$$FS_{OT} = \frac{M_R}{M_{OT}} \tag{6}$$

This parametric study was structured in two stages. In the first stage, stability analyses were performed on cantilever retaining walls with and without shear keys at different heights to comprehensively assess their performance under static lateral earth pressure and surcharge loading. Factors of safety against sliding and overturning were calculated for each configuration by evaluating the driving and resisting forces and corresponding moments.

This stage enabled the identification of the controlling failure modes at each wall height and shear key condition, providing essential comparative insights into how the presence of a shear key affects the stability performance before design optimization.

In the second stage, a process for improving the design was carried out by adjusting the base slab dimensions to reach a target safety of 1.5 for both sliding and overturning. This started with the initial shape and gradually increased the base width and heel length while keeping the stem thickness constant. The key dimensions for walls with shear keys were fixed.

This study repeated stability calculations during each iteration until the safety criteria were met for all wall heights studied. The optimized shapes were then used to calculate the related concrete volumes. This provided a measure of design efficiency to compare retaining walls with and without shear keys. This approach helps to understand the trade-offs between stability performance and material use. It offers useful guidance for engineers who want to design retaining walls that meet safety standards efficiently and cost-effectively.

3. Results and discussion

This section presents the results of the stability evaluations and design optimizations for cantilever retaining walls, both with and without shear keys, at three different heights. The findings are divided into two parts.

First, this study compares the safety factors for sliding and overturning to identify the main failure modes. Second, this study assesses the optimized wall shapes and their concrete volumes to evaluate design efficiency. The discussion brings these results together to offer practical insights into the structural benefits and material effects of adding shear keys to retaining wall design.

Figure 2 shows the safety factors against Sliding (SL) and Overturning (OT) for cantilever retaining walls, both with and without shear keys, at the wall heights studied. The results clearly show that the presence of a shear key has a pronounced impact on sliding stability, particularly at lower wall heights. At a height of 1 m, the factor of safety against sliding increases markedly from approximately 2.1 without a shear key to 3.6

with a shear key, demonstrating the effectiveness of the key in mobilizing additional passive resistance to counteract lateral earth pressures. However, as the wall height increases to 2 m and 3 m, the improvement in sliding stability provided by the shear key diminishes, and the factors of safety for both configurations converge toward similar values at the tallest height.

In contrast, the presence of a shear key had only a minor influence on overturning stability across all wall heights. The factors of safety against overturning remain consistently higher than those for sliding and decrease steadily with increasing height; however, the differences between walls with and without shear keys are negligible. This indicates that the overturning stability is primarily governed by the weight and geometry of the wall and backfill, with shear keys contributing little to resisting the overturning moments.

These findings highlight that while shear keys can significantly enhance the sliding resistance of shorter retaining walls, their relative benefit decreases as the wall height and lateral driving forces increase. This trend suggests that relying solely on shear keys to maintain stability in taller walls may be insufficient, and alternative design strategies, such as increasing the base width or employing additional reinforcement, may be necessary to satisfy the safety requirements.

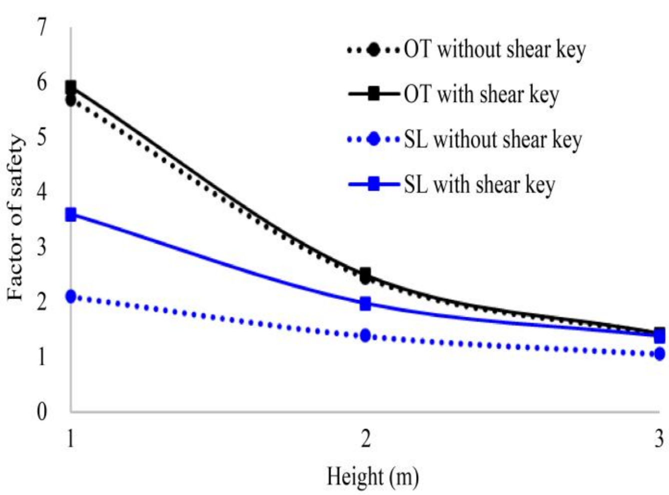


Fig. 2 Factors of safety against sliding and overturning for retaining walls with and without shear keys

Building on these observations, the design optimization results provide further insights into the practical implications of incorporating shear keys. Figure 3 shows the required base widths determined through the optimization process for retaining walls with and without shear keys at various wall heights. The results demonstrate that including a shear key significantly reduces the base width necessary to achieve the target safety factor 1.5 for both sliding and overturning stability.

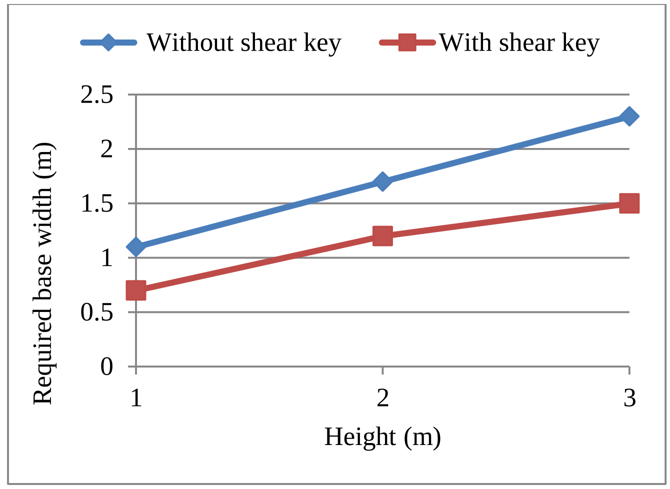
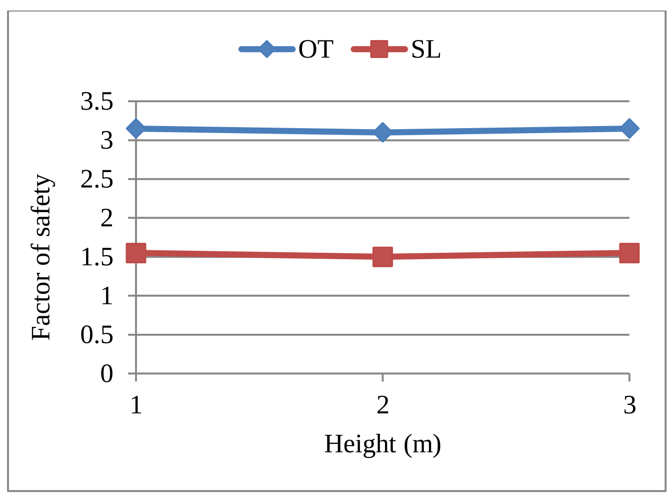


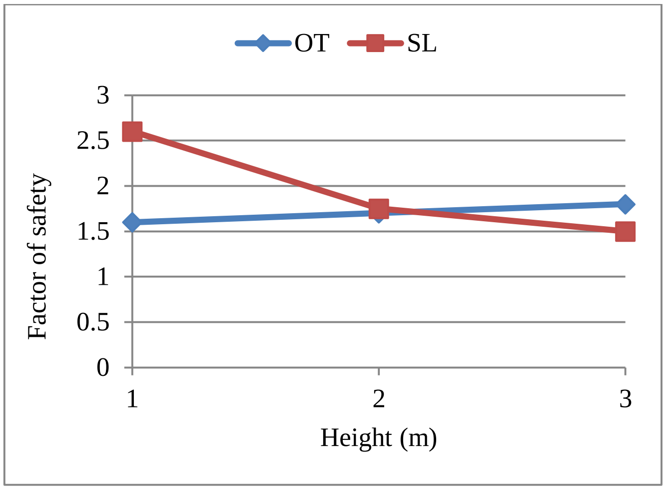
Fig. 3 Required base width for retaining walls with and without shear keys

Further insights into the governing stability mechanisms during the optimization process are provided in Figure 4, which shows the factors of safety for Overturning (OT) and Sliding (SL) in the optimized designs for walls with and without shear keys. For retaining walls without shear keys, the results clearly indicate that sliding consistently controls the design across all wall heights studied, as the factor of safety for sliding remains tightly aligned with the target value of 1.5, whereas the factor of safety for overturning consistently exceeds 3.0. This confirms that in the absence of shear keys, optimization efforts must primarily focus on increasing the base width or heel length to counteract sliding instability.



(a) Without shear key

In contrast, the optimized designs for walls with shear keys revealed a transition in the controlling failure mode depending on the wall height. At a lower wall height of 1 m, overturning dictates the design, as the factor of safety for overturning aligns with the target value of 1.5, whereas sliding stability provides a substantial safety margin. However, as the wall height increases to 2 m and 3 m, the safety factor for sliding decreases and becomes the controlling criterion, converging with the target safety level while the safety factor for overturning rises above it.



(b) With shear key
Fig. 4 Factor of safety for optimized retaining walls with and without shear keys

This shift in the governing failure mode with height demonstrates that shear keys are highly effective in improving the sliding stability of short walls, thereby shifting the design focus toward ensuring adequate resistance to overturning. Conversely, for taller walls, the increasing lateral forces eventually reduce the effectiveness of the shear key in controlling sliding, causing the sliding resistance to govern the optimized design once again. These observations emphasize the importance of considering wall height when deciding whether the addition of a shear key will provide meaningful improvements in stability and material efficiency.

Building on the stability and optimized base width analyses, the concrete volume required for each optimized design provides a direct measure of the design efficiency and material usage. Figure 5 shows the calculated concrete volumes for the retaining walls with and without shear keys across the three studied wall heights. As expected, the concrete volume increased with wall height owing to the need for larger base dimensions to maintain stability under greater lateral earth pressures.

However, the comparison reveals that the addition of a shear key offers only a modest reduction in concrete volume. For example, at a wall height of 3 m, the optimized design with a shear key requires approximately 1.45 m^3 of concrete compared to 1.6 m^3 without a shear key, representing less than a 10% reduction in material use. This small difference indicates that despite the significant benefit of the shear key in reducing the base width, the additional concrete required to construct the shear key offsets much of the material savings achieved through a narrower foundation.

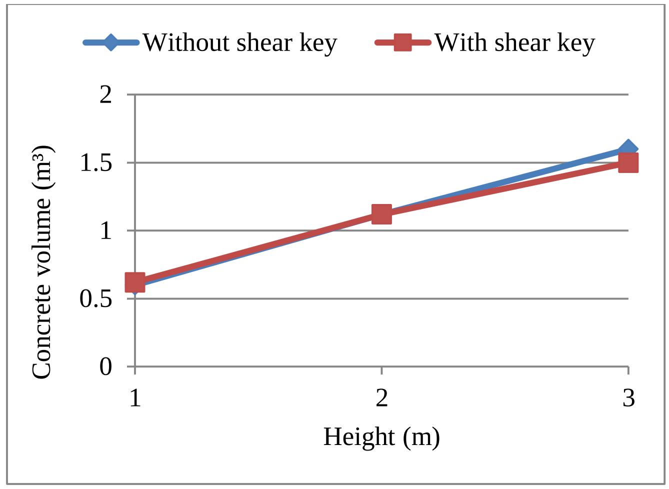


Fig. 5 Concrete volume for optimized retaining walls with and without shear keys

These findings highlight that while shear keys can improve stability performance, particularly by enhancing sliding resistance, their contribution to the overall material efficiency, measured by concrete volume, remains limited. Unlike previous studies that primarily emphasized geometric optimization using algorithmic or metaheuristic approaches, this study employed a practical, iterative method rooted in fundamental stability checks, allowing for a direct assessment of structural performance and concrete usage.

The marginal reduction in concrete volume observed in the presence of shear keys suggests that the additional material required for the key offsets much of the savings from the reduced base dimensions. Therefore, the inclusion of shear keys should be motivated by specific stability requirements, especially in cases where sliding is critical, rather than by the expectations of substantial savings in construction materials or costs.

The findings of this study also have important implications for the design of cantilever retaining walls. First, the analysis confirmed that shear keys significantly improve sliding stability, particularly for shorter walls, allowing reductions in the required base width that can ease construction on constrained sites. However, as the wall height increased, the effectiveness of the shear keys in enhancing the sliding resistance diminished, and sliding once again became the governing failure mode, highlighting the need for alternative design strategies, such as wider bases or soil improvement, for taller walls. Despite these stability benefits, the results demonstrated that the presence of a shear key yielded only marginal reductions in the total concrete volume, indicating limited improvements in material efficiency. Therefore, decisions to incorporate shear keys should prioritize their functional contribution to stability rather than the anticipated savings in concrete quantity.

Additionally, for walls below approximately 2 m in height, where overturning may control the design in the presence of a shear key, careful attention should be paid to balancing the base dimensions to maintain adequate resistance to both failure modes. Overall, this study suggests that shear keys are a valuable design feature in specific scenarios where enhancing sliding stability is critical; however, their adoption should be weighed against the potential for increased construction complexity and minimal material savings, especially for higher retaining walls.

4. Conclusion

This study investigated the effects of shear keys on the stability and design efficiency of cantilever retaining walls subjected to lateral earth pressure by evaluating walls with and without shear keys at heights of 1, 2, and 3 m.

The results demonstrated that including a shear key significantly enhanced the sliding stability, particularly for shorter walls, allowing substantial reductions in the base width required to meet the target safety factor of 1.5. However, the benefit of shear keys diminishes with increasing wall height as lateral earth pressures increase, causing the sliding resistance to become the controlling design criterion in taller walls. The optimization results revealed that although shear keys reduce the base width requirements, they offer only minor reductions in the overall concrete volume, indicating limited improvements in material efficiency.

Additionally, the study showed that in the absence of a shear key, sliding consistently governs the design, whereas in walls with shear keys, the controlling failure mode shifts from overturning at lower heights to sliding at higher heights. These findings indicate that shear keys are an effective design feature for enhancing stability against sliding in shorter retaining walls, particularly where site constraints limit the foundation width. However, their adoption should be based primarily on stability needs rather than the expectations of significant material savings, particularly for taller walls, where their relative contribution decreases. This study provides practical guidance for engineers in designing cantilever retaining walls that balance stability requirements with material efficiency, supporting informed and cost-effective decision-making in retaining wall construction.

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Author Contribution

RS prepared the manuscript, MK performed the analysis, AK reviewed the manuscript, and MA reviewed the manuscript.

Data availability

Data analysis https://zenodo.org/records/15774614

References

[1] Bingdong Ding et al., "Optimizing Shape Design in Drystone Retaining Walls: A Multi-Scope Approach Focusing on Failure Mechanisms," *Construction and Building* Materials, vol. 489, pp. 1-27, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] Amir H. Gandomi, and Ali R. Kashani, "Automating Pseudo-Static Analysis of Concrete Cantilever Retaining Wall Using Evolutionary Algorithms," *Measurement*, vol. 115, pp. 104-124, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[3] Prajakta R. Jadhav, and Amit Prashant, "Computation of Seismic Translational and Rotational Displacements of Cantilever Retaining Wall with Shear Key," *Soil Dynamics and Earthquake* Engineering, vol. 130, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[4] G. Candia, and N. Sitar, "*Seismic Earth Pressures on Retaining Structures with Cohesive Backfills*," *State of California Department of Transportation*, Technical Report, pp. 1-171, 2013. [Google Scholar] [Publisher Link]

[5] Gogot Setyo Budi et al., "Optimization of Counterfort Retaining Wall Structure with Shear Key using Metaheuristic Method," *Civil Engineering Dimension*, vol. 26, pp. 151-159, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] Nisha Sarath, R. Shivashankar, and A.U. Ravi Shankar, "Role of Shear Keys in Cantilever Retaining Wall," *Proceedings of Indian Geotechnical Conference*, Kochi, pp. 627-630, 2011. [Google Scholar]

[7] Majid Ebad Sichani, and Khosro Bargi "Seismic Behavior of Concrete Retaining Wall with Shear Key, Considering Soil-Structure Interaction," *15th World Conference on Earthquake Engineering*, pp. 1-6, 2012. [Google Scholar] [Publisher Link]

[8] Gowshikan Arulananthan, and Nalin de Silva, "Effect of a Shear Key on the Behaviour and Stability of Cantilever Type Retaining Walls," *Moratuwa Engineering Research Conference*, Moratuwa, Sri Lanka, pp. 1-5, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[9] U.S. Department of Transportation Federal Highway Administration, "*LRFD Seismic Analysis and Design of Transportation Geotechnical Features and Structural Foundations*," pp. 1-588, 2011. [Publisher Link]

[10] Caltrans Seismic Design Criteria, "*Seismic Design Criteria Version 2.0 Caltrans: Sacramento*," CA, USA, pp. 1-250, 2019. [Publisher Link]

[11] *NAVFAC Design Manual 7.2: Foundations and Earth Structures*, Technical Report, Washington, DC, 1982. [Publisher Link]

[12] Elif Nur Kalemci et al., "Design of Reinforced Concrete Cantilever Retaining Wall Using Grey Wolf Optimization Algorithm," *Structures*, vol. 23, pp. 245-253, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Hasan Tahsin Öztürk, Tayfun Dede, and Emel Türker, "Optimum Design of Reinforced Concrete Counterfort Retaining Walls Using TLBO, Jaya Algorithm," *Structures*, vol. 25, pp. 285-296, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[14] William John Macquorn Rankine, "On the Stability of Loose Earth," *Philosophical Transactions Royal Society*, vol. 147, pp. 9-27, 1857. [CrossRef] [Google Scholar] [Publisher Link]