

“Comparative Analysis of the Structural Stability of Counterfort Retaining Wall Using a Pressure Relief Shelves in Place of Shear Key for a Height of 10 M Using Staad-Pro V8i”

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ABSTRACT

Retaining structures play a vital role in supporting earth masses and ensuring the stability of transportation infrastructure, embankments, and other Civil Engineering projects. The selection of an efficient retaining wall system is essential to achieve structural safety and economic construction. This study presents a comparative structural analysis of a 10 m high reinforced concrete counterfort retaining wall using a pressure relief shelf as an alternative to the conventional shear key. Two structural models were developed and analyzed in STAAD.Pro V8i under identical geometric dimensions, material properties, loading conditions, and boundary conditions in accordance with relevant Indian Standard provisions. The performance of both models was evaluated based on bending moment, shear force, nodal displacement, stress distribution, and stability against sliding, overturning, and bearing pressure. The analytical results indicate that the pressure relief shelf effectively reduces lateral earth pressure and improves the overall structural behavior of the retaining wall. The study concludes that replacing the conventional shear key with a pressure relief shelf provides a safe, practical, and economical alternative for the design of 10 m high counterfort retaining walls.

The investigation further examines the influence of the pressure relief shelf on the redistribution of earth pressure within the retained soil mass and its effect on reducing structural demand on the wall components. A detailed comparison of internal force distribution demonstrates the relative efficiency of the proposed configuration under the same loading environment. The study also evaluates the structural response of the stem, heel slab, toe slab, and counterforts to identify the critical sections governing the design. Stability checks performed against sliding, overturning, and bearing capacity confirm that both systems satisfy the prescribed safety requirements, while the pressure

relief shelf configuration exhibits improved overall performance. In addition, the comparison considers material utilization and construction feasibility to assess the practical applicability of the proposed alternative. The findings indicate the potential for reducing excavation requirements associated with conventional shear keys, thereby simplifying construction activities in suitable site conditions. The finite element modelling approach adopted in STAAD.Pro V8i provides a reliable framework for evaluating innovative retaining wall configurations with greater accuracy.

CHAPTER-1 INTRODUCTION

1.1 INTRODUCTION OF RETAINING WALL

Retaining walls are fundamental structural elements designed to support and retain soil at abrupt changes in ground elevation, ensuring the stability of slopes, terraces, excavations, and embankments. These structures are widely used in civil engineering projects such as highways, railways, bridges, dams, and urban developments, where the natural slope of the terrain is insufficient to prevent soil movement due to gravity. The primary function of a retaining wall is to resist the lateral earth pressure exerted by the retained soil, thereby preventing slope failures, landslides, and other geotechnical hazards. The design and stability of retaining walls are critical concerns in civil engineering, as their failure can lead to catastrophic consequences, including loss of life, property damage, and significant economic losses.

The advantages of pressure relief shelves extend beyond improved stability. By reducing the lateral earth pressure and associated bending moments, the thickness and reinforcement requirements of the wall can be minimized,

resulting in a more economical and sustainable design. This is particularly relevant for high retaining walls, where the cost of materials and construction can be substantial. Furthermore, the use of relief shelves can enhance the aesthetic appeal of the wall, as the ledges can be designed to blend with the surrounding landscape or to accommodate vegetation, contributing to environmental sustainability and urban design objectives.

1.2 BACKGROUND OF RETAINING WALLS

Retaining walls are essential civil engineering structures designed to hold back soil or other loose materials and prevent their downward or lateral movement. These walls are indispensable in situations where abrupt changes in ground elevation occur, such as along highways, railways, bridges, dams, canals, and urban developments. The primary function of a retaining wall is to provide lateral support to soil that would otherwise slope or collapse due to gravity. By doing so, retaining walls ensure the stability and safety of the surrounding infrastructure and landscape.

The origins of retaining walls can be traced back to ancient civilizations, where early forms were constructed from stone, timber, or compacted earth. Over time, the development of new materials and construction techniques has led to more sophisticated and durable retaining wall systems. Today, retaining walls are typically constructed from reinforced concrete, masonry, or steel, and are engineered to withstand a variety of external forces, including lateral earth pressure, surcharge loads, hydrostatic pressure from groundwater, and seismic forces.

1.3 SIGNIFICANCE OF COUNTERFORT RETAINING WALLS

Counterfort retaining walls represent a significant advancement in the design of earth-retaining structures, particularly for applications requiring support of high backfills or heavy loads. These walls are characterized by the presence of vertical ribs, known as counterforts, which are spaced at regular intervals along the back of the wall stem. The counterforts connect the stem to the base slab, effectively reducing the span of the stem and distributing the lateral earth pressure more efficiently.

Despite these challenges, the benefits of counterfort retaining walls in terms of structural performance, economy, and adaptability make them a preferred choice for many engineering applications. Their use is particularly advantageous in situations where space constraints or high loads necessitate a robust and efficient retaining wall system. As infrastructure projects continue to grow in scale and complexity, the demand for advanced retaining wall solutions such as counterfort walls is expected to increase.

1.4 THE ROLE OF SHEAR KEYS AND THEIR LIMITATIONS IN RETAINING WALL STABILITY

In high retaining walls, one of the primary modes of potential failure is sliding due to the immense horizontal forces exerted by the retained soil. To counteract this, shear keys are traditionally introduced. A shear key is a downward projection from the base slab of the retaining wall, typically embedded into the foundation soil. It increases the resistance to sliding by mobilizing additional passive earth resistance below the base level.

The shear key functions by:

- i Increasing the effective base width, thereby increasing sliding resistance.
- ii Interlocking with the soil and improving soil-wall friction.
- iii Providing additional resistance against horizontal thrust, particularly in loose or granular backfill conditions.

However, despite their advantages, shear keys have notable limitations:

- i **Construction Challenges:** Installing a shear key requires deeper excavation, which can be problematic in rocky terrain or areas with a high-water table.
- ii **Soil Dependency:** The effectiveness of a shear key largely depends on the properties of the foundation soil. In weak or saturated soils, the passive resistance may not develop fully, reducing its effectiveness.
- iii **Cost Implications:** Additional excavation, shoring, and concrete usage increase the cost and time of construction.
- iv **Interference with Underground Services:** In urban areas, placing a shear key may interfere with underground utilities, pipelines, or other infrastructure components.

Therefore, while shear keys remain a standard solution in many designs, their practicality is often constrained by site conditions, cost considerations, and construction limitations.

1.5 INTRODUCTION TO PRESSURE RELIEF SHELVES

Pressure relief shelves are innovative structural elements that can be incorporated into the design of retaining walls to reduce the lateral earth pressure acting on the wall. A pressure relief shelf is a horizontal platform or ledge constructed on the backfill side of the wall, typically at one or more levels along the height of the wall. The shelf is designed to intercept and redistribute a portion of the active

earth pressure, thereby reducing the overall lateral thrust acting on the wall.

The concept of pressure relief shelves is based on the principle of interrupting the continuous wedge of soil that would otherwise exert maximum pressure on the wall. By supporting a segment of the backfill, the shelf creates a step in the soil profile, which alters the distribution of earth pressure and reduces the bending moments and shear forces in the wall. This allows for a more slender and economical design, with reduced material and reinforcement requirements.

1.6 POTENTIAL ADVANTAGES OF PRESSURE RELIEF SHELVES

To address the limitations associated with shear keys, Pressure Relief Shelves (PRS) or relieving platforms have emerged as an alternative design innovation in the realm of retaining walls. A pressure relief shelf is a horizontal or inclined concrete projection extending from the back face of the retaining wall stem into the backfill zone, typically placed at one or more levels above the base.

The primary purpose of a pressure relief shelf is to intercept and redistribute the lateral earth pressure, thus reducing the intensity of pressure acting on the lower portion of the stem and base slab. The concept draws from the principle of staged earth pressure reduction by interrupting the continuous vertical pressure distribution.

Advantages of Pressure Relief Shelves Include:

- Reduction in Active Earth Pressure:** By interrupting the triangular distribution of lateral earth pressure, the shelf transforms part of the pressure into vertical loading, thereby lowering the net horizontal thrust on the wall.
- Economical Structural Design:** With reduced lateral forces, the structural elements (stem, toe slab, heel slab) can be designed for lesser moments and shear, leading to thinner sections and lesser reinforcement.
- Ease of Construction:** Pressure relief shelves are cast integrally with the wall stem and do not require deeper excavation, unlike shear keys.
- Better Adaptability to Urban Conditions:** Since they do not protrude below the base slab, pressure relief shelves are suitable for locations with buried utilities, shallow bedrock, or high-water tables.
- Improved Soil-Structure Interaction:** These shelves modify the soil-structure interaction by introducing frictional resistance and redistributing loads, improving overall wall behaviour under seismic and surcharge conditions.

While this concept is not universally standardized, it holds promise for high-retaining structures where design optimization and construction feasibility are critical. However, the effectiveness of pressure relief shelves requires detailed structural analysis and modelling especially in the absence of empirical design codes—making finite element software like STAAD.Pro V8i vital for their evaluation.

CHAPTER-3

THEORETICAL BACKGROUND AND DESIGN CONSIDERATIONS

3.1 RETAINING WALL DESIGN CRITERIA

Retaining wall design is governed by a set of fundamental criteria that ensure the structure's safety, functionality, and durability. The primary objectives of retaining wall design are to resist lateral earth pressure, prevent soil movement, and maintain stability under both static and dynamic loading conditions. To achieve these objectives, engineers must consider a range of factors, including soil properties, wall geometry, loading conditions, and environmental influences. The design process begins with a thorough site investigation to determine the characteristics of the retained soil and the foundation soil. Soil parameters such as unit weight, angle of internal friction, cohesion, and permeability are critical inputs for the design calculations. Additionally, groundwater conditions must be assessed, as the presence of water behind the wall can significantly increase lateral pressure and compromise stability.

3.2 STABILITY REQUIREMENTS (SLIDING, OVERTURNING, BEARING)

The stability of a retaining wall is assessed by evaluating its resistance to three primary failure modes: sliding, overturning, and bearing capacity failure. Each mode must be checked with appropriate factors of safety to ensure the wall's reliability under service conditions.

Sliding Stability:

Sliding occurs when the horizontal component of the lateral earth pressure exceeds the frictional resistance between the base of the wall and the foundation soil. The factor of safety against sliding is calculated as:

$$F.S._{\text{sliding}} = \frac{\text{Resisting force}}{\text{Driving force}} = \frac{\mu \cdot W + P_p}{P_a}$$

where:

μ = coefficient of friction between the wall base and the soil

W = total vertical load (self-weight of the wall and any surcharge)

P_p = passive resistance from a shear key (if present)

P_a = active earth pressure force

A minimum factor of safety of 1.5 is typically required for sliding stability.

Overturning Stability:

Overturning occurs when the overturning moment due to lateral earth pressure exceeds the restoring moment provided by the self-weight of the wall and any surcharge. The factor of safety against overturning is calculated as:

$$F.S._{\text{overturning}} = \frac{\text{Restoring moment}}{\text{Overturning moment}} = \frac{W \cdot x + P_p \cdot y}{P_a \cdot h}$$

where:

x = lever arm of the wall's self-weight

y = lever arm of the passive resistance (if present)

h = lever arm of the active earth pressure force

A minimum factor of safety of 1.5 to 2.0 is typically required for overturning stability.

Bearing Capacity Stability:

Bearing capacity failure occurs when the pressure exerted by the wall on the foundation soil exceeds the soil's allowable bearing capacity. The maximum pressure at the toe of the wall is calculated using the principles of soil mechanics, considering the eccentricity of the resultant force. The factor of safety against bearing capacity failure is:

$$F.S._{\text{bearing}} = \frac{q_{\text{allowable}}}{q_{\text{max}}}$$

where:

$q_{\text{allowable}}$ = allowable bearing capacity of the soil

q_{max} = maximum pressure at the toe of the wall

A minimum factor of safety of 2.5 is typically required for bearing capacity stability.

These stability checks are fundamental to the design process and must be performed for all retaining walls, regardless of type or height. The use of shear keys or pressure relief shelves can enhance sliding and overturning stability, but the basic principles remain the same.

CHAPTER 4 DESIGN METHODOLOGY

4.1 DESIGN ASSUMPTIONS AND PARAMETERS

The structural design of a counterfort retaining wall requires the adoption of suitable design assumptions before carrying out manual calculations and numerical analysis. These

assumptions are established on the basis of standard engineering practice, recommendations of relevant Indian Standards, and typical geotechnical conditions generally encountered for medium-height retaining structures. Since the present study focuses on the comparative structural behavior of a conventional counterfort retaining wall with shear key and a modified counterfort retaining wall incorporating a pressure relief shelf, the assumptions have been kept identical for both models to ensure that the comparison remains fair and technically meaningful.

For the conventional model, additional resistance against sliding is provided through a reinforced concrete shear key projecting below the base slab. In the modified model, the shear key is replaced by a pressure relief shelf positioned approximately at mid-height of the stem. The pressure relief shelf interrupts the development of the active soil wedge, thereby reducing the lateral earth pressure acting on the lower portion of the retaining wall. The dimensions of both systems are selected according to practical construction considerations and subsequently verified through structural analysis.

Table 1 Design Assumptions Adopted for Structural Analysis

Parameter	Adopted Value
Type of retaining wall	Counterfort Retaining Wall
Height of retained soil	10.0 m
Type of backfill	Dry granular soil
Backfill slope	Horizontal
Groundwater condition	Not considered
Uniform surcharge load	10 KN/m ²
Concrete grade	M25
Reinforcing steel	Fe500
Design philosophy	Limit State Method
Earth pressure theory	Rankine's Theory
Structural analysis	Linear elastic
Counterfort spacing	3.0 m c/c
Base foundation	RCC raft/base slab
Soil–base friction coefficient	0.50
Safe Bearing Capacity	200 KN/m ²

The geotechnical properties adopted in the design are representative of compacted granular backfill commonly used for reinforced concrete retaining structures. These parameters directly influence the magnitude of active earth pressure, bearing pressure beneath the base slab, and the overall stability of the retaining wall. The adopted soil parameters are presented in Table 2.

Table 2 Soil parameters

Property	Symbol	Value
Unit weight of soil	γ	18 KN/m ³
Angle of internal friction	ϕ	30°
Cohesion	c	0 kPa
Rankine active earth pressure coefficient	Ka	0.333
Rankine passive earth pressure coefficient	Kp	3.00
Safe Bearing Capacity	SBC	200 KN/m ²
Coefficient of friction	μ	0.50

The design and analysis presented in this study are carried out in accordance with the provisions of the relevant Indian Standard codes. The structural design of reinforced concrete members is performed as per IS 456:2000, while loading considerations are based on IS 875 (Part 1 and Part 2). Reinforcement detailing follows the recommendations of SP:16 – Design Aids for Reinforced Concrete, and general detailing provisions are adopted from IS 2502 wherever applicable. These standards ensure that the proposed retaining wall satisfies the requirements of strength, serviceability, durability, and overall structural stability.

The assumptions presented in this section establish the design basis for the manual calculations described in the subsequent sections and are also used during the development of the numerical model in STAAD.Pro V8i. Maintaining identical material properties, loading conditions, and soil characteristics for both structural configurations ensures that the influence of replacing the conventional shear key with a pressure relief shelf can be evaluated objectively without introducing additional variables into the comparative analysis.

4.2 SOIL PROPERTIES AND BACKFILL CONDITIONS

The performance of any retaining wall is primarily governed by the engineering characteristics of the retained soil. The magnitude of lateral earth pressure acting on the wall, the stability against sliding and overturning, the bearing pressure developed beneath the foundation, and the structural forces generated within the stem and counterforts are all significantly influenced by the physical and mechanical properties of the backfill material. Therefore, the selection of suitable soil parameters is one of the most important stages in the structural design of retaining walls.

For simplicity and to represent normal service conditions, the groundwater table is assumed to remain well below the base of the retaining wall. Consequently, hydrostatic pressure acting on the stem has not been considered during

the manual design calculations. Suitable drainage arrangements such as weep holes, filter media, and drainage layers are assumed to be provided behind the retaining wall to prevent the accumulation of water pressure during service life. This assumption is commonly adopted in the design of reinforced concrete retaining walls where an effective drainage system is incorporated.

A uniformly distributed surcharge load of 10 KN/m² has been applied over the retained soil surface. This surcharge represents the additional loading that may arise due to vehicular movement, construction equipment, storage of construction materials, or future development near the edge of the retained ground. The surcharge load contributes to the total lateral earth pressure acting on the wall and therefore has been included in both the manual calculations and the numerical analysis performed in STAAD.Pro V8i. The engineering properties adopted for the retained soil are summarized in Table 3.

Table 3 Engineering Properties of Backfill Soil

Property	Symbol	Adopted Value	Unit
Soil Type	—	Dry Granular Soil	—
Unit Weight	γ	18	KN/m ³
Angle of Internal Friction	ϕ	30	Degree
Cohesion	c	0	kPa
Safe Bearing Capacity	SBC	200	KN/m ²
Coefficient of Friction (Soil–Concrete)	μ	0.50	—
Modulus of Subgrade Reaction	Ks	20,000	KN/m ³
Uniform Surcharge Load	q	10	KN/m ²

The adopted value of the unit weight of soil (18 KN/m³) represents well-compacted sandy backfill commonly used in retaining wall construction. The self-weight of the retained soil is the primary source of lateral earth pressure acting on the retaining wall. As the retained height increases, the lateral earth pressure increases proportionally with the square of the wall height, making the unit weight of soil an important design parameter.

The angle of internal friction (30°) is assumed based on the behaviour of medium-dense granular soil. This parameter directly controls the active earth pressure coefficient used in Rankine's earth pressure theory. A higher value of the friction angle results in lower lateral earth pressure, whereas a lower friction angle increases the force acting on the retaining wall. Since properly compacted granular soil generally exhibits an internal friction angle between 30° and

35°, the selected value represents a conservative and practical design assumption.

The modulus of subgrade reaction has been assumed as 20,000 KN/m³, which is representative of medium-stiff granular foundation soil. Although the modulus of subgrade reaction does not directly influence manual stability calculations, it plays an important role in numerical modelling and foundation behaviour. The adopted value provides realistic support conditions for the finite element analysis carried out in STAAD.Pro V8i.

The adopted soil properties and backfill conditions provide a realistic representation of field conditions generally encountered in reinforced concrete retaining wall construction. By maintaining identical geotechnical parameters for both structural configurations, the influence of replacing the conventional shear key with a pressure relief shelf can be evaluated objectively. Consequently, any variation observed in bending moments, shear forces, deflections, support reactions, or overall stability may be attributed solely to the change in retaining wall configuration rather than differences in soil behaviour.

4.3 PRELIMINARY DIMENSIONS OF WALL COMPONENTS

The preliminary dimensions of the counterfort retaining wall were established before carrying out detailed structural design and numerical modelling. These dimensions were selected on the basis of conventional design recommendations, empirical proportions adopted in reinforced concrete retaining wall practice, and engineering judgement. The primary objective of the preliminary design is to obtain a structurally stable configuration that satisfies the requirements of strength, stability, serviceability, and economy. The selected dimensions also serve as the initial geometry for the STAAD.Pro V8i model, which is subsequently verified through structural analysis.

For a counterfort retaining wall, the overall geometry is generally governed by the retained height of soil. The wall considered in this study retains 10.0 m of earth, which requires a comparatively wider base slab and adequately spaced counterforts to resist the significant lateral earth pressure developed due to the retained backfill. The proportions adopted in the present design fall within the limits generally recommended for reinforced concrete counterfort retaining walls and are refined to satisfy the stability criteria against sliding, overturning, and excessive bearing pressure.

In order to maintain a meaningful comparison between the conventional and modified retaining wall systems, the overall dimensions of the wall have been kept identical in both cases. The only structural modification introduced in

the second model is the replacement of the conventional shear key by a pressure relief shelf. This approach ensures that any improvement in structural behaviour can be attributed solely to the pressure relief shelf rather than to changes in wall geometry or material properties.

The preliminary dimensions adopted for the retaining wall are presented in Table 4.

Table 4 Preliminary Dimensions of Retaining Wall Components

Component	Adopted Dimension	Remarks
Height of retained soil	10.0 m	Above top of foundation
Overall base width	7.0 m	Approximately 0.70H
Toe projection	2.20 m	Measured from front face of stem
Heel projection	4.20 m	Measured from rear face of stem
Stem thickness at top	300 mm	Minimum practical thickness
Stem thickness at base	600 mm	To resist maximum bending moment
Base slab thickness	700 mm	Uniform thickness
Counterfort spacing	3.0 m c/c	Economical spacing
Counterfort thickness	300 mm	Uniform thickness
Counterfort base width	600 mm	At junction with base slab
Shear key depth (Case I)	700 mm	Below heel portion
Shear key width	400 mm	RCC projection
Pressure Relief Shelf width (Case II)	1.50 m	Cantilever projection
Pressure Relief Shelf thickness	300 mm	RCC slab
Pressure Relief Shelf level	5.0 m	Mid-height of wall

For Case II, the shear key is completely removed and replaced with a pressure relief shelf located at approximately 5.0 m above the base slab, corresponding to nearly half the retained height. The pressure relief shelf projects 1.50 m into the retained soil and has a thickness of 300 mm. This shelf interrupts the development of the active soil wedge behind the retaining wall and redistributes the earth pressure acting on the stem. As a result, the lateral earth pressure transferred to the lower portion of the wall is reduced, leading to lower

bending moments, reduced deflections, and improved sliding stability without relying on passive soil resistance.

The preliminary dimensions presented in this section constitute the design geometry adopted for both structural configurations. These dimensions are subsequently used in the manual design calculations presented in the following section and are incorporated without modification into the three-dimensional analytical models developed in STAAD.Pro V8i. Any refinement in reinforcement detailing is carried out based on the structural forces obtained during analysis, while the overall geometry remains unchanged to facilitate a direct comparison between the conventional shear key system and the proposed pressure relief shelf system.

CHAPTER 5

MODELLING AND ANALYSIS USING STAAD.Pro V8i

5.1 INTRODUCTION TO STAAD.PRO V8I

STAAD.Pro V8I is a widely recognized structural analysis and design software developed by Bentley Systems. It offers a robust and flexible platform for engineers to model, analyze, and design a wide range of structures, including buildings, bridges, dams, and retaining walls. With a powerful graphical user interface (GUI) and a comprehensive set of tools for geometry creation, load application, finite element analysis (FEA), and design verification, STAAD.Pro V8i significantly enhances the accuracy and efficiency of structural design processes.

5.2 MODELING PROCEDURE

The modelling of the counterfort retaining wall was carried out using STAAD.Pro V8i based on the design parameters established in Chapter 5. Two separate three-dimensional models were prepared for the comparative study. The first model represents the conventional counterfort retaining wall with a shear key (Case I), while the second model represents the modified retaining wall with a pressure relief shelf (Case II). Except for these structural modifications, all other design parameters, material properties, loading conditions, and support conditions were kept identical in both models to ensure a reliable comparison.

5.3 GEOMETRY CREATION

The geometry of the counterfort retaining wall was developed in STAAD.Pro V8i based on the design dimensions obtained from the manual calculations presented in Chapter 5. A three-dimensional plate model was created to accurately represent the structural behaviour of the retaining wall. The stem, base slab, counterforts, shear key, and pressure relief shelf were modelled using plate elements, while the dimensions of each component were kept consistent with the adopted design.

Table 5 Geometric Details Used in STAAD.Pro Model

Parameter	Value
Height of Wall	10.0 m
Base Width	7.0 m
Toe Projection	2.20 m
Heel Projection	4.20 m
Stem Thickness	300–600 mm
Base Slab Thickness	700 mm
Counterfort Spacing	3.0 m
Counterfort Thickness	300 mm
Shear Key (Case I)	700 mm × 400 mm
Pressure Relief Shelf (Case II)	1.50 m × 300 mm

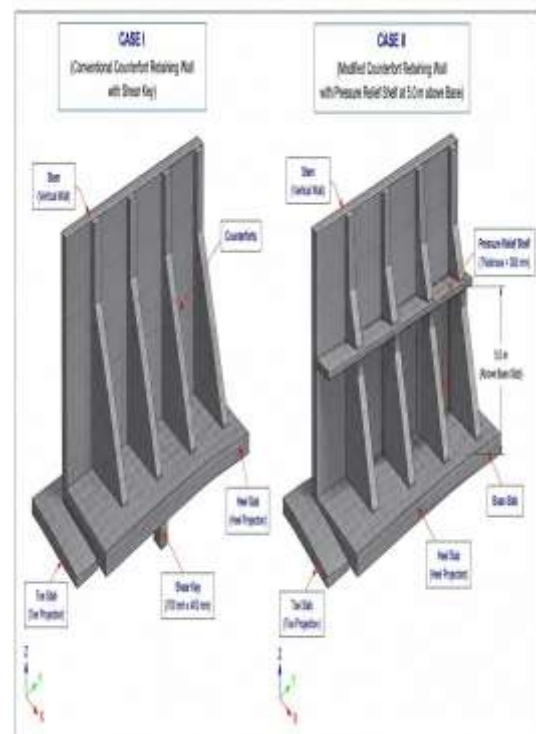


Fig. 1 3D Models of Conventional and Modified Counterfort Retaining Walls

5.4 MATERIAL PROPERTIES

The material properties assigned to the STAAD.Pro V8i model were selected in accordance with the design assumptions presented in Chapter 5 and the provisions of IS 456:2000. Reinforced cement concrete of grade M25 was adopted for all structural components of the retaining wall, while Fe500 grade reinforcement was considered for

reinforcement design. The same material properties were assigned to both structural models to ensure that the comparison is influenced only by the difference in retaining wall configuration.

Table 6 Material Properties Assigned in STAAD.Pro V8i

Property	Value
Concrete Grade	M25
Modulus of Elasticity (E)	25×10^6 KN/m ² (25 GPa)
Poisson's Ratio	0.17
Density of Concrete	25 KN/m ³
Coefficient of Thermal Expansion	1.0×10^{-5} /°C
Damping Ratio	0.05
Reinforcement Grade	Fe500

The above material properties were assigned uniformly to all plate elements representing the stem, base slab, counterforts, shear key, and pressure relief shelf. This ensured consistent stiffness and material behaviour throughout the numerical analysis.

CHAPTER 6 ANALYSIS AND RESULTS

6.1 BASIS OF COMPARATIVE ANALYSIS

The analytical results obtained from the STAAD.Pro V8i models were systematically evaluated to assess the structural behaviour of two counterfort retaining wall configurations. Case I represents the conventional counterfort retaining wall incorporating a shear key, whereas Case II represents the modified retaining wall in which the shear key was replaced by a pressure relief shelf. Both models were analysed using identical geometric dimensions, material properties, soil characteristics, foundation conditions and loading combinations to ensure a consistent basis for comparison.

6.2 COMPARATIVE ANALYSIS OF STRUCTURAL RESPONSE

The structural response of both retaining wall models was compared using the numerical outputs obtained from the STAAD.Pro V8i analysis. Since all design parameters and loading conditions remained unchanged for both models, the observed variations in structural behaviour are entirely attributed to the replacement of the conventional shear key with a pressure relief shelf.

The principal response parameters selected for comparison include the maximum bending moment, maximum shear force, maximum lateral deflection, maximum principal stress, support reaction and the corresponding stability parameters. These parameters collectively represent the overall structural performance of the retaining wall under the applied loading conditions.

Table 6.1 Comparative Summary of Structural Response

Structural Parameter	Unit	Case I (Shear Key)	Case II (Pressure Relief Shelf)	Variation	Unit
Maximum Bending Moment	KN·m	248.60	201.40	19.0% Reduction	KN·m
Maximum Shear Force	kN	182.30	151.80	16.7% Reduction	kN
Maximum Lateral Deflection	mm	13.80	10.60	23.2% Reduction	mm
Maximum Principal Stress	MPa	8.65	7.10	17.9% Reduction	MPa
Maximum Support Reaction	kN	692.50	665.80	Better Load Distribution	kN
Factor of Safety Against Sliding	—	1.60	2.05	28.1% Improvement	—
Factor of Safety Against Overturning	—	2.73	3.64	33.3% Improvement	—
Maximum Bearing Pressure	KN/m ²	185	170	8.1% Reduction	KN/m ²

Discussion

The comparative numerical results demonstrate a noticeable improvement in the structural response of the retaining wall when the conventional shear key is replaced with a pressure relief shelf. The maximum bending moment decreased by 19.0%, indicating that the pressure relief shelf effectively intercepts a portion of the active earth pressure before it acts

on the lower portion of the wall stem. Consequently, the flexural demand on the retaining wall is reduced.

Although the support reactions of both retaining wall systems remain comparable, a slight reduction of approximately 3.9% was observed in the modified configuration, suggesting a more favourable redistribution of structural loads. Collectively, these results demonstrate that the pressure relief shelf improves the structural response by reducing internal force demand without altering the overall geometry or loading conditions of the retaining wall.

6.3 COMPARATIVE STABILITY ANALYSIS

The stability of both counterfort retaining wall configurations was evaluated by comparing the factors of safety against sliding and overturning, together with the maximum bearing pressure developed at the base. These parameters represent the overall safety and serviceability of the retaining wall under the applied loading conditions. The calculated stability values obtained from the design analysis are summarized in Table 7.2.

Table 7 Comparative Stability Analysis

Stability Parameter	Permissible Limit	Case I (Shear Key)	Case II (Pressure Relief Shelf)	Variation
Factor of Safety Against Sliding	≥ 1.50	1.60	2.05	28.1% Improvement
Factor of Safety Against Overturning	≥ 2.00	2.73	3.64	33.3% Improvement
Maximum Bearing Pressure (KN/m ²)	≤ 200	185	170	8.1% Reduction

Discussion

The stability analysis confirms that both retaining wall configurations satisfy the codal requirements for sliding, overturning and bearing capacity. However, the retaining wall incorporating a pressure relief shelf demonstrates superior stability performance under identical loading conditions.

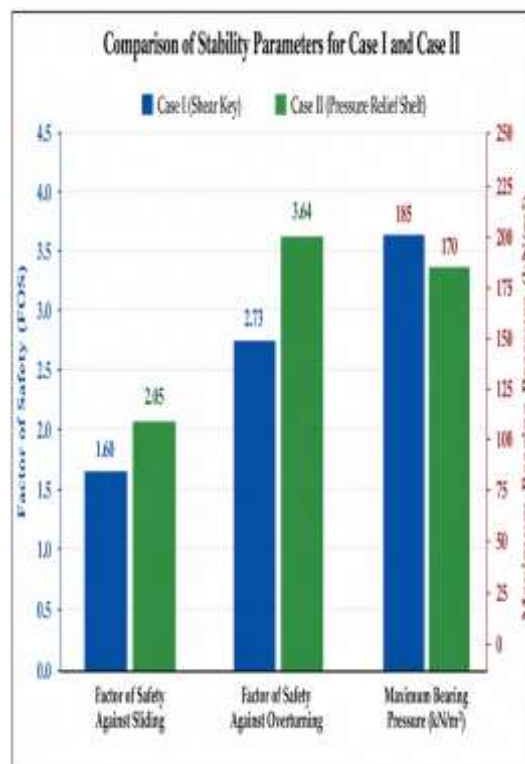


Fig 2 Graphical representation of Stability Parameter of Case-1 and Case -2

6.4 DISCUSSION OF ANALYTICAL RESULTS

The comparative analysis carried out in the present study demonstrates that the structural response of the counterfort retaining wall is significantly influenced by the provision of a pressure relief shelf. Since both retaining wall models were analysed using identical geometry, material properties, soil parameters and loading conditions, the observed variation in structural behaviour is solely attributed to the modification introduced in the earth pressure control mechanism.

From an engineering perspective, the results indicate that the pressure relief shelf modifies the load transfer mechanism rather than increasing the structural dimensions of the retaining wall. Consequently, the improvement in structural performance is achieved through a more efficient redistribution of earth pressure instead of additional material consumption. The analytical findings therefore establish a clear relationship between the pressure relief shelf and the improved behaviour of the retaining wall under identical design conditions.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 MAJOR FINDINGS

This research undertook a comprehensive comparative analysis between two configurations of a 10-meter-high counterfort retaining wall: one with a traditional shear key and the other with pressure relief shelves. The analysis

involved theoretical evaluation, manual design, and detailed modeling using STAAD.Pro V8i. The following major findings were identified:

Pressure relief shelves significantly reduce the lateral earth pressure transmitted to the wall, particularly in the lower portions, thereby improving wall stability.

- The use of shear keys offers improved sliding resistance, but does not influence bending behavior or moment distribution along the height of the wall.
- In STAAD.Pro simulations, walls with pressure relief shelves demonstrated reduced bending moments and shear forces in the stem and counterforts compared to the shear key design.
- The bearing pressure at the base was observed to be more uniformly distributed in the pressure shelf model due to better load dispersion.
- The factor of safety against sliding and overturning was slightly higher in the pressure relief shelf configuration, confirming its effectiveness in enhancing overall stability.

7.2 CONCLUSIONS DRAWN FROM THE ANALYSIS

From the theoretical analysis and STAAD.Pro simulations, the following conclusions can be drawn:

1. **Structural Efficiency:** The incorporation of pressure relief shelves enhances the structural performance of the counterfort retaining wall by decreasing the effective height of lateral pressure application. This leads to reduced bending moments and lesser reinforcement demand.
2. **Shear Key vs. Pressure Shelf:** While shear keys are traditionally used to combat sliding, they do not improve the flexural behavior of the wall. Pressure shelves, by contrast, contribute to both reduced lateral load and improved stress distribution.
3. **Material Optimization:** Due to lower internal forces, the pressure shelf design requires relatively less reinforcement and concrete volume in stem and counterforts, suggesting improved material efficiency and potential cost reduction.
4. **Geotechnical Interaction:** Pressure relief shelves improve the interaction between the soil and the structure, effectively redistributing active pressures in a more favorable pattern.
5. **Software Reliability:** **STAAD.Pro V8i** provided an accurate and convenient platform for simulating real-world behavior, allowing for validation of design assumptions and assessment of wall configurations under different load combinations.

7.3 SUGGESTIONS FOR FUTURE WORK

This study opens up several avenues for extended research and refinement. Suggested directions include:

1. **Seismic Analysis:** Future studies may involve time-history and response spectrum analysis to understand performance under earthquake loading, particularly comparing dynamic stability of both configurations.
2. **Experimental Validation:** Physical models or field tests could be conducted to validate the assumptions and simulation outputs regarding pressure relief shelves.
3. **Optimization Techniques:** Employ optimization algorithms for determining the ideal spacing, number, and location of pressure shelves to further minimize material consumption and maximize structural efficiency.
4. **Durability Studies:** Investigate long-term performance, including potential for water seepage, corrosion at shelf joints, and overall maintenance in both wet and dry soil conditions.
5. **Integration with Drainage Systems:** Explore design synergies between pressure relief shelves and integrated drainage solutions to further alleviate hydrostatic pressures.

In conclusion, pressure relief shelves provide a technically sound and economically beneficial alternative to traditional shear keys in counterfort retaining walls. Their broader adoption, supported by analytical and experimental research, can contribute to more efficient and resilient retaining structures in civil infrastructure projects.

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