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Flood Resilience Assessment of Reinforced Concrete Highway Bridges: A Computational Investigation

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Abstract

India has much rain throughout the months of June, July, and August. During this time of year, several rivers experience severe flooding. In extreme climatic conditions, the river flood washed the bridges and roads. Hence it is customary to analyze bridges and roads through numerical techniques or simulations. In this context, computational fluid dynamics (C.F.D.) is the most reliable technique and is the core of this chapter. The present study aims to simulate water pressure on a bridge pier and investigate the structural performance through numerical modeling. The present study considers circular and rectangular pier shapes to analyze the water distribution through pressure and velocity fields. The bridge piers of circular shape with a diameter of 0.355m and rectangular shape of similar size have been analyzed and compared. Both piers have the same elevation of 3.5 meters and are exposed to a water velocity rate of 0.5 to 4 meters per second. The performance of both piers has been investigated by varying the water velocity by 0.5 meters per second in magnitude. ANSYS Fluent has been used to study the flood scenario in the present work. It was noticed that the flow field was significantly affected by the circular shape. However, the performance of the rectangular shape was observed to be superior to the circular shape.

Keywords

CFD, Reinforced Concrete, Highway Bridges, Flood, Water Velocity.

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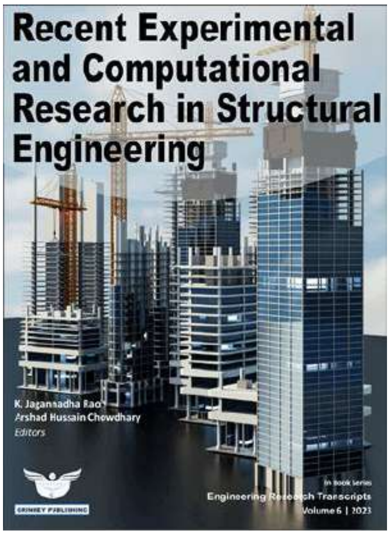

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1. Introduction

As a consequence of climate change, India has experienced significant casualties and the destruction of infrastructure. Also, as our population increases, so does the possibility of even more significant damage in these locations. Floods always have the most prominent risk perception of any natural catastrophe, impacting most people globally. Bridge collapses occur during the rainy season as well as during the development phases. However, most of these incidents were caused by negligence and could have been avoided with sufficient measures.

Bridges are essential constituents of both highway and railway transportation networks, serving a crucial function. As a result, bridge safety and serviceability are always significant issues in practice. Bridges are susceptible to environmental and artificial events such as earthquakes, floods, heavy winds, explosions, and vehicular contact at bridge piers [1-2]. Bridge damage caused by such catastrophic occurrences may cause considerable interruptions in the routine operation of transportation networks [3-4]. It might affect massive financial losses for the community and harm the most significant number of individuals.

The reliability of essential assets such as highways and bridges are critical in disaster management and recovery transportation efforts [5]. Bridge structures substantially influence the durability of road infrastructure, and bridge destruction can influence the susceptibility of the community serviced by the transportation systems. During a crisis, the centralization of the road network allows people to escape the area quickly. Bridges are essential in enabling access to impacted regions throughout the restoration after a major incident.

As a result, they know the fundamental elements that impact bridges are critical to ensuring that design criteria and management establishments for bridges deliberate the robustness and susceptibility of bridges throughout such a disaster [6]. In flood occurrences, officials confront the difficulty of making proper judgments about bridge traffic control. Keeping bridges operational during a disaster is essential for backup and recovery. However, significant deaths and damage to property can occur if bridges at risk of collapsing are not stopped in a reasonable timeframe [7-8]. Hence, there is a high demand for a reliable bridge stability evaluation approach during flood events. This section provides a short overview of the research. It brings a summary of the present study's requirements, the importance of flood analysis, and its practical applications in bridge designs.

Regarding the types of piers, circular and rectangular piers are common choices due to their simplicity and ease of construction. However, they are not the only options available. Other pier shapes, such as triangular, hexagonal, or octagonal, can be considered based on the project's specific requirements and engineering considerations. In some cases, specialized piers with unique shapes may be designed to meet specific needs. Ultimately, the optimal shape for a pier will depend on a comprehensive evaluation of functional requirements, environmental conditions, engineering considerations, and economic factors. Making the best decision for a project requires consulting with qualified experts and doing detailed analysis.

Much research has concentrated on bridges that floods might harm. Riverside bridges on the water channel have previously been extensively investigated. These researchers concentrated on conductive structural behaviour, while water drift received little attention [9]. On the other hand, a wide range of computational models, including those for water drift, net power, and Reynolds number, have all been studied using fluid dynamics. Because of the issue's fluid behaviour and fluid-structure interaction, a unique study has been done on these topics. Additionally, experts believe that scouring and fluid soil interactions are difficult jobs in other domains of computational fluid dynamics [10].

Confrontation with flood and particle loading are obligatory constraints for troubling the bridge configuration in fluid loading circumstances [11]. Flood moderation is a severe problem in the Indian subcontinent and a serious concern for government authorities. An evaluation of the present bridge codes has been done by scientists in light of the consequences of climate change. Using the flow around a cylinder, a mathematical and experimental study on the movement of a flow is conducted [12-13]. Water distribution is a complex and mostly uncharted area of study. Undertaking an investigation of the piers and the water flow amongst them is important for evaluating the bridge's response to fluid impacts.

This study employs a recent approach to investigate the finite volume method, utilizing specific bridge measurements sourced from the Maharashtra state's Public Works Department (P.W.D.). It assesses pressure on bridge piers using Indian standard codal expressions and simplifies water flow at the fluid zone's nonslip border. The research takes into account critical factors, such as pressure distribution and pier height, suggesting the Australian Standard, Indian Railway Standard, and Indian Road Congress 6 approach for conservative flow measurements in square-shaped bridge piers; however, caution is advised when applying it to circular cross-section bridge piers due to potential negative effects on safety margins [14].

In order to evaluate the effects of floods on transportation networks and access to necessary infrastructure in significant Iowa communities under 100- and 500-year flood scenarios, this research uses graph theory, especially mono shortest route analysis. It aims to develop a real-time decision-support tool for administrators to assess flood-related vulnerabilities, finding that environmental conditions and flood-induced changes in road structures have significant effects on transportation network losses and access to vital services, including the possibility of shifts in the shortest travel distances to essential facilities following floods [15].

One of the highest-quality characteristics of the recent temporary street exceeded a constant reinforced concrete channel under the piers. With the assistance of the street building, the additional masses precipitated then well along on operating through substantial vehicles, eventually threatening bridge protection. Considering the interrelationships among pile foundations, pier columns, contiguous soils, and a large number of trucks, this research devised a original three-dimensional finite factor model. The established setup was used to study the enactment of the bridge for the united results from conditional avenue loads and, after that, validate the model with the help of a systematic analytical process. They concluded that the metallic sheet walls have been first-class in protecting current bridge piers [16].

This paper focuses on the interaction between multiple cylindrical structures and seismic forces, employing practical finite element models to compute sesmic-induced forces on vertical cylinders with irregular cross-sections. The findings highlight that fluid-cylinder interaction becomes important when the space between neighboring piles is less than 3, and the research provides simplified formulas for pile groups' mass coefficients based on factors such as pile spacing, dimensions, wave characteristics, and seismic waveforms, which have practical engineering applications [17].

This literature survey explores various aspects of coastal bridge resilience, including the classification of wave-induced stresses, bridge structural responses, vulnerability assessments, and post-disaster rehabilitation strategies. It offers a comprehensive framework to predict structural resilience under wave-induced pressures and introduces innovative perspectives for post-disaster recovery, considering factors like time, energy, and environmental implications, with relevance to different stakeholders [18].

They studied the flood intensity outcome on piers, typically in ANSYS Fluent software. The effect comprised the finite volume approach. Because the flows mentioned above constitute an entity comparable to a bridge pier in terms of force distribution and pier height, the fluid's effect is an essential component of our inquiry. The findings revealed that the AS5100 approach is excellent for estimating the stress on rectangular bridge piers. In contrast, the strategy would need a risky protective verge for piers with a spherical cross-section and be utilized cautiously [19].

This paper used coastal bridge structures for investigation. The stagnant water's remarkable sanction in the bridge floor's lower chord was considered. The tremendous wave pressure on the bridge surface is prone to wave-induced destruction during a storm or typhoon. This revision provides an investigative explanation based on the linear theory of potential for hydrodynamic forces on girder decks subjected to hurricane-generated indirect water waves. The recommended method evaluates wave forces on a deck while accounting for the effects of the direction of wave propagation, wave characteristics, and structural behavior. This parametric research illustrates how structural design optimization may be utilized to reduce wave pressure [20].

Mostly, river water flowing on bridge piers is used to measure the drag force. The drag coefficients specified in the design rules or requirements are determined using empirical force. In the literature, drag coefficient values were studied. This paper examines the drag factor nearby the square, semi-circular nose and helical and circular-shaped piers. The findings revealed that the American Association of State Highway and Transportation Officials (AASHTO) drag force coefficient values ranged from under-recognized to over-recognized. According to the findings, the AASHTO drag coefficient estimates should be revised under more complex situations and scenarios [21].

This study evaluates the resilience of bridge piers under the effects of frequent floods and seismic activity. An evaluation rule is established for a probabilistic technique to generate an analysis matrix. This probabilistic technique is used in the research study to identify variations in systemic reactions and the integrity of a bridge pier. Structure stability is measured using six distinct flood situations and four distinct seismic occurrences. The moderate seismic activity and low-level flood events employed in this work have been shown to have a negative effect on structural response. Flexure in a column, pile moment, pile axial load, and shear capacity are tested for structural performance decrease [22].

They studied typical factors distressing the model of a bridge below flood stuffing: resistance to flood and particle loading tested. The water bodies should be wholly or substantially submerged for bridges under heavy flooding, causing in significant hydrodynamic stresses on the deck and piers. The main focus was on how different types of piers fared under flood stresses. The impact of water on piers was modelled using ANSYS Fluent. This model simulates the shape of a pier that is both square and round. The Australian Standard (AS 5100) equivalent hydrostatic load was correlated to the statistical study results. They determined that the AS5100 technique is effective in lieu of assessing pressure on square piers but inadequate for estimating pressure on circular piers [23].

It is a long-standing and essential problem in fluid mechanics to determine the flow rate of bluff structures, especially those with circular and rectangular (square) cross-sections. Cylinders may simulate various technical applications, such as offshore construction, bridge piers, and pipelines. The shear force transportation k-omega turbulence close model and software platform were used for 2 dimensional recreations. This recreation results agreed well with the literature. This flow field was shown to be considerably affected by cylinder form. Under the same initial flow patterns, the trailing down of the solid body was more turbulent than the circular one. They concluded that as Reynolds number (Re) improved and the turbulence of the flow field amplified, as did its length down the cylinders [24].

Instead of focusing on the immediate threat to humans, the researchers analysed the measurable characteristics of flood waves. Rapid catchment reactions to infiltrating precipitation, openings of flood barriers, tidal surges, or hurricane swells can have a substantial effect on infrastructure strain, perhaps successive in physical loss or widespread catastrophes. This paper fully comprehends the correlation among stimulating drift hydrodynamics and hydraulic patterns. This paper introduces laboratory experiments and practices that restrained statistics from authenticating a mathematical model. The simulation stands used to replicate dual nominated test evaluations by unique sets, and pleasant mathematical outcomes are achieved, confirming its analytical potential. This paper model simulation would offer an attainable device intended for field-scale implementations that are wider and more bendy for use [25].

This study investigated the optimal scour depth on symmetrical single-bridge pillars with various characteristics, including cross-section shapes and streamflow angles. The findings indicate that for certain cross-sectional shapes, the form factor can be considered as 1.0 or 1.2, and the aspect ratio is significant when it's less than four, emphasizing the importance of considering both form and skew angle in assessing regional scour effects on bridge pillars [26].

In this study, an analytical technique for evaluating earthquake risk in bridges is presented, taking into account the critical scour depth that may cause a bridge's seismic response to depart from its original design idea. The method utilizes response spectrum analysis to evaluate the bridge's seismic behavior, comparing it to component and foundation capacities to determine the likelihood of damage. The study shows that even bridges built to withstand earthquakes can sustain damage from shallow scour depths [27].

According to this article, bridge piers should be redesigned to have a more streamlined shape. This will lower localized flow rates and reduce the likelihood of local scour. The study employs fluid mechanics and numerical simulations to examine the effects of different pier cross-sectional shapes, and it identifies an ideal design that significantly lowers peak bed shear stresses, the risk of scour, and falling velocities, which could guide the design of more durable bridge structures. [28].

In this study, the performance of pressure-based and density-based approaches is compared across various flow velocities, with a focus on developing methods that work effectively across a wide range of Mach number regimes. The research employs a finite-volume method and introduces a unique pressure modification strategy applicable to both compressible and incompressible flows. The study evaluates these techniques' efficiency in simulating problems in the Mach number range of 0-6 and provides recommendations based on their respective merits [29].

In this study, they looked at how the fluid-cutting-edge impact and fluid-structure interaction affected the bridge piers. As such, this study is useful for comprehending the present fluid result on the bridge pier. This research focused on the comparable knowledge between the impact effects of fluid, the effect of fluid-structure coupling, theoretic investigation, and the findings obtained from using different formulas at home and abroad design codes. They concluded that the fluid-structure coupling finding on the bridge pier could be overlooked since the water flows around it. The approach described in China's standard code for road bridges and culverts tends toward producing a considerable output [30].

The hydrodynamic force appearance established primarily on the radiation concept is an intricate and time-based convolution that measures their values. The Morison equation is a semi-empirical solution, and it is difficult to precisely calculate its inertia factor and drag coefficient. The basic equation based on radiation theory is valid. Three dimensionless limitations indicating international decoupling in the time domain are the frequency relation, enormous depth ratio, and extreme top of the bridge pier. This study is focused on the equation, which indicates that more straightforward approaches are perfectly in compliance with the analytic solution [31].

This research examined the effect of scouring on piers during flood events and how retrofitting affects their vulnerability. Using a dynamic 3-dimensional finite element model, the research assessed numerous act indicators, comprising strength, horizontal rigidity, strength retention, and plastic catastrophe mechanisms, to analyze the effects of scour depth and base revisions on bridge pier behavior. The findings suggest that maintaining scouring depth below a critical threshold can enhance the resilience of bridge piers, and the paper provides guidelines for evaluating pier safety during floods [32].

They studied the traditional approach to estimating the hydrodynamic loading pressure on a pier. It is built entirely on prototypical evaluations of stand-alone piers. They're using a solitary wave produced in a hydraulic wave flume. These findings indicate that the deck's presence affects the piers' hydrodynamic pressure. This research investigates the influence on the deck of preventing free splashing and forming a covering over the wave. They determined that the hydrodynamic pressure recorded on separate piers should be considered non-conservative [33].

This paper employs computational fluid dynamics techniques to assess a 3 D mathematical model based on the Reynolds Navier Stokes equations for modeling the flow patterns around various bridge types, with and without piers, in a composite waterway. The study verifies the model's accuracy using open-source experimental data, demonstrating its effectiveness in accurately representing flow field profiles across a wide range of flow velocities [34].

It was claimed that scarcity in lookup considers the influence of water pressure on a continuous entity like a bridge pier to handle more than a few constituents of fluid dynamics. The research aims to simulate fluid stress on a bridge pier and better understand numerical modeling approaches for inspecting structural performance. Assessing the fluid drift distribution is critical for determining the cause of a bridge pier failure. It was aimed at the forecast of fluid flow dispersion and the assessment of a bridge piers reaction. A complete study of flow field behavior around piers is required.

2. Methodology

Extensive literature review on computational fluid dynamics, fluid-structure interaction, and finite volume method for bridge pier subjected to flood loading. Collecting data related to the bridge and using original data for modeling. ANSYS Fluent software was used to build a simulation model that assessed the outcome of fluid load on the bridge pier. The finite volume method is used in the investigation to assess the pressure dispersal.

2.1 Construction of Finite Volume Model

The setup parameters for each rectangular and circular pier model are identical, and the velocity of a fluid field varies to cause stress deviation. The shape's behavior at this phase is no longer relevant. The piers were presented in the form of a nonstructural model. As margin requirements and for nanostructured piers, nonslip sidewalls are anticipated. The expanded range of plan periods can reduce test time, resulting in an optimum strategy. ANSYS Fluent 18.0 deals with the flow domain in this current scenario.

Table 1. Model Details

Sr. No.	Setup Parameters	Specifics
1.	Type of shapes	a) Rectangular b) Circular
2.	No. of the pier	Single
3.	Dimensions of pier	a) Rectangle (0.355 x 0.355 m^2) b) Circular (dia. 0.355m)
4.	Height of pier	3.5 m
5.	Flow Domain	5 x 7 x 3.5 m
6.	Water velocity	0.5 m/s – 4 m/s
7.	Velocity increments	0.5 m/s
8.	Meshing method	Patch conforming method
9.	Domain	Solid
10.	Type of domain - solid	Cell
11.	Boundaries - inlet1	Velocity inlet
12.	Boundaries - outlet1	Outflow
13.	Boundaries - wall	Wall
14.	Boundaries - zone1	Wall

The subject is mathematically modeled in ANSYS Fluent, with the following characteristics entered for each material.

Table 2. Material Properties

Material Parameters	**Standards**
Density of solid pier (ρ_1)	2400 kg/m^3
Water density (ρ_2)	1000 kg/m^3

To demonstrate the mathematical model for the bridge's piers, we utilized a commercial C.F.D. Programme, ANSYS Fluent 18. Fig. 1 and 2 show a schematic model of the pier in Fluent. The flow domain is restricted to the cutting-edge direction of the cuboid box.

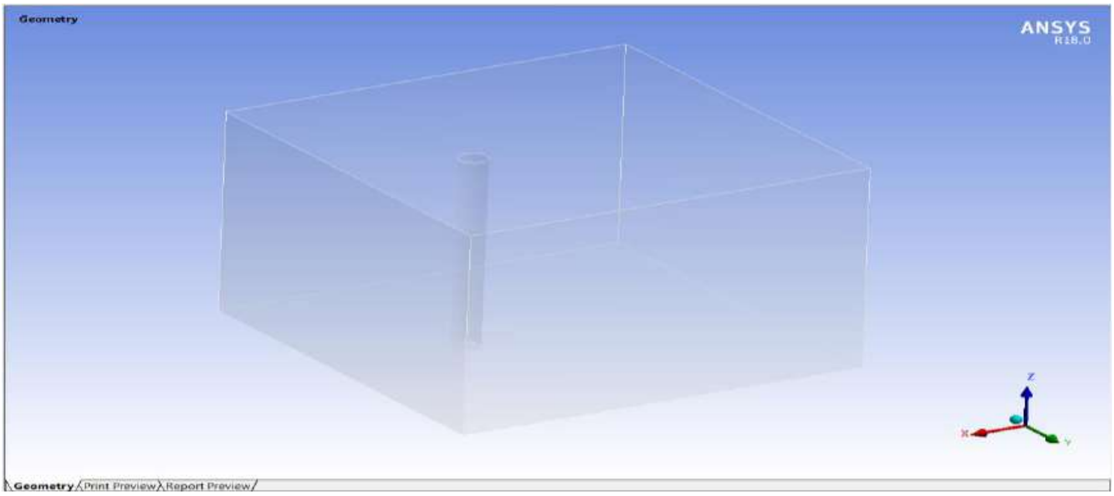

Fig. 1. The model geometry of a circular-shaped pier

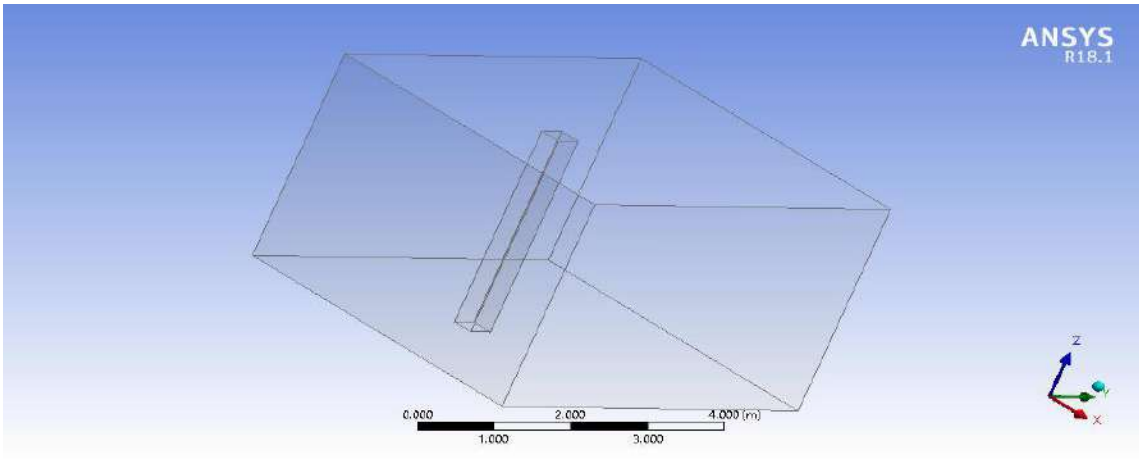

Fig. 2. The model geometry of a rectangle-shaped pier

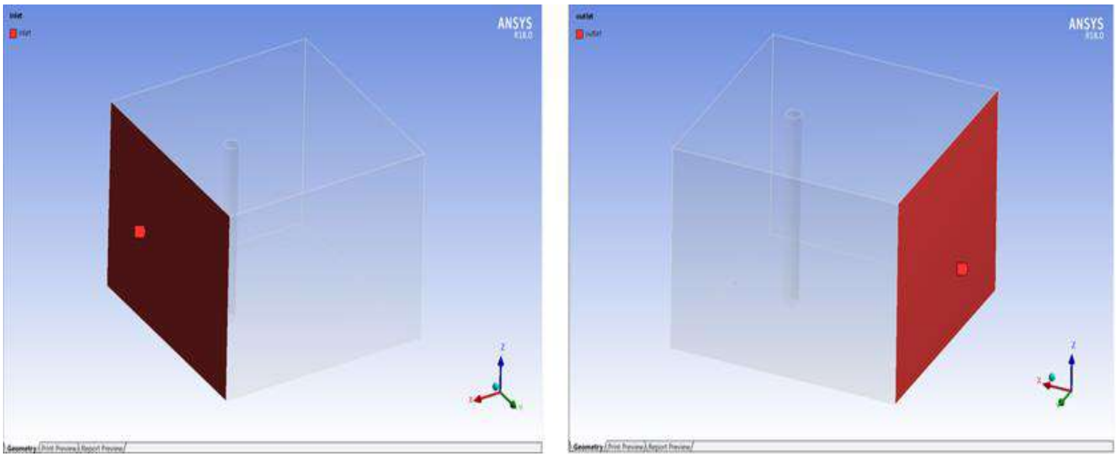

Fig. 3. The model boundary conditions for circular-shaped pier a) inlet b) outlet

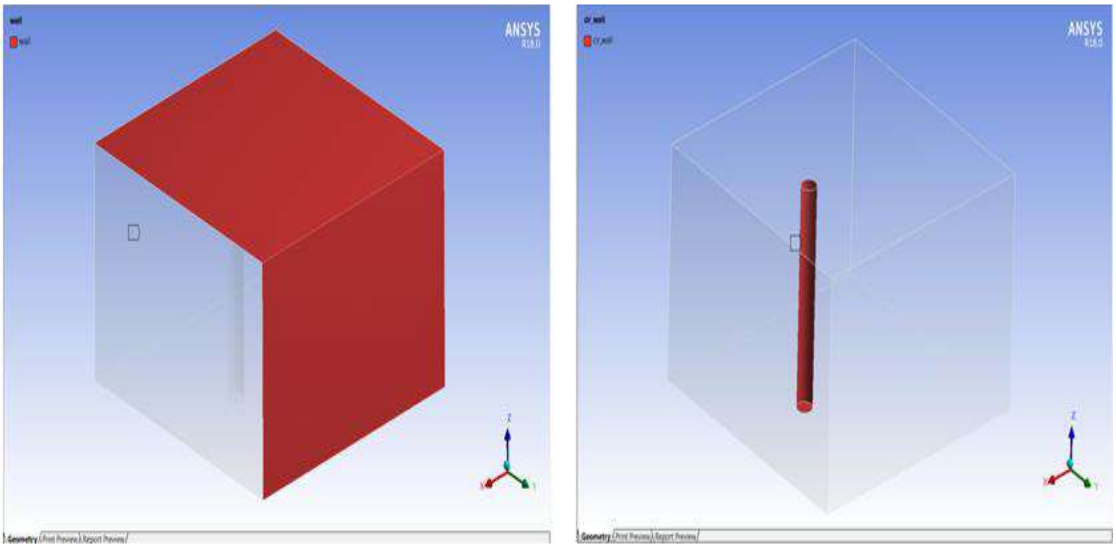

Fig. 4. The model boundary conditions for circular pier c) wall d) circular area

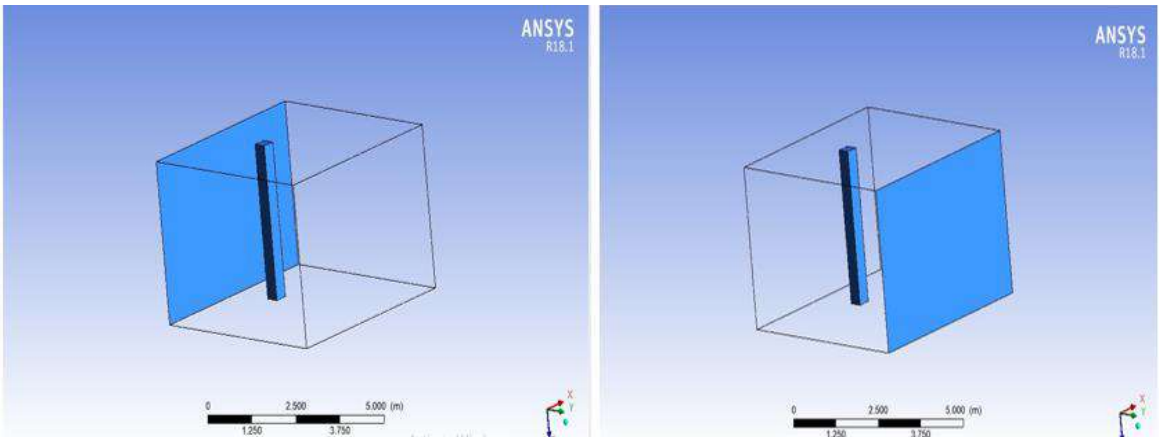

Fig. 5. The model boundary conditions for rectangular-shaped pier a) inlet b) outlet

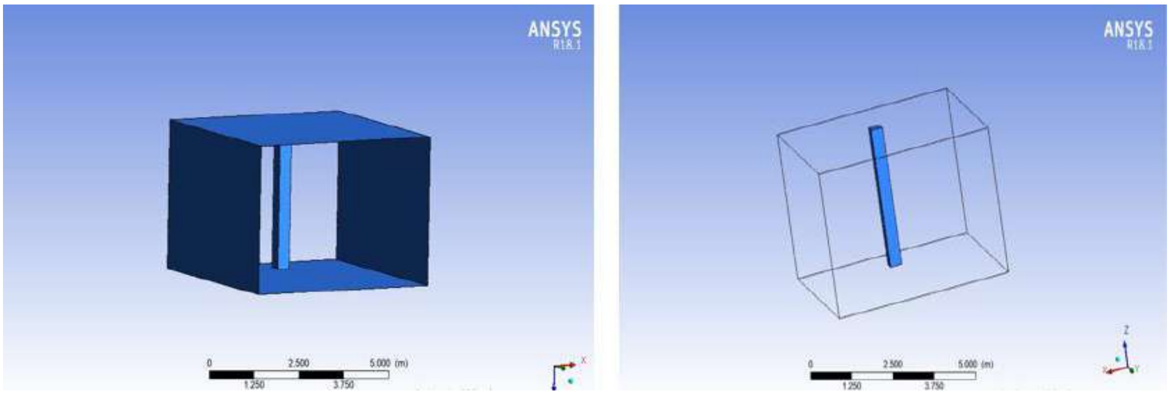

Fig. 6. The model boundary conditions for rectangular pier c) wall d) circular area

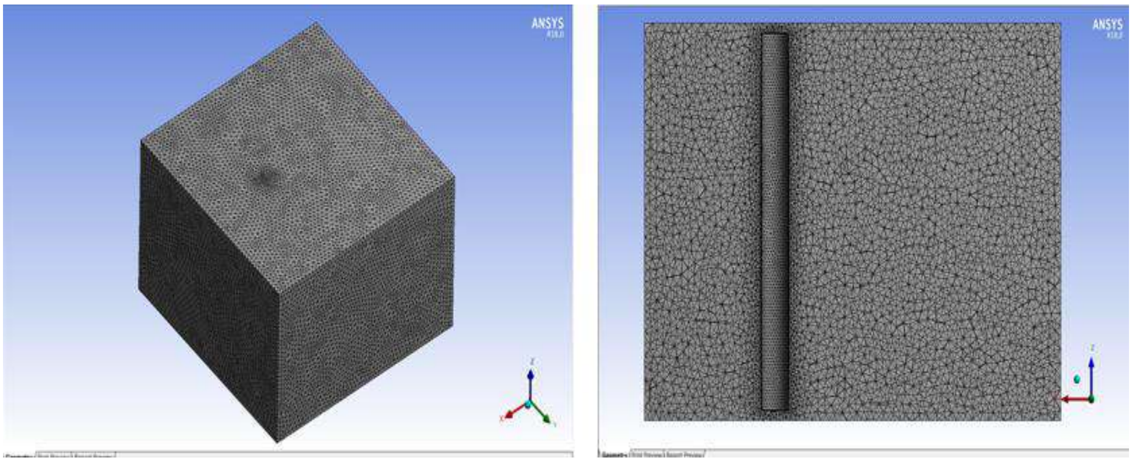

Fig. 7. The model was discretized in adaptive mesh

It should be illustrious that the flow domain is limited to cutting-edge cuboids with dimensions of 5 X 7 X 3.5 m in X, Y, and Z ways. The arrangement circumstances for representations of the rectangular and round pier are similar, as shown in Fig. 3-7. The rate of the fluid field varies to originate the force deviation. In this phase, the configuration's performance is insignificant. The bridge piers were shown as an amorphous form. Fig. 4 and 6 shows that the nonslip partitions are presumed to be margin circumstances for unstructured piers. Fig. 7 demonstrates that an adaptive mesh was developed to minimize analysis time and lead to an optimum design. The current research work is concerned with the flow domain and uses ANSYS Fluent 18.0.

3. Results and Discussions

As recommended by AS5100.2 as an acute flood situation, the flood range considered is 3.5 m high. For the region at various velocities, at 0.5 - 4 m/s, increasing by 0.5 m/s has been employed. Fig. 8 and 9 depict a flow region surrounded by a pier by a flooding domain and show pressure contours.

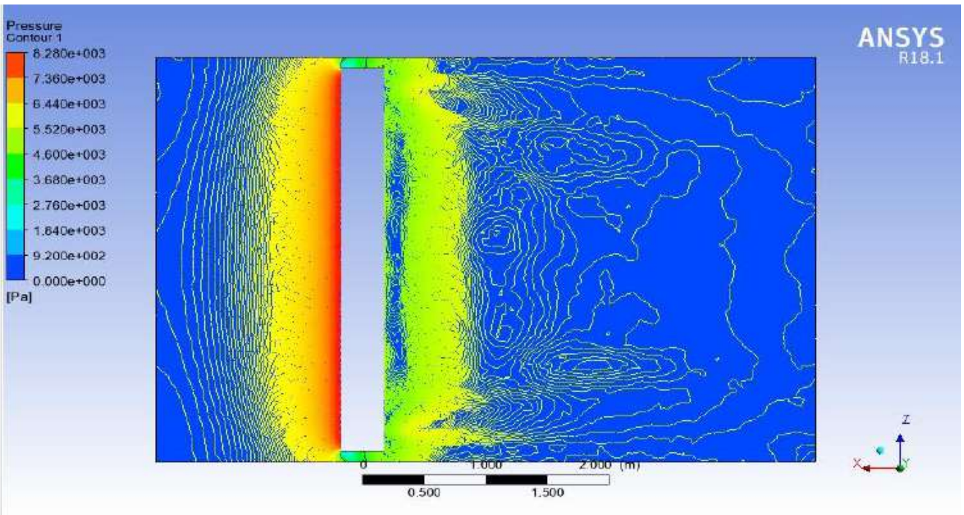

Fig. 8. Pressure contours are obtained on a circular pier with an inlet water velocity of 4 m/s.

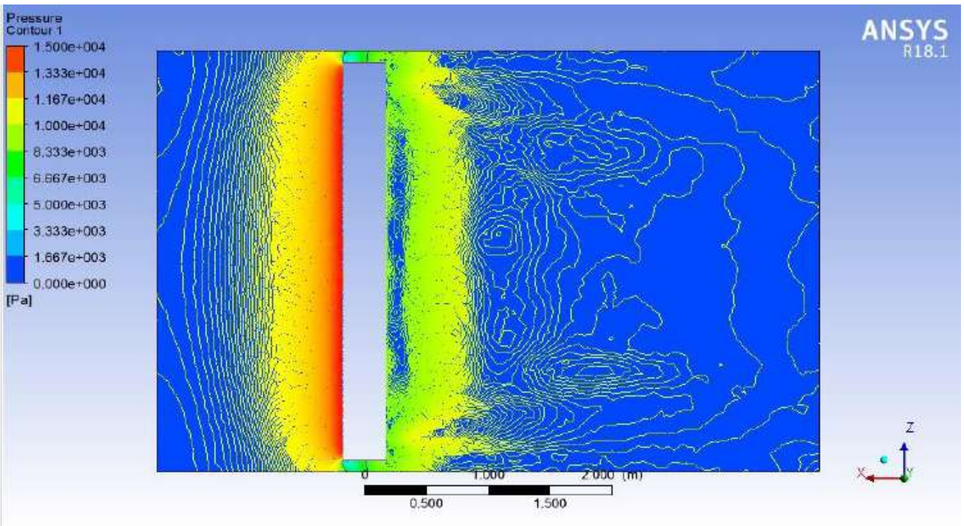

Fig. 9. Pressure contours are obtained on a rectangular pier with an inlet water velocity of 4 m/s

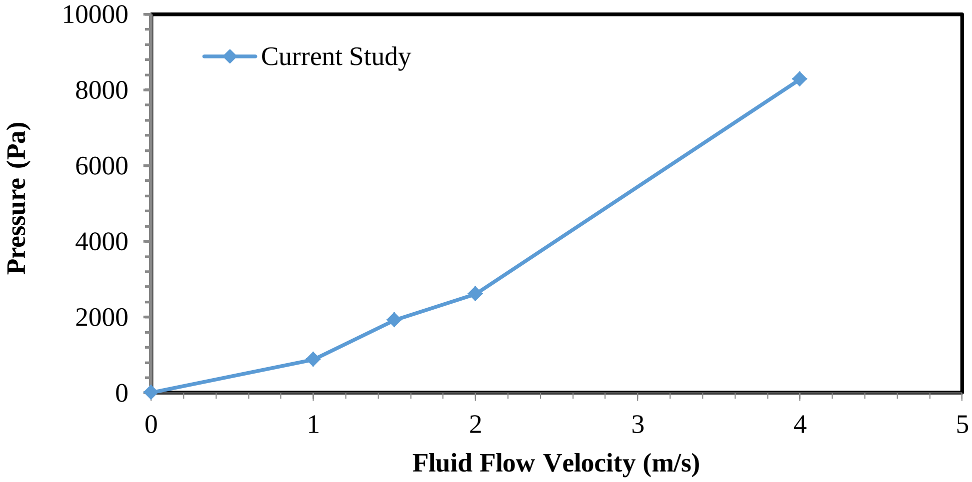

Fig. 10. C.F.D. pressure results on a circular pier with various water flow velocities

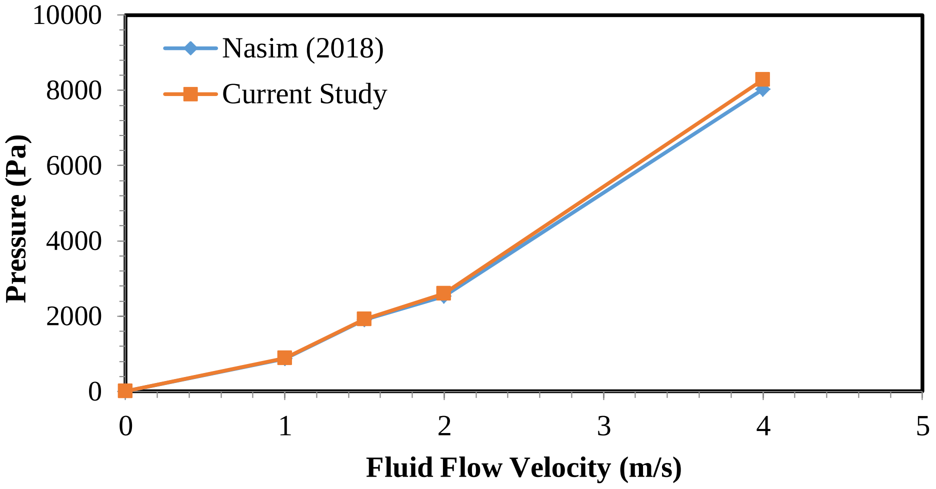

Fig. 11. Comparative graphs of pressure vs. velocity results for circular pier

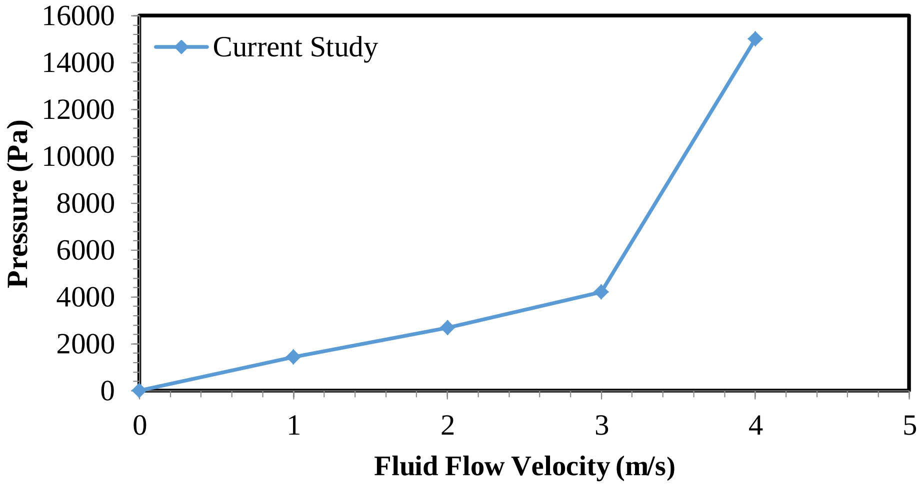

Fig. 12. C.F.D. pressure results on a rectangle pier with various water flow velocities

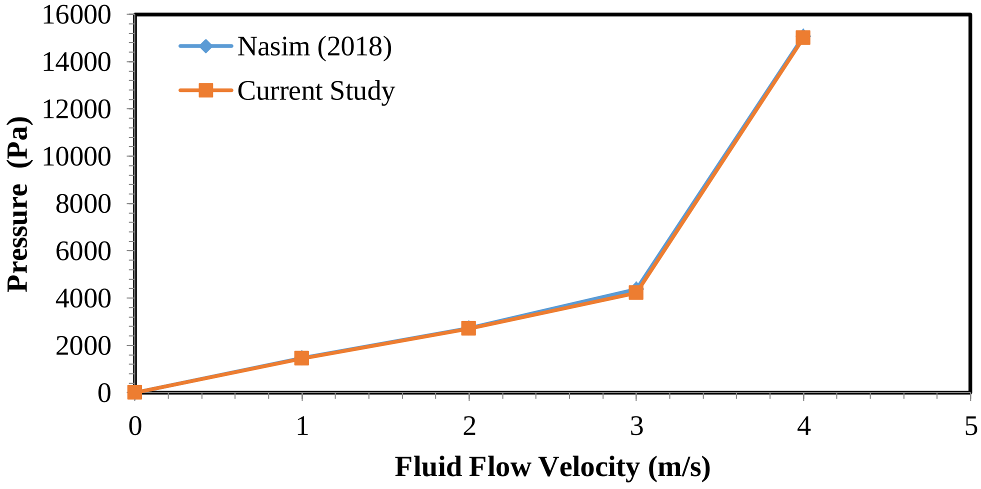

Fig. 13. Comparative graphs of pressure vs. velocity results for rectangular pier

The positive forces were chosen on the rectangular and circular pier at different rates from 0.5 m/s to 4 m/s in Fig. 10 and 12. For validation on the rectangular, in addition to the circular pier at a rate of 4 m/s entry, Fig. 8 and 9 display pressurized contours findings. The findings agreed well with Nasim 2018 results for both shapes, as shown in Fig. 11 and 13. These forces may be seen via the usage of C.F.D. Simulation [35].

The pressure circulation on the rectangular pier along the pier top implies a reasonable curve by the usual rate (excluding the apex and bottommost); however, the stress dispersal on the circular pier changes. The standards in the circular pier are equally accurate (except for the apex and bottommost) as those in the rectangular pier. There is a major variance in severe stress on a pier aspect. The pressure distribution shows that the shape significantly impacts the water flow pressures.

Pier pressure parallel to the course of the water flow will be calculated by equation 1 [36]:

$$P = 52\,K\,V^2 \text{ ………………….. (1)}$$

Where,

P is the pressure intensity (kilograms per square meter) that is out of the ordinary in the path of the water current, V is the velocity (Meters per second) of the water flow, and K is a constant with the subsequent standards for the numerous pier forms shown in the figures [6, 34]. (a) Square ends piers = 1.5 (b) Circular ends piers = 0.66

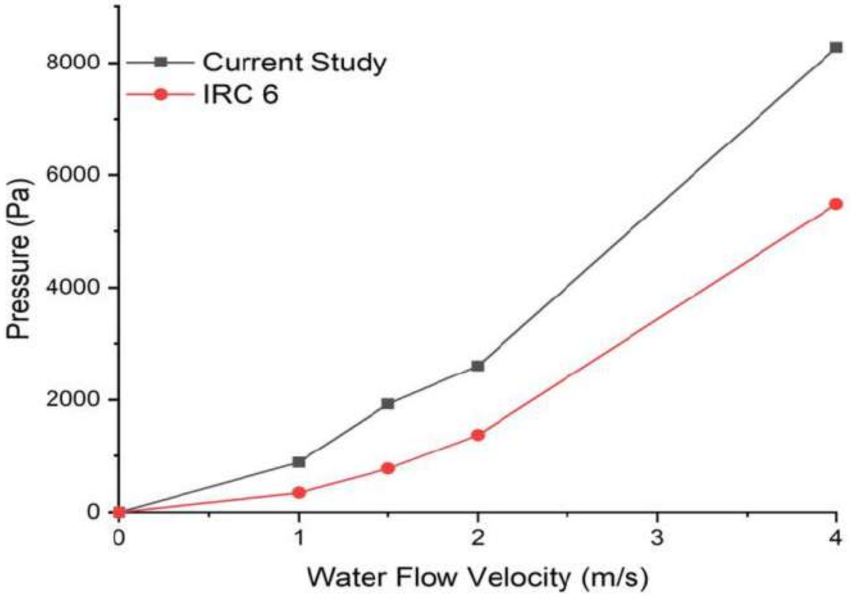

Fig. 14. Positive pressure data from a circular pier were compared to the Indian Road Congress (IRC) 6 code equation.

The findings from Figure 14 indicate that at lower water velocities, the pressure values for the circular pier are similar, indicating a relatively calm and less turbulent flow. However, as the fluid velocity increases, the pressure difference between different points on the circular pier becomes more significant, suggesting that turbulence in the fluid domain is higher. This observation raises concerns about the reliability of the standard equations used for analyzing the circular pier's pressure distribution. The standard equations seem to be less accurate and conservative as they do not fully capture the effects of increased turbulence at higher fluid velocities.

On the other hand, the C.F.D. pressure readings for the rectangular pier are consistent and agree well with the results at faster fluid velocities, indicating a more stable and reliable analysis as shown in Figure 15. In contrast to the circular pier, the rectangular pier's pressure distribution shows conservatism, meaning that the calculated pressures tend to be on the safer side compared to the standard equations [36]. The rectangular pier has more streamlined edges and faces compared to the circular pier, which results in smoother flow around the pier. This streamlined shape reduces turbulence and separation of the flow, leading to more predictable and conservative pressure distributions.

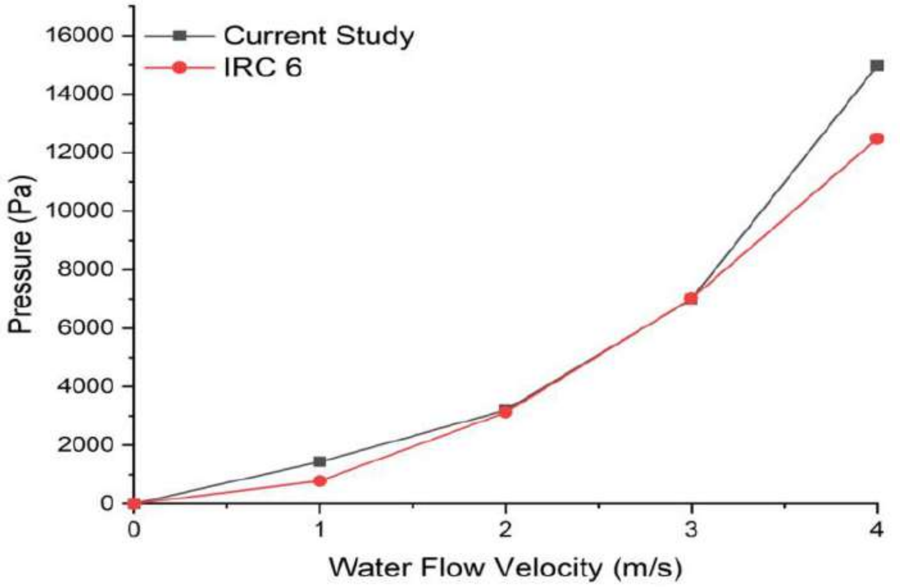

Fig. 15. Positive pressure data from a rectangular pier were compared to the Indian Road Congress (IRC) 6 code equation.

4. Conclusion

Bridges are among the utmost susceptible constituents of transportation infrastructure. As a result, load assessments can assist bridge design codes. The water pressure generated by flow nearby two alternative configurations of a particular pier is investigated in this work to understand how the pressure might be reproduced in structural investigation. Two distinct forms with the similar diameter, rectangular and circular, were subjected to replicated water flow. The research described here proposes a methodology for determining the effects of floods and objects on bridge piers. Outcomes are useful in determining the vulnerabilities of infrastructures to flood loading and the extent of the damage. To estimate the susceptibility of piers in flood loading, it is necessary to identify the kinds of loads applied to flood-prone bridge piers. According to a literature survey, this area lacks information, with utmost research assuming a simplified uniformly distributed static load (U.D.L.) on a bridge pier. In this investigation, Ansys Fluent was used to simulate fluid dynamics. This study reveals that a U.D.L. can be safely assumed to represent flood loads. However, the intensity of the applied load was influenced by the form of the pier. A major influence on the flow field is introduced by the circular shape. A study showed that a rectangular shape performed better than a circular shape. The I. R. C. 6 approach is appropriate for calculating the pressure of a rectangular pier in a conservative manner. Overall, this comparison between the circular and rectangular piers highlights the importance of using more advanced methods like C.F.D. for accurate analysis, especially when dealing with turbulent flow conditions, and raises doubts about the reliability of standard equations for certain scenarios.

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