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Review Study on the Effect of the End Sill Geometry on the Downstream Scour

Haneen Mutni Ibrahim[1], Layla Ali. M. Saleh[1], Aysar Tuama Al-Awadi[1]
[1]Civil Engineering Department, College of Engineering, University of Karbala, Karbala 56001, Iraq
[a]corresponding author: alawsihaneen@gmail.com ; layla.a@uokerbala.edi.iq; Aysar.t@uokerbala.edu.iq
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Abstract Excessive downstream scour and inefficient energy dissipation in hydraulic structures remain critical challenges that can compromise structural stability and channel safety. The aim of this study is to evaluate the performance of various end sill geometries in reducing scour depth and improving energy dissipation efficiency. In terms of methodology, a comprehensive review was conducted based on 52 peer-reviewed studies published between 2000 and 2025, covering five primary end sill geometries: rectangular, inclined (sloped), semi-circular, convex, and perforated. The collected data were systematically analyzed to compare hydraulic performance under a wide range of flow conditions. The results indicate that inclined end sills with slopes between 45° and 60° provide significant scour reduction, typically ranging from 50% to 95%. Perforated end sills with porosity ratios of 40–50% demonstrate the highest energy dissipation efficiency, reaching 74% to 94%. Convex geometries are more effective in protecting the channel centerline, whereas concave configurations offer improved bank protection. Additionally, recent studies incorporating computational fluid dynamics (CFD) and machine learning models report high predictive accuracy, with coefficients of determination exceeding 0.98. In conclusion, despite these advancements, several research gaps remain, particularly regarding long-term scour evolution, the effects of sediment gradation, and the interaction between multiple energy dissipation devices. Addressing these gaps is essential for optimizing end sill design under varying hydraulic conditions, including different Froude numbers, sediment characteristics, and structural configurations.

Keywords: End Sill Geometry, Froude Number, Scour, Sediment Size, Stilling Basin.

1. Introduction

Hydraulic structures such as spillways, weirs, drop structures, and stilling basins are designed to dissipate excess flow energy in order to prevent downstream scour, which may compromise structural stability and integrity [1], [2], [3]. Among the most commonly used energy dissipation devices, end sills—raised structures located at the downstream end of stilling basins—play a critical role in stabilizing hydraulic jumps, enhancing energy dissipation efficiency, and reducing erosive flow velocities [4], [5]. The geometric configuration of end sills significantly influences flow characteristics, turbulence intensity, sediment transport processes, and the size and shape of scour holes formed downstream of hydraulic structures [6], [7].

Traditionally, rectangular (vertical) end sills have been widely adopted based on conventional design guidelines, such as USBR Type III and Type VI stilling basin configurations [2], [5]. However, recent hydraulic studies have demonstrated that alternative geometries, including inclined, convex, semi-circular, and perforated end sills, can significantly improve hydraulic performance under specific flow conditions [6], [7], [8]. Despite the increasing number of experimental, numerical, and analytical studies investigating alternative end sill configurations, the available literature remains fragmented and lacks a comprehensive and systematic comparison of their hydraulic performance. In addition, variations in hydraulic conditions, sediment characteristics, and experimental setups introduce uncertainties that limit the generalization of design recommendations.

Existing studies provide valuable insights into individual end sill geometries; however, a unified understanding of their comparative performance and the underlying hydraulic mechanisms is still lacking. In particular, inconsistencies in Froude number ranges, sediment properties, and tailwater conditions make it difficult to establish reliable design guidelines across different hydraulic scenarios.

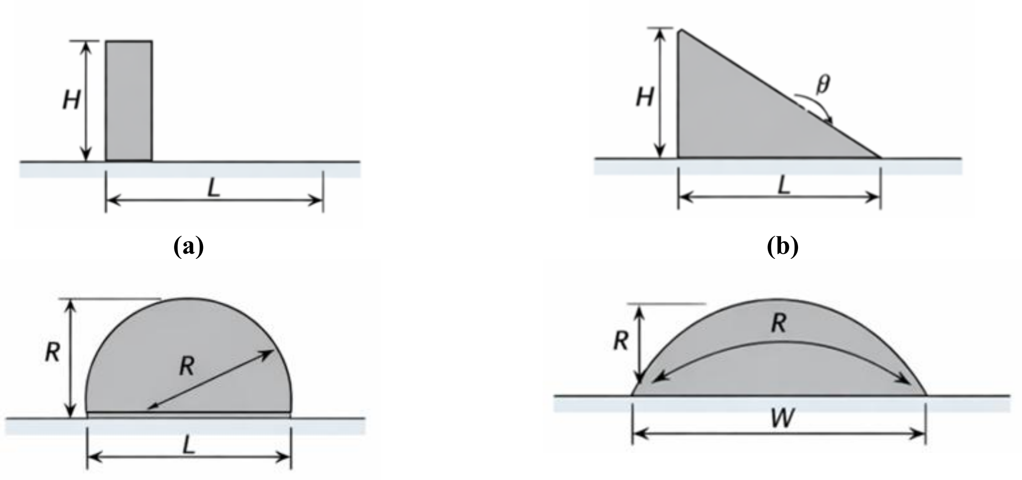
Therefore, this study aims to provide a comprehensive and structured review of the hydraulic performance of different end sill geometries used in energy dissipation basins. The analysis is based on 52 peer-reviewed studies published between 2000 and 2025. The review primarily focuses on recent advancements over the past 5–10 years, while also incorporating foundational studies to establish the theoretical basis of scour formation and energy dissipation processes downstream of hydraulic structures [8], [9], [10], [11].

The main objective of this study is to evaluate the effectiveness of different end sill geometries in reducing downstream scour and improving energy dissipation efficiency. The specific objectives include:

- Quantifying the performance of different geometrical configurations in reducing scour depth.
- Explaining the hydraulic flow mechanisms associated with different end sill geometries.
- Synthesizing optimal design parameters, including end sill angle, curvature radii, and porosity ratio.
- Assessing the reliability and accuracy of CFD-based numerical simulations reported in previous studies.
- Identifying research gaps and proposing directions for future improvements in hydraulic design.

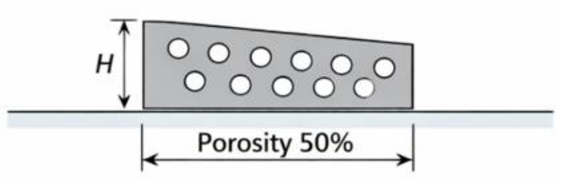
In addition, this review goes beyond conventional descriptive analysis by providing a unified synthesis of hydraulic mechanisms governing different end sill geometries, establishing comparative performance trends across varying flow conditions, and offering a design-oriented framework for selecting optimal sill configurations. This integrative approach enhances the practical applicability of the review for hydraulic engineers and contributes to bridging the gap between laboratory findings and real-world design requirements.

The remainder of this paper is organized as follows. Section 2 presents the methodology adopted for the review process. Section 3 discusses the hydraulic performance of different end sill geometries. Section 4 provides a comparative analysis of the results. Section 5 presents the computational fluid dynamics (CFD) analysis. Section 6 discusses recent advances and machine learning applications. Section 7 provides a design-oriented discussion framework, including performance evaluation and research gaps. Finally, Section 8 concludes the study.



(a) **(b)**

(c) **(e)**



(e)

Figure 1. Schematic of five end sill geometries with dimensional parameters (a) Rectangular End Sill; (b) Inclined End Sill; (c) Semi-Circular End Sill; (d) Convex End Sill; (e) Perforated End Sill.

2. Methodology of Review

This study adopts a systematic review approach to evaluate the hydraulic performance of various end sill geometries, following PRISMA-informed methodologies commonly applied in engineering review studies [1,2]. This approach ensures transparency, reproducibility, and a structured synthesis of existing research. A clear and systematic workflow was followed, including study identification, screening, eligibility assessment, and final inclusion, in order to minimize selection bias and ensure the reliability of the review process.

2.1 Data Sources and Search Strategy

Relevant studies were identified through a comprehensive search of major scientific databases, including Scopus, Web of Science, and Google Scholar, due to their extensive coverage of peer-reviewed literature in hydraulic engineering.

The search strategy employed a combination of Boolean operators and keywords, including “end sill,” “stilling basin,” “energy dissipation,” “scour,” “hydraulic jump,” and “CFD modeling.” These keywords were selected to capture studies addressing both hydraulic performance and numerical modeling aspects. To ensure the inclusion of recent advancements in experimental techniques and computational modeling approaches, the search was limited to studies published between 2000 and 2025.

2.2 Inclusion and Exclusion Criteria

To ensure consistency and scientific reliability, clearly defined inclusion and exclusion criteria were applied:

- Inclusion criteria: Peer-reviewed journal articles; studies focusing on end sill geometry and hydraulic performance; and experimental, numerical (CFD), or analytical investigations providing quantitative data such as scour depth, energy dissipation, or flow characteristics.
- Exclusion criteria: Conference papers, grey literature, theses, and studies lacking sufficient technical details or clearly defined hydraulic parameters.

2.3 Study Selection Process

An initial screening of titles and abstracts resulted in the identification of 84 potentially relevant studies. These studies were then subjected to a detailed full-text review based on the defined inclusion and exclusion criteria. Following this rigorous selection process, a total of 52 studies were deemed suitable and selected for comprehensive analysis. The study selection process adopted in this review is summarized in Figure 2. The PRISMA-informed workflow included identification, screening, eligibility assessment, and final inclusion of the reviewed studies. This systematic approach was used to ensure transparency, consistency, and reliability during the literature selection process.

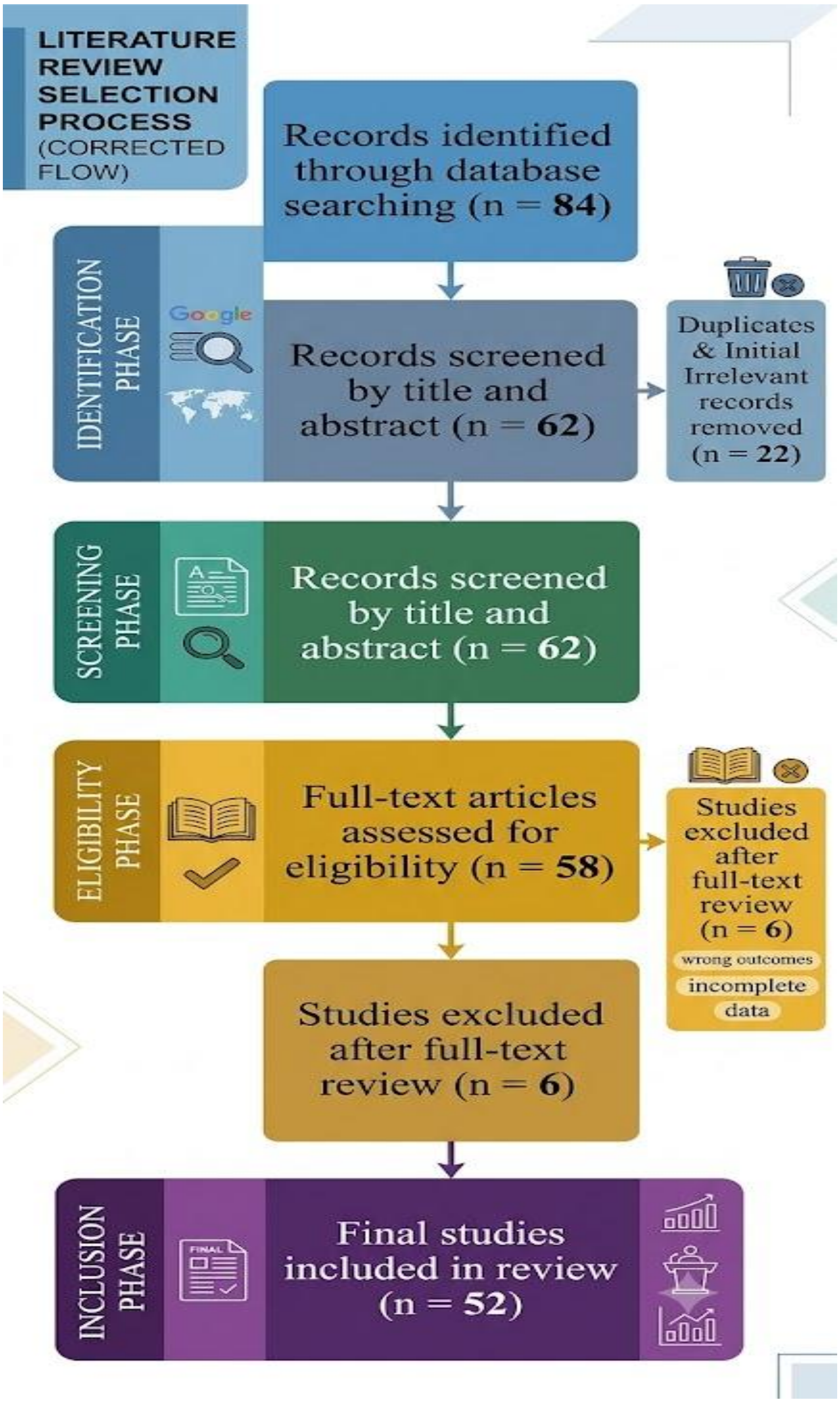


Figure 2. PRISMA-informed flow diagram of the study selection process.

2.4 Data Extraction and Categorization

Relevant data were systematically extracted from the selected studies, including flow conditions (e.g., Froude number and discharge), sediment characteristics, and study type (experimental or numerical).

To enable a consistent and structured comparative analysis, the studies were categorized into five primary end sill geometries: rectangular, inclined (sloped), semi-circular, convex/concave, and perforated. This classification was based on the most frequently investigated configurations reported in the literature. This categorization framework facilitates a systematic comparison of hydraulic performance across different geometrical configurations under varying hydraulic conditions. A summary of the reviewed studies based on year, methodology, geometry type, and main findings is presented in Table 1.

Table 1 provides a structured summary of the reviewed studies based on geometry, method, and key findings

Author (Year)	**Geometry Type**	**Method**	**Key Findings**
Tiwari and Goel (2014)	Rectangular, triangular, trapezoidal	Experimental	Triangular and sloped geometries outperform rectangular shapes in reducing scour depth.
Hamidifar et al. (2018)	Rectangular sill	Experimental	Proper placement of bed sill reduces scour by up to 95%.
Tajabadi et al. (2018)	Inclined sill	CFD (RNG k-ε + VOF)	Optimal angle (60°) achieved highest energy dissipation (~62%).
El-Mahdy (2021)	V-notch sill	Experimental	Reduced scour depth, length, and volume significantly.
Abdelhaleem (2013)	Semi-circular	Experimental	Improved flow spreading and reduced scour depth up to 50%.
Rashed et al. (2022)	Semi-circular	Experimental	Optimal placement reduces scour depth by 50% and length by 31%.
Keshavarzi et al. (2010)	Convex/Concave	Experimental	Convex reduces centerline scour; concave protects banks.
Sohrabi et al. (2019)	Multiple shapes	Experimental	Convex gives lowest scour depth overall.
Elshahat et al. (2023)	Perforated	Experimental	Porosity ~40–50% gives best energy dissipation.
Singh & Roy (2022)	Perforated screens	Experimental	Energy dissipation reached up to 94%.

3. Type of Sills

3.1 Rectangular End Sills: Baseline Performance

3.1.1 Theoretical Framework

Rectangular sills are defined as vertical solid faces perpendicular to flow and represent the conventional configuration adopted in hydraulic engineering practice. They form the foundation for the design of USBR Type II and Type VI stilling basins [2], [5]. The theoretical framework for sill-controlled energy dissipation was established in [8], who demonstrated that rectangular sill geometry directly influences hydraulic jump regimes, including transitions from classical jump flow to wave-type flow. In this context, the relationship between sill height, tailwater depth, and energy dissipation remains the primary design reference for rectangular sill configurations [8], [12]. This relationship governs the interaction between flow structure and energy loss mechanisms within stilling basins.

3.1.2 Performance Characterization

Comparative studies have indicated that rectangular sills provide a moderate level of scour reduction; however, their performance is generally surpassed by modified geometrical configurations. Ref. [13] studied rectangular, square, triangular, and trapezoidal shapes for PEBs over Froude number ranges of Fr = 1.85–3.85. The study indicated that higher scour depths are obtained for rectangular shapes compared to triangular and sloping shapes, establishing that, among the tested configurations, rectangular sills exhibit comparatively lower hydraulic performance.

Hamidifar et al. [14] investigated the performance of rectangular bed sills located downstream of rigid aprons under turbulent jet conditions. The results showed that optimal placement of these bed sills resulted in a 95 percent reduction in scour compared to unprotected configurations. However, the placement of these bed sills is a critical parameter, as complete burial of the sill resulted in no measurable scour reduction. In addition, regression equations were developed for predicting scour hole morphology based on hydraulic and geometric parameters [8], [14]. These findings highlight that the effectiveness of rectangular sills is strongly dependent on installation conditions and hydraulic configuration.

3.1.3 Influence of Upstream Geometry and Stepped Spillway Applications

The performance of rectangular sills is also significantly influenced by upstream structure geometry and basin configuration. The authors in [15], carried out 216 experimental tests to investigate scour downstream of stepped chutes with rectangular sills. The results demonstrated that equilibrium scour depth is directly related to both step geometry and sill height. Increasing the height of rectangular sills was found to reduce downstream scour. Empirical formulas were also developed to predict maximum scour depth under these conditions [15], [16].

In addition, the effect of basin slope was identified as a critical parameter. A positive slope of +0.02 increased scour by 47%, while a negative slope of −0.02 reduced scour by 52.2% [17]. The temporal evolution of scour was also examined, showing that scour depth increases logarithmically with time. Furthermore, self-similar scour profiles were observed during the development of scour holes [10]. Despite these improvements, optimized rectangular sills consistently perform poorer compared to inclined or curved sill configurations under similar hydraulic conditions [18], [19].

3.2 Inclined and Sloped Sills: Enhanced Performance

3.2.1 Hydraulic Mechanism and Optimal Angle Selection

Inclined sills with upstream-facing slopes have shown better performance than rectangular ones under different hydraulic conditions. The main reason for the better performance of these structures is the redirection of flows, where the inclined surface deflects high-velocity flows in an upward and outward direction, resulting in flow expansion and increased turbulent mixing [18], [20]. This hydraulic mechanism reduces near-bed velocities and shear stresses while enhancing turbulence intensity, which contributes to improved energy dissipation and scour control. It was found in previous studies that the optimal range of inclination for these structures, in terms of their angle with the horizontal, lies between 45° and 60° [20], [21].

To further study this phenomenon, Tajabadi et al. [20] carried out an analysis of different sill angles of 30°, 45°, 60°, and 90° using the Renormalization Group k-epsilon (RNG k-ε) turbulence model along with the Volume of Fluid (VOF) method, as presented in Figure 2. The study indicated that triangular-shaped sills with an inclination of 60° provided the best hydraulic performance, dissipating up to 62% of flow energy, whereas other angles only dissipated between 45–52%. Further analysis of pressure fields, velocity fields, turbulence intensity, vorticity, and energy dissipation also indicated that a triangular-shaped stilling basin with an inclination of 60° provided better performance compared to other angles, resulting in better energy dissipation in the stilling basin. These findings highlight that the effectiveness of inclined sills is strongly governed by geometric optimization and flow redirection mechanisms.

3.2.2 V-Notch Configurations

The use of a V-notch sill allows for the inclusion of a lateral convergence that can help in the concentration of flow redirection and increased effects of turbulence. This configuration enhances flow contraction and intensifies mixing processes, which contributes to improved energy dissipation. This study [21] created methodologies for prediction that can be used for the calculation of characteristics associated with the process of scouring that follows a spillway that has a stepped design and a V-notch end sill. The results obtained from the experiments indicated that all the V-notch configurations were effective in increasing energy dissipation and reducing the depth, length, and volume of the scour. The results also indicated that a reduction in the angle of the V-notch can increase energy dissipation and improve the process of scouring. On the basis of the results obtained from the experiments, three equations were developed for the calculation of the depth of the scour, the length of the scour, and the volume of the scour in terms of the Froude number, discharge intensity, and median sediment size (d50) and gradation coefficient [21]. These results demonstrate the strong dependence of hydraulic performance on both geometric configuration and flow conditions.

3.2.3 Negative Steps and Reverse Slopes

Negative steps (i.e., downward-sloping basin floors) are an extension of the concept of inclined stilling configurations. These configurations modify flow structure by altering reattachment behavior and reducing near-bed velocity. An analysis was carried out for different negative step heights (0–15 cm) and incident angles (0°–20°) using ANSYS Fluent code with the Renormalization Group k-epsilon model [22]. The results revealed that an increase in the height of the negative step results in an increase in the relative depth and reattachment length while simultaneously reducing the bottom velocity and roller length. The results also revealed that the incident angle has a strong influence on bottom velocity and reattachment length but a relatively minor influence on the overall flow pattern topology. In addition, in low-gradient and high-gradient streams, different characteristics of the scour require separate predictive equations for accurate prediction [23].

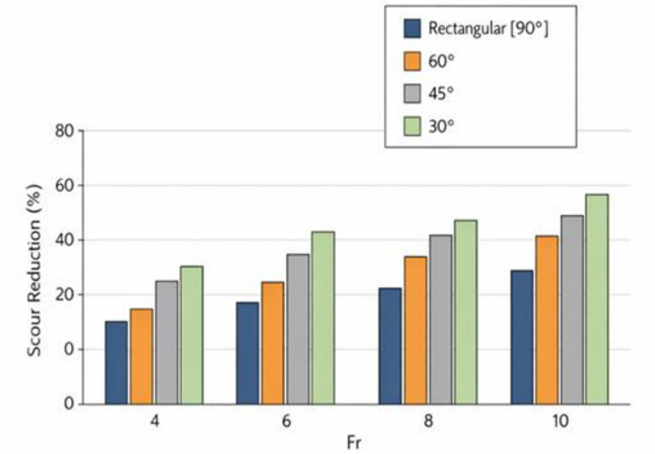


Figure 2. Scour reduction performance across rectangular (90°), 60°, 45°, and 30° inclined sills for Fr=4-10

3.3 Semi-Circular Geometries: Flow Spreading Effects

3.3.1 Curved Surface Flow Mechanics

Semi-circular geometries utilize design features based on streamlined geometry for enhancing lateral flow spreading, resulting in a maximum of 50–78% in scour reduction under optimal conditions [6], [24]. Unlike rectangular or inclined geometries, which cause sudden changes in flow, semi-circular geometries cause smooth transition in flow with minimal separation, hence maximum dissipation of momentum [9], [23]. This streamlined behavior promotes gradual energy loss and reduces localized flow disturbances. Three-dimensional flow characteristics are induced in semi-circular geometries, with lateral velocity redistribution and mixing in the water column. These hydraulic mechanisms contribute to improved flow stability and enhanced energy dissipation efficiency.

3.3.2 Baffle Block Applications

The authors in [6], performed 153 experiments to study semi-circular baffles placed downstream of a Fayoum-type weir. The results showed that semi-circular geometry is significant for the development of three-dimensional scour holes. The optimal position of semi-circular baffles resulted in increased upstream and downstream scour slopes, where the downstream scour slopes are steeper than upstream scour slopes. The semi-circular geometry is advantageous for easy implementation on existing structures without reconstruction.

The study in [24] was based on 54 live-bed experiments for hollow semi-circular baffles. The optimal position of baffles at one-third of the basin floor with a relative diameter 0.74 times flow depth resulted in 50% reduction of scour depth and 31% reduction of scour length for flat floors. Different baffle blocks of various shapes (V-shape, semi-cylinder positioned vertically and horizontally) showed that semi-cylindrical baffles are advantageous for efficient dissipation of energy. The optimized position of semi-cylindrical baffles increased dissipation efficiency by 9.31% and reduced jump length by 38.6% [25]. These findings highlight the importance of both geometric configuration and placement in controlling scour development and enhancing hydraulic performance.

3.3.3 Discharge Enhancement and Hydraulic Performance

Semi-circular shapes are also used to increase the capacity of the discharge. Daneshfaraz et al. [26] have studied the comparison of semi-cylindrical, cylindrical, pyramid-shaped, and rectangular cube sills under sluice gates. Semi-cylindrical sills have the highest coefficient of discharge, where the capacity increased by 19.1% compared to the absence of sills. Energy dissipation increased by 119% in section A and 268% in section B. In addition, wedge-shaped splitter blocks along with rounded end sills reduced the basin length by 25% compared to the USBR Type VI configuration. Wedge-shaped sills produced smooth downstream flow along with reduced scour [4]. These results demonstrate that semi-circular configurations improve energy dissipation, flow stability, and discharge performance; however, these findings should be interpreted with caution due to variations in hydraulic conditions and sediment characteristics.

3.4 Convex Sills: Centerline Protection

3.4.1 Hydraulic Behavior and Performance Characteristics

Convex bed sills, with their outward curvature (arch shape), are good for centerline protection. The outward curvature deflects the lateral flows to the channel banks, which affects the scour location as well as the depth distribution compared to linear or inward-curvature designs [7], [27]. This geometric configuration redistributes the flow away from the centerline toward the channel sides, thereby reducing the intensity of scour at the central region. Convex designs have the smallest overall scour depth for the tested designs, although the enhanced centerline protection can result in greater bank scour for certain flows [27]. These findings indicate that convex geometries primarily act as flow-redistribution elements, rather than uniformly reducing scour across the entire channel width.

3.4.2 Optimal Curvature Ratios

Ref. [7] studied different configurations of convex, concave, and linear shapes for variable flows. The results indicated that the convex shape for a ratio of 0.35 resulted in the least bed scour depth at the centerline. The concave shape for a ratio of 0.23 resulted in the least bed scour depth at the wall boundaries. The convex pattern resulted in the maximum protection against erosion at the centerline. The centerline is normally the deepest erosion point in an unprotected section.

Sohrabi et al. [27] studied different configurations for six different shapes: concave, convex, sine, butterfly, wing, and rectilinear shapes. The results indicated that the overall least depth for bed scour was obtained by using a convex shape.The results also indicated that the maximum depth for bed scour at the centerline in a downstream direction occurred for a convex configuration. The sine configuration resulted in the least bed scour depth at both the centerline and the boundaries. The sine configuration is recommended for simultaneous protection at both the centerline and the boundaries. These results highlight that the effectiveness of convex configurations is strongly dependent on curvature ratio and design geometry, particularly in relation to the redistribution of flow and scour patterns.

3.4.3 Computational Modeling and Advanced Configurations

Advanced computational techniques have been successfully implemented to simulate convex sill scour patterns. Keshavarzi et al. [28] created an ANFIS system based on 2,754 data points for concave and convex arch-shaped sill scour. The author showed that the geometry of the convex shape has a significant effect on the scour depth and location. The author was successful in predicting three-dimensional scour topography for D/W ratios of 1.0 and 1.2 using ANFIS, where D and W represent , achieving strong correlations. Cylindrical deflectors placed above standard sills can achieve 78% scour reduction and 68% scour length reduction for Fr = 4–8 when optimally placed at 0.85z vertically and 0.5z horizontally (z is the height of the sill). The diameter of the deflector is 0.5z [29]. The authors in [30], presented an analysis of curved end sills for stepped spillways. The results showed an increase of 10.5% in dissipation for curved sills compared to straight-edged steps. The curved design also shifted the skimming flow regime to higher discharge ranges. The results were validated using CFD with the k-ε model, showing strong correlation with experimental results. Ref. [31] studied gabion sills as grade control structures. Scour depth is reduced to 44% with a reduction of 51% in scour length due to the presence of gabion sills with an Lg/h value of 1 under free tailwater conditions. The configuration with an Lg/h value of 1.5 is the best configuration for reducing scour depth under high discharge conditions.

The gabion configuration accelerates the bed stabilization process from 6 to 2 hours. This is useful for temporary flood protection. Cylinder blocks on the back slopes of the spillway in a staggered configuration are the best configuration for reducing scour depth compared to the diagonal configuration. The empirical formula is developed for the estimation of scour and deposition [32]. Overall, convex sill configurations effectively enhance centerline protection through flow redistribution mechanisms, although their performance depends on geometric design, flow conditions, and channel characteristics.

3.5 Perforated Sills: Maximum Energy Dissipation

3.5.1 Flow Passage Mechanisms

The dissipation of energy is around 60–94% for perforated, holed, and porous sills, which is higher than that of the conventional hydraulic jump [33], [34], [35]. The increased dissipation of energy is attributed to several interacting hydraulic mechanisms, including:

- contraction or expansion of flow through perforations resulting in turbulent flow,

- interaction between two jets of fluid coming through two adjacent perforations,
- separation of fluid resulting in vorticity, and
- redistribution of velocity profile resulting in uniform velocity downstream [36], [37].

These mechanisms enhance turbulence generation and energy loss, leading to improved downstream flow stability. The optimum porosity ratios lie between 40–50% based on previous studies [34], [35].

3.5.2 Porosity Optimization

In another study [35], studied the performance of perforated sills with porosity ratios between 10.3% and 41.1% with different shapes of the holes, such as circular, rectangular, and square. The results revealed that the scour depth is reduced by 50% for a porosity ratio of 41.1% for the perforated sill compared to the solid sill. However, the scour depth is reduced by 60% for the square-shaped holes. The results also revealed that the circular-shaped holes had the best efficiency in terms of energy dissipation. The porosity ratio of 41.1% for the circular-shaped holes had an efficiency of nearly 80% compared to the solid sill configuration. In this study [35], it is revealed that the energy dissipation for the perforated sill with a porosity ratio of 50% is greater than 60% for Froude numbers ranging from 4.5 to 12. The optimal spacing of the sill is important to maximize the hydraulic efficiency. The number of the sill also affects the head loss as well as the hydraulic jump for the single and double perforated sill configurations. The spacing of the two sills from the entrance of the basin is important. These findings indicate that both porosity ratio and geometric configuration (including hole shape and spacing) are critical parameters governing hydraulic performance. . The influence of perforation shape on relative scour depth under different hydraulic conditions is illustrated in Figure 5.

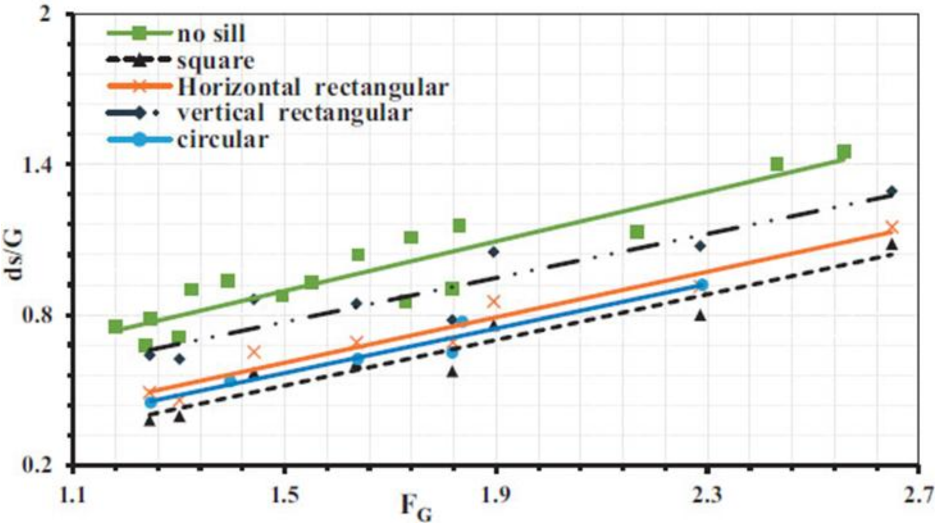


Figure 5. Effect of perforation shape on relative scour depth downstream of perforated sills under different Froude numbers.

3.5.3 Multi-Layer Screen Systems

The multi-layer porous screens provide higher dissipation of energy through cumulative resistance offered by each layer of screens.. Singh & Roy [33] investigated triple-wall perforated screens of 45% porosity per layer (circle, square, triangle) for Fr range of 3.2–19.3. The dissipation of energy is significantly higher than that of classical hydraulic jump, i.e., 74% compared to 55% at

Fr = 4, and almost 94% compared to 90% at Fr = 13. The length of the basin for triple porous baffles is almost 2.7 times sequent depth, which is comparable to USBR III but with higher dissipation of energy. The porous screens on negative slopes (−0.015, −0.025) of 50% porosity show that double screens are more effective in dissipating energy than single screens, but −0.025 is better than −0.015 [36]. The roughness elements of height 1.4 cm and 2.8 cm are effective on beds for Fr range of 5–11, which stabilize jump location, sequent depth, and length of jump compared to smooth beds [37]. These results demonstrate that multi-layer and combined configurations significantly enhance hydraulic performance through increased resistance, turbulence, and flow redistribution.

4. Comparative Performance Analysis of End Sill Geometries

The strongest empirical evidence for establishing the performance ranking of different end sill geometries is based on direct comparisons where multiple geometries are tested under the same hydraulic conditions [38]. Such comparisons provide the most reliable basis for evaluating relative performance, as they eliminate variability associated with flow conditions, sediment properties, and basin configurations. In this regard, Ref. [13] showed that triangular and sloping geometries consistently outperformed rectangular and trapezoidal geometries for Froude numbers ranging from Fr = 1.85 to 3.85, with trapezoidal geometries showing the poorest performance. This improvement is primarily attributed to the ability of sloped geometries to redirect high-velocity flow upward and outward, thereby reducing near-bed shear stresses and enhancing turbulent energy dissipation.

Further experimental studies were also performed in [38], who examined scour downstream of block ramps with continuous, dentated, and rock sills based on 300 experiments for ramp slopes ranging from 1V:4H to 1V:12H. The results showed that the presence of the sill had dominant effects on scour hole geometry. Dentated sills also showed enhanced turbulence and increased energy dissipation due to flow splitting compared to continuous sills. Additionally, the position of the sill within the basin was found to be an important variable for scour control design, depending on the Froude number and tail water depth. This indicates that hydraulic performance is not governed by geometry alone, but also by its interaction with flow conditions and basin configuration. Similarly, studies on modifications to USBR stilling basins showed that changes to the geometry of the end sill had significant effects on hydraulic jump behavior, particularly in terms of flow structure, turbulence intensity, and energy dissipation processes.

In particular, Padulano et al. [39] examined Type II basins with dentated sills and found different hydraulic jumps that vary from submerged to spray conditions depending on boundary conditions. The results obtained by these authors indicated that the coefficient of pressure fluctuation is reduced substantially in the downstream region of dentated sills. The results obtained in this study also revealed that dimensionless relationships can be developed to predict different hydraulic jumps depending on the approach Froude number and geometrical characteristics. Furthermore, the study of vertical end sills revealed that these characteristics have a significant influence on energy dissipation in hydraulic jumps and that new relationships between the height of the sill, the position of the sill, the sequent depth ratio, and the length of the basin can be developed in the presence of unpredictable tailwater conditions [12].

4.1 Hydraulic Mechanism Synthesis Across Geometries

Different end sill geometries modify flow behavior through distinct hydraulic mechanisms, which directly influence scour development and energy dissipation efficiency. Inclined and sloped sills enhance flow redirection, promoting upward deflection and reducing near-bed velocities. Perforated sills increase energy dissipation through jet interaction, turbulence generation, and velocity redistribution. Semi-circular geometries promote smooth flow transition and lateral spreading, reducing flow separation and enhancing mixing. Convex geometries redistribute flow toward channel banks, reducing centerline scour while potentially increasing side erosion. These mechanisms demonstrate that the effectiveness of each geometry is governed by its ability to control flow structure, turbulence intensity, recirculation zones, jet diffusion, and sediment entrainment processes.

4.2 Limitations and Practical Considerations

Although the reviewed studies provide strong insights into the hydraulic performance of different end sill geometries, most of the available results are derived from controlled laboratory flume experiments. Therefore, direct application of these findings to real hydraulic structures should be approached with caution. Practical considerations such as constructability, maintenance requirements, sediment clogging (particularly for perforated sills), and site-specific hydraulic conditions may significantly influence field performance.

Table 2 demonstrates that no single end sill geometry is universally optimal under all hydraulic conditions. Instead, the suitability of each configuration depends on the required hydraulic function, flow intensity, sediment characteristics, and operational constraints

Table 2. The values presented are synthesized from the cited studies and represent typical ranges under varying hydraulic and experimental conditions.

End Sill Type	**Main Performance**	**Optimal Parameters**	**Typical Fr Range**	**Flow Conditions**	**Sediment Type**	**Study Type**	**References**	**Ideal Application**	**Design Notes**
Triangular / Sloped	Scour reduction 50–95%	45–60° (Best: 60°)	2 – 10	Subcritical – supercritical transition	Uniform sand	Experimental / CFD	[13], [20], [21]	General scour control	Balances flow deflection and turbulence
Perforated / Porous	Energy dissipation 74–94%	Porosity 40–50%	4.5 – 12	High-energy turbulent flow	Fine–medium sand	Experimental / CFD	[33], [34], [35]	High-energy flows	Hole distribution affects efficiency
Convex	Centerline protection	r/w = 0.35	2 – 8	Transitional flow	Uniform sediment	Experimental / CFD	[7], [27]	Central channel protection	May increase bank scour
Concave	Bank protection	r/w = 0.23	2 – 8	Asymmetric flow conditions	Non-uniform sediment	Experimental	[7]	Side erosion control	Higher centerline scour
Semi-Circular	Scour reduction 50–78%	D ≈ 0.74h	2 – 9	Gradual flow transition	Uniform sand	Experimental / CFD	[6], [23], [24]	Capacity-limited sites	Smooth lateral spreading
Rectangular	Baseline performance	Vertical	1.8 – 4	Classical hydraulic jump	Uniform sand/gravel	Experimental	[12], [13]	USBR standard basins	Proven reliability
Curved	Energy dissipation +10.5%	Design-dependent	3 – 10	Stepped flow regimes	Mixed sediment	CFD / Experimental	[29], [31]	Stepped spillways	Delays skimming flow
Cylindrical Deflectors	Scour reduction 78%	Height ≈ 0.5z	4 – 8	Strong hydraulic jump	Coarse sediment	Experimental	[29]	Jump stabilization	Requires precise placement
Gabion Sills	Rapid bed stabilization	Lg/h = 1–1.5	2 – 6	Variable flow	Coarse material	Experimental	[32], [40]	Temporary protection	Easy installation

4.3 Interpretation of Comparative Results

It should be emphasized that the reported hydraulic performance values were not obtained under identical experimental and hydraulic conditions. Most of the reported ranges for scour reduction and energy dissipation were synthesized from studies conducted under different Froude numbers, sediment properties, tailwater depths, and basin configurations. Consequently, direct comparison among end sill geometries should be approached with caution, and greater emphasis should be placed on studies performed under comparable hydraulic conditions when establishing design recommendations.

Among the reviewed configurations, inclined and perforated end sills generally demonstrated superior hydraulic performance due to their enhanced capability to redistribute turbulent flow structures, reduce near-bed velocity concentration, and improve energy dissipation efficiency. Nevertheless, the effectiveness of these geometries remains highly dependent on geometric optimization parameters such as sill inclination angle, porosity ratio, and sill location within the stilling basin.

In contrast, convex and concave geometries primarily influence the spatial distribution of scour rather than uniformly minimizing the overall scour magnitude. Therefore, these configurations are considered more suitable for site-specific protection strategies depending on whether centerline or bank protection is required.

Overall, the reviewed studies indicate that the selection of an appropriate end sill geometry should account for hydraulic conditions, sediment characteristics, structural requirements, and operational considerations to achieve optimal hydraulic performance in practical engineering applications.

5. Computational Fluid Dynamics (CFD)

5.1 CFD Modeling and Validation

Computational Fluid Dynamics (CFD) modeling has been widely employed as a supporting tool in experimental approaches in hydraulic engineering, as it provides a clear visualization of complex flow structures, thus allowing parametric optimization at relatively low cost [41], [42]. In many hydraulic engineering problems, the Renormalization Group k-Epsilon (RNG k-ε) turbulence model coupled with the Volume of Fluid (VOF) free surface tracking method has been found to show a strong agreement with experimental results in terms of measured scour depth, velocity distribution, and energy dissipation [43], [44]. In validation studies, prediction accuracy was found to range within $R^2 = 0.82$ and 0.91, where R^2 is a statistical measure of goodness of fit, or coefficient of determination, used for assessing the agreement between predicted results and experimental results, particularly when sediment transport parameters are employed in model calibrations [44], [45]. These CFD models capture key hydraulic processes such as turbulence generation, recirculation zones, and velocity redistribution, which are essential for predicting scour development and energy dissipation in stilling basins. A summary of CFD-based studies, including turbulence models and validation metrics, is presented in Table 3.

Table 3 summarizes the main CFD studies used in this review, including turbulence models, numerical tools, and validation metrics reported in the literature.

Author	Model	Software	Validation Metric	Accuracy
Tajabadi et al. (2018)	RNG k-ε + VOF	ANSYS Fluent	Experimental comparison	Good agreement
Zaffar and Hassan (2023)	RNG k-ε	FLOW-3D	R^2	0.823
Zaffar et al. (2023)	FLOW-3D	FLOW-3D	R^2, NSE	$R^2 = 0.909$, NSE = 0.896
Fatima et al. (2024)	CFD model	FLOW-3D	Velocity validation	High accuracy
Macián-Pérez et al. (2021)	RNG k-ε + VOF	OpenFOAM	Error analysis	<5% error
Bayón-Barrachina (2015)	CFD	OpenFOAM	Experimental comparison	Good agreement

5.2 Applications in Stilling Basin Configurations

In addition, several studies have employed commercial software, FLOW-3D, for CFD computations.. Fatima et al. [51] carried out a simulation of USBR Type III stilling basins with wall convergence using CFD software FLOW-3D. The results revealed that wall convergence improves hydraulic jump efficiency, with maximum efficiency achieved when the convergence angle is 2.5 degrees. In addition, velocity analysis revealed a velocity decrease from 57 m/s, as observed in the chute, to 6 m/s near the sill, with the position of the sill playing a crucial role in efficiency improvement.

Similarly, Soori et al. [46] carried out a simulation of a USBR II stilling basin with an adverse end slope using numerical modeling of flow characteristics in stilling basins. The results revealed that replacing the end sill with adverse slope steps, with two, three, or four steps, enhances efficiency as well as jump stability, with the optimal configuration consisting of chute blocks with heights of 1 and 1.5 times the standard height, combined with three adverse steps.

This is a numerical simulation technique that is commonly used for modeling free-surface flow in hydraulic structures. For example, The authors in [41], [42], [43], [44], [45], [47] carried out numerical simulations of various stilling basin designs before and after remodeling of the structure.

The initial study focused on comparing friction blocks, also referred to as baffle blocks that are constructed of concrete and placed on the floor of the stilling basin, with chute blocks and modified end sills. The study established that the best numerical result was obtained using the RNG k-ε turbulence model, which provided good numerical accuracy in comparison to experimental data with a determination coefficient of $R^2 = 0.823$. The remodeled stilling basin with an end sill had a net sediment variation of between 88-95%, whereas the original design had a variation of 51%.

5.3 Performance Evaluation and Comparative Analysis

Further, several numerical analyses were carried out for different stilling basin configurations, such as USBR Type II, USBR Type III with chute blocks and end sills, and WSBB configuration (Wall Supported Baffle Blocks) [43], [44], [45], [47]. From these analyses, it was observed that chute blocks with dentated end sills had lower energy dissipation compared with impact baffle blocks, resulting in apron washout. Numerical validation confirmed that CFD results were in close agreement with experimental results, as evidenced by R^2 and NSE, where $R^2 = 0.9094$ and NSE = 0.896, with NSE being a hydrological performance index for evaluating model accuracy. At design discharge conditions, conventional end sills had complete sediment exposure, while WSBB had lower bed shear stress with lower scour development. In addition, experimental and numerical studies on T-shaped blocks for energy dissipation in Type III stilling basins were carried out, resulting in higher dissipation ratios, with results from FLOW-3D being consistent with experimental results [42].

5.4 Open-Source Modeling and Validation

Open-source CFD software has also ensured that reliable alternatives exist for commercial software in simulating hydraulic parameters in stilling basins. For example, Macián-Pérez et al. [46] used numerical models based on OpenFOAM, an open-source CFD software, along with the RNG k-ε turbulence model and VOF for simulating free surface flows in order to analyze the hydraulic parameters in modified USBR Type II stilling basins. The results from these numerical models were found to be accurate in predicting hydraulic parameters, such as sequent depth with an error of less than 5%, roller length with an underestimation of about 6%, and hydraulic jump efficiency. This ensured that basin appurtenances, such as end sills, play a significant role in stabilizing hydraulic jumps and enhancing their efficiency in energy dissipation. The results were further validated in [45], who used CFD models in order to analyze hydraulic parameters, such as roller length within an estimation of about 6%, as well as hydraulic jump efficiency, in order to ensure a validated framework for analyzing complex stilling basin geometries.

5.5 Model Limitations and Applicability

However, the accuracy of CFD simulations is strongly dependent on turbulence model selection, boundary conditions, and sediment transport formulations. Therefore, model performance may vary across different hydraulic configurations, and caution should be exercised when generalizing CFD results for design purposes. Although CFD provides detailed insight into flow behavior and hydraulic performance, its reliability depends on proper calibration and validation against experimental data.

6. Recent Advances and Machine Learning (2022–2025)

Recent studies have increasingly integrated machine learning techniques with conventional hydraulic modeling approaches to improve the prediction accuracy of scour behavior and energy dissipation characteristics [19], [48]. Compared with traditional empirical equations, machine learning models have demonstrated superior capability in capturing complex nonlinear relationships between hydraulic and sediment transport parameters.

Chooplou et al. [48] conducted an experimental investigation on Piano Key Weirs (PKW) equipped with baffles in combination with Multi-Layer Perceptron (MLP) neural network modeling. The experimental results showed that the incorporation of baffles increased energy dissipation by 18–22%, while reducing scour depth by 11–14%, scour area by 26.7–31.6%, and scour volume by 30.3–32.2%.

The developed MLP model achieved a prediction accuracy of $R^2 = 0.988$ for scour estimation, indicating a strong capability to model complex hydraulic interactions that are difficult to represent using conventional regression approaches. In addition, soft computing techniques such as Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have shown promising performance in predicting scour geometry and bed sill behavior with limited experimental datasets [19]. Table 4 summarizes recent machine learning applications and their reported prediction accuracy in scour-related hydraulic studies.

Table 4 summarizes recent applications of machine learning models used for scour prediction and their reported accuracy in the literature.

Author	Model	Application	Output	Accuracy
Chooplou et al. (2024)	MLP	Scour prediction in PKW	Depth, area, volume	$R^2 = 0.988$
Aminpour et al. (2017)	Neural Network	Scour modeling	Scour depth	High accuracy
Keshavarzi et al. (2012)	ANFIS	3D scour prediction	Scour geometry	Strong correlation

7. Discussion: Design Selection Framework

7.1 Critical Performance Evaluation and Comparative Analysis

This section provides a critical analysis of the reviewed studies by comparing the hydraulic performance, advantages, limitations, and practical applicability of different end sill geometries.

The synthesis of the reviewed literature indicates that the performance of end sill geometries is primarily controlled by their ability to modify flow structure, turbulence intensity, and sediment transport mechanisms. However, the reported performance ranges are derived from studies conducted under different hydraulic conditions, including variations in Froude number, sediment characteristics, and basin configurations. Therefore, the comparison between geometries should be interpreted with caution, particularly when results are obtained under non-identical conditions, and design decisions should prioritize studies conducted under consistent hydraulic scenarios.

Inclined (sloped) end sills exhibit the most consistent and balanced hydraulic performance among all configurations. Their main advantage lies in their ability to redirect high-velocity flow upward and outward, reducing near-bed velocities and shear stress while enhancing turbulence. This results in significant scour reduction ranging from 50% to 95% for inclination angles between 45° and 60°. In addition to their hydraulic efficiency, inclined sills are relatively simple to construct, making them suitable for practical engineering applications. However, their performance remains sensitive to the selected inclination angle and may vary under different tailwater conditions.

Perforated end sills provide the highest energy dissipation efficiency, with reported values ranging from 74% to 94%. Their effectiveness is attributed to complex hydraulic mechanisms, including jet interaction, flow contraction and expansion through perforations, and turbulence generation. Despite these advantages, their practical application may be limited by maintenance requirements and the risk of sediment clogging, particularly in sediment-laden flows, which may reduce long-term efficiency.

Semi-circular geometries offer moderate hydraulic performance, mainly through smooth flow transition and lateral spreading. Their advantage lies in reducing flow separation and improving flow stability. However, their scour reduction efficiency is generally lower compared to inclined and perforated geometries, especially under high-energy flow conditions, which limits their use in extreme hydraulic scenarios.

Convex and concave geometries influence the spatial distribution of scour rather than reducing its overall magnitude. Convex sills are effective in protecting the channel centerline by deflecting flow toward the banks, whereas concave geometries provide enhanced protection for channel banks but may increase scour depth at the centerline. These configurations are therefore more suitable for site-specific design applications rather than general-purpose use, particularly in channels where erosion patterns are non-uniform.

Rectangular end sills, although widely used in standard hydraulic structures such as USBR stilling basins, show comparatively lower hydraulic performance. Their main advantages are structural simplicity, ease of construction, and well-established design guidelines. However, from a hydraulic efficiency perspective, they are generally less effective than modified geometries, particularly under high-energy flow conditions.

7.2 Design Considerations and Practical Applicability

The selection of an appropriate end sill geometry should consider not only hydraulic performance but also practical design constraints and operational conditions.

Inclined sills represent the most practical and balanced solution for general applications due to their high efficiency, predictable behavior, and ease of implementation. Perforated sills are more suitable for high-energy flows where maximum energy dissipation is required; however, their use should account for maintenance challenges and clogging risks, particularly in sediment-rich environments. Semi-circular geometries are suitable for applications requiring smooth flow transition and integration with existing structures. Convex and concave geometries are recommended for targeted protection, depending on whether centerline or bank erosion is dominant, highlighting their importance in site-specific hydraulic design.

It is important to emphasize that most of the reviewed results are based on laboratory experiments. Therefore, direct application of these findings to real hydraulic structures should consider additional factors such as constructability, maintenance requirements, sediment clogging, and site-specific hydraulic conditions.

7.2.1 Engineering Design Recommendations

Based on the reviewed literature, inclined end sills with inclination angles ranging from 45° to 60° are generally recommended as the most effective configuration for overall scour mitigation under a broad range of hydraulic conditions. Perforated end sills are recommended for high-energy flows where maximum energy dissipation is required, provided that maintenance and sediment clogging issues can be properly managed.

Convex geometries are preferable for protecting the channel centerline, whereas concave configurations are more suitable for mitigating bank erosion. Semi-circular geometries may be adopted in applications requiring smoother flow transition and improved hydraulic stability.

Accordingly, the selection of end sill geometry should be based on flow intensity, sediment characteristics, tailwater conditions, structural requirements, and operational constraints rather than adopting a single universal design configuration.

7.3 Research Gaps and Future Directions

Despite extensive research, several important gaps remain that limit the direct applicability of current findings. High-priority gaps include the lack of field validation and the limited understanding of interactions between multiple energy dissipation components. These aspects are critical for real-world applications, where hydraulic structures operate under complex and variable conditions.

Medium-priority gaps include the simplified representation of sediment conditions in laboratory studies. Natural riverbeds consist of heterogeneous and cohesive sediments that significantly affect scour behavior and are not adequately represented in many experiments. Future research should also address the potential impacts of climate change, particularly the effect of extreme discharge events on the performance of end sill geometries and the reliability of existing design relationships. A structured summary of research gaps and future research directions is presented in Table 5. To facilitate practical interpretation of the reviewed findings, the dominant hydraulic behavior, engineering applicability, and major limitations of the investigated end sill geometries are summarized in Table 6, which summarizes the dominant hydraulic effects, best-use conditions, and limitations associated with the reviewed end sill geometries. The figure highlights that the hydraulic performance of each configuration depends on both flow conditions and practical engineering requirements.

Table 5 summarizes the main research gaps identified in the literature along with their importance and potential impact on hydraulic design.

Research Gap	Importance	Feasibility	Impact on Design
Lack of field validation	High	Medium	Improves reliability of design guidelines
Simplified sediment conditions	High	High	Enhances prediction accuracy
Interaction of dissipators	High	Medium	Critical for real stilling basin design
Climate change effects	Medium	Low	Important for future hydraulic safety
Long-term scour evolution	High	Medium	Essential for structural stability

Table 6 summarizes of hydraulic effects, best-use conditions, and limitations of different end sill geometries.

Geometry Type	Dominant Hydraulic Effect	Best-Use Condition	Main Limitation
Inclined (Sloped)	Flow deflection and turbulence redistribution	General scour reduction	Sensitive to angle selection
Perforated	High turbulence and jet dissipation	High-energy flow conditions	Sediment clogging
Convex	Lateral flow redistribution	Centerline protection	Possible bank erosion
Concave	Bank protection	Channels with bank scour	Increased centerline scour
Semi-circular	Smooth flow transition	Moderate hydraulic conditions	Moderate efficiency
Rectangular	Stable hydraulic control	Conventional stilling basins	Lower hydraulic efficiency

8. Conclusion

This review synthesized the findings of 52 peer-reviewed studies published between 2000 and 2025 to provide a structured evaluation of the hydraulic performance of different end sill geometries under varying flow conditions and protection requirements. The reviewed literature demonstrates that inclined and sloped end sills with inclination angles ranging between 45° and 60° represent highly effective general-purpose configurations for scour mitigation, with reported scour reduction efficiencies ranging from 50% to 95%. Among the investigated configurations, the 60° inclined sill exhibited the most balanced hydraulic behavior in terms of flow deflection, turbulence redistribution, and energy dissipation efficiency. For hydraulic conditions requiring maximum energy dissipation, perforated end sill geometries with porosity ratios between 40% and 50% showed the highest hydraulic efficiency, achieving energy dissipation rates ranging from 74% to 94%, occasionally exceeding those associated with conventional hydraulic jumps under comparable flow conditions. In addition, convex geometries were found to provide effective centerline protection through lateral flow redistribution, whereas concave geometries demonstrated improved resistance against bank erosion. Semi-circular geometries promoted smoother flow transition and enhanced flow spreading, resulting in moderate to high scour reduction performance. Recent developments in computational fluid dynamics (CFD) and numerical modeling have significantly enhanced the capability to investigate complex hydraulic behavior and optimize stilling basin configurations. Advanced turbulence models generally demonstrated good agreement with experimental observations; however, the reliability of CFD predictions remains strongly dependent on model calibration, boundary conditions, and sediment transport formulations. Overall, the reviewed studies confirm that no single end sill geometry can be considered universally optimal under all hydraulic conditions. Consequently, the selection of end sill configurations should be based on an integrated assessment of hydraulic performance, sediment characteristics, structural requirements, operational conditions, and long-term stability considerations. Future progress in experimental investigations, CFD simulations, and data-driven prediction techniques is expected to further improve the reliability and adaptability of scour mitigation design in hydro.

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