Journal of Applied Fluid Mechanics, Vol. 16, No. 7, pp. 1296-1315, 2023.
Available online at www.jafmonline.net, ISSN 1735-3572, EISSN 1735-3645.
https://doi.org/10.47176/jafm.16.07.1691

Optimizing Pier Design to Mitigate Scour: A Comprehensive Review and Large Eddy Simulation Study

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(Received December 8, 2022; accepted March 26, 2023)

ABSTRACT

Scour-induced sediment erosion poses a significant threat to the safety and longevity of infrastructure, including bridges, wind turbines, elevated buildings, and coastal infrastructure. Despite the well-known destructive consequences of scour, accurate models that capture the complexity of its dynamics remain elusive, impeding the development of effective countermeasures. We provide a comprehensive review of existing literature on scour dynamics and examine the fluid dynamics and bed shear stress surrounding bridge piers. We propose CFD (Computational Fluid Dynamics) simulations with LES (Large-Eddy Simulation). The current paper demonstrate that LES is a more effective technique than RANS (Reynolds averaged Navier-Stokes) for investigating bridge scouring. The LES simulations study local scour induced effects and compare the findings with RANS simulation results. Besides, two countermeasures are modeled, delta vane and plate footings, to decrease scour around piers. The results show that both countermeasures effectively reduce the shear stress, and we also suggest a combination of a delta vane and a plate footing as a promising solution to reduce upstream and downstream bed shear stress. The paper highlights the importance of thorough investigations on bridge scouring and the need for effective countermeasures to protect infrastructure from scour-related damage or collapse. The recommended countermeasures hold significant promise to reduce construction and maintenance costs and extend infrastructure longevity.

Keywords: Scouring; Bridge pier; Flood, Large eddy simulation; Hydrodynamic countermeasures.

1. INTRODUCTION

1.1 Background and Motivation

Scouring is a complex phenomenon in which soil, sediment, and rock are eroded from the foundation of a pier or a support, leading to instability and potential collapse (Estes and Frangopol 2001; LeBeau and Wadia-Fascetti 2007). The disastrous consequences of bridge failures, such as the 2007 Minnesota I-35 W Bridge collapse resulting in 13 deaths and 145 injuries, as well as a direct loss of 60 million USD in 2007 and 2008 (Xie and Levinson 2011), have highlighted the critical need for research to improve bridge stability and safety. Among the frequent causes of bridge failure is scour near bridge piers, responsible for approximately 80% of pier wash-out failures (Pasiok and Stilger-Szydło 2010). Flooding and scour are also major causes of damage, accounting for 53% of bridge failures in a study of 500 bridges between 1989 and 2000 (Wardhana and Hadipriono 2003). The susceptibility of bridges to scour is evidenced by the 20,000 bridges in the USA identified as highly vulnerable to scour (Gee 2008). In addition, a study of 1,502 bridge failures between 1966 and 2005 showed that approximately 60% of these failures were attributed to scour (Hunt 2009), with flooding and scour being common reasons of bridge failure, as illustrated in Fig. 1. Scour caused 29 of the 108 instances of bridge failure in New Zealand (Melville 1992). Therefore, a thorough investigation of scour depth is imperative to ensure resilient and economical design of bridges.

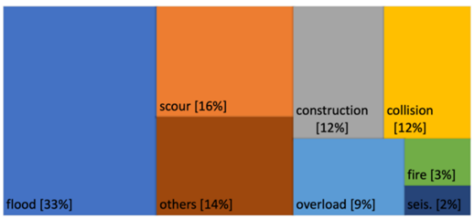


Fig. 1. Leading causes of failures in bridges in the U.S. (Wardhana and Hadipriono 2003).

1.2 Scouring Mechanisms

Scour is a phenomenon of riverbed lowering, induced by hydrodynamic forces that are generated due to the interaction of flowing water with bridge piers. This phenomenon can occur under both normal and flood conditions (Pasiok and Stilger-Szydło 2010). Scour initiation at piers involves sediment removal. Water flow around the pier creates a descending motion and elevated speed, leading to the development of horseshoe-shaped vortices near the pier's structure, which cause erosion of sediment beneath the foundation, ultimately causing a scour hole near the pier (Aly and Dougherty 2021) (Fig. 2). To overcome the obstruction caused by abutments and piers, bridges are often built across rivers. However, due to the nonuniform velocity profiles, the pressure in the stagnation plane decreases from surface to bed according to the following equation (Singh *et al*. 2022).

$$P_{Stag} = \rho . g . h + \ 0.5\, \rho . V^2 \tag{1}$$

The alteration of stagnation pressure induces three distinct changes in the flow regime. Firstly, the pressure gradient results in a downward flow, which then triggers erosion and consequently leads to the development of a scour hole in the upstream flow direction, next to the pier. Secondly, the upstream flow separation caused by adverse pressure creates a horseshoe vortex with a helical flow pattern. Lastly, the interaction between the horseshoe-shaped vortex and the downward flow detaches sediment from the bed in the vicinity of the pier, causing sediment dislodgement (Fig. 2).

The scouring mechanism is significantly influenced by three flow phenomena, namely horseshoe vortices, accelerated flow near pier sides, and vertical wake vortices (Moncada-M *et al*. 2009). Among these, horseshoe vortices are considered the most dominant as they occur upstream and have the greatest intensity (Dargahi 1990; S. Das *et al*. 2013). Accelerated flow near pier sides increases the shear stress and initiates scouring near the edges (Ettema *et al*. 2017), while wake vortices trigger entrainment and downward sediment movement, depending on the Reynolds number (Ali and Karim 2002; Graf and Istiarto 2002; Raudkivi 1986).

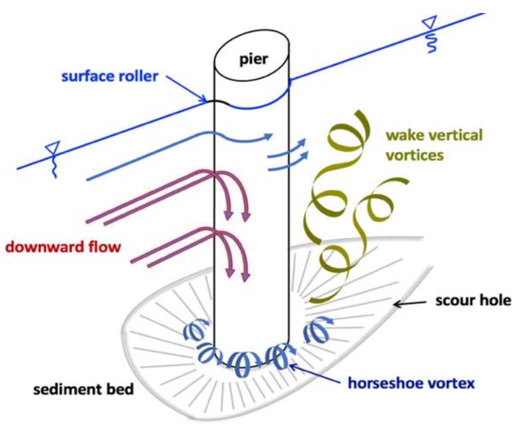


Fig. 2. Mechanism of scour formation around bridge piers.

Scour may be classified based on changes in flow patterns into three types, namely local, contraction, and general scour (Richardson and Davis 2001a). General scour occurs without obstacles in the flow and typically happens for short-term bed elevation changes like flooding (Melville and Coleman 2000). Contraction scouring is due to the width reduction of the channel or river. Local scour, on the other hand, occurs around structural impediments such as a pier or pile that causes bed sediment removal or river bank degradation, making it the most common scour for bridges (Kothyari and Kumar 2010; Singh *et al.* 2022. The current study focuses on local scour, which may be characterized by processes such as aggradation and degradation (Pasiok and Stilger-Szydło 2010).

Local scouring is a complex phenomenon that presents a significant challenge in prediction (Zaid *et al.* 2019). It may be classified as clear-water scouring and live-bed scouring, based on the extent of upstream rubble movement. Contraction scour is produced due to a contraction such as a bridge (Wang *et al.* 2017). Many factors influence scouring, including but not limited to the pier's shape and flow velocity.

It is worth noting that wind-induced scour is a different issue. To explain the annual mean oxygen-isotope ratio at an ice divide, the scouring caused by wind-driven snow removal must be considered (Fisher *et al*. 1983). When analyzing ice-core climatic records, adjustments must be made to account for the impact of scouring. Winds near the surface over Antarctica intensify as they descend along relatively sharp surface gradients, leading to erosion and sublimation of snow. Accurate quantification of wind-induced scouring is essential for estimating the Antarctic surface mass balance (I. Das *et al.* 2013). Wind-induced iceberg scouring reduces the survival rate of Antarctic benthic organisms (Barnes and Souster 2011).

1.3 Objectives and Paper Organization

The objectives of this paper are to comprehensively review existing research on scour dynamics and investigate the fluid dynamics and bed shear stress surrounding bridge piers using computational fluid dynamics simulations with Large Eddy Simulation (LES), to compare the effectiveness of LES and Reynolds averaged Navier-Stokes (RANS) for investigating bridge scouring, to model and evaluate the effectiveness of two countermeasures (delta vanes and plate footings) in reducing scour around piers, and to provide recommendations for effective countermeasures to protect infrastructure from scour-related damage or collapse, ultimately contributing to the reduction of construction and maintenance costs and extension of infrastructure longevity.

The remainder of this paper is organized as follows: Section 2 presents a comprehensive review of existing research on scour dynamics, including hydrodynamic and geotechnical effects, and the engineering side of scour. Section 3 details the methodology for the CFD simulations with LES used to investigate bridge scouring, including Reynolds averaged RANS simulations and eddy resolving turbulence models. In Section 4, we present the results of the LES simulations on a cylindrical pier, including the effects of two different sub-grid scales (SGS) models, and the comparison with RANS simulations. Section 5 explores the application of two countermeasures to decrease scour around piers, namely delta vanes and plate footings, and presents the simulation results. Finally, Section 6 provides a summary of the study's findings and recommendations for effective countermeasures to mitigate scour-induced sediment erosion and protect critical infrastructure.

2. Literature Review and Knowledge Gaps

Melville and Coleman (2000) present a comprehensive and detailed analysis of bridge scour, including its causes, types, and methodologies for scour depth estimation. Their research indicates that bridge scour is a complex phenomenon induced by various factors such as sediment properties, flow characteristics, and bridge geometry. Based on their findings, methods that integrate field observations and numerical modeling are deemed the most reliable for scour depth estimation (Melville and Coleman 2000). The scouring mechanism is a complex process that has been explored by researchers from diverse disciplines and expertise. Studies conducted in the past four decades are categorized into two main groups (Wang *et al.* 2017). The first category emphases the scientific aspects of the scouring mechanism, addressing the fundamental questions of why and how it occurs. The second category concentrates on the engineering aspects, aiming to develop practical solutions and methods to mitigate the effects of scouring.

2.1 Hydrodynamic Effects on Scouring

The study of scouring encompasses various research disciplines that seek to investigate the mechanisms behind this complex process. Specifically, researchers aim to address critical questions related to the hydraulic, geotechnical, and structural aspects of scouring. Over the years, scholars from diverse fields have made significant contributions towards advancing our understanding of this phenomenon.

Hydraulic Factors. The hydraulic aspect of scouring research investigates the development of horseshoe-shaped vortices, downward flow, and other wake vortices that mobilize sediments near piers. Bluff body wakes, in general, exhibit instability that can impact the scour mechanism (Bhattacharya and Gregory 2015, 2018, Joshi and Bhattacharya 2019; Bhattacharya and Gregory 2020). To achieve accurate results, researchers have attempted to replicate real-world conditions in the laboratory. To understand the effects of contributing factors, simple pier shapes were utilized in most experiments. Under standard laboratory conditions, steady current situations were established, and empirical equations were developed by studying the role of various factors on scour depth. Empirical formulations were derived from these investigations by (Melville and Sutherland 1988; Breusers and Raudkivi 1991; Dey *et al.* 1995; Sheppard *et al.* 1995). The normalized depth of local scour is predominantly induced by the combination of velocity, water depth, and the pile-diameter to the median sediment grain-size ratio. Another group of researchers investigated scouring in the presence of waves, which is complicated due to unique factors such as wave period, wavelength, and wave height. In addition, waves introduce the circulatory motion of water particles. Initially, limited experimental data hindered extensive research into this sub-branch of scouring (Wang *et al.* 2017). In the early stages, attempts were made to study scouring under waves in the publication by (Sumer *et al*. 1992). Besides the scale, other effects such as Reynolds number and pile roughness were identified in the study (Sumer *et al.* 1993). Furthermore, prediction models for estimating scouring in random waves were developed in (Myrhaug and Rue 2005). Moreover, recent papers have investigated scouring in the joined presence of wave and current (Zanke *et al.* 2011; Qi and Gao 2014).

Structural Factors. The structural aspect of the investigation into the scouring mechanism is of equal importance to the hydraulic factors. This research domain focuses primarily on examining the influence of the shape and orientation of the pier on scouring phenomena, comprising two distinct components: the superstructure and foundation. Initially, this area focused on single piles placed in sandy soil. However, with the increasing demand for larger and longer bridges, engineers must employ other types of piers and piles in practice (Wang *et al.* 2017). To develop the technology and theory, several researchers explored scouring by using simple pier shapes under current and wave conditions in the embryonic stage (Raudkivi and Ettema 1983; Whitehouse 1998; Richardson and Davis 2001a; Sumer *et al.* 2007). Although the findings are beneficial for those particular situations, the growing demand for longer bridges has driven researchers to study complex bridge foundations using established technology. Over time, research attempts to investigate scouring around pile groups have increased, but it is still limited and needs further exploration.

Notable research papers that investigate the scouring mechanism around group piles include (Salim and Jones 1996; Ataie-Ashtiani and Beheshti 2006; Amini *et al.* 2011; Liang *et al*. 2017, 2015). These studies reveal the differences in scouring mechanisms between single piers and group piles. In group piles, the mutual interaction of multiple individual piles complicates the process and is accompanied by the 'shielding effect' and 'jetting effect.' In the case of group piles, the piles in the front experience higher scouring depth, while those in the rear experience lower scouring depth, known as the 'shielding effect.' Additionally, when the flow accelerates between piles, creating a narrowed-down channel, it causes higher sediment/soil removal on the riverbed, resulting in a larger scour depth in group piles compared to single piers. However, the research field concerning the combined effects of 'shielding' and 'jetting' is limited and requires further attention. Furthermore, scouring investigation of more complex pier shapes requires considerable research to improve bridge safety.

2.2 Geotechnical Effects on Scouring

The scouring mechanism is influenced by several hydraulic factors that trigger geotechnical consequences. The hydraulic factors dictate the behavior of particles, and the performance of the riverbed is further influenced by the particle type. For example, coarse and fine sand exhibit different behaviors under similar hydrodynamic forces, highlighting the importance of geotechnical aspects in scouring research. Soil particle mobilization is dependent on factors such as adhesion properties, particle size, soil composition, and degree of saturation, making it crucial to consider the geotechnical factors in scouring research.

Previous studies have investigated the scouring mechanism around piles driven into sandy soil (Imberger *et al*. 1983; Melville 1984; Melville and Sutherland 1988). Cohesionless soil particles are more prone to scouring and can erode particle by particle, resulting in a rapid attainment of maximum scour depth in a few hours or days. Conversely, cohesive soil particles exhibit a slower scour rate, leading to a longer duration to reach scour equilibrium. In some cases, significant scour depths may not appear until years after bridge construction. Cohesive riverbeds have been the focus of several research studies to understand scour phenomena (Rambabu *et al*. 2003; Najafzadeh and Barani 2014), , and predict scouring in similar conditions of such soil types depends on several parameters such as plasticity index, temperature, and void ratio (Briaud *et al*. 1999; Briaud *et al.* 2001; Dolinar 2010).

Scouring can also occur in cases where the bridge pier rests on a rock foundation. When the flow's scouring ability surpasses the resistance limit of rock foundation, scouring is observed, which is a practical concern for dams and spillways (García 2007). Scouring of rock foundations can manifest in four forms: brittle fracture, block removal, abrasion, and subcritical failure (Bollaert 2004; Bollaert and Schleiss 2005). Future studies may address the investigation of other particle types in the riverbed.

2.3 Engineering Solutions to Scouring

The domain of scouring-related research concerned with engineering aims to prevent bridge failures by developing strategies and technologies to mitigate scouring. This domain comprises three branches, namely (a) the precise estimation and prediction of the depth of scouring, (b) the development of countermeasure strategies, and (c) the monitoring of scouring during the service life of bridges.

Estimating Scour Depth. To estimate the depth of scouring, dependable models based on computational and experimental investigations are essential (Blessing *et al.* 2009; Ramos et *al.* 2016; Zhang and Shi 2016) (Espa and Sibilla 2014). Richardson and Davis (2001a) describe various methods for evaluating scour at bridges, including field observations, physical modeling, and numerical modeling. They found that numerical modeling is a useful tool for predicting scour at bridges, but that physical modeling and field observations are also important for calibrating and validating the numerical models (Richardson and Davis 2001b). However, the accuracy of these models can be limited by several factors, including but not limited to (a) scaling issues in experiments, (b) over-simplification of flow and bed materials in the laboratory, (c) the paucity of field data for validation, and (d) difficulty in retrieving accurate field data due to rough river or sea conditions (Wang *et al*. 2017). The underestimation of the depth of the scour hole can lead to fatal bridge failures, while overestimation leads to uneconomical designs. Several researchers have attempted to develop reliable empirical models by considering single piers and group piles (Jain and Fischer 1979; Melville and Sutherland 1988; Mohamed *et al*. 2005; Kumar and Sreeja 2012). The depth of scour depends on critical parameters outlined in previous sub-sections. Some studies have compared previously developed numerical equations from experiments with measured field data (Lu *et al.* 2008; Park *et al*. 2017; M. Qi *et al*. 2016; W. Qi *et al*. 2016). These reports suggest that empirical equations can offer conservative predictions. However, some experimental studies report overestimating scour depth compared to field data (Lee and Sturm 2008). Furthermore, some researchers have employed techniques such as neural networks to develop algorithms to forecast scour depth (Lee *et al.* 2007; Kaya 2010).

Countermeasure for Scour. To mitigate the effects of local scour, countermeasure strategies are developed. Most bridges over waterways rest on submerged piers or piles, and fluid motion around the bridge piers often results in sediment loss. This phenomenon reduces the ability of the pier to transmit the load to the bed of the water body and is considered the leading reason of failure (Arneson *et al.* 2012).

Several researchers have investigated scouring and suggested techniques to potentially reduce its effects. The most effective countermeasures to bridge scour are those that prevent or minimize water flow around the bridge supports. Bed armoring techniques, flow-altering devices, and wider mudmat can be broadly classified as effective countermeasures. Rock riprap is one of the bed armoring techniques explored in earlier studies (Chiew and Lim 2000; Dey and Raikar 2007). Multiple types of flow-altering countermeasures like vanes (Odgaard and Wang 1987), slots (Chiew 1992), and collars (Zarrati *et al.* 2006) have also been employed. The efficacy of the mudmat foundation, a less explored technique that adopts a skirted foundation around the pier or pile, has been demonstrated in experimental studies

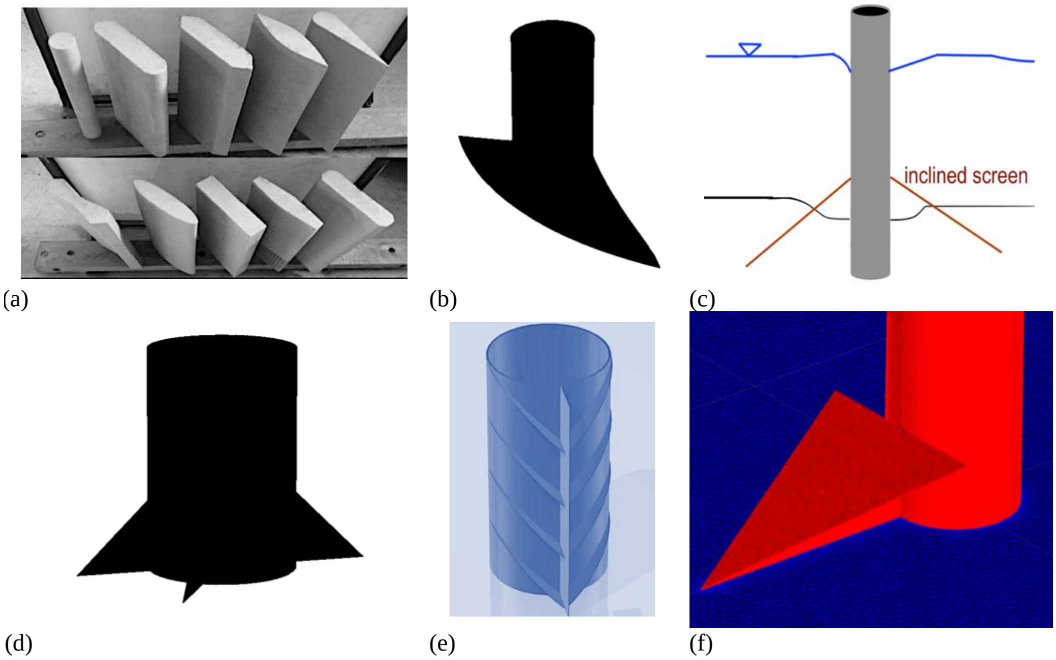


Fig. 3. Various pier shapes and countermeasures can be implemented to mitigate scouring. These include (a) different pier shapes, such as circular, rectangular, hexagonal, sharp nose, or elliptical, which can affect the flow patterns around the pier; (b) streamlined shapes that reduce the resistance to flow and turbulence; (c) inclined screens that help dissipate the kinetic energy of the flow; (d) angled plates that break up the flow and reduce the velocity near the bed; (e) slanting plates that can decrease the power of the horseshoe vortex; and (f) delta-vane that reduces the bed shear stress (Daido and Yano 1995; Parker *et al*. 1998; Tafarojnoruz *et al*. 2010; Al-Shukur and Obeid 2016; Aly and Dougherty 2021).

(Yao *et al.* 2020). Researchers have developed both flow altering, as well as bed armoring devices to reduce the effects of scouring. While a flow-altering device is an active countermeasure, bed armoring is considered passive (Wang *et al*. 2017).

Pier geometry and pier openings are two categories of countermeasures. Streamlined pier shapes have been shown to significantly reduce scour depth (Al-Shukur and Obeid 2016). Exposed pile caps and collars at the base of piers can interrupt and minimize downflow, thereby reducing scour (Baghbadorani *et al.* 2018). Vertical slots and sacrificial piles with openings have also been demonstrated to reduce scour depth, but they present other problems such as debris blockage and a reduction in pier strength (Tafarojnoruz *et al*. 2010).

It is well-known that the shape of an object influences fluid motion around it. Flow separation and consequent reattachment occur around bluff bodies, whereas attached flow occurs around streamlined objects such as airfoil wings. Modifying the shape of piers or piles could potentially counteract the flow features that instigate scouring around pier foundations (Fig. 3). Active countermeasures are fundamentally based on this theoretical approach. However, both active and passive countermeasures enable the reduction of triggering flow characteristics such as downflow and horseshoe-shaped vortices (Melville and Coleman 2000).

Analysis and interpretation of seabed bathymetric monitoring data near offshore wind farms revealed how scour progressed over time and revealed differences between sites with different sediment characteristics (Whitehouse *et al*. 2011). Some loss prevention devices such as rock armor are installed for foundation and cable protection to ensure structural stability. However, the interaction of rock armor with ocean currents causes marginal or secondary erosion of the seafloor.

2.4 Research Needs and Future Directions

Based on the literature reviewed, several knowledge gaps exist in the area of local scour around piers. One major gap is the lack of a comprehensive understanding of the mechanisms of scour formation and erosion around piers, particularly in complex flow conditions. Another gap is the limited availability of reliable data on the effects of different hydraulic and geotechnical factors on the magnitude and extent of scour. Additionally, developing efficient and accurate numerical modeling techniques to predict scour depth and designing effective countermeasures remains an ongoing challenge. Further research work is necessary to tackle these gaps in knowledge and improve our understanding of the complex interplay between flow dynamics, erosion, sediment transport, and scour formation around bridge piers.

3. CFD SIMULATIONS FOR LOCAL SCOUR

Computational fluid dynamics (CFD) simulations are a valuable tool for investigating complex flow patterns and changes in shear stress distribution during various phases of scouring around bridge piers. Utilizing CFD simulations can provide critical insights into flow patterns and induced turbulent structures around piers, which can inform optimized pier design and potentially reduce construction and maintenance costs (Moghanloo *et al*. 2020; Aly and Dougherty 2021). Although experimental and numerical approaches are followed to study scouring around bridge piers and develop equations for predicting local scour (Zaid *et al*. 2019), recent advancements in computational power have led to the widespread adoption of numerical modeling in engineering research.

Numerical simulations, such as CFD, offer a solution to overcome limitations encountered in experimental studies. CFD simulations can mitigate scaling effects in experiments and model the flow environment around the pile better than experiments. In addition, CFD allows for better visualization of flow physics near the base of piles and systematic investigation of individual factors that influence local scour (Yu and Zhu 2020). To understand the riverbed, flow, and structure interaction, the powerful tool of CFD is essential for studying scouring mechanisms.

Several pioneering studies have attempted to predict flow and subsequent scouring through numerical simulations (Kocaman *et al*. 2010; Zhu and Liu 2012), and some publications have compared CFD results with experimental results (Lu *et al*. 2008; Zhao *et al*. 2010). The use of a discrete element model (DEM) to model sediment in combination with CFD has shown promising results, but this approach is relatively less explored and presents significant challenges in accurately coupling solid and fluid phases (Kirkil *et al*. 2009; Baranya *et al*. 2014; Zhu *et al*. 2014; Xiong *et al*. 2016; Jia *et al*. 2018; Moussa 2018; Ahmad *et al*. 2020). Therefore, employing CFD and DEM represents a potential area of research for advancing our understanding of local scouring.

3.1 RANS Simulations

Numerous investigations were directed to examine the phenomenon of local scour near bridge piers by utilizing RANS ((Reynolds-Averaged Navier-Stokes) equations with sediment models to analyze the sediment temporal variation around the pier foundation (Olsen and Kjellesvig 1998; Olsen and Melaaen 1993; Salaheldin *et al*. 2004; Zhu and Liu 2012). The use of RANS models has proven to be crucial in reducing the demand for computational resources. RANS turbulence closures allow for the investigation of scouring at field-level Reynolds numbers and can be employed in association with wall functions to reduce computational time. However, inaccurate predictions from RANS simulations have been noticed for flow scenarios accompanied by adverse pressure gradients and vortex shedding (Ettema *et al*. 2017).

To accurately model the upstream horseshoe and vertical vortices in the wake, which are crucial in realizing the effects of scouring using CFD, it is necessary to employ transient turbulence models such as LES and DES (Zhang and Ishihara 2018). RANS closures are inadequate for predicting such complex flow behavior and are not the ideal CFD tool for investigating bridge scouring (Ettema *et al*. 2017). While unsteady RANS turbulence closures perform better than steady RANS closures in addressing such flow problems (Paik *et al*. 2004; Ge *et al*. 2005), they still exhibit inadequacies in accurately predicting crucial attributes of the separation identified by vortex shedding (Rodi 1997; Tokyay and Constantinescu 2006; McCoy *et al*. 2008)

Several studies have utilized RANS turbulence closures in combination with movable bed modules to forecast the hydrodynamics and the evolution of the scour phenomena adjacent to bridge piers (Chen 2002; Nurtjahyo *et al*. 2002; Roulund *et al*. 2005). However, this approach is still in the research phase and has not evolved as a robust design tool mainly because of the uncertainties associated with transport modeling and entrainment of sediments. The fundamental limitations of RANS closures in addressing separated turbulent flows contribute to the identified uncertainties (Zhang and Ishihara 2018).

In summary, the limitations of RANS turbulence closures demand the application of more accurate transient turbulence models such as LES and DES, which can address the inadequacies of RANS simulations in predicting the temporal characteristics of eddies that govern the scouring phenomenon and the emergence and progression of the horseshoe vortex.

3.2 Eddy-Resolving Turbulence Models

In recent years, research has shown the significant potential of eddy-resolving CFD simulation methods to improve the modeling of flow fields and turbulence around bridge piers compared to experimental procedures (Damroudi *et al*. 2021; Pereira *et al*. 2021). Specifically, the use of time-dependent scale-resolving CFD simulations has made it possible to understand the impact of primary flow and pier geometry on the flow field, turbulent structures, and the onset of scouring mechanisms in the vicinity of bridge piers. Scale-resolving CFD techniques, like LES, have proven effective in capturing the physics of coherent turbulent structures near piers. However, conventional scour depth estimation equations have limitations in accounting for the impact of large-scale vortical structures surrounding the piers (Ettema *et al*. 2017). Therefore, adopting numerical techniques that facilitate a better understanding of turbulence is vital for developing reliable equations for scour depth prediction, and LES is widely recognized as a reliable and accurate eddy-resolving CFD simulation technique.

LES resolves large-scale eddies structure and replicates smaller eddies by using the SGS models. This approach effectively addresses spatial scales that exceed the predetermined grid size and accurately represents turbulent eddies that are smaller than the size of the grid. The motivation for adopting LES arises from resolving dominating eddies in the flow field while maintaining a lower cost of computation than DNS (direct numerical simulations).

In the context of studying scouring around piers, it is critical to investigate the large-scale vortical structures that govern the initiation of the scouring mechanism. However, the computational demand required to resolve the fluctuations over the entire frequency range in the flow using traditional DNS methods is unmanageable. Therefore, LES is a suitable simulation technique for this purpose, as it can resolve the higher energy-containing large eddies in the flow. LES enables a more comprehensive understanding of the dynamics and evolution of large-scale eddies and their interactions with the pier and the bed of the water body (Ettema *et al.* 2017). Furthermore, LES is more comprehensive and less expensive than physical experiments, such as PIV (particle image velocimetry). Additionally, LES allows for the visualization of essential flow quantities such as bed shear stress, pressure variations, near-ground velocity field, and the evolution of the wake and horseshoe vortices near the piers.

Earlier LES studies focused on bridge scouring at lower Reynolds numbers for multiple pier shapes and bed orientations. The effects of scouring around piers were examined using LES and RNG k-ϵ (a version of RANS) (Choi and Yang 2002). The cited article concludes that LES captures the upstream vortices much better compared to RNG k-ϵ closure. Also, near the pier, stronger downflow is predicted by LES compared to the employed RANS simulation (Choi and Yang 2002). Another research article (Tseng *et al.* 2000) demonstrated the superior performance of LES in conjunction with the Smagorinsky SGS model in reproducing complex flow physics, such as horseshoe-shaped vortex, the wake vortex in the downstream, and downflow around the pier. Besides, the findings of the cited article are in harmony with experimental results documented in (Melville and Sutherland 1988; Dargahi 1989). However, these two LES studies with relatively coarser grids at low Reynolds numbers were deficient in accurately predicting the mean and instantaneous horseshoe vortices.

Notwithstanding, recent scholarly works (Ge *et al.* 2005; Kirkil *et al*. 2008; Koken and Constantinescu 2008; Kirki and Constantinescu 2015) have conducted analogous investigations while maintaining Reynolds numbers comparable to experimental values of $R_e \approx 15000$ to 50000. The literature cited affirms the promising potential of LES in accurately capturing intricate flow phenomena, including horseshoe and wake vortices and other turbulent structures, which prior attempts inadequately represented. Additionally, LES has demonstrated proficiency in modeling the stages of scour evolution and growth resulting from interactions of large-scale vortical structures, a realm where LES affords a reliable representation. Furthermore, LES enables the visualization of necklace vortices at the pier's base and the variations of mean and instantaneous bed shear stress, which pose challenges for experimental measurements. LES has demonstrated the capacity to capture bimodal oscillations within the horseshoe vortex system (Kirkil *et al.* 2008). LES simulations within the boundary layer, particularly in the lower layers, involve highly resolved calculations akin to those of DNS. Consequently, LES is not well-suited for modeling forces accurately. To address this, RANS-LES hybrid models are employed to model small scales within the boundary layer using RANS, which enables accurate computation of forces, and to simulate large shear layer scales outside the boundary layer using LES.

Hybrid Reynolds-Averaged Navier-Stokes and Large Eddy Simulation (RANS-LES) simulations have emerged as a practical alternative to traditional LES models due to their lower computational cost. Amongst the Hybrid RANS-LES simulations, DES (detached eddy simulation) is a well-established method that can simulate the flow around piers, reducing the reliance on wall functions. A significant difference between LES and DES models is the definition of the sub-grid eddy viscosity. Recent studies have investigated the effectiveness of DES for analyzing flow behavior around bridge piers (Paik *et al.* 2007; Kirkil *et al.* 2009; Koken and Constantinescu 2009; Kirki and Constantinescu 2015). For Reynolds numbers between 10^5 and 10^6, the computational cost of DES is two orders of magnitude less than wall-resolved LES. However, the SGS models utilized with DES dissipate more of the unresolved scales than the traditional SGS models employed with LES, such as the Smagorinsky SGS model. DES has the ability to resolve the large-scale coherent flow structure, like LES. The aforementioned studies have reported the successful application of DES models in investigating scouring.

4. Case Study Using Large Eddy Simulation (LES)

Considering the detailed literature review presented above, the current study will focus on LES to investigate the effects of local scouring. The study explores the velocity field variations and bed shear stress around a cylindrical pier (Triatmadja 2019). The present study continues the exploration of scouring effects using RANS simulations, which was documented in a publication by the first author (Aly and Dougherty 2021).

4.1 Mathematical Formulation of LES

The principle of momentum conservation ismathematically represented by the Navier-Stokes

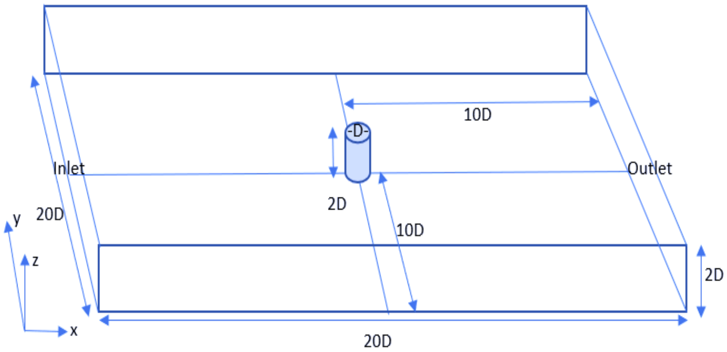


Fig. 4. Computational domain (Aly and Dougherty 2021).

Table 1 Model parameters (Roulund *et al.* 2005)

parameter	value
depth of water [cm]	54
velocity [cm/s]	32.6
boundary layer thickness [cm]	54
diameter of the pier [cm]	53.6
Reynolds Number [-]	1.7×10^5
Froude Number [-]	0.14
friction velocity [cm/s]	1.3

equations, which are frequently coupled with equations governing the conservation of mass. The governing equations associated with large-eddy simulations are expressed as follows (Khaled *et al.* 2021).

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0; \quad \frac{\partial \overline{u_i}}{\partial t} + \overline{u_j}\frac{\partial(\overline{u_i})}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} - \frac{\partial}{\partial x_j}\left(\nu \frac{\partial \overline{u_i}}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j}; \qquad \tau_{ij} = \overline{u_i u_j} - \overline{u_i}\overline{u_j} \tag{2}$$

LES resolves scales that are larger than the filter width, while smaller scales are represented using SGS models. The τ_{ij} expression is a measure of the unresolved LES scales. The Boussinesq assumption provides an alternative to the SGS stress expression. Various SGS models exist for the formulation utilized to elucidate the ν_{SGS} term.

$$\tau_{ij} - {}^{1}/_{3}\,\tau_{kk}\delta_{ij} = -2\nu_{SGS}\overline{S_{ij}} \tag{3}$$

4.2 LES Simulation of Cylindrical Pier Scouring

The present investigation employs an identical computational domain size and boundary condition setup for a rigorous comparison with the RANS results published by the primary author in a prior study. This approach enables the direct comparison of outcomes obtained in the current study with those reported in the previous research and facilitates the evaluation of any differences or similarities observed between the two sets of findings (Aly and Dougherty 2021). Only the numerical settings are modified to execute the large eddy simulation. Furthermore, several trial runs are executed to settle on a suitable courant number that allows stable and computationally efficient LES simulation.

The LES analysis was conducted using the computational domain illustrated in Fig. 4. The dimensions were normalized by the pier's diameter (D = 0.54 m). The domain spanned 20D in the flow and orthogonal directions and had a height of 2D.

This study utilized symmetry boundary conditions at the computational domain's side boundaries and top surface, which assumes zero flux of all flow quantities across a symmetry plane, including mass, momentum, and energy. A slip surface may occur since the shear stress is zero at the symmetry plane. The symmetry condition at the top surface placed a "lid" on the fluid surface. This approach simplifies modeling flows where the free surface is not a critical problem component. A logarithmic inlet velocity profile was applied (Aly and Dougherty 2021). The Reynolds number was set to Re = 1.7×10^5 (Table 1), corresponding to an average flow velocity of 32.6 cm/s. The identical mesh was employed in approximately 2 million cells for both RANS and LES simulations. We first tried a structures mesh, as shown in Fig. 5. By using blocks, a high quality mesh can be produces. For optimization, we conducted a mesh independence study, and the CFD findings are compared with their experimental counterparts. Table 2 lists the mesh detail for each trial, used in the mesh independence study. The 'element count' quantification is contingent upon the computational domain's dimensional properties along the x, y, and z axes, which correspond to the domain's length, width, and height (see Table 2). To account for the flow countermeasures in the computational domain, and to allow for capturing all the geometric detail, and well as flow physics near the wall, unstructured grid was determined to be a reliable choice. Several trials were conducted to obtain the optimum grid. For each grid trials, the detail are listed in Table 3 (mesh 1, 2, 3, and 4). We optimized the unstructured grid in a previous study by the first author, to match the data from a physical experiment. Later the knowledge was applied to other shapes of countermeasures around the pier.

Table 2 Detail of the structured grid with elements count

no. of elements	x-count	y-count	z-count
113,324	60	60	20
277,264	100	100	20
436,796	100	100	32
476,504	100	100	35

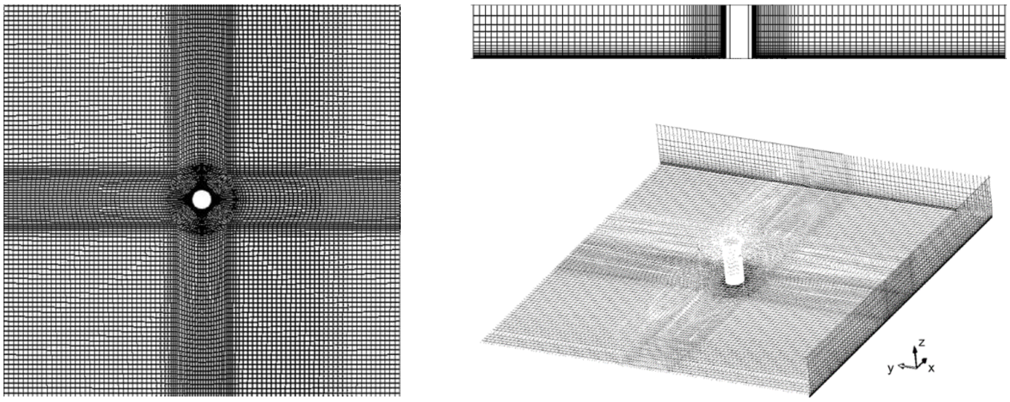


Fig. 5. Structured grid with size of elements being reduced near the ground and the pier (wall).

Table 3 Unstructured mesh parameters specified in meters

grid	elements	density	bottom size	height (bottom)	layers (bottom)	pier size	height (pier)	layers (pier)
i	317,000	0.1	0.1	0.005	5	0.05	0.001	10
ii	372,000	0.1	0.1	0.005	5	0.01	0.005	5
iii	391,000	0.1	0.1	0.005	5	0.01	0.001	5
iv	1.2 million	0.1	0.05	0.005	3	0.01	0.001	3

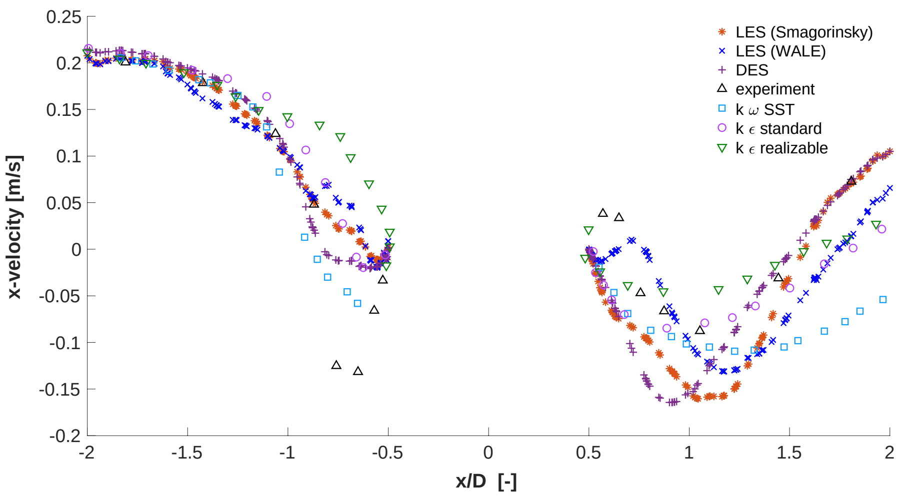


Fig. 6. Velocity component in the along flow direction at elevation 1.9% D.

Figure 5 shows the mesh in a few representative views. Such fine grid is used around the piers to accurately capture the flow structures, which most significantly affect the pier of bridges. The generated mesh indicates how the size of elements decreases towards the cylinder and the bottom surface. Figure 5 presents a high-quality meshing strategy used to investigate the variations in shear stress and velocity distribution. A velocity of 0.326 m/s, a turbulence length scale of 0.54 m, and a turbulence intensity of 5% were used for all the simulation cases.

LES on a Cylindrical Pier. This study aims to check if LES can improve fluid flow prediction in the pier's wake. The flow velocities were recorded with probes at two elevations for a reasonable comparison with the physical experiment. The performance of LES simulations can be significantly varied by employing different SGS models. The current study adopted two different SGS models: WALE and the Smagorinsky-lily model. Results from the two LES cases are reported in this study.

More detail about the experiment is listed in Table 1. Some velocity measurements are compared with experimental data to demonstrate improvements over the previously conducted RANS results.

In the previous RANS simulations, the velocity comparisons are made at elevations 1.9% and 9.3% D. Figure 6-Fig. 7 presents the variation of x-component velocities before and after the pier in the domain. The observations are compared with those from the experiment and the previously conducted RANS simulations (Aly and Dougherty 2021). The figures show that the LES simulation with the WALE SGS model at both elevations offers the best conformance in the wake upon comparing with the experiment. However, k-omiga SST still provide a good match with the experimental results. More

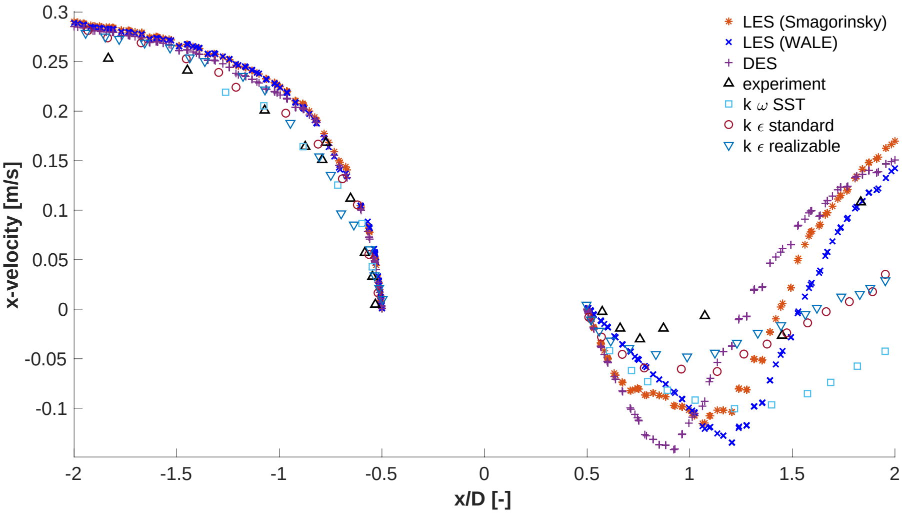
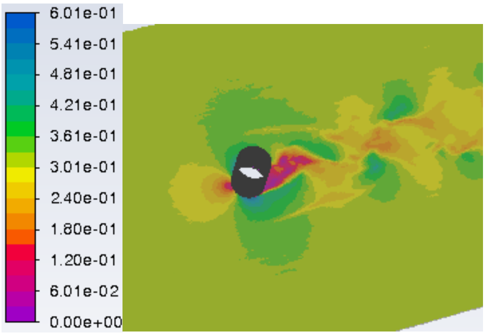
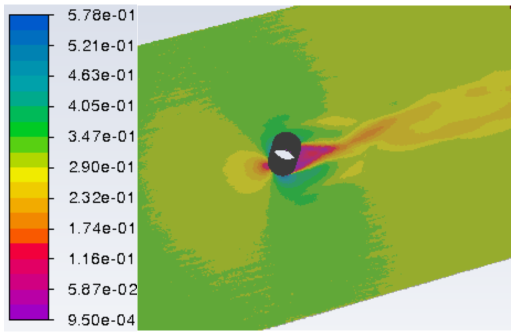


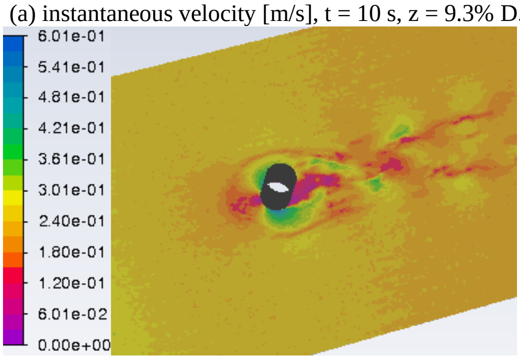
Fig. 7. Velocity component in the along flow direction at elevation 9.3% D.



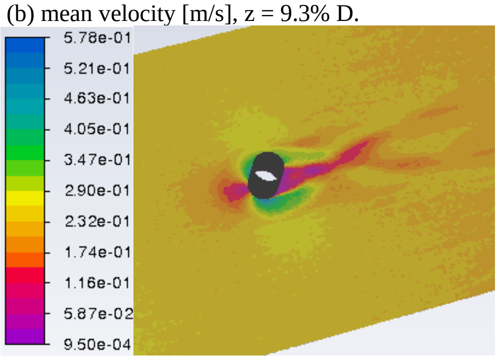
(a) instantaneous velocity [m/s], t = 10 s, z = 9.3% D.



(b) mean velocity [m/s], z = 9.3% D.



(c) instantaneous velocity [m/s], t = 10 s, z = 1.9% D.



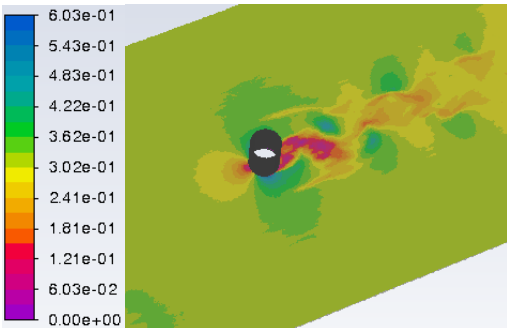
(d) mean velocity [m/s], z = 1.9% D.

Fig. 8. LES simulation with WALE SGS model after 10 s.

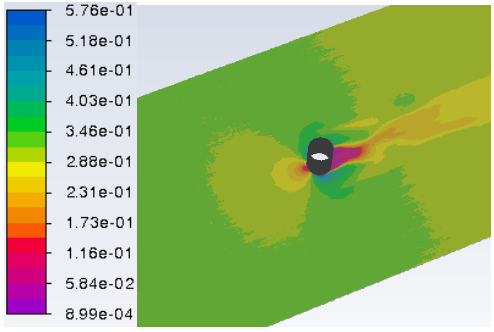
details of the RANS study are available in the first author's previous publication (Aly and Dougherty 2021). Figure 8 and Fig. 9 show the contours of the bed shear stress and the velocity field. This study demonstrates LES as a powerful tool for the investigation of scour near piers. The shear stress and velocity field contours presented in Fig. 8 and Fig. 9 exemplify the effectiveness of LES as a valuable technique for exploring pier scour phenomena. The findings of this study underscore the utilization of LES as a dominant tool for investigating the hydrodynamic processes underlying pier scour and highlight its potential for informing the design of structures and protective measures in marine and coastal environments.

5. RESULTS AND DISCUSSIONS

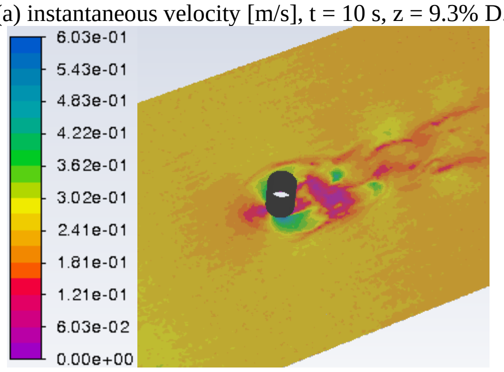
The efficacy of the delta vane and plate footing in performing as a countermeasure device is demonstrated in the study (Aly and Dougherty 2021). The previous study used the realizable $k - \epsilon$ turbulence closure to investigate the performance. In the current study, large eddy simulations with the Smagorinsky-lilly SGS model are adopted to investigate the performance of the two countermeasures. The 3D model of the countermeasure was modeled in AutoCAD and was meshed using an unstructured meshing strategy.



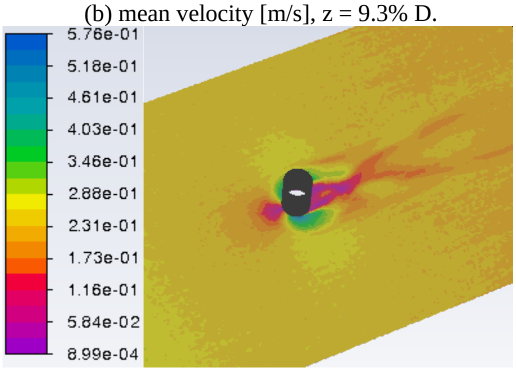
(a) instantaneous velocity [m/s], t = 10 s, z = 9.3% D.



(b) mean velocity [m/s], z = 9.3% D.

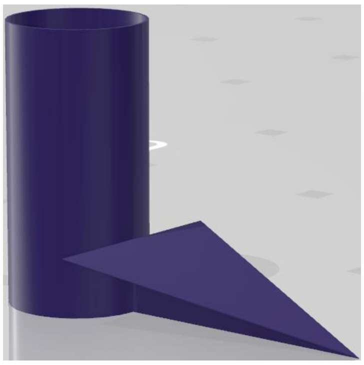


(c) instantaneous velocity [m/s], t = 10 s, z = 1.9% D.

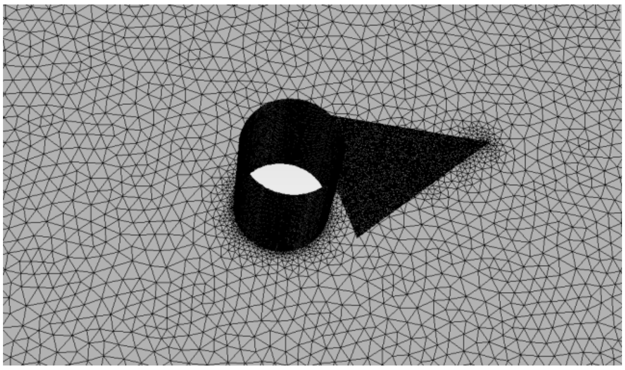


(d) mean velocity [m/s], z = 1.9% D.

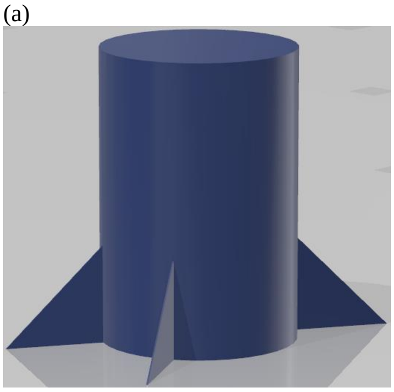
Fig. 9. LES simulation with Smagorinsky-lily SGS model after 10 s.



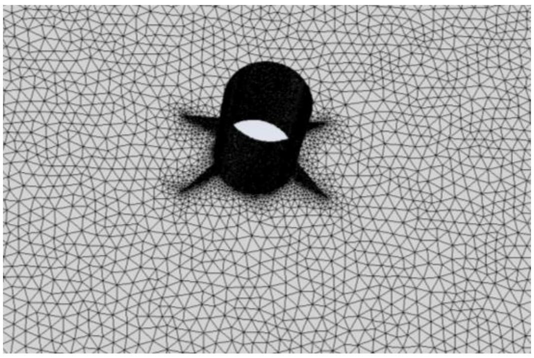
(a)



(b)



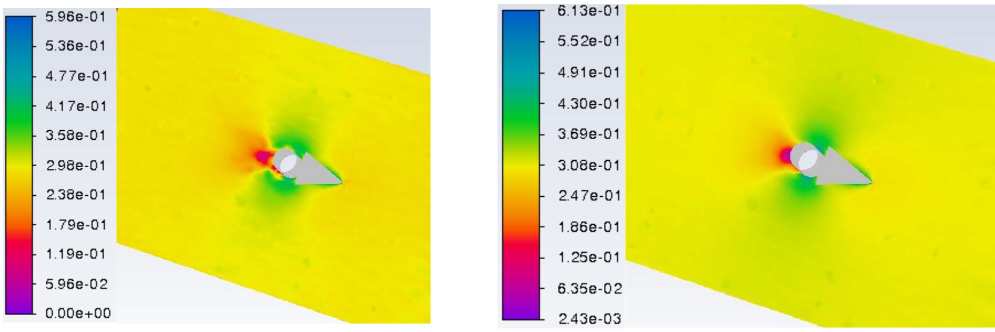
(c)



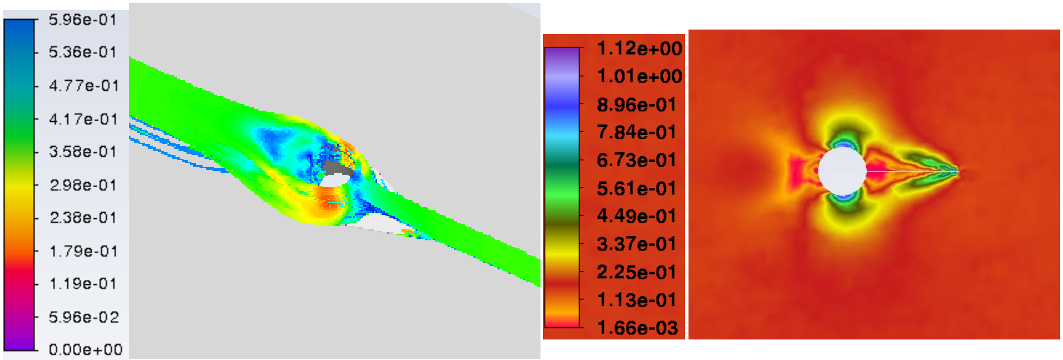
(d)

Fig. 10. Countermeasures: (a & b) delta vane, and (c & d) plate footing.

Figure 10 presents the two countermeasure devices used (delta vane and plate footing). Also, the mesh around the cylinder and the countermeasures is shown. The AutoCAD model of the delta vane included dimensions of 2D from the apex to other side and 1.5D for the side opposite to the apex (Fig. 10-a). The apex was securely fixed in the pier's upstream, while the opposite side was fixed to the pier at a 15º angle with the bed. Additionally, a spinal rib was incorporated to provide additional structural reinforcement. The countermeasure mesh was composed of tetrahedral-shaped elements and consisted of three (3) prismatic layers, with a rate of growth of 20%, starting from the wall. The resulting



(a) instantaneous velocity [m/s], t = 10 s, z = 9.3% D. (b) mean velocity [m/s], z = 9.3% D.



(c) path of instantaneous velocity [m/s], at t = 10 s. (d) time-averaged shear stress [Pa].

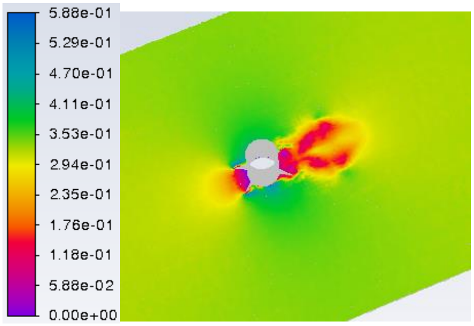
Fig. 11. LES simulation with Smagorinsky-lily SGS: delta vane countermeasure after 10 s.

flow structures were compared to those from previous simulations using the same boundary conditions, and a total of 1.5 million elements were used.

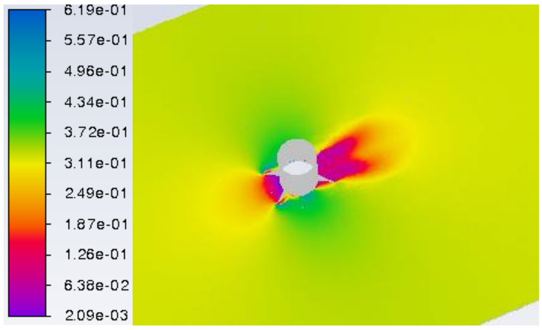
The plate footing was modeled in the software AutoCAD, consisting of four plates. Two plates were angled at 30º toward the inlet, and two plates were angled at 30º toward the outlet. Each plate extended 0.5D from the pier's outside surface and had a height of 0.5D, as illustrated in Fig. 10-c. The countermeasure was discretized into tetrahedral-shaped elements, and a mesh was generated using three (3) prismatic layers, with a rate of growth of 20%, starting from the wall. The resulting mesh comprised approximately 450,000 elements. Flow structures obtained from the simulation were compared with those obtained in previous studies using identical boundary conditions.

The large eddy simulation was run for 10 s with a time-step of 0.001 s to study the performance of the countermeasure. The contours of instantaneous (at 10 s) and averaged velocity fields at two elevations are obtained after the simulation. Also, the contour of shear stress and path-line of the instantaneous velocity field along the longitudinal section are obtained. Figures 11 and 12 show the variations in the velocity field and the shear stress field after the adoption of delta vane and plate footing countermeasures. Both countermeasures reported a 30% decrease in the shear stress on the bed (Aly and Dougherty 2021). In this paper, we will attempt to present the reduction of shear stress using LES. Velocity and shear stress contours are attained after executing LES with Smagorinsky-lily SGS model, for the two countermeasures (Fig. 11 and Fig. 12). Figure 13 compares bed shear stress along three lines in the transverse direction. The first line (L 1) is drawn along the upstream side, the mid-line is drawn along the centerline, and the third line (L 2) is drawn touching the downstream side. The shear stress is tracked along these three lines, and the variations are observed based on the usage of the countermeasure. Figure 13(b) shows that the delta vane is more effective in reducing the shear stress, in the upstream direction. The midline indicates similar performance for the two countermeasures.

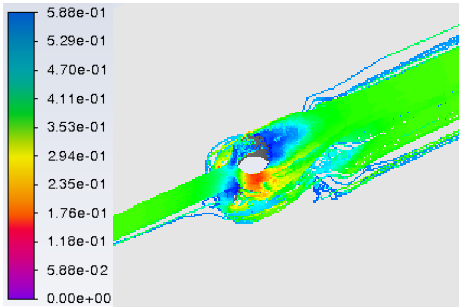
In Fig. 13, it is demonstrated that the delta vane exhibits a favorable capability to decrease the shear stress on the bed. Specifically, in the upstream direction (L1), a maximum shear stress of only 0.3 Pa, significantly lower than the 0.9 Pa maximum bed shear stress experienced by the cylindrical pier. The observed shear stress indicates that sediment with a critical bed shear stress of approximately 0.5 Pa, such as sand, will likely be transported without countermeasures for pier protection. Both flow countermeasures exhibit shear stress values lower than 0.5 Pa, which reduces the potential for sediment transport. Implementing a delta vane reduces the shear stress in both the upstream and wake zones, thereby decreasing the probability of the transport of sediment near the pier and the delta vane defense strategy. Moreover, the delta vane defense strategy effectively deflects the incoming flow. For the downstream (L 2) case, Fig. 13 (c) shows improved performance with the plate footing countermeasure. The ability to lower the shear stress is promising.



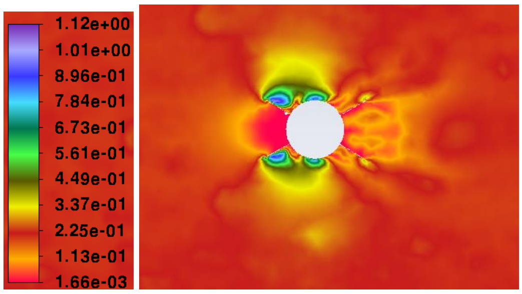
(a) instantaneous velocity [m/s], t = 10 s, z = 9.3% D.



(b) mean velocity [m/s], z = 9.3% D.

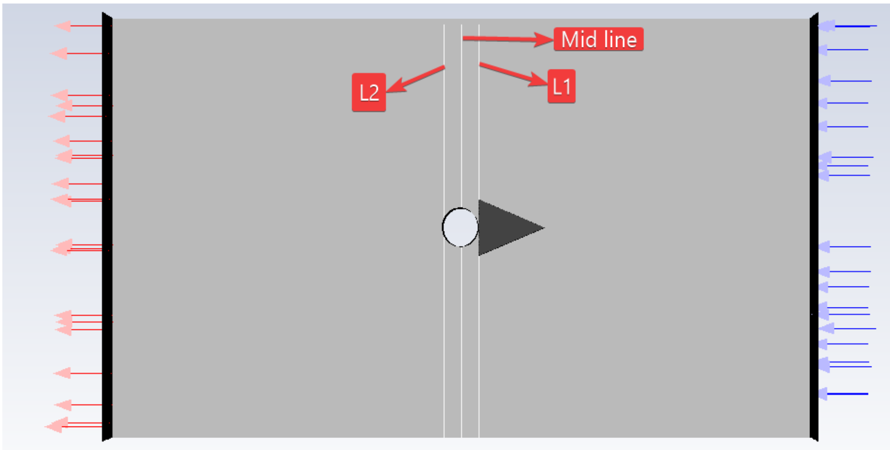


(e) path of instantaneous velocity [m/s], at t = 10 s.

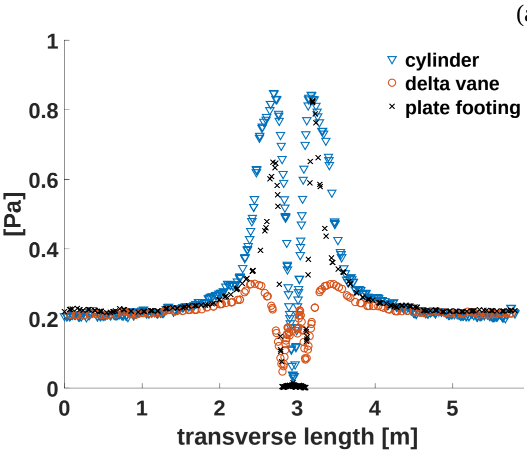


(f) time-averaged shear stress [Pa].

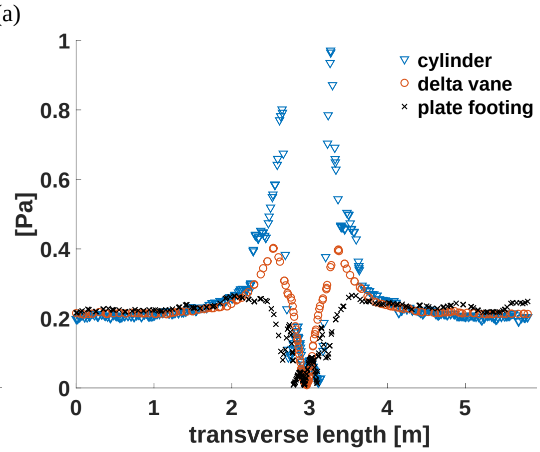
Fig. 12. LES simulation with Smagorinsky-lily SGS: plate-footing countermeasure after 10 s.



(a)



(b)



(c)

Fig. 13. Shear stress with/without the use of delta vane & plate footing along three lines: (a) location of the three lines, (b) comparison along L 1, and (c) comparison along L 2.

However, the plate footing slightly decrease the maximum shear stress in the upstream (L1), and the shear stress is still higher than 0.5 Pa, demonstrating that sediment like sand, with critical shear stresses equal to or lower than this value will be transported.

The combination of a delta vane located upstream and a plate footing situated downstream represents a promising and innovative solution to mitigate the problem of local scour. Alterations to the alignment of delta vane relative to the pier/bed would significantly impact the flow and the shear stress. Therefore, if the vane were to be deployed on an actual pier, it would be imperative to maintain the intended design alignment. This idea can be achieved by safeguarding the bed to guarantee that the vane maintains connection with the bed surface.

Combining a countermeasure for flow alteration with a bed-armoring device can potentially prolong its lifespan by reducing the shear stress, which could lead to longer inspection intervals. However, additional research is necessary to determine if the financial benefits of reduced maintenance costs would outweigh the expenses associated with constructing a delta vane on a pier for the bed-armoring method.

Having infrastructure that is resistant to damage can help reduce the impacts of disasters on the population and economy. By having resilient infrastructure in place, the effects of a disaster can be minimized, which can help reduce the losses and speed up the recovery process.

While this study provides valuable insights into the flow dynamics around a single cylinder under different flow conditions and with the application of countermeasures, there are some limitations. The free surface of the flow was not modeled, which may affect the flow behavior and the accuracy of the results. Also, the simulations were based on specific flow conditions to predict the bed shear stress under local scour. Therefore, future studies should consider more comprehensive and realistic models with free surface effects and a broader range of scour-influencing parameters, such as wave and current.

6. CONCLUSIONS

The paper offers a comprehensive review of current knowledge state on scouring and identifies gaps in the existing literature, emphasizing the need for further research to improve our understanding of bridge scouring and its mitigation. Furthermore, this study investigates the effects of local scouring around a cylindrical pier using LES and evaluates the effectiveness of countermeasures such as the delta vane and plate footing in reducing shear stress that can initiate scour. Overall, this paper underscores the critical role of CFD simulation techniques in advancing the design of bridge piers and countermeasures to develop safer and more reliable bridge structures. The research findings can be summarized as follows:

Literature Review. This paper highlights several areas of research that require more attention, including:

- Investigating scour mechanisms in the presence of waves and currents, which involves complex tasks that require careful consideration of parameters such as scale, Reynolds number, and pile roughness.
- Conducting experimentation with natural materials, rock foundations, and pier shapes representative of practical applications to study the hydrodynamic performance of riverbeds.
- Advancing scour depth estimation and validating laboratory experiments and CFD simulations by utilizing neural networks based on precise and extensive field datasets.
- Using LES and DES methods to accurately model the coherent structures near the pier, including horseshoe and wake vortices.

CFD Case Study. The application of LES to study the velocity distribution near a pier, and the associated shear stress, reveals its capability to meet the experimental results. Adopting LES improved the prediction of the along flow velocity component that concurs well with the experiments. Besides, a comparison with previously conducted RANS simulations demonstrates improvement using LES. LES offers better performance in the wake compared to the RANS. Furthermore, away from the pier, in the wake, the performance of DES is comparable to the experimental results. The LES WALE SGS model efficiently models the flow field in the wake. Furthermore, shear stress under upstream and downstream flow can be decreased by using a delta vane countermeasure. The plate footing countermeasure offers enhanced performance in decreasing the shear stress downstream. Adopting a countermeasure by combining delta vane upstream and plate footing downstream could be a more effective technique.

Future Work. This study identifies several research gaps and recommends areas for future investigation, including:

- Developing and validating numerical models for predicting scour depth and the effectiveness of countermeasures.
- Conducting field and laboratory experiments to assess the efficacy of various scouring countermeasures and investigate the underlying mechanisms.
- Conducting more comprehensive and systematic studies on the effects of sediment characteristics, flow conditions, and structure geometries on local scour.

Addressing these research needs will significantly enhance our understanding of scour processes and enable the design of more effective and sustainable structures in riverine environments.

ACKNOWLEDGMENTS

This research was made possible through generous funding from the Louisiana Board of Regents (LA-BoR) [RCS: LEQSF(2021-22)-RD-A-30]. The findings of the paper are solely those of the authors and do not reflect the views of the funding agency.

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