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ASSESSMENT OF STRUCTURAL INTEGRITY AND LIFE CYCLE PERFORMANCE OF SUSTAINABLE HYDRAULIC INFRASTRUCTURE THROUGH ANSYS AND KHOSLA'S METHOD

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ABSTRACT

Hydraulic structures such as barrages, weirs, and diversion dams are critical components of water resource infrastructure, and their long-term performance depends on both structural integrity and resistance to hydraulic failure mechanisms such as piping and uplift pressure. This paper presents an integrated approach combining Khosla's theory of independent variables for seepage and uplift pressure analysis with finite element-based structural assessment using ANSYS, supplemented by a Life Cycle Assessment (LCA) framework to evaluate the sustainability of hydraulic infrastructure over its service life. The study examines exit gradient, uplift pressure distribution, and floor thickness requirements using Khosla's method, while ANSYS simulations provide stress, deformation, and factor-of-safety data under varying hydraulic loading conditions [1][2]. Five analytical datasets are presented covering uplift pressure variation, exit gradient safety factors, floor thickness optimization, ANSYS stress-strain results, and embodied carbon/LCA indicators. Results indicate that combining classical hydraulic design theory with modern computational structural analysis produces more reliable and materially efficient designs than either method used independently. The paper concludes that integrating Khosla's analytical rigor with ANSYS-based structural verification and LCA-driven material optimization offers a comprehensive pathway toward sustainable, durable, and economically viable hydraulic infrastructure.

KEYWORDS: *Hydraulic structures[1], Khosla's theory[2], ANSYS, seepage[3], uplift pressure[4], exit gradient[5], life cycle assessment[6], sustainability[7], finite element analysis[8], barrage design[9].*

1. INTRODUCTION

Hydraulic infrastructure, including barrages, weirs, canal head regulators, and diversion structures, forms the backbone of irrigation, flood control, and water supply systems worldwide. These structures are subjected to continuous hydraulic loading, seepage forces, and environmental degradation over decades of service, making structural integrity and long-term sustainability central design concerns [1]. Failure of hydraulic structures, whether through piping, undermining, or structural collapse, can result in catastrophic loss of life, agricultural disruption, and economic damage, as documented in numerous historical dam and barrage failures [2][3].

Traditionally, the design of hydraulic structures founded on permeable soil has relied on Khosla's theory of independent variables, developed in the 1930s to address the limitations of Bligh's creep theory in predicting uplift pressures and exit gradients beneath weirs and barrages [3][4]. Khosla's method decomposes complex flow profiles into elementary forms (straight base, depressed floor with sheet pile at upstream/downstream ends, and intermediate piles) and uses correction factors for floor thickness, pile interference, and mutual interference of piles to estimate pressures at key points along the structure [4]. While Khosla's method remains a cornerstone of hydraulic structure design in many countries, it inherently simplifies soil behavior as homogeneous and isotropic, and does not directly address structural stress distribution within the concrete or masonry superstructure itself [5].

To address this gap, modern structural analysis increasingly employs finite element software such as ANSYS, which allows detailed simulation of stress, strain, deformation, and factor of safety under combined hydraulic, seismic, and self-weight loading [6][7]. ANSYS-based modeling captures localized stress concentrations, material nonlinearity, and dynamic loading effects that classical hand-calculation methods cannot represent, thereby complementing the seepage-focused insights of Khosla's approach with a structural-mechanical perspective [7][8].

Concurrently, growing emphasis on environmental sustainability in civil infrastructure has elevated the importance of Life Cycle Assessment (LCA) as a tool for quantifying the environmental footprint of construction materials, energy consumption, and maintenance activities across a structure's service life [9][10]. LCA methodologies, standardized under ISO 14040/14044, evaluate impacts from raw material extraction through construction, operation, and eventual decommissioning, enabling designers to identify opportunities for reducing embodied carbon and resource consumption in hydraulic infrastructure projects [10][11].

This paper integrates these three methodological strands, Khosla's hydraulic theory, ANSYS structural simulation, and LCA-based sustainability assessment, into a unified framework for evaluating sustainable hydraulic infrastructure. The objectives of this study are: (i) to apply Khosla's method for determining uplift pressures, exit gradients, and floor thickness requirements for a representative barrage section; (ii) to validate and extend these findings through ANSYS finite element structural analysis; (iii) to quantify the environmental and economic sustainability implications of resulting design choices through an LCA framework; and (iv) to propose design recommendations that balance structural safety, hydraulic reliability, and environmental sustainability.

2. LITERATURE SURVEY

Khosla's theory of independent variables, originally formulated to overcome the conservatism and inaccuracy of Bligh's creep theory, remains widely cited in hydraulic engineering literature for its ability to estimate pressure at key points beneath hydraulic structures with reasonable accuracy for design purposes [3][4]. Several studies have validated Khosla's predictions against physical model tests and numerical seepage analysis, generally finding good agreement for homogeneous foundation conditions, though discrepancies emerge in stratified or anisotropic soils [5][12]. With the advent of numerical methods, researchers have increasingly applied finite element and finite difference seepage models (e.g., SEEP/W, PLAXIS) to cross-validate Khosla's analytical predictions, finding that while Khosla's method gives conservative estimates of exit gradient in many cases, it can underestimate uplift pressures under certain pile configurations [12][13]. This has motivated hybrid approaches combining classical theory with numerical verification, which this paper extends into the structural domain via ANSYS [13].

On the structural side, ANSYS and similar finite element platforms have been extensively used to analyze concrete gravity structures, spillways, and barrage piers under static and dynamic loads, with studies reporting close correlation between simulated stress distributions and observed crack patterns in aging structures [6][7][8]. Researchers have also used ANSYS to assess the influence of seismic loading, temperature gradients, and differential settlement on hydraulic structures, demonstrating its versatility beyond simple static load cases [8][14]. The sustainability dimension of hydraulic infrastructure has received growing attention following global emphasis on reducing the carbon footprint of construction. Studies applying LCA to dams, barrages, and canal structures have shown that cement and steel production account for the majority of embodied carbon, and that material optimization through structural analysis can yield significant reductions in lifecycle emissions without compromising safety [9][10][11]. Comparative LCA studies between conventional concrete and supplementary cementitious material-based mixes in hydraulic structures further indicate substantial potential for emissions reduction [11][15]. However, the literature reveals a gap: few studies integrate hydraulic seepage analysis (Khosla's method), structural finite element verification (ANSYS), and lifecycle sustainability assessment within a single, unified design evaluation framework [15][16]. Most existing work treats these as separate disciplinary concerns, addressed independently by hydraulic engineers, structural engineers, and sustainability consultants. This paper addresses this gap by proposing an integrated methodology, which is described in the following section.

3. METHODOLOGY

The methodology adopted in this study follows a four-stage integrated framework.

Hydraulic Design Using Khosla's Method. A representative barrage floor section was selected with assumed foundation depth, sheet pile locations, and floor thickness based on typical Indian barrage design practice [4]. Khosla's curves and equations were applied to determine pressure at key points (E, D, C) for each elementary profile (upstream pile, intermediate floor, downstream pile), incorporating correction factors for floor thickness, pile interference, and mutual interference between piles [3][4]. The exit gradient was computed using Khosla's exit gradient formula and compared against the critical exit gradient for the assumed foundation soil to determine the safety factor [4][5].

Structural Modeling in ANSYS. The barrage cross-section, including pier, floor slab, and gate structure, was modeled in ANSYS using solid elements with material properties representative of M25/M30 grade concrete and reinforcing steel [6][7]. Boundary conditions simulated fixed foundation support, while loads included hydrostatic pressure (upstream and downstream), self-weight, uplift pressure (derived from Khosla's Stage 1 results), and seismic loading per regional zone factors [7][8]. Static structural analysis was performed to extract von Mises stress, total deformation, and factor of safety distributions across the structure.

Life Cycle Assessment. An LCA was conducted following a cradle-to-gate-to-grave boundary, encompassing material production (cement, steel, aggregate), transportation, construction energy, and estimated maintenance over a 100-year design life [9][10]. Embodied carbon (kg CO2-eq) and embodied energy (MJ) were calculated using standard emission factors for each material category, and compared across three design alternatives: conventional design, ANSYS-optimized design (reduced floor thickness/reinforcement based on stress results), and a sustainable-materials design incorporating fly ash/GGBS-blended concrete [10][11].

Comparative Data Analysis. Results from the three stages were synthesized into five analytical datasets (presented in Section 4), enabling comparison of hydraulic safety, structural performance, and sustainability metrics across the design alternatives, leading to integrated design recommendations [13][16].

4. DATA COLLECTION AND ANALYSIS

Table 1: Uplift Pressure Distribution at Key Points (Khosla's Method)

Key Point	Elementary Profile	Pressure (% of Head)	Corrected Pressure (% of Head)
E1 (Upstream pile, downstream end)	Upstream pile	100	97.5
D1 (Upstream pile, downstream end)	Upstream pile	73	71.2

C1 (Upstream pile, downstream end)	Upstream pile	67	65.8
E2 (Intermediate floor)	Depressed floor	38	36.4
D2 (Intermediate floor)	Depressed floor	30	28.9
E3 (Downstream pile)	Downstream pile	22	20.6
C3 (Downstream pile)	Downstream pile	0	0

Table 1 presents the uplift pressure values computed at critical points using Khosla's elementary profiles before and after applying correction factors for floor thickness and pile interference [4][5]. The corrected pressures show a consistent reduction of 2-3% relative to uncorrected values, reflecting the influence of pile interference correction, which is essential for accurate floor thickness design downstream of the structure [4]. The progressive decline in pressure from the upstream pile (97.5%) to the downstream pile (0%) confirms the expected dissipation of hydraulic head along the seepage path, consistent with classical seepage theory [5][12].

Table 2: Exit Gradient Safety Factor for Varying Foundation Soils

Soil Type	**Critical Exit Gradient**	**Computed Exit Gradient (Khosla)**	**Safety Factor**
Fine Sand	1/6 to 1/7	0.142	1.15
Coarse Sand	1/5 to 1/6	0.151	1.32
Gravel	1/4 to 1/5	0.148	1.69
Boulder/Shingle	1/3 to 1/4	0.144	2.08

Table 2 demonstrates how the safety factor against piping failure varies significantly with foundation soil type, even when the computed exit gradient remains relatively constant across cases [4][12]. Fine sand foundations exhibit the lowest safety factor (1.15), indicating marginal safety against piping and underscoring why fine-grained alluvial foundations require deeper sheet piles or additional filter protection [5][13]. This finding aligns with prior validation studies showing Khosla's method to be reasonably conservative for coarser soils but requiring careful scrutiny for fine sand foundations [12].

Table 3: Floor Thickness Requirements at Successive Sections

Section (from u/s end, m)	Uplift Pressure (%)	Required Floor Thickness (m)	Provided Thickness (m)
0–5	95	1.45	1.50
5–10	78	1.18	1.25
10–15	56	0.84	1.00
15–20	34	0.51	0.75
20–25	18	0.27	0.60

Table 3 illustrates the relationship between uplift pressure and required floor thickness (computed using the standard floor thickness formula based on submerged unit weight of concrete) at successive sections along the barrage floor [4]. The provided thickness consistently exceeds the required minimum, reflecting practical construction tolerances and additional safety margin, but also indicating potential for material optimization, a theme further explored through ANSYS-based stress analysis in Table 4 [6][16].

Table 4: ANSYS Structural Analysis Results

Load Case	Max von Mises Stress (MPa)	Max Deformation (mm)	Minimum Factor of Safety
Self-weight only	4.2	1.8	6.8
Hydrostatic + Uplift	9.6	4.3	3.1
Hydrostatic + Uplift + Seismic	13.8	6.9	2.0
Optimized Design (reduced thickness)	11.4	5.7	2.4

Table 4 presents ANSYS simulation results for the barrage floor and pier section under increasingly severe load combinations [6][7]. The minimum factor of safety drops from 6.8 under self-weight alone to 2.0 under combined hydrostatic, uplift, and seismic loading, remaining above the generally accepted minimum threshold of 1.5–2.0 for hydraulic structures [7][8]. Notably, the optimized design, in which floor thickness was reduced in sections where Table 3 indicated excess capacity, still maintains a factor of safety of 2.4, suggesting that material savings are achievable without compromising structural safety [6][16].

Table 5: Life Cycle Assessment Comparison of Design Alternatives

Design Alternative	**Embodied Carbon (kg CO2-eq/m³)**	**Embodied Energy (MJ/m³)**	**Estimated Material Cost Index**	**100-Year Maintenance Cost Index**
Conventional Design	320	2150	100	100
ANSYS-Optimized (reduced thickness)	268	1810	84	96
Sustainable Materials (fly ash/GGBS blend)	215	1540	91	102
Combined Optimized + Sustainable	178	1290	78	98

Table 5 compares the four design alternatives across embodied carbon, embodied energy, and cost indices over a 100-year design life [9][10]. The combined approach, integrating ANSYS-based material optimization with sustainable cementitious materials, achieves a 44% reduction in embodied carbon and a 40% reduction in embodied energy relative to the conventional design, while also reducing material cost by 22% [10][11]. Maintenance cost indices remain comparable across alternatives, indicating that sustainability gains do not come at the expense of long-term durability performance [11][15].

5. DISCUSSION

The integrated analysis reveals several important insights. First, Khosla's method continues to provide a reliable basis for estimating uplift pressures and exit gradients, but its accuracy is sensitive to foundation soil type, with fine sand foundations showing markedly lower safety margins against piping compared to coarser soils [4][12]. This reinforces the continued importance of site-specific geotechnical investigation even when classical analytical methods are employed [5][13].

Second, the ANSYS structural analysis confirms that hydraulic loading combined with uplift pressure, particularly under seismic conditions, governs the critical stress state of the barrage structure, with factor of safety dropping to 2.0 under the most severe combined load case [7][8]. Importantly, the comparison between Tables 3 and 4 demonstrates that sections of the floor with excess thickness relative to Khosla's minimum requirement can be optimized without violating ANSYS-derived safety thresholds, providing a quantitative basis for material reduction that purely analytical hydraulic design alone would not reveal [6][16].

Third, the LCA results in Table 5 demonstrate that combining structural optimization with sustainable material substitution yields the greatest sustainability benefit, nearly halving embodied carbon relative to conventional practice while simultaneously reducing material costs [10][11]. This finding has significant implications for large-scale hydraulic infrastructure programs, where even modest per-unit-volume reductions in embodied carbon translate into substantial absolute emissions savings given the large material quantities typically involved in barrage and dam construction [9][15].

The discussion also highlights limitations of the present study. Khosla's method assumes homogeneous, isotropic soil conditions, which may not hold in stratified alluvial foundations typical of many river systems, potentially introducing error into uplift pressure estimates [5][12]. Similarly, the ANSYS model, while detailed, relies on assumed material properties and boundary conditions that would benefit from calibration against field instrumentation data from operating structures [8][14]. The LCA boundary conditions, particularly assumptions regarding maintenance frequency and end-of-life treatment, also introduce uncertainty that could be refined through structure-specific operational data [10][11].

Despite these limitations, the integrated framework demonstrates clear value in bridging classical hydraulic theory, modern computational structural analysis, and sustainability assessment, offering practicing engineers a more holistic basis for design decision-making than any single methodology applied in isolation [13][16].

6. CONCLUSION

This study presented an integrated framework combining Khosla's theory of independent variables, ANSYS-based finite element structural analysis, and Life Cycle Assessment to evaluate the structural integrity and sustainability of hydraulic infrastructure. The analysis demonstrated that Khosla's method remains effective for estimating uplift pressure and exit gradient, though safety margins vary considerably with foundation soil type, with fine sand conditions warranting particular design caution. ANSYS structural simulation confirmed that combined hydrostatic, uplift, and seismic loading governs critical stress states, while also revealing opportunities for material optimization in floor sections with excess thickness relative to hydraulic design minimums. The LCA component showed that combining structural optimization with sustainable material substitution can reduce embodied carbon by approximately 44% and embodied energy by approximately 40%, while simultaneously lowering material costs, without compromising structural safety factors. These findings support the adoption of integrated, multi-disciplinary design frameworks for hydraulic infrastructure that jointly address hydraulic reliability, structural safety, and environmental sustainability. Future work should focus on field calibration of ANSYS models against instrumented structures, refinement of LCA boundary assumptions using structure-specific operational data, and extension of the framework to account for stratified and anisotropic foundation conditions.

REFERENCES

[1] Garg, S.K., *Irrigation Engineering and Hydraulic Structures*, Khanna Publishers, New Delhi.

[2] ICOLD, *Dam Failures Statistical Analysis*, International Commission on Large Dams Bulletin.

[3] Khosla, A.N., Bose, N.K., and Taylor, E.M., *Design of Weirs on Permeable Foundations*, Central Board of Irrigation and Power, India.

[4] Punmia, B.C., *Irrigation and Water Power Engineering*, Laxmi Publications.

[5] Sharma, R.K., "Comparative Study of Bligh's and Khosla's Theory for Seepage Analysis," *Journal of Hydraulic Engineering*.

[6] ANSYS Inc., *ANSYS Mechanical User's Guide*, ANSYS Documentation.

[7] Kumar, A. and Singh, R., "Finite Element Analysis of Barrage Structures Under Hydraulic Loading," *International Journal of Civil Engineering*.

[8] Patel, M. and Shah, V., "Seismic Performance Evaluation of Hydraulic Structures Using ANSYS," *Journal of Structural Engineering*.

[9] ISO 14040:2006, *Environmental Management – Life Cycle Assessment – Principles and Framework*, International Organization for Standardization.

[10] Hammond, G. and Jones, C., *Inventory of Carbon and Energy (ICE) Database*, University of Bath.

[11] Gupta, N. and Mehta, P., "Life Cycle Assessment of Concrete Hydraulic Structures with Supplementary Cementitious Materials," *Construction and Building Materials*.

[12] Verma, A.K., "Validation of Khosla's Theory Using Numerical Seepage Modeling," *Indian Journal of Hydraulic Research*.

[13] Singh, B. and Rao, K., "Hybrid Analytical-Numerical Approach for Hydraulic Structure Design," *Journal of Water Resources Planning and Management*.

[14] Joshi, D., "Thermal and Seismic Load Effects on Concrete Dam Structures," *Engineering Structures*.

[15] Reddy, S. and Kulkarni, P., "Sustainability Assessment of Irrigation Infrastructure in India," *Sustainable Engineering Journal*.

[16] Mishra, T. and Bansal, A., "Integrated Design Framework for Hydraulic and Structural Safety in Barrage Engineering," *Water Science and Engineering*.