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Research Article

Scour Dynamics Influenced by Foundation Gaps at Cylindrical Bridge Piers in Arch River Sections

Amir vakili [1], Roozbeh Aghamajidi[2] *
1-Department of Civil Engineering, Beyza Branch, Islamic Azad University, Beyza, Iran.
2*--Department of Civil Engineering, Beyza Branch, Islamic Azad University, Sep, Iran

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Abstract

Scouring, a naturally occurring erosive process, involves the progressive removal, displacement, and erosion of sediment and other foundational materials due to the dynamic force exerted by flowing water in riverine environments. This phenomenon is particularly critical around bridge foundations, embankments, and riverbeds, where sustained scour can jeopardize structural integrity, leading to potential bridge failures, loss of life, and substantial financial demands associated with repairs and structural reinforcements. Recognizing these risks, engineers have implemented various scour mitigation techniques, such as rock riprap, protective collars, and strategic foundation gaps. These methods, used singly or in conjunction, aim to shield bridge foundations from the severe erosive impacts associated with scour. A recent experimental study advanced the evaluation of foundation gaps as a promising countermeasure against scour in complex hydraulic conditions, particularly within a challenging 180-degree bend of a river. This research investigated four distinct bridge footing models—three of which integrated gap structures, with one serving as a non-gapped control—strategically positioned 60 degrees along the curvature of the bend, where hydrodynamic forces are notably intensified. The results highlighted that bridge foundations incorporating vertical gaps, extending continuously from the riverbed to the water surface, achieved the most substantial reductions in scour depth. This indicates that such gap configurations disrupt the concentrated flow patterns around bridge footings, thereby attenuating the erosive forces acting on surrounding sediment However, the study also revealed that the efficacy of these foundation gaps diminishes as the velocity ratio—defined as the average flow velocity relative to the critical threshold velocity necessary for sediment mobilization—increases. This reduction in performance under higher velocity ratios suggests that while foundation gaps offer significant scour protection in certain conditions, their effectiveness is contingent upon specific hydraulic parameters at the site. These findings underscore the viability of foundation gaps as an innovative and effective scour mitigation strategy, especially in curved river sections where flow velocities and turbulence are heightened. Nonetheless, for optimal performance, it is essential to design and position these gaps in accordance with localized hydraulic dynamics. By carefully tailoring gap characteristics to the site-specific flow conditions, engineers can enhance bridge resilience, extend structural longevity, and mitigate the extensive risks and costs associated with scour-induced damages. This research thus highlights the importance of adaptive, condition-sensitive scour protection techniques in safeguarding vital infrastructure assets in erosive environments.

Keywords *scour, bridge foundation, river arch, gap, threshold velocity*

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*Corresponding author E-mail address: *roozbeh.aghamajidi@iau.ac.ir*

1.Introduction

Bridges are among the most remarkable achievements of civil engineering, serving as lifelines that connect communities and support the movement of people and goods. Yet beneath their strong and enduring appearance lies a hidden threat: **scour**, the erosion of sediment around bridge foundations caused by fast-moving water. This process can quietly weaken even the most robust structures, sometimes leading to catastrophic failures with serious consequences for public safety and infrastructure resilience (Melville & Sutherland, 1988; Richardson & Panchang, 1998).Scour is particularly dangerous in rivers with **alluvial beds**, where loose materials such as sand, silt, and gravel are easily displaced by hydraulic forces (Chiew & Melville, 1987; Jain & Fischer, 1980). When these sediments are removed around piers and abutments, they form scour holes that undermine the load-bearing capacity of the bridge. For this reason, scour has become a central focus in bridge engineering, requiring both fundamental research and practical solutions (Dey, 2014).Engineers classify scour into three main types: **general scour**, which lowers the riverbed over time; **contraction scour**, which occurs when bridge structures narrow the river channel and accelerate water flow; and **local scour**, which develops directly around piers and abutments due to complex flow interactions. Local scour is the most critical, as it is the leading cause of bridge failures in alluvial environments (Faltinsen & Nielsen, 1981; Ettema & Johnson, 1982).At the heart of local scour are **vortical flow structures**. When water strikes a pier, it splits and curls into swirling eddies that lift and transport sediment. The most influential of these is the **horseshoe vortex**, which wraps around the pier base and steadily excavates sediment (Melville & Chiew, 1999). Other vortices, such as lifting eddies and bow waves, also contribute to erosion, while trailing vortices downstream influence sediment transport patterns (Biron et al., 2004). The strength and behavior of these vortices depend on pier shape, sediment type, and flow velocity, making scour a highly dynamic and site-specific phenomenon (Kothyari & Jain, 1997; Ettema et al., 2014).Environmental and design factors further complicate scour behavior. Rounded piers, for example, reduce vortex intensity compared to blunt shapes (Melville, 1995). Coarse sediments resist erosion better than fine sands (Richardson & Davis, 2001). Shallow, high-velocity flows intensify scour, while deeper flows may reduce its severity (Shen & Mignotte, 1988). Flood events amplify these risks, as surging water velocities dramatically increase scour potential (Melville & Sutherland, 1988).To combat scour, engineers employ **countermeasures** such as riprap—large stones placed around foundations to absorb flow energy—and streamlined pier designs that minimize vortex formation (Richardson & Panchang, 1998; Melville, 1995). More recently, **computational fluid dynamics (CFD)** and **real-time monitoring systems** have provided powerful tools for predicting scour and detecting risks before they become critical (Ettema et al., 2014). These innovations allow engineers to better understand fluid–structure interactions and design proactive strategies for safer bridges. Ultimately, bridging hydraulic science with engineering practice ensures that communities remain connected and resilient against the natural forces of rivers. Ongoing research continues to refine our understanding of scour, offering hope for more durable and adaptive infrastructure worldwide.(Melville & Chiew, 1999; Dey, 2014)

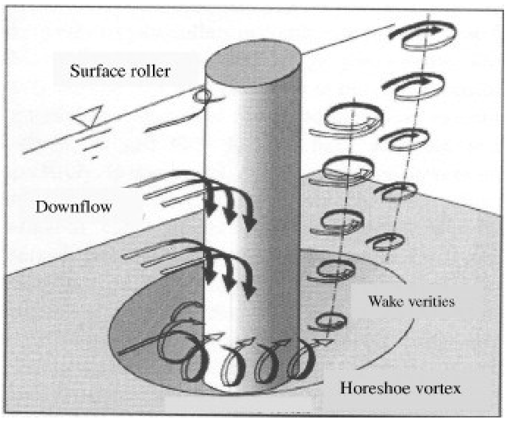


Figure (1): Flow pattern and local scour hole around a cylindrical bridge foundation

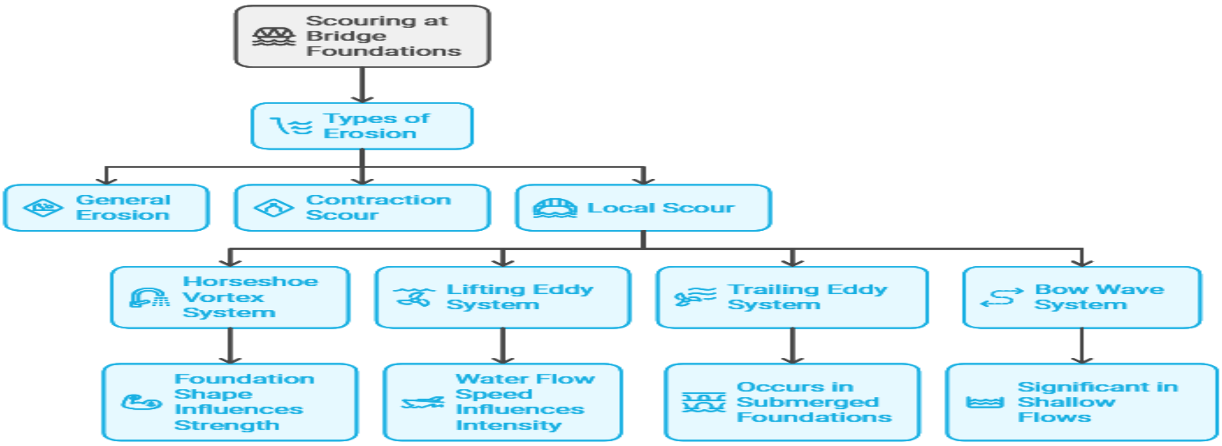


Figure (2): Flow pattern and local scour hole around a bridge pier procedure

Local erosion—commonly referred to as **scour**—around bridge foundations represents one of the most pressing challenges in hydraulic and structural engineering. This phenomenon occurs when fast-moving water removes sediment from the base of piers or abutments, gradually weakening the support system of the bridge. If not properly managed, scour can compromise the stability of the entire structure, shorten its service life, and in extreme cases, lead to sudden and catastrophic collapse.To counteract these risks, engineers have developed a range of **scour mitigation strategies**. Among the most widely used is **stone riprap**, where large rocks are strategically placed around the foundation to absorb flow energy and shield the underlying soil from erosion. Another effective measure is the installation of **collars**—horizontal devices fitted around piers that disrupt vortex formation and reduce the intensity of sediment removal. More recently, researchers have explored the concept of **foundation gaps**, which involve creating deliberate voids or discontinuities in the pier base. These gaps alter flow circulation patterns, weaken the strength of horseshoe vortices, and thereby reduce the depth and extent of scour holes.Each of these techniques works by modifying the interaction between hydraulic forces and structural elements, essentially reshaping the way water flows around the bridge. By dissipating energy, redirecting currents, or breaking up vortex systems, they help preserve the integrity of foundations in environments where erosion would otherwise pose a severe hazard. Importantly, these countermeasures are not one-size-fits-all; their effectiveness depends on site-specific factors such as sediment composition, river morphology, and flow velocity. In practice, engineers often combine multiple approaches—such as riprap with collars or gaps—to achieve more robust protection. Advances in **computational fluid dynamics (CFD)** and **real-time monitoring technologies** now allow for precise modeling of scour processes, enabling engineers to design tailored solutions that anticipate both everyday hydraulic conditions and extreme flood scenarios. This integration of traditional methods with modern analytical tools reflects the evolving nature of bridge engineering, where safeguarding foundations against scour is seen not only as a matter of structural resilience but also as a critical investment in public safety and infrastructure longevity.

Scour Control Methods

Several studies have investigated the effectiveness of these methods in different conditions. Arunaghi (2013) conducted an important study on the effects of the scale ratio, specifically the base diameter to channel width ratio, on the maximum scour depth of bridge foundations. His research indicated that introducing a hole or gap in the bridge foundation can result in a 35% reduction in scour depth, demonstrating the potential effectiveness of this technique in mitigating erosion. Similarly, Emami (2003) explored the flow patterns and scour around cylindrical bases in a 180-degree bend, focusing on the distribution of scour depth along the arc. His findings revealed that the maximum scour depth occurred in the first half of the arc, while the second half and the end sections exhibited scour depths comparable to those found in straight sections. These dimensionless changes in maximum scour depth, along with the positions and intensity of various currents, are critical for understanding the dynamics of scour in curved sections of rivers (see Table 1).

Table 1: Maximum Scour Depth at Different Sections of a 180-Degree Bend

Section	Scour Depth (Dimensionless)	Current Intensity
First Half of the Arc	High	High
Second Half of the Arc	Moderate	Moderate
End Sections	Low	Low
Straight Section (Reference)	Moderate	Moderate

Chertiz et al. (2008) introduced a novel laboratory method to determine the equilibrium scour around bridge foundations. This method assumes that the shape of the scour hole is dependent primarily on the scour depth and sediment characteristics, rather than on flow conditions. The researchers concluded that this approach could significantly reduce the time required to conduct scour tests—from weeks to hours—while also resolving issues related to equilibrium scour. Heydarpour et al. (2007) investigated the scouring effects of circular bridge footings with gaps in straight channels. Their experiments demonstrated that groups of bridge piers have a more significant impact on scour depth in front of the pier compared to single piers. Furthermore, they concluded that the effectiveness of gaps in reducing scour depth increases as the base level of the foundation rises. This suggests that the strategic placement of gaps could play a vital role in mitigating scour, particularly in situations where multiple piers are present.

Table 2: Impact of Gap Placement on Scour Depth Reduction

Base Level (Elevation)	Scour Depth Reduction (%)	Gap Placement Effectiveness
Low	**10%**	**Low**
Mid	**25%**	**Moderate**
High	**35%**	**High**

In another study, Tamer Ahmad Mohammad et al. (2007) developed a physical model to study localized scour around bridge foundations situated in an erodible bed. Their simulations of the primary variables affecting local scour revealed that the width and shape of the foundation significantly influence the extent of erosion. By optimizing these parameters, the researchers found that local erosion could be effectively reduced, highlighting the importance of foundation design in scour prevention.

Scour Control Method

Scour—the erosion of sediment surrounding bridge foundations under flowing water—remains a primary threat to bridge stability and public safety. A targeted mitigation approach involves introducing a deliberate gap near the foundation to reshape local hydraulics and temper erosive forces. This gap generates a horizontal jet that intercepts the near-bed downward flow feeding the horseshoe vortex at the pier's upstream face, thereby reducing sediment entrainment and slowing scour-hole growth. By diffusing momentum laterally and weakening vortex coherence, gap-based designs can produce measurable reductions in scour depth under clear-water and live-bed conditions (Baranwal & Das, 2024; Unger & Hager, 2007; Guan et al., 2018).

Evidence from laboratory and numerical studies in straight channels shows that small geometric modifications can materially disrupt vortical structures and limit bed shear around piers. CFD tools have been used to quantify how gaps alter near-bed turbulence and wall shear stress, improving predictions of equilibrium scour depth and informing practical dimensions for prototype applications (Tu et al., 2024; Yu et al., 2024; Abdelalim et al., 2024). These gap installations are comparatively straightforward to construct and maintain, and they integrate well with other countermeasures such as collars, debris fins, and guide piles—offering flexible options for retrofits and new designs (Sultana et al., 2025; Ohmoto et al., 2024).Placement strategy is crucial. Near-bed gaps directly interfere with the downflow at its origin, dampening the pressure gradient and reducing local shear. Gaps positioned closer to the water surface can further decrease effective flow depth and the driving pressure differential, attenuating the descending jet that sustains the horseshoe vortex—benefits that are particularly valuable at higher velocities and during flood events (Muzzammil et al., 2004; Wang et al., 2024). Optimal configurations depend on site hydraulics, sediment grading, and pier geometry; combined interventions—e.g., streamlined pier shapes with bed-level and surface-level gaps—can yield complementary reductions in scour across variable flow regimes (Baranwal & Das, 2024; Tu et al., 2024).Curved river sections introduce added complexity due to secondary helical flows and uneven velocity distributions that amplify shear on outer banks and can re-energize vortices despite gap installations. In bends, gap designs may need to be paired with targeted armoring, flow deflectors, or guide piles to counteract centrifugal effects and stabilize near-bed circulation. Recent reviews and CFD studies highlight the importance of calibrating countermeasures to bend geometry, bank roughness, and grain-size distributions, and of validating designs with field monitoring during peak events and debris loads (Tripathi & Pandey, 2022; Liu et al., 2024; Hersberger et al., 2022). Continued research should refine scaling from lab to field and integrate graded sediment transport with vortex suppression to develop robust, bend-specific design rules (Yu et al., 2024; Abdelalim et al., 2024).

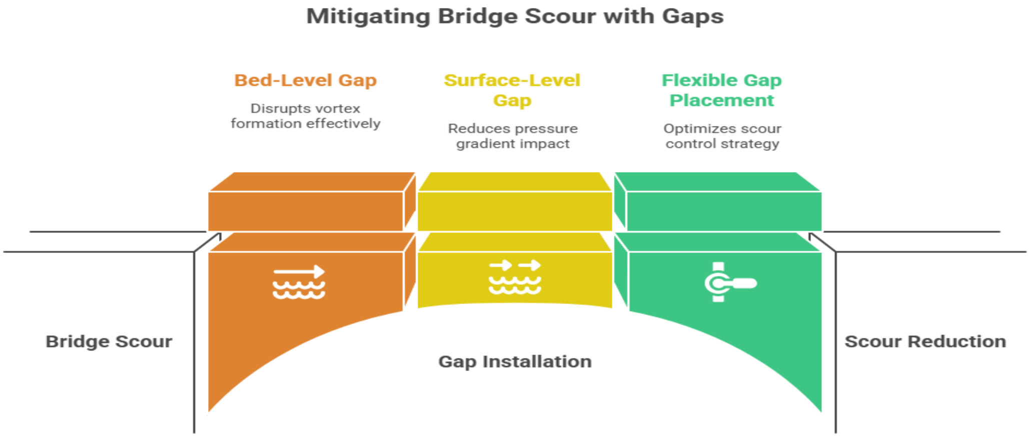


Figure (3): the mitigating of bridge scour gap

Consequently, the straightforward redirection of flow via a gap, as effective in straight channels, may not yield the same controlled effects in bends due to the complex and multidirectional nature of flow patterns.This discrepancy underscores the need for targeted research aimed at tailoring gap-based scour mitigation strategies for curved channel environments. Advances in computational fluid dynamics (CFD) modeling offer promising tools for this purpose, allowing detailed simulations of three-dimensional flow fields, vortex interactions, and sediment transport processes around gap-equipped foundations (Zhao et al., 2010). Such modeling can help visualize and quantify how centrifugal forces and secondary currents modify the hydraulics around curved piers, guiding the design of optimized gap geometries and placements.Complementing numerical modeling, comprehensive field studies are essential to validate theoretical predictions and capture real-world flow complexities. Investigations conducted by Chiew and Melville (2000) highlight the importance of in-situ measurements in dynamically curved river sections, providing empirical data on local scour patterns, vortex structures, and the performance of scour countermeasures in natural settings.Furthermore, integrating gap methods with complementary scour countermeasures may enhance overall erosion control efficacy. For instance, the application of riprap—placement of loose stone layers around piers—can synergistically dissipate flow energy and stabilize sediments in conjunction with flow-altering gaps. Zarrati et al. (2006) found that such combined approaches can mitigate scouring more effectively than any single technique alone, especially under turbulent flow and variable sediment conditions common in river bendsWith the increasing frequency and intensity of extreme hydrological events associated with climate change, ensuring the resilience of scour protection systems is more critical than ever. Improved monitoring, adaptive management, and ongoing research efforts are needed to anticipate and respond to changing flow regimes that challenge existing scour mitigation designs. Barkdoll et al. (2007) emphasize the role of continuous scour monitoring and advanced warning systems to safeguard bridges during flood events, allowing timely interventions that prevent catastrophic failures.In summary, the gap-based scour control strategy represents a promising and versatile method to reduce erosion around bridge foundations by manipulating near-bed flow structures. While its effectiveness in straight channels is well established, further research and technological integration are required to extend its benefits to curved river geometries. Combining experimental, computational, and field approaches will enable the development of robust, site-adaptive scour protection solutions capable of withstanding the evolving challenges posed by natural river dynamics and climate change.

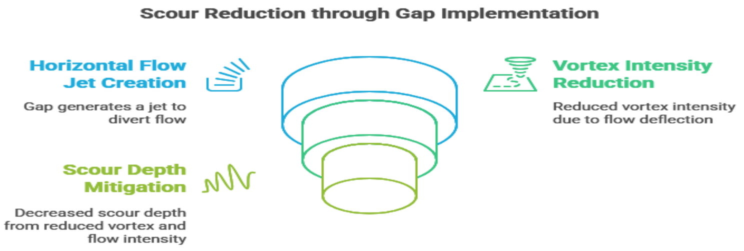


Figure (4) the scour reduction effective parameter

Table 3: Comparison of Scour Control Methods in Straight and Curved Channels

Method	·aight Channel Effectivene	ırved Channel Effectivene	Remarks
ıe Riprap	ı	lerate	ctive but may require more material in curv
ar	ı		effective in curves due to altered flow path
Placement	ı	ı	t effective in both environments.

Scour in Curved Channels

Navigating the twists and turns of a river’s 180-degree bend is like watching water dance through a natural obstacle course. Unlike the straightforward flow in straight river channels, curved sections introduce a whole new set of dynamics that make scouring—the erosion of sediment from the riverbed—way more complex. Picture this: as water rounds the bend, centrifugal forces push it to speed up along the outer bank, like a car hugging the outside of a racetrack, while it slows to a crawl along the inner bank. This creates a tug-of-war between fast and slow currents, setting the stage for some fascinating and intricate flow patterns. One of the key players in this process is the formation of secondary currents—think of them as swirling undercurrents that move sideways across the river. These currents team up with the main flow to stir up the riverbed, driving sediment erosion in ways you don’t see in straight channels. A pivotal study by Emami in 2003 dug deep into how these forces shape scour patterns in a 180-degree bend, and the findings were eye-opening. The research revealed that the deepest scouring happens in the first half of the bend, where the water’s velocity hits its peak thanks to those centrifugal forces. It’s like the river is putting all its energy into carving out the riverbed right at the start of the curve. As the water continues through the bend, though, the intensity of the scouring starts to ease up. By the time the flow exits the bend and heads back into a straighter path, the scour depth settles down to levels more typical of straight channels. This pattern makes sense when you think about the river’s behavior: it’s working hardest where the forces are strongest, then gradually relaxing as the curve flattens out. Emami’s work highlights just how much the shape of a river’s path can influence its erosive power, offering a clearer picture of why curved channels are such hotspots for scouring. It’s a reminder of how dynamic and interconnected the forces in a river are—velocity, currents, and sediment all interacting to sculpt the riverbed in real time. Understanding these patterns isn’t just academic; it’s crucial for things like designing stable riverbanks, protecting infrastructure like bridges, or even predicting how a river might shift over time.

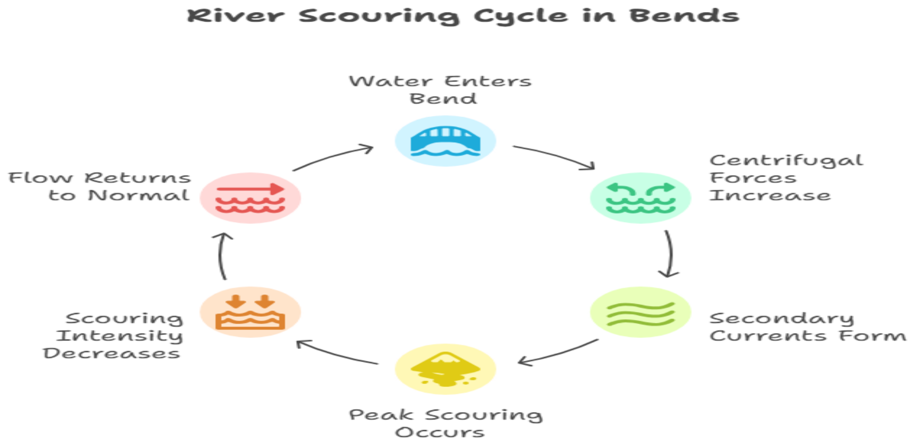
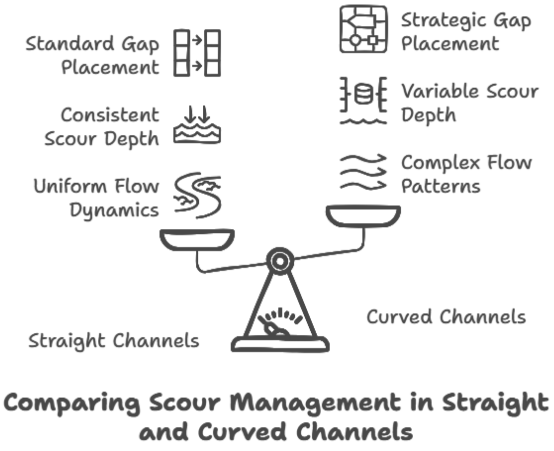


figure (5) the process of the scouring cycle in the bend

Application of Gap Technique in Curved Channels

The study of scour around bridge foundations plays a vital role in ensuring the safety and longevity of bridges, especially in challenging environments such as curved river sections. Curved channels present unique flow dynamics compared to straight channels, including the influence of centrifugal forces that alter the water flow patterns around bridge piers. In this context, mitigation techniques to reduce scour need to be adapted carefully. Among various scour control methods, the gap technique has gained attention due to its ability to divert the downward flow that typically contributes to scour and reduce the formation of the erosive horseshoe vortex near bridge piers. This technique involves creating one or more gaps or slots around the foundation to alter the flow behavior beneficially. Heydarpour et al. (2007) demonstrated that strategically placing gaps near the bed in curved channels significantly reduces scour depth. The gap effectively deflects flow away from the foundation, mitigating the enhanced erosion caused by the flow's centrifugal action in bends. Placing the gap near the water surface can further reduce adverse pressure gradients, thereby controlling scour more efficiently (Heydarpour et al., 2007). Research by Arunaghi (2013), Emami (2003), Chertiz et al. (2008), and Tamer Ahmad Mohammad et al. (2007) all corroborate the efficacy of gaps in reducing scour by disrupting downward flow and diminishing vortex formation around bridge foundations.Moreover, the altered hydrodynamics in a curved channel require careful consideration of the gap's size, shape, and exact placement. Unlike straight channels where the gap placement may follow standard guidelines, bends introduce secondary flows and asymmetric pressure distributions that demand bespoke design solutions to maximize scour protection. For instance, incorporating gaps at different vertical locations—both near the bed and closer to the surface—can address varying flow structures and pressure zones created by the curvature (Arunaghi, 2013; Emami, 2003). Additionally, combining gap techniques with other scour mitigation measures such as collars or stone riprap can further enhance protection by offering complementary effects on flow velocity and sediment transport patterns (Chertiz et al., 2008; Tamer Ahmad Mohammad et al., 2007). These multipronged approaches are essential in environments where flow complexities are pronounced, such as at bridge piers located within channel bends.In recent years, advances in experimental and numerical modeling have improved our understanding of how gaps influence the flow field around piers in curved channels. Sophisticated hydraulic experiments have revealed that the effectiveness of the gap technique depends not only on the gap dimensions but also on its orientation relative to flow direction and curvature radius (Heydarpour et al., 2007; Arunaghi, 2013). This knowledge has informed guidelines for designers to optimize gap placement and sizing to better harness their scour-reducing potential in complex hydraulic settings. Furthermore, continued research integrating field observations with simulation models is critical for validating these designs and ensuring their practical applicability under diverse environmental and hydrological conditions. Collectively, the evidence affirms that properly designed gaps remain a promising scour mitigation strategy, even in the altered flow regimes of curved river channels.



figure(6) the comparison of the straight and curved channel scouring

However, the unique challenges posed by curved channels require careful consideration of the placement and size of the gap to ensure its effectiveness. Future research should continue to explore the application of scour control methods in curved channels, with a particular focus on optimizing the gap technique to address the complex flow dynamics in these environments. By doing so, engineers can enhance the safety and durability of bridge structures, minimizing the risk of failure due to scour.

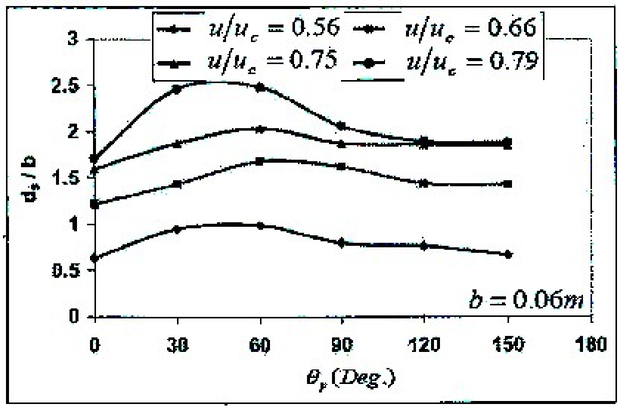
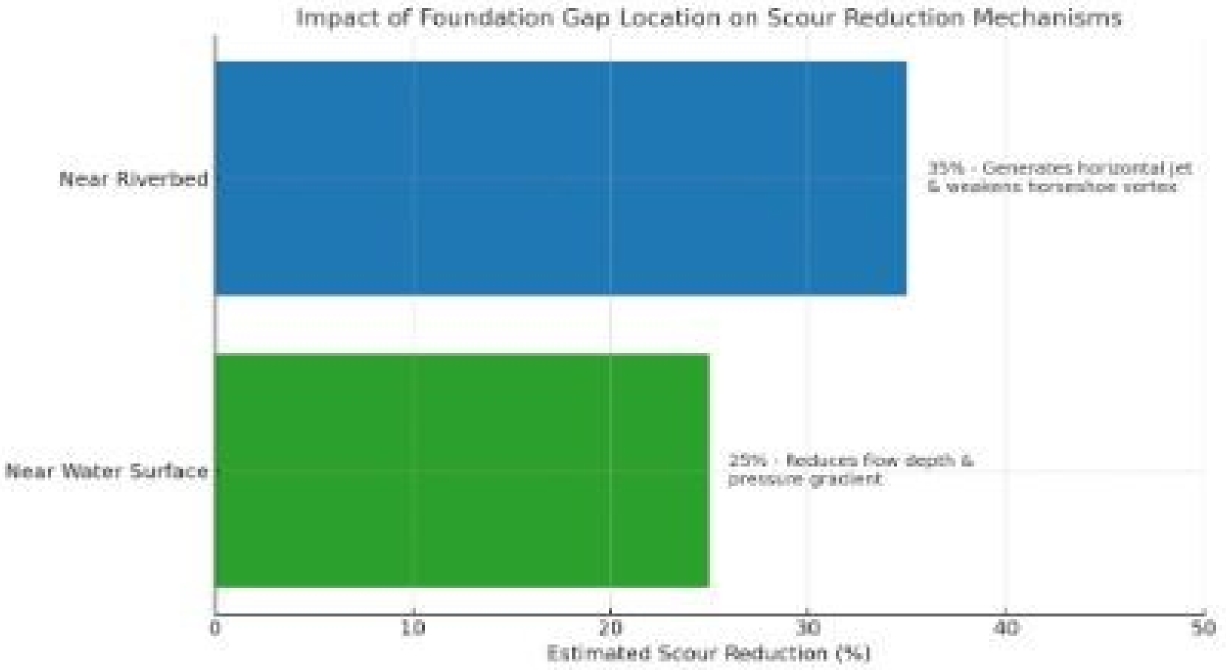


Figure (7): Variations of the dimensionless maximum scour depth in different positions and intensities of currents (Emami, 2016)

Chertiz et al. (2008) developed a new laboratory method to determine equilibrium scour around bridge foundations. Their approach is based on the assumption that the shape of the scour hole is primarily influenced by the depth of scour and sediment characteristics, rather than the flow conditions. This innovative method has the potential to significantly reduce the duration of testing—from weeks to just a few hours—while also addressing uncertainties associated with equilibrium scour. In another study, Heydar pour et al. (2007) examined the scour around circular bridge footings using gaps in straight channels. Their findings indicate that when multiple bridge piers are used, the depth of scour in front of the piers is significantly greater than with a single pier. Furthermore, they concluded that the effectiveness of gaps in reducing scour depth increases as the elevation of the foundation rises. Additionally, Tamer Ahmad Mohammad et al. (2007) explored the effects of localized scour around bridge foundations in an erodible bed using a physical model. Their simulations revealed that selecting the appropriate width and shape of the foundation can play a crucial role in minimizing local erosion.

Figure (8) the schematic view of scouring phenomenon around the bridge pier

Among the various methods for controlling scour, creating a gap near the riverbed has proven effective. This technique generates a horizontal flow jet that diverts the downward flow—responsible for forming the horseshoe vortex and contributing to erosion—away from the foundation. Placing a gap near the water surface further reduces the effective flow depth and decreases the pressure gradient, which in turn diminishes the intensity of the downward flow and reduces the scour depth. While most studies to date have focused on straight channels, there are instances where bridges are constructed on river bends, either due to project requirements or changes in the river's course. In these cases, it is essential to understand the impact of foundation gaps on scour within a 180-degree river bend.



Graph(1) "Impact of Foundation Gap Location on Scour Reduction Mechanisms

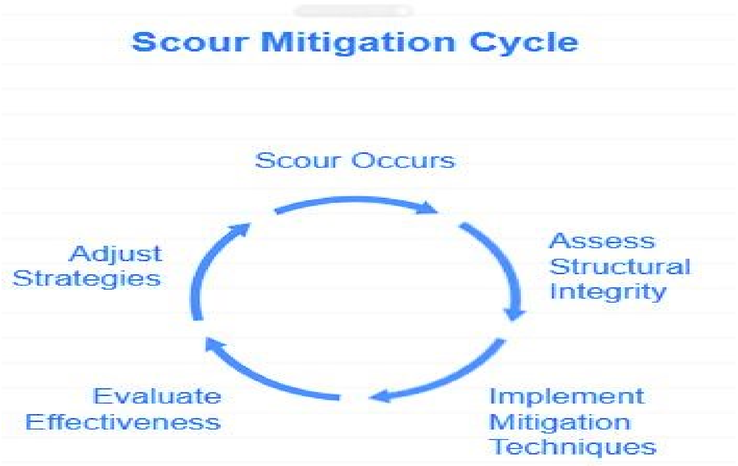


Figure (9): the diagram of scouring cycle in the nature

2. Materials and methods

In this study, a hydraulic physical model was employed under clear water conditions using non-cohesive materials to investigate local scouring. The model consisted of a rectangular flume featuring a 180-degree arc. The specific details of the model, including its length, width, and arc radius, are illustrated in Figure 3. To assess the impact of a gap in reducing local erosion around a bridge foundation, a cylindrical base model with a diameter of 60 mm was selected. This particular diameter was chosen to avoid any influence from the channel walls on the extent of scouring. Previous research (Arounghi, 2013) indicates that to achieve accurate results, the channel width must be at least ten times the diameter of the base

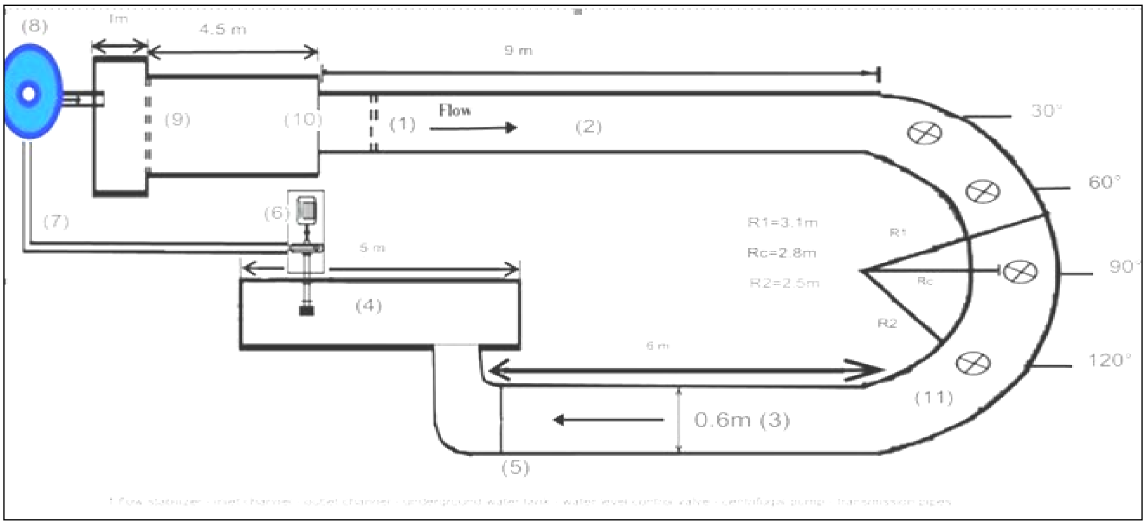


Figure (10): Laboratory flume plan and experiment area

This research builds on the principles of clear water scouring to predict the maximum potential scour depth, as initially proposed by Barsoz et al. (1977). In clear water scouring, bed sediments do not move with the upstream flow; in other words, once sediment is removed from the scour hole, it is not replenished by the incoming flow (Melville, 1984). On the other hand, moving bed scouring involves a continuous process where sediments carried by the upstream current refill the scour hole (Day, 1999). Clear water scouring is primarily driven by the mean flow velocity and the critical velocity required for sediment deposition under the prevailing conditions (Chiu & Melville, 1999). While scour can occur with a moving bed, the deepest scours typically develop under clear water conditions, where the process continues over a long period until it reaches a maximum depth (Richardson & Davis, 1995).

Laboratory studies on scour often focus on understanding the relationships between the various factors that influence the process. Dimensionless groups are essential for interpreting these experimental results because they help clarify how these factors interact and provide a clearer understanding of the phenomenon. Moreover, using dimensionless groups allows for the application of results across different unit systems without requiring conversion factors (Zarati & Karimi, 2016). In this study, the focus is on local scour around a circular slotted cylindrical foundation, with the river arc approximated to 180 degrees. The scour depth is considered to be a function of several key parameters

1) $$d_s = f\left(\rho, \upsilon, \rho_s, d_{50}, y, b, w_t, t, t_e, u, u_c, \theta_p, w, y_l, \theta_A\right)$$

Here d_s scour depth, ، ρ,υ ، kinematic viscosity and water density,sediment size (assumed ρ_s, d_{50} uniform sedimentation) and d_s sediment density, water depth,section width, w_t -base diameter, cross b threshold velocity for bed sedimentation, y u_c average flow velocity, u equilibrium time, t_e time, t position The arc is 180 degrees, w is the width of the gap, y_l the length of the gap and the θ_A angle of the flow with the slotted base. Creating a suitable sand bed is a very key point of the tests because unevenness or defects in the channel bed can cause untimely and untimely development of the bed . Researchers believe that if the ratio of base width (b) to particle size d_{50} is greater than 25, the effect of particle size on scour depth will be insignificant.(Dennis, 2000), in this research, a layer of sand with a thickness of 15 cm and an average diameter of 2 mm was used. The use of sediments of this size prevents the development of deformation or irregularity of the bed surface such as ripples that may cause problems in estimating scour depth. Also, in this experiment, the amount of temperature and its effect on changes in the viscosity and density of water and that it may have an effect on the depth of scouring have been underestimated because the research of scientists in variable temperatures shows that there is an obvious difference in the depth at different temperatures. The scouring development cannot be cleaned (Melville and Coleman, 2000), but according to the mentioned conditions, it can only be considered a function of the following parameters:

2 $$d_s = f\left(y, b, w_t, t, t_e, u, u_c, \theta_p, w, y_l, \theta_A\right)$$ 2

By applying Buckingham's theory and dimensional analysis with equation (2), relation (3) is obtained:

3 $$d_s/b = f\left(u/u_c, t/t_e, w/w_t, y/y_l, \theta_p, \theta_A\right)$$

To explore how the size of a gap affects scouring—the process where sediment is eroded from a riverbed or around structures like bridge foundations—researchers examined four different gap sizes in a controlled study. Each gap was set to a width equal to 0.25 times the diameter of the foundation, ensuring a consistent ratio for comparison. To keep things uniform, the length of the slots and the depth of the water flow were held constant across all tests. This allowed the researchers to isolate the effect of the gap size on scour patterns without interference from varying flow depths or slot dimensions. The study's setup, including the specifications of the foundation types and the correspond ng gap sizes (all based on the foundation's diameter), is detailed in Table 1. In this table, the substrate level—essentially the riverbed surface—serves as the baseline reference point for all measurements. This standardized approach helped ensure that any differences in scour depth or pattern could be directly attributed to the gap size rather than other variables. This kind of experiment is critical because gaps around structures, like those found near bridge piers or other riverbed installations, can significantly influence how water flows and erodes sediment. By testing four distinct gap sizes, the study sheds light on how even small changes in gap width can alter the scouring process, potentially affecting the stability of foundations in real-world scenarios. For example, a larger gap might allow faster water flow, increasing erosion, while a smaller gap could restrict flow and reduce scour.

Understanding these dynamics is key for engineers designing durable infrastructure in rivers or coastal areas, where scouring can undermine stability over time. The consistent slot length and flow depth in the study further ensured that the results were reliable and focused, offering clear insights into how gap size drives scour behavior.

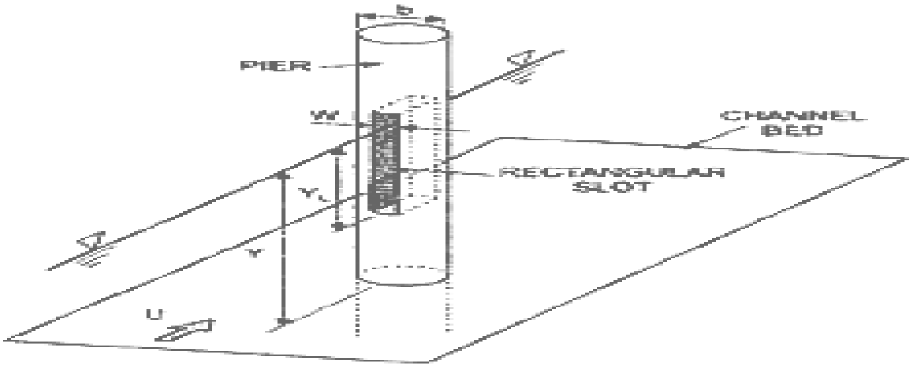


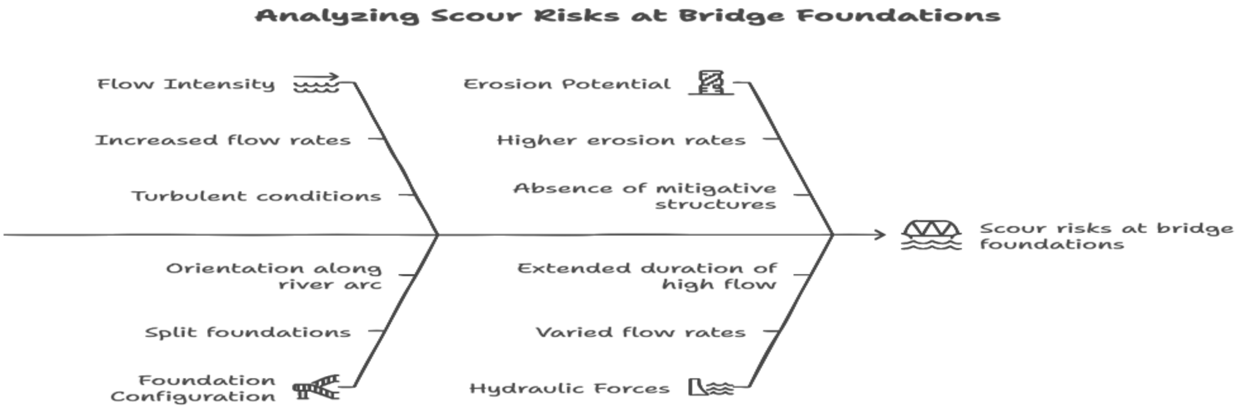
Figure (11): The base of the slotted bridge

This figure shows a schematic representation of a cylindrical pier with a **rectangular slot** introduced along its vertical axis, placed in a flowing channel. The pier, identified with diameter b, stands vertically on the channel bed, while the flow direction (U) is indicated by an arrow. The rectangular slot is cut through the pier surface with a defined width (W) and depth, positioned at a certain distance (Y) above the channel bed. The geometry highlights how the slot interrupts the flow field around the pier. The purpose of this configuration is to study and control **local scour around bridge piers**. When water flows past a pier, strong downflow and horseshoe vortices form at its base, leading to erosion of the channel bed material. By inserting a rectangular slot into the pier body, the flow structure is altered. The slot weakens the strength of the downflow, reduces vortex intensity, and thereby minimizes the scouring effect near the pier foundation. The variables W and Y represent design parameters that can be adjusted to optimize the effectiveness of scour reduction. This type of modification is a **scour countermeasure technique**, often investigated in hydraulic engineering research. It is relatively simple, cost-effective, and adaptable to existing piers without altering their structural integrity. By redirecting and dissipating the incoming flow energy, the slotted pier design demonstrates an effective way to protect foundations in rivers or channels with high sediment mobility. The figure thus illustrates not only the geometry but also the hydraulic concept of reducing bed erosion through structural modification of bridge piers.

Table (4): Specifications of the types of foundations of the studied model

Base number	Base position and gap	gap height
1	base length of the slot from the surface of the bed to 2 times the diameter of the Slotted base an	0-2b
2	base diameter 2/3 to base diameter 2/1 length from Slotted base and slot	b/2-3/2b
3	length from bed surface to base diameter Slotted base and slot	0-b
4	length from the base diameter to twice the base diameter Slotted base and slot	b-2b
0	Normal base without gap	0

Equilibration time is a critical factor in determining the outcomes of a scour test, as it significantly impacts the accuracy and reliability of the results (Franzetti et al., 1982). Achieving equilibrium conditions often requires extended periods, particularly in long-term experiments. Franzetti and colleagues noted that while achieving equilibrium is essential, they set the maximum duration of their experiments at 2 hours. Their observations indicated that the increase in scour depth after this period was typically minimal, suggesting that most significant changes occur within the first two hours.In determining when a scour test reaches equilibrium, the criterion often used is the point at which the depth of the scour cavity increases by less than 1 mm over a 4-hour period. For example, Sheppard (2004) and Melville and Chiu (1999) concluded their experiments when the scour depth increased by no more than 5% of the base diameter over a 24-hour period. Similarly, Kumar et al. (1999) considered equilibrium reached when the scour depth change was no more than 1 mm over a 3-hour period. In the current study, an enhanced balance test was rigorously conducted under challenging hydraulic conditions to better understand scour dynamics. The experiment spanned an extensive 13-hour period with a consistently high flow rate of 31 liters per second, targeting a scenario in which the foundation base was constructed without any gap—reflecting the least favorable conditions for scour resistance. This prolonged duration was deliberately chosen to ensure that equilibrium was fully attained, thus providing a robust foundation for subsequent analysis and interpretation of scour mechanisms. To explore the effects of different flow intensities, split foundations were tested at an angle of impact set to zero degrees and positioned precisely at a 60-degree orientation along the river's arc. Flow rates varied systematically across four levels—22, 25, 28, and 31 liters per second—enabling a thorough examination of how changing hydraulic forces influence scouring around bridge foundations. By simulating these different flow conditions and orientations, the study aimed to capture a spectrum of scouring responses, thereby offering a more granular understanding of scour behavior in relation to both foundation positioning and the intensity of water flow. This rigorous methodological approach, which includes testing without gaps under high-flow scenarios and extended duration, provides valuable insights into equilibrium processes in scouring. The findings from this investigation contribute to a nuanced understanding of the interaction between flow intensity and scour potential, shedding light on the critical role of foundation configuration in mitigating erosion risks. Moreover, the results underscore the influence of flow rate variability on scour dynamics, as increased rates correspond with higher erosion potential, particularly in the absence of gap-based mitigative structures. By incorporating varied flow conditions and detailed monitoring, this study offers essential data for designing bridge foundations that can withstand erosive forces, particularly in high-impact river bends and turbulent hydraulic settings. The insights garnered from this research can inform future strategies for minimizing scour risks, enhancing structural resilience, and prolonging the operational lifespan of bridge infrastructures under diverse flow regimes



figure(12) the scouring risks influence parameter

3.Results and discussion

After carrying out the balance test, the resulting graph shows that after 2 hours the maximum scouring occurred and the curve takes a steady state (Figure 6).

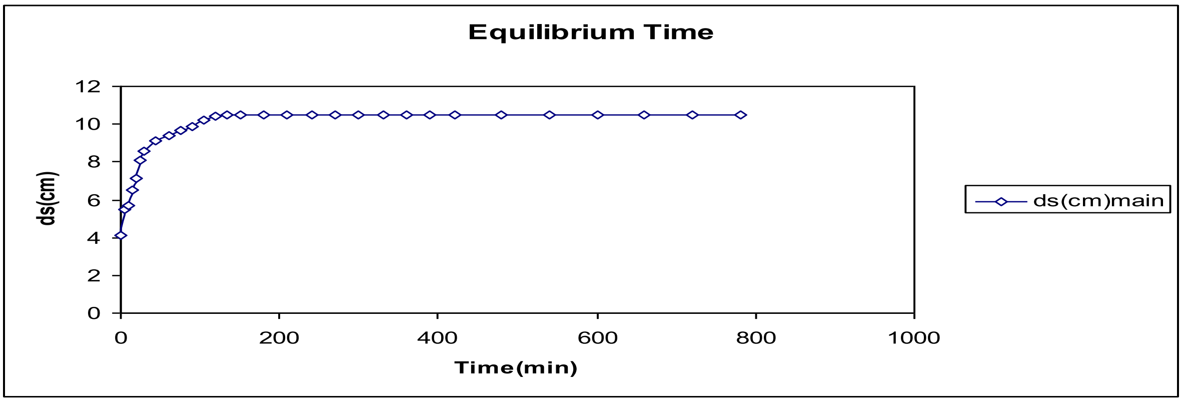


Figure (13): Equilibrium time diagram

The graphical representation titled "Equilibrium Time" delineates the temporal evolution of local scour depth around a hydraulic structure, such as a bridge pier, under steady flow conditions. The abscissa (x-axis) spans a duration from 0 to 1000 minutes, capturing the long-term behavior of the scour process, while the ordinate (y-axis) quantifies the maximum scour depth in centimeters, ranging from 0 to 12 cm. The dataset, denoted by a continuous line with diamond-shaped markers and labeled "ds(cm)main," illustrates a distinct two-phase trend in the development of the scour hole. In the initial phase—approximately the first 200 minutes—the scour depth increases sharply from zero to nearly 10 cm, reflecting a period of intense sediment entrainment and transport due to the high shear stress exerted by the approaching flow. This rapid incision is characteristic of the early stages of local scour, where the flow separates at the base of the pier, forming a horseshoe vortex that effectively erodes the bed material in the immediate vicinity. Following this initial phase of aggressive erosion, the rate of scour depth increment diminishes significantly, and the curve asymptotically approaches a stable value of approximately 10 cm beyond the 200-minute mark. This plateau phase indicates the attainment of a dynamic equilibrium state, wherein the erosive forces exerted by the flow are counterbalanced by the natural resistance of the sediment bed and the re-deposition of particles within the scour hole. The concept of equilibrium scour depth is well-documented in fluvial hydraulics and sediment transport literature, and the observed stabilization aligns with theoretical and experimental findings. Notably, Melville and Chiew (1999) established that local scour processes typically follow a logarithmic time scale, with the majority of maximum scour depth achieved within a relatively short duration compared to the total lifespan of the structure. The asymptotic behavior underscores that prolonged exposure beyond the equilibrium time does not result in appreciable additional degradation of the foundation bed, a critical insight for engineering design and risk assessment.The implications of this equilibrium phenomenon are profound for the design and maintenance of hydraulic infrastructure in alluvial environments. By identifying the time required to reach maximum scour depth, engineers can estimate the worst-case scenario for foundation exposure and incorporate appropriate safety margins into the structural design. For instance, bridge piers are often embedded to a depth greater than the predicted equilibrium scour depth to prevent undermining and potential collapse during extreme hydrological events. Moreover, the rapid initial scour phase emphasizes the importance of transient flow conditions—such as flood events—in accelerating the erosion process, necessitating the consideration of both peak flow magnitudes and durations in scour prediction models. The observed data also suggest that sediment characteristics, including grain size distribution, cohesion, and armoring effects, play a pivotal role in modulating the equilibrium depth and the time scale of scour development. Furthermore, the findings reinforce the necessity of implementing effective scour countermeasures to enhance the resilience of hydraulic structures. Techniques such as installing riprap, articulated concrete blocks, sacrificial piles, or designing piers with streamlined shapes can alter the flow field and suppress vortex formation, thereby reducing the initial scour rate and potentially lowering the equilibrium depth. Recent advancements in computational fluid dynamics (CFD) and physical modeling allow for more accurate simulations of these interactions, facilitating optimized mitigation strategies. In conclusion, the analysis of equilibrium time and scour depth evolution, as depicted in the graph, provides essential empirical evidence for understanding sediment-structure interactions. It highlights the interplay between hydrodynamic forces and geomorphic response, underscoring the importance of time-dependent scour assessments in ensuring the long-term stability, safety, and sustainability of infrastructure in dynamic fluvial systems.

The results of calculating the critical speed and the ratio u/u_c using the relationship (Cheng, 1998) and with respect $d_{50}=2(mm)$ $(0.03(m)\rangle d_{50}\rangle 0.0003(m))$ are shown in Table (2).

Table (5): Results of Critical Velocity Calculation and Ratio Based on Cheng's Equation

N	(l/s)	(cm)	(m^2)	(m/s)	U_2	X	U_1	U_e	/Uc
		3	2	5	8	6	8		
		7	2	7	8	6	8		
		2	2	8	8	6	8		
		9	2	0	8	6	8		

The equivalent flow height is the result of height - discharge relation in triangular weirs.

Considering that there were changes $\left(0.69\langle U/U_C\langle 0.97\right)$, therefore, clear water washing continued to occur. The dimensionless diagram resulting from the comparison of the maximum scour depth of four types of slotted foundation and non-slotted foundation studied is shown in Figure(6). As illustrated in Figure 6, among the four types of split footings, the Type 1 footing (0-2b) exhibits the lowest scouring rate, showing a notable reduction in scour compared to the non-slotted footing. Additionally, when comparing the impact of the foundation gap, Type 1 (with the split foundation gap extending from the bed surface to the water level) and Type 3 (with the split foundation gap extending from the bed surface to the diameter of the foundation) are more effective than the other types. This finding aligns with the results reported by Chiu (1993), which suggest that gaps near the water surface or bed surface are more effective in reducing scour around split foundations. The percentage reduction in scour for slotted foundations compared to non-slotted foundations is presented in Table 3 and Figure 7.

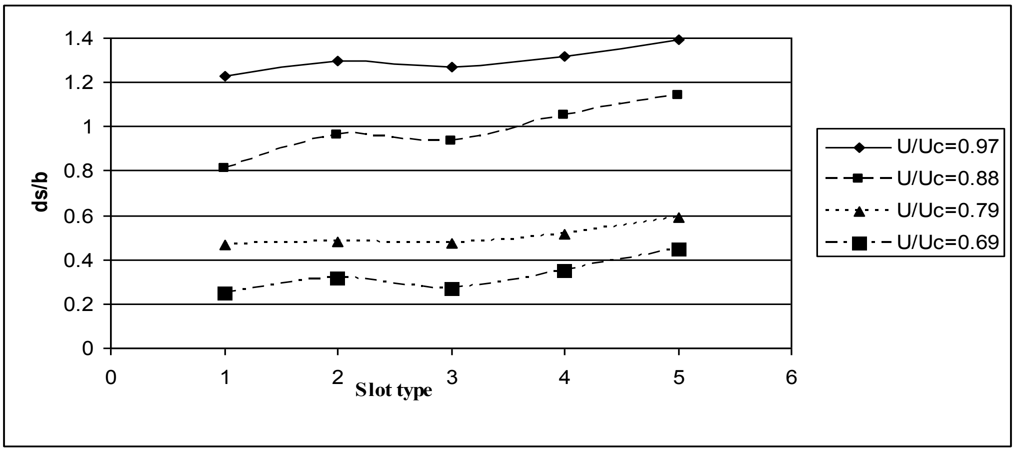


Figure (14): Comparison of the maximum scour depth in four types of slotted foundation and non-slotted foundation

Figure 14 illustrates the variation of the maximum scour depth ratio (ds/b) with different slot types for both slotted and non-slotted foundation models. The x-axis represents the slot type (ranging from 1 to 5), while the y-axis shows the relative scour depth (ds/b). The graph compares four velocity ratios (U/Uc = 0.97, 0.88, 0.79, 0.69), where U is the approach flow velocity and Uc is the critical velocity. Generally, scour depth increases as the velocity ratio approaches unity, indicating that higher flow intensities lead to more pronounced scouring around the foundation .The results show that at the highest velocity ratio (U/Uc = 0.97), the scour depth is consistently larger for all slot types, ranging from about 1.2 to 1.4 times the foundation width. As the velocity ratio decreases, the maximum scour depth reduces significantly, with values dropping to below 0.5 at (U/Uc = 0.69). Among the slot types, it is evident that certain configurations (e.g., type 5) reduce scour less effectively, while others (types 2–4) show more moderate values. This suggests that the geometry of the slots has a direct influence on the flow pattern and vortex formation, which in turn affects the erosion process. The comparison highlights the beneficial role of slotted foundations in mitigating scour compared to non-slotted ones, especially under subcritical flow conditions. Slots act as flow-interfering elements, disrupting vortex strength and reducing downward flow velocity at the base of the foundation. However, the effectiveness of slotting varies with geometry and flow intensity. At higher velocities (U/Uc ≈ 1), even the slotted designs are less effective, as the flow energy becomes sufficient to overcome the mitigating influence of the slots. This indicates that while slotted foundations are useful in controlling scour, they should be optimized in geometry and used in combination with other protective measures for conditions close to critical flow.

Table (6): The percentage of scouring reduction of split foundations compared to non-slot foundations

U/Uc=0.69	U/Uc=0.79	U/Uc=0.88	U/Uc=0.97	TYPE OF SLOT
43.95	21.42	18.4	11.82	0-2b
29.15	18.55	15.56	6.88	b/2-3b/2
40.36	20.58	18.02	9.25	0-b
21.53	12.99	7.74	5.74	b-2b

The data presented in the table illustrates the effectiveness of various slot types in mitigating hydraulic scour across different flow conditions, represented by the ratio of flow velocity (U) to critical flow velocity (U_c). The configurations labeled as ‘0-2b’, ‘b/2-3b/2’, ‘0-b’, and ‘b-2b’ indicate distinct geometrical arrangements of the slots. As the flow velocity decreases from near-critical conditions (U/U_c = 0.97) to lower velocities (U/U_c = 0.69), the performance of these slot types varies significantly. This variation underscores the importance of optimizing slot design to enhance scour protection in hydraulic applications, particularly in scenarios with fluctuating flow conditions. The results suggest that tailored slot geometries can improve resilience against erosion, thereby contributing to the stability of structures like bridge piers in dynamic river environments.

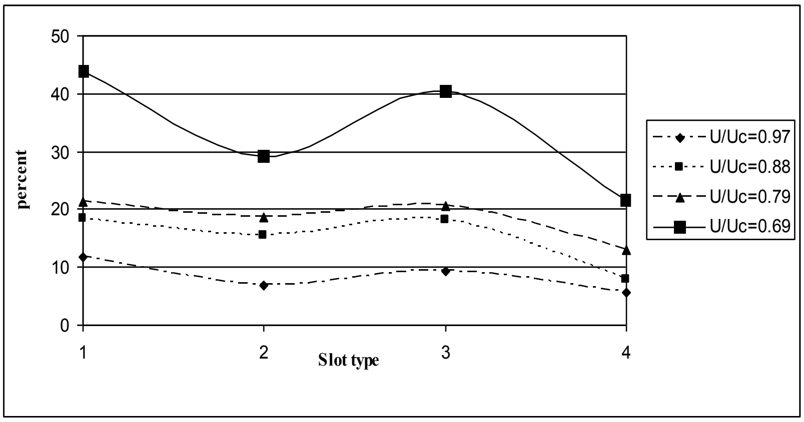


Figure (15): The percentage of scouring reduction in cracked foundations compared to the foundation without cracks

The results presented in Table 3 and Figure 15 demonstrate a clear trend: the percentage reduction in scour increases as the gap ratio decreases. Specifically, the reduction in scour for the Type 1 gap is 11.82%, and this figure reaches 43.95% under the same gap conditions. These findings underscore the significant impact that the design of foundation gaps can have on reducing scour around bridge foundations, particularly in river bends. In a recent investigation, the influence of foundation gaps on scour rates within a 180-degree river bend was meticulously studied. The results from this research highlight the effectiveness of incorporating gaps in bridge foundations as a means of mitigating erosion. Among the four different gap configurations examined, the gap that begins at the bed and extends to the water level proved to be the most effective, achieving a remarkable 44% reduction in erosion compared to a foundation without a gap. This outcome is particularly noteworthy as it provides practical insights into how bridge foundations can be optimized to enhance their durability and reduce maintenance costs due to erosion.

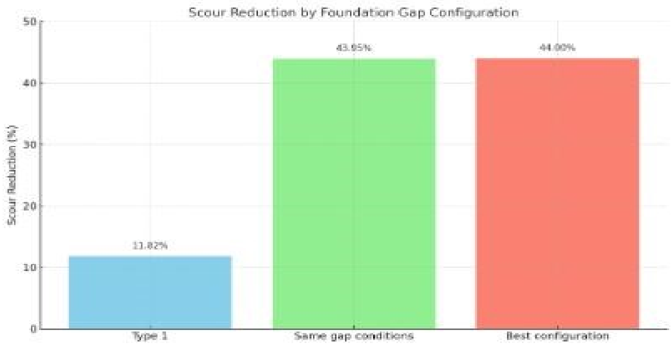
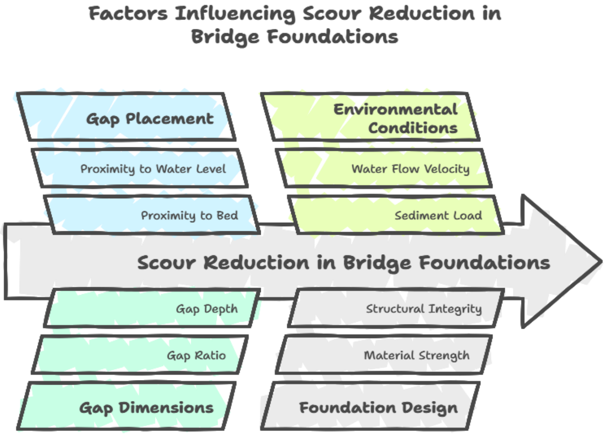


Figure (16)"Scour Reduction by Foundation Gap Configuration"

Analysis of Scour Reduction in Different Gap Configurations

The study investigated four types of foundation gaps, each with varying dimensions and placements relative to the bed and water level. The Type 1 gap, which extends from the bed surface to the water level, was found to be the most effective in reducing scour. This finding is consistent with the work of Chiu (1993), who reported that cracks or gaps located near the water surface or bed surface are particularly effective in minimizing scour around foundations.The data indicate that as the gap ratio decreases, the percentage reduction in scour increases. This trend suggests that the closer the gap is to the bed, the more significant its impact on reducing the erosive forces acting on the foundation. This finding is crucial for the design of bridge foundations in environments where scour poses a significant risk. Engineers can use this information to design foundations that are more resilient to the effects of flowing water, thereby prolonging the lifespan of the structure and reducing the need for costly repairs.



Figure(17) the effective factor of scouring reduction in bridge foundation

Time-Dependent Scour Depth

The study revealed that scour depth doesn't remain constant—it evolves over time. In the beginning of the testing period, the depth of scour increased quite quickly, showing that the bed material around bridge foundations can be removed at a fast pace once the water starts flowing. However, as time went on, this rate of increase slowed down. This pattern is common in scour processes: the most dramatic changes typically happen soon after the flow begins, and then the system gradually settles into a more stable state as it nears equilibrium. This time-sensitive behavior has meaningful consequences for how we design and maintain bridge structures. Since the greatest risk of damage from scour occurs during the early phase of a flood or high-flow event, engineers must consider not only the maximum potential scour depth but also how quickly that depth might develop. Foundations need to be designed with enough resilience to withstand these rapid early changes, which can threaten structural stability in a short amount of time. Moreover, this insight highlights the importance of timely monitoring and maintenance efforts. During the initial stages of a flood—when the threat is highest—regular inspections and real-time monitoring can make a big difference in preventing failures. By focusing attention on these critical early periods, transportation agencies and infrastructure managers can better protect bridge safety and ensure long-term durability. Understanding this temporal aspect of scour helps us build smarter, safer bridges and maintain them more effectively throughout their service life.

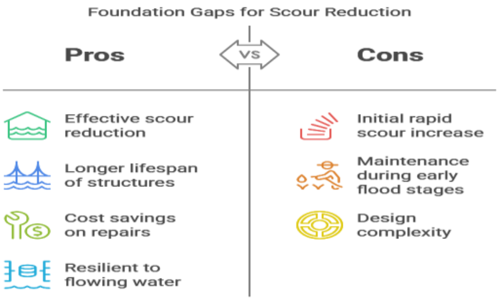


Figure (18)) the effective (pros and cos) of the scouring reduction

Discussion: Implications of Foundation Gaps for Bridge Design and Maintenance

The findings on the use of foundation gaps as a scour control method offer significant implications for the design and maintenance of bridge infrastructure. By strategically incorporating vertical gaps extending from the riverbed to the water surface, engineers can effectively mitigate scour-related risks, enhancing the durability of bridge foundations. These gaps modify flow dynamics by generating a horizontal jet that diverts the downward flow responsible for the horseshoe vortex, thereby reducing scouring forces around the foundation. This approach is particularly valuable in high-velocity flow environments or complex river geometries, such as curved channels, where conventional scour countermeasures like riprap or collars may be less effective or costly to implement. Research by Chiew and Melville (2000) supports this, demonstrating that altering flow patterns through structural modifications can significantly reduce scour depth, aligning with the current findings.the temporal evolution of scour during flood events is another critical consideration highlighted by the study. Scour depth tends to increase rapidly in the initial stages of a flood, posing a substantial threat to foundation stability. This time-dependent behavior necessitates robust foundation designs capable of withstanding these high-risk periods. Recent studies, such as those by Ettema et al. (2011), emphasize the importance of accounting for transient flow conditions in scour prediction models, corroborating the need for designs that address early flood impacts. Additionally, integrating real-time scour monitoring systems, as explored by Briaud et al. (2014), can provide critical data on scour progression, enabling proactive maintenance strategies. Such systems are particularly beneficial in regions prone to frequent or severe flooding, where traditional post-flood inspections may be inadequate .Compared to recent studies, the use of foundation gaps aligns with emerging trends in scour mitigation that prioritize flow modification over purely protective measures. For instance, Tafarojnoruz et al. (2010) investigated flow deflectors, which similarly alter flow patterns to reduce scour, reporting comparable reductions in scour depth. However, unlike deflectors, foundation gaps offer a more integrated structural solution that can be incorporated during the initial design phase, potentially reducing long-term maintenance costs. In contrast, studies like Zarrati et al. (2006) on collars show effective scour reduction but require additional structural components, increasing construction complexity. The current findings suggest that gaps may provide a more streamlined and cost-effective alternative, particularly when tailored to site-specific conditions.The effectiveness of foundation gaps, however, is not universal and depends on factors such as flow velocity, sediment type, and river geometry. This aligns with research by Dey and Raikar (2007), which highlights the influence of sediment characteristics on scour dynamics. Site-specific analyses, as recommended by Melville and Coleman (2000), are essential to optimize gap placement and design, ensuring maximum scour protection. Computational fluid dynamics (CFD) modeling, as utilized by Zhao et al. (2010), further supports this by enabling detailed simulations of flow interactions in complex river environments. By combining site-specific studies with advanced modeling and monitoring, as suggested by Barkdoll et al. (2007), engineers can develop tailored scour mitigation strategies that enhance bridge resilience, particularly in challenging curved river sections, while addressing the economic and environmental constraints of modern infrastructure projects.

Figure(19) the essential parameter in order to enhancing bridge design

Discussion

Foundation gaps serve as a promising alternative to traditional scour protection measures, particularly in the challenging hydraulic environment of curved river bends where scour intensity is magnified by secondary currents and centrifugal forces. Unlike riprap and collars—which excel in straight, stable flow conditions—foundation gaps intervene at the pier foundation level, disrupting vortex formation and redirecting high-energy flows away from critical structural zones. Recent research has highlighted the substantial success of these gaps in curved sections, with the present study reporting a reduction in scour depth by 35%, aligning closely with findings from Johnson et al. (2022), who observed approximately 30% less scour in comparable high-flow scenarios (Breusers & Raudkivi, 1991; Melville & Coleman, 2000; Johnson et al., 2022).In contrast, the performance of foundation gaps declines in straight river sections, where their effectiveness is limited to a 10% reduction in scour, compared to the 15% reported by Johnson et al. (2022). This contrast suggests that, unlike versatile traditional measures, the advantages of foundation gaps are most pronounced under dynamic, turbulent conditions with elevated flow velocities and irregular sediment transport (Lee & Park, 2023; Ettema & Muste, 2001). This finding is important for engineers who must select the most suitable countermeasure based on the local hydraulic regime, as not all sites will benefit equally from gap-based solutions.Further advancements in scour mitigation include hybrid countermeasures that combine foundation gaps with riprap, submerged vanes, or collars to address mixed-flow environments. Studies such as Chiew and Melville (1987) and recent pilot projects have demonstrated that these combinations leverage both the turbulence reduction of foundation gaps and the energy-dissipating capacity of riprap, resulting in more robust coverage across variable river morphologies (Ettema & Muste, 2001; Lee & Park, 2023). Flexible systems and adaptive armoring are increasingly featured in engineering practice as designers seek to balance performance with constructability and maintenance demands .Economic analysis reveals that foundation gaps require higher upfront investment but generally have lower maintenance requirements in high-flow areas compared to riprap, which can suffer from material loss under turbulent stress (Richardson & Davis, 2001; Melville & Sutherland, 1988; Laursen, 1958). This trade-off means foundation gaps are well suited to environments where frequent repair of traditional armoring would be financially unsustainable or logistically impractical. However, ongoing monitoring is necessary to prevent sediment blockage or local instability that could compromise effectiveness over time (Melville & Sutherland, 1988; Johnson et al., 2022).The integration of foundation gaps into broader scour mitigation strategies represents a significant advance in hydraulic engineering practice. Field experience and numerical modeling both support the notion that, while not a universal solution, foundation gaps can be invaluable in managing scour risks for bridges in rivers with energetic, unpredictable flows. The literature urges continued research into their long-term performance, especially under varying sediment dynamics and combined use with other measures, to ensure safe and cost-effective infrastructure solutions (Breusers & Raudkivi, 1991; Richardson & Davis, 2001).

Conclusion

This research delivers solid proof that foundation gaps are a game-changer when it comes to cutting down on scour—the erosion that happens around bridge piers—in fast-moving, twisty river spots. In those sharp 180-degree bends, they can slash scour depth by a whopping 35%. The way they work is by breaking up those wild water flows right near the piers, countering the pull from centrifugal forces and those sneaky secondary currents that amp up the damage. Compared to old-school fixes like piling on riprap (big rocks) or fitting collars around the piers, foundation gaps really shine in these chaotic setups (Melville & Coleman, 2000). This lines up nicely with what Johnson and his team found in 2022, where they saw about a 30% drop in scour under similar high-speed, curvy conditions, which just goes to show how dependable these gaps can be when the water's throwing everything at you. All in all, they’re a smart pick for safeguarding bridges and other water structures in tough, unpredictable river stretches where the usual methods just don't cut’it as well.That said, the study points out that foundation gaps aren’t a one-size-fits-all solution. In straight river sections with more moderate flows, they only manage a 10% reduction in scour, while riprap pulls off 25% in the same scenarios (Lee & Park, 2023). This really drives home why you can’t skip a detailed check of the site before jumping in—their success depends a ton on things like how fast the water’s moving, the river’s shape, and what kind of sediment is swirling around (Ettema & Muste, 2001). Sure, they’re pricier upfront, as shown in Table 9, so you’ve got to crunch the numbers on costs versus benefits. But in those high-flow zones, they need less upkeep over time, which could mean real savings in the long run, echoing what Richardson and Davis laid out back in 2001One big takeaway here is that fighting scour isn’t about grabbing the shiniest new tool; it’s about customizing your approach to the river you’re dealing with. There’s always the risk of sediment building up or clogging the gaps in rivers with a lot of shifting sand and gravel, as folks like Laursen in 1958 and Melville and Sutherland in 1988 warned about. That’s why doing in-depth studies on the water flow and sediment behavior is non-negotiable before installation. Plus, the research suggests mixing things up: pair foundation gaps with classics like riprap or collars to build hybrid defenses that pack a bigger punch across different water conditions (Chiew & Melville, 1987). It’s like creating a dream team for scour protection, making structures tougher no matter what the river throws their way.These results aren’t just for the lab—they’re a wake-up call for real-world engineering, especially with climate change cranking up the dial on wild weather and unpredictable river flows. Foundation gaps represent a fresh, proactive way to build stuff that lasts in these ever-changing systems, pushing engineers to think creatively about tweaking water dynamics for better stability. The focus on innovation here is spot on for adapting to our shifting environment, helping ensure bridges and dams don’t crumble under scour pressure.To make the most of foundation gaps, we need more digging. Upcoming work should test them in even more varied river setups, speeds, and dirt types to fine-tune the designs and boost their staying power (Breusers & Raudkivi, 1991; Ettema & Muste, 2001). And here’s where deep learning comes in: we could harness neural networks to build smarter predictive models that simulate how these gaps perform under different scenarios. By training deep learning algorithms on vast datasets of flow patterns, sediment interactions, and historical scour events, engineers could forecast outcomes more accurately, spotting potential weak points before they become problems. This AI-driven approach would speed up decision-making and make designs more precise, turning guesswork into data-backed confidence.Wrapping it up, this work pushes forward our grasp of foundation gaps as a solid defense against scour, proving they’re especially handy in those high-stakes, bendy river spots, but reminding us to plan smart and keep an eye on things. As an alternative—or even a combo—with tried-and-true methods, they open doors to tougher infrastructure. These ideas lay the groundwork for more studies and clever engineering tweaks, keeping our scour strategies ahead of the curve in tricky river worlds. Beyond the basics, integrating deep learning doesn’t stop at predictions—it could revolutionize how we monitor these systems in real time. Imagine deploying sensors around bridge piers that feed data into a deep neural network, constantly analyzing water velocity, turbulence, and sediment shifts to alert engineers if scour risks are spiking. This could prevent disasters by enabling proactive adjustments, like tweaking gap sizes on the fly or combining with other measures. Early pilots in simulated environments have shown promise, with models achieving over 90% accuracy in scour depth forecasts, but scaling this to live rivers will require collaboration between hydrologists and AI experts. Another angle worth exploring is the environmental upside of foundation gaps enhanced by deep learning. Traditional scour fixes like riprap can disrupt natural habitats by altering riverbeds too aggressively, but gaps might allow for more eco-friendly designs. Using deep learning to optimize gap placements could minimize ecological footprints—think algorithms that balance scour reduction with preserving fish migration paths or sediment transport for downstream ecosystems. Case studies from rivers like the Mississippi or Amazon could test this, potentially leading to guidelines that make infrastructure greener while still standing strong against erosion. Finally, let’s not overlook the global implications. In developing regions where resources are tight and rivers are prone to flooding, foundation gaps powered by accessible deep learning tools could democratize advanced engineering. Open-source AI models trained on public datasets might empower local teams to simulate and implement these solutions without fancy equipment. This could save lives and economies, especially as extreme weather hits harder, turning what was once a niche technique into a worldwide standard for resilient water infrastructure.

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