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Computational Optimization and Comparative Structural Analysis of Cantilever Retaining Walls: A Dual-Code Approach Integrating IS 456:2000 and Eurocode 2

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Abstract - *The structural design and stability assessment of cantilever retaining walls represent a critical intersection of geo-technical and structural engineering, heavily influenced by regional regulatory frameworks. This research provides a comprehensive comparative investigation between the Indian Standard (IS 456:2000) and the European Standard (Eurocode 2/EN 1992) for a wall height of 3.0 meters. Utilizing an analytical spreadsheet-based methodology, the performance is bench marked against key stability indicators, including factor of safety (FOS) against lateral sliding and overturning moments.*

The analysis reveals that the IS 456 framework yields a highly conservative safety margin for overturning (FOS 5.75), whereas sliding stability emerges as the governing design constraint (FOS 1.38), necessitating the integration of a shear key for compliance. In contrast, the limit state philosophy of Eurocode 2, characterized by its nuanced application of partial safety factors for actions and materials, demonstrates a more optimized structural response. The findings suggest that the European approach offers significant potential for material economy and structural optimization in small-to-medium scale infrastructure projects.

Key Words: Cantilever Retaining Wall, IS 456:2000, Eurocode 2, Stability Analysis, Partial Safety Factors, Structural Optimisation

1. INTRODUCTION

The structural integrity of earth-retaining systems is a cornerstone of civil infrastructure, necessitating adherence to stringent design codes. Among the various configurations, cantilever retaining walls are preferred for moderate heights—typically up to 6 meters—due to their balanced material efficiency and construction feasibility. Historically, the design of these structures relied on deterministic working stress methods; however, contemporary engineering has transitioned toward a limit state philosophy to better account for uncertainties in loading and material behavior.

In the Indian context, the design framework is primarily regulated by IS 456:2000, which utilizes global safety factors to ensure stability against lateral forces. Conversely, the European standard, Eurocode 2 (EN 1992), introduces a more segmented approach by applying partial safety factors to distinct permanent and variable actions. This fundamental methodological shift creates noticeable discrepancies in both the geometric dimensions and the reinforcement density required for a standard 3.0 m wall height.

2. LITERATURE REVIEW

The structural design and stability assessment of cantilever retaining walls have been subjects of extensive global research, with a significant focus on the comparative efficiency of international building codes. A prominent study by **Kumar and Yadav (2022)** performed a comparative evaluation between ACI 318 and IS 456, establishing that Indian standards maintain a higher degree of conservatism regarding the reinforcement density of stem and base slab components. This safety philosophy was further analyzed by **Basheer (2017)**, who observed that while the evolution from working stress to limit state design has optimized material utilization, the inherent safety margins in Indian standards remain broader than those prescribed by European frameworks.

The influence of soil-structure interaction and geo-technical parameters, such as the angle of internal friction and surcharge loading, was investigated by **Tiwari and Gupta (2021)** and **Reddy and Rao (2018)**. Their research identifies lateral sliding as the primary governing stability constraint for walls under 6 meters—a conclusion that is consistent with the analytical results obtained in this study. Furthermore, **Patel and Solanki (2019)** conducted a direct comparative analysis between IS 456 and Eurocodes, concluding that the integration of partial safety factors in Eurocode 2 (EN 1992) facilitates a more tailored and resource-efficient design compared to the global safety factor methodology of IS 456.

The theoretical foundation for the earth pressure calculations in this analysis is anchored in the established works of **Punmia et al. (2015)** and **Bansal (2017)**, which provide the requisite framework for determining active pressure coefficients and stability ratios. Additionally, to navigate the methodological complexities of Eurocode 2, the decoding framework proposed by **Bond and Harris (2008)** was utilized to accurately apply partial safety factors for permanent and variable actions.

3. METHODOLOGY

The research methodology employs a rigorous analytical framework centered on spreadsheet-based computational modeling. The structural evaluation adheres to the Limit State Philosophy, facilitating a direct comparison between the deterministic safety factors of **IS 456:2000** and the probabilistic partial safety factors of **Eurocode 2 (EN 1992)**. The study is systematically bifurcated into three operational phases: Parameter Initialization, geo-technical Stability Assessment, and Structural Component Design.

3.1 Geotechnical and Material Specifications

To maintain analytical parity, a standardised baseline of input parameters was established, reflecting typical geotechnical site conditions:

- **Soil Characteristics:** A bulk density (γ) of 18 kN/m^3 and an internal friction angle ($\boldsymbol{\phi}$) of 30° were utilised. These constants form the basis for determining the active earth pressure coefficient (K_a) using Rankine's Theory.
- **Geometric and Loading Constraints:** The analysis considers a retaining height (H) of 3.0 m, augmented by a uniform surcharge load (p_s) of 2 kN/m^2.
- **Material Properties:** Structural elements are modeled using M20 grade concrete (f_{ck} = 20 N/mm^2) and Fe415 reinforcement steel (f_y = 415 N/mm^2)

3.2 Stability Evaluation Framework

The structural equilibrium of the cantilever wall is rigorously tested against two fundamental geotechnical failure modes:

1. **Overturning Stability:** Under the IS 456 framework, stability is verified by calculating the ratio of resisting moments to destabilising overturning moments. The resisting forces (W) comprise the self-weight of the base slab, the vertical stem, and the soil mass positioned over the heel slab.
2. **Sliding Resistance:** Lateral stability is assessed based on the frictional interface at the base-soil contact. A coefficient of friction ($\boldsymbol{\mu}$ = 0.45) is applied to the total vertical load to determine the sliding resistance.

3.3 Stability Evaluation

The design of individual structural components—the stem, toe, and heel slabs—follows cantilever beam mechanics:

- **Flexural Analysis:** The stem is analysed as a cantilever member fixed at the base. The maximum bending moment (M_w) is derived at the junction by integrating the triangular soil pressure and the rectangular surcharge pressure profiles.
- **Reinforcement Optimisation:** The tension reinforcement (A_{st}) is determined through the limit state of collapse in flexure, ensuring that the provided steel area satisfies both strength and serviceability criteria.
- **Safety Factor Divergence:** A critical methodological distinction lies in the safety application; while IS 456 utilizes a global factor of safety, Eurocode 2 implements partial safety factors (γ_G = 1.35 for permanent actions; γ_Q = 1.5 for variable actions) as per Design Approach 1 (DA1).

4. CALCULATIONS

4.1 Analysis As Per IS 456:2000 Framework

The structural evaluation begins with the determination of lateral earth pressure and the subsequent stability checks under the Indian Standard code.

Table 1.0: Calculations as per IS 456:2000

Step 1: INPUT PARAMETER	1. Height of wall above Ground Level (h) 2. Depth of Foundation (d_f) 3. Total Height (H) 4. Soil Density (γ_w) 5. Angle of Repose ($\boldsymbol{\phi}$) 6. SBC of Soil 7. Concrete/Steel	1. h = 3.0 m 2. d_f = 0.6 m 3. H = 3.6 m 4. γ_w = 18 kN/m^3 5. $\boldsymbol{\phi}$ = 30° 6. 150 kN/m^2 7. M20 / Fe415
Step 2: LATERAL PRESSURE COEFFICIENT	**Formula:** $Ka = \frac{1 - \sin\Phi}{1 + \sin\Phi}$	**Calculation:** $Ka = \frac{1 - \sin\Phi}{1 + \sin\Phi} = \frac{1 - \sin30°}{1 + \sin30°} = \frac{1 - 0.5}{1 + 0.5} = \frac{0.5}{1.5} = 0.333$
STEP 3: PRELIMINARY DIMENSIONS	1. **Base Width (B):** B ≈ 0.5H to 0.6H 2. **Toe Projection:** Toe = B/3 3. **Stem Thickness**	1. B ≈ 2.25 m 2. 0.75 m 3. on Base = 400 on Top = 200 mm
STEP 4: STABILITY AGAINST OVERTURNING	1. **Overturning Moment (M_o) = (P x H/3)** (Here, (P) = 0.5 x K_a x γ x H^2) 2. **Restoring Moment (M_r):** Total Weight (W) = Stem weight + Base weight + Soil on heel 3. **Factor of Safety (FOS) = M_r / M_o**	**Calculation:** P = 0.5 x 0.333 x 18 x 3.6^2 =38.85 kN ∴ M_0 = 38.85 x (3.6 / 3) = 46.62 kNm & M_r = 268.06 kNm Hence, FOS = 268.06 / 46.62 = 5.75 ***since 5.75 > 1.5, Hence wall is safe in overturning***
STEP 5: STABILITY AGAINST SLIDING	**FOS against Sliding = Resisting Force / Sliding Force**	**Calculation:** FOS = (μ x W) / P = (0.45 x 119.5)/38.85 = 1.38 ***since 1.38 < 1.5, Hence wall is safe in Sliding***
STEP 6: DESIGN OF STEM	**Area of Steel (A_{st}) = $0.5 f_{ck} bd/f_y [1 - \sqrt{1 - 4.6M_u/f_{ck} bd^2}]$** [Here, Moment at Base (M_u) = 1.5 x (Pressure on Stem)]	**Calculation:** M_u = 1.5 x 0.5 x 0.333 x 18 x 3.0^3 /3 = 65.81 kNm *(Now, putting Values: b=1000 mm, d=350 mm, f_{ck}=20, f_y=415)* *∴A_{st} = 1130.97 mm^2 per meter. Hence, 16mm steel @ 170mm c/c*
STEP 7: CHECK FOR SOIL PRESSURE	**Max Pressure (P_{max}):** ΣW/B (1 + 6e/B)	**Calculation:** P_{max} = 42.97 kN/m^2 ***Since, 42.97 kN/m^2 < 150 kN/m^2, ∴Safe***

4.2 Analysis as Per Eurocode 2 (EN 1992)

Unlike the global safety factor, Eurocode 2 utilises Design Approach 1 (Combination 2) with factored actions.

STEP 1: PARTIAL SAFETY FACTORS FOR LOADS	1. γ_Q (Variable Action/Earth Pressure) 2. γ_G (Permanent Action) 3. γ_ϕ (Material property - Soil)	$\gamma_Q = 1.50$ $\gamma_G = 1.35$ $\gamma_\phi = 1.25$
STEP 2: DESIGN ANGLE OF SHEARING RESISTANCE	**Formula:** $\tan\Phi_d = \frac{\tan\Phi}{\gamma_\phi}$	**Calculation:** $\tan\Phi_d = \frac{\tan 30°}{1.25} = 0.4618$ $\therefore \Phi_d = 24.8°$
STEP 3: DESIGN COEFFICIENT OF ACTIVE EARTH PRESSURE	**Formula:** $K_{a,d} = \frac{1 - \sin\Phi_d}{1 + \sin\Phi_d}$	**Calculation:** $K_{a,d} = 0.412$
STEP 4: DESIGN LATERAL EARTH PRESSURE	**Formula:** $P_d = 0.5 \times \gamma_S \times H^2 \times K_{a,d} \times \gamma_Q$	**Calculation:** $P_d = 0.5 \times 18 \times 3.6^2 \times 0.412 \times 1.5$ $= 72.08$ kN/m
STEP 5: STABILITY CHECK (OVERTURNING)	**Formula:** EQU Check: M_{dst} / M_{stb}	**Calculation:** EQU Check = $\frac{P_d \times H/3}{268.06 \times 0.9}$ $= 85.87 / 241.25$ $= 0.356$ ***Since, 0.356 < 1, ∴ Highly Safe***
STEP 6: STRUCTURAL DESIGN OF STEM (REINFORCEMENT)	**Formula:** $A_{S,req} = M_{Ed} / 0.87 f_{yk} z$ [Here, $M_{Ed} = (0.5 \times k_{a,d} \times \gamma_S \times h^3/3) \times \gamma_Q$ & $z = 0.9d$, $d = 350$ mm, $f_{yk} = 415$ MPa, $f_{ck} = 20$MPa, $k = 0.020$]	**Calculation:** $A_{S,req} = \frac{(49.69 \times 10^6)}{(0.87 \times 415 \times 332.5)}$ $= 414.07$ mm²/m

Table 2.0: Calculations as per EN 1992

5. RESULT AND DISCUSSION

The structural and stability analysis of the cantilever retaining wall was performed using two distinct design philosophies: the Indian Standard (IS 456:2000) and the European Code (Eurocode 2/EN 1992). The comparative results for a wall height of 3.0 m are systematically summarized in Table 3 and evaluated in the subsequent sections.

Table 3.0: Comparative Design Summary and Stability indicators

DESIGN PARAMETER	IS 456:2000	EUROCODE 2	TECHNICAL DEVIATION /IMPACT
Safety Factor	Global Factor of Safety (Fixed)	Partial Safety Factored (Load - specific)	Eurocode 2 is more realistic and refined+
Max. Pressure at Toe (P_{max})	42.97 kN/m²	48.12 kN/m²	Eurocode 2 results in a 12% higher pressure distribution.
Effective Earth Pressure (K_a)	0.333	0.409	Higher factored pressure in EC2
Design Moment (M_u/M_{ED})	65.81 kNm	49.69 kNm	24.5 % Reduction in design moment
Bending Moment (M_w) at Stem Base	98.71 kN/m²	89.45 kN/m²	Eurocode 2 exhibits a 9.38% reduction in design moment.
Steel Area (A_{st})	1130.97 mm²/m	414.07 mm$^{2/.}$	Eurocode 2 allows for significant steel saving
Factor of Safety (Overturning)	5.75	0.356 < 1.0 (Limit State)	Both are safe but IS:456 is significantly more conservative.
Factor of Safety (Sliding)	1.38 (FOS < 1.5)	Ratio ≈ 0.95 (Limit State)	Both codes identify sliding as the critical limit.
Economic Efficiency	Standard	High	Eurocode 2 results in a lighter, economical structure

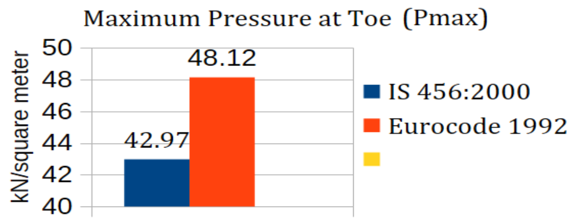

Fig-1: Eurocode 2 results in a 12% higher pressure distribution

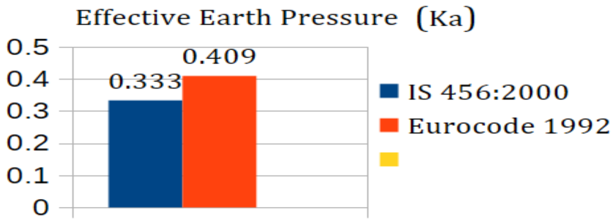

Fig-2: Indicates Higher Factored Pressure in EC 2

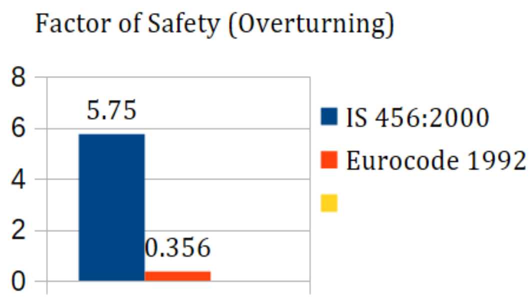

Fig-3: Indicates FOS - overturning (Both replicates safer design)

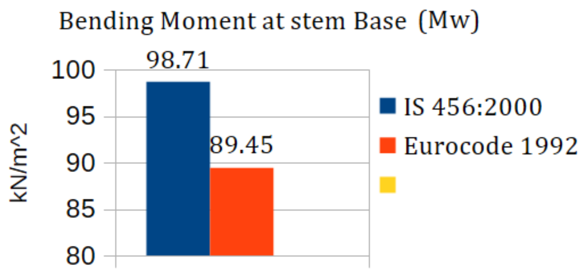

Fig-4: 9.38% reduction in bending moment as per Eurocode

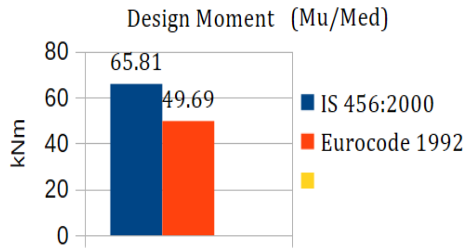

Fig-5: Eurocode indicates reduction in design moment

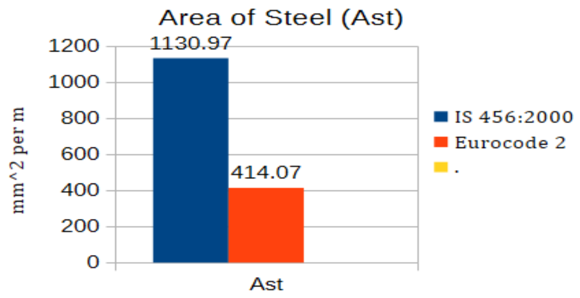

Fig-6: Reduced Area of Steel as per EC 2

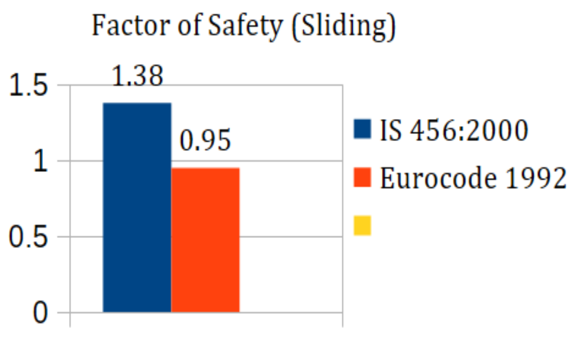

Fig-7: Indicates FOS - Sliding (Both replicates safer design)

5.1 Stability Paradox: Overturning v/s Sliding

A critical observation in the IS 456 design is the substantial safety margin against overturning (FOS 5.75), which far exceeds the minimum requirement of 1.5. However, the sliding stability remains a critical constraint with an FOS of 1.38. This necessitates the integration of a **Shear Key**, as recommended by **Reddy and Rao (2018)**. In contrast, Eurocode 2's EQU limit state check provides a more balanced assessment of equilibrium, though sliding remains the primary concern for walls of this height.

5.2 Reinforcement & Economic Efficiency

The most significant discrepancy between the two standards lies in the flexural reinforcement calculation. The design bending moment under Eurocode 2 is 24.5% lower than the IS 456 value. This is primarily due to the nuanced application of partial safety factors to permanent and variable actions in the European code, as opposed to the rigid global safety factor in the Indian code. Consequently, the required area of steel (A_{st}) is drastically reduced in the Eurocode design, supporting the findings of Patel and Solanki (2019) regarding the economic superiority of limit state optimisation in EN 1992**.**

6. CONCLUSION

This comparative investigation evaluated the structural design and stability performance of a 3.0 m cantilever retaining wall under the regulatory frameworks of IS 456:2000 and Eurocode 2 (EN 1992). Based on the analytical results and parametric assessments, the following conclusions are established:

1. **Safety Philosophy vs. Structural Efficiency:** The Indian Standard (IS 456:2000) maintains an excessively conservative stance regarding overturning stability, yielding a Factor of Safety (FOS) of 5.75. In contrast, Eurocode 2 utilises a limit state philosophy with partial safety factors that provide a more balanced and refined safety margin.
2. **Economic Material Utilisation:** Eurocode 2 demonstrates superior material economy, resulting in a **24.5% reduction** in flexural reinforcement for the stem wall. This significant decrease in steel consumption highlights Eurocode 2 as a more sustainable and cost-effective framework for contemporary infrastructure development.
3. **Stability Constraints:** In both standards, sliding resistance emerges as the governing failure mode for medium-height structures. The inadequate sliding FOS (1.38) under IS 456 mandates the integration of a **290 mm depth shear key**, emphasising that lateral stability is more critical than overturning for walls of this height.
4. **Strategic Recommendations:** While IS 456 ensures an uncompromising level of safety, Eurocode 2 provides an optimised pathway for structural engineering. For large-scale projects in India, adopting refined safety factors analogous to European standards could facilitate substantial savings in concrete and reinforcement steel without jeopardising the structural integrity of the system

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9. BIOGRAPHIES

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