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Computer Vision Solutions for Bridge Pier Scour – Prospects, Limitations and Future Recommendations

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Abstract

Scour at bridge piers, characterised by the erosion of geomaterials around a bridge pier's foundation support system due to the erosive action of flowing water, is a critical problem in engineering. It poses significant risks to bridge safety, often leading to structural failures, economic losses, and, in severe cases, loss of life. Conventional methods for bridge pier scour typically rely on empirical equations. However, these methods have some limitations as they may not accurately account for the complex and uncertain nature of scour phenomena across different bridge types and the interaction of unexpected environmental conditions. To mitigate the constraints and enhance the sustainability of conventional methods, especially considering recent changes in climate, the management of bridge pier scour has prompted an exploration of computer vision technologies to complement traditional approaches and adapt to climate induced alterations. Recent developments in computer vision technologies have revolutionised many industries in providing economical and non-intrusive solutions to problems. In the context of bridge scour, a computer vision solution can facilitate the detection of scouring and can be used to issue real-time alerts related to pier scour-based bridge collapse. In this paper, the authors reviewed recent studies and provided a detailed account on the different prospects in which computer vision technologies can be used to address the bridge pier scour problem. In addition, the authors provided a subjective analysis of existing limitations, challenges, and future potentials. Specifically targeting the operational solutions, the constraints and limitations related to in-field deployment are also discussed. The findings reveal that computer vision technology can offer promising solutions for real-time detection and monitoring of bridge pier scour, providing a nonchalant and non-intrusive approach to bridge safety assessment. By addressing the limitations of traditional methods and changes to the climate, the findings aim to contribute to the development of more robust and comprehensive strategies for mitigating the risks associated with scour phenomena.

Keywords: Computer Vision, Bridge Pier, Scouring, Artificial Intelligence, Water Resource Management

1. INTRODUCTION

Bridge pier scouring is one of the critical phenomena which significantly impacts the safety and stability of the bridge. In principle, scouring across bridge piers occurs due to fast moving water which erodes the sediment across the pier and compromises the integrity of structure (Wang et al. 2017). Literature suggests that bridge pier scouring is one of the major reasons for the failure of bridge structure (Pizarro et al. 2020; Shahriar et al. 2021). Involvement of complex hydrodynamic interactions (Riaz et al. 2021; Riaz & Lay 2023) , non-linear nature of scouring process and unpredicted water interactions makes it essential to periodically monitor the scouring for long-term safety of bridges (Pizarro et al. 2020).

Traditionally, the bridge pier scour is monitored using manual expert inspections, sonar sensors and underwater sensing equipment (Pregnolato et al. 2021; Vardanega et al. 2021). Manual expert inspections are one of the commonly practiced approaches, however, is inefficient for non-accessible sites and unsafe during high flow currents. On the other hand, the sonar and underwater sensing equipment do provide some accurate information, however, at the expense of high costs, regular maintenance, and challenging data interpretation. Furthermore, their operation is impacted by extreme weather events such as floods.

Recently, computer vision, a domain of Artificial Intelligence (AI) which interprets the visual information captured by cameras, has emerged as a promising technique for real-time monitoring of remote sites (Iqbal et al. 2024; Iqbal et al. 2023). The ability of computer vision systems to automatically process and analyse visual information offers a non-invasive alternative for bridge pier scour monitoring. Computer vision techniques, such as image segmentation, object detection, and 3D reconstruction, can provide real-time monitoring of scour progression, even in remote or hazardous locations. Furthermore, the integration of computer vision with emerging technologies such as drones has the potential to automate scour assessment at a scale and precision previously unattainable with conventional methods. This paper aims to explore different prospects in applying computer vision to bridge pier scour detection, discussing the challenges faced and opportunities that lie ahead for this rapidly developing field.

2. PROSPECTS OF COMPUTER VISION FOR BRIDGE PIER SCOUR DETECTION

Computer vision technologies have the potential to explore the problem of bridge pier scour monitoring from a non-intrusive and economical perspective and, therefore, can overcome some of the limitations offered by the traditional approaches, such as the inability to handle the non-linear and uncertain nature of the scouring process. Computer vision, with its capability for real-time image processing and automation, presents an innovative alternative for identifying, monitoring, and assessing scour around bridge piers. In this section, various prospects of computer vision applications in scour detection are explored, focusing on their benefits and real-world deployment potential.

2.1. Image Segmentation for Scour Detection

Image segmentation technique can be implemented towards addressing scour by visually classifying regions of the image such as water, sediment and bridge pier. The visuals can be acquired by mounting the cameras on strategic locations near the bridge. The images captured by the cameras can then be processed using the latest image segmentation models such as UNet (Du et al. 2020) and SegFormer (Xie et al. 2021) to classify it into distinct categories pixelwise. This will help in identifying the areas where scouring has exposed the bridge pier foundation.

This approach is particularly useful for identifying scoured regions that are difficult to reach with manual inspection or underwater sensors. The non-invasive nature of image segmentation means that cameras can capture continuous data from locations where human access is limited or unsafe, such as during high-water events or in remote areas. The ability to monitor the scouring process in real-time offers a significant advantage over traditional methods, which often provide intermittent data. The benefits include higher accuracy, real-time feedback, and a reduction in the need for costly periodic inspections.

In practice, such a system could be deployed by installing fixed cameras on bridge structures or using drones to conduct aerial surveys at regular intervals. The visual data could be processed on board using edge computers or could be sent to a cloud-based system where segmentation algorithms would process the images in real-time, automatically flagging areas where scouring is detected. Alerts could be sent to maintenance teams, allowing for timely intervention before the scour becomes critical.

2.2. 3D Reconstruction for Scour Depth Estimation

3D reconstruction provides an accurate and detailed method for estimating the depth of scour around bridge piers by creating a three-dimensional model of the bridge and its surrounding environment. This technology relies on photogrammetry techniques or Structure from Motion (SfM), where multiple images of the same area are captured from different angles and stitched together to form a 3D representation. Drones equipped with high-resolution cameras are well-suited to capture these images, offering an efficient and cost-effective means of gathering data across large or hard-to-access bridge sites.

Using 3D models to estimate scour depth provides a more precise measurement than traditional sonar or manual inspection, especially when integrated with LiDAR or other depth-sensing technologies. These models offer a clear visual comparison between pre-scour and post-scour conditions, allowing engineers to track the progression of scouring over time. Moreover, the reconstruction method enables long-term monitoring, offering a historical record of changes to the bridge pier's environment.

For practical deployment, Drones could be scheduled for periodic flights over bridges, capturing high-resolution images of the piers. These images would then be processed using 3D reconstruction software to create models that allow for detailed scour depth analysis. The system could be set up to automatically compare these models with baseline data and issue alerts if significant changes in depth are detected.

2.3. Object Detection for Monitoring Debris and Sediment Buildup

Object detection algorithms can play a crucial role in monitoring debris and sediment buildup around bridge piers, which often exacerbates scouring. Using deep learning models like YOLO (You Only Look Once) (Redmon 2016) or Faster R-CNN (Ren et al. 2016), computer vision systems can automatically detect and classify objects such as logs, sediment deposits, or other debris that may contribute to scour formation. Cameras installed on the bridge structure or nearby can continuously capture footage, which is analysed in real-time by these algorithms to identify the presence and movement of debris.

The value of this approach lies in its ability to provide a proactive solution to scour monitoring. Unlike traditional methods that may only capture periodic snapshots, real-time object detection allows for continuous surveillance of debris, enabling maintenance teams to take early action. The system can also be used to monitor the rate of sediment deposition, providing insight into how quickly a bridge is being affected by environmental conditions.

In a real-world use case, object detection systems could be integrated into existing bridge monitoring setups. Cameras would be installed at various vantage points around the bridge and processed through an edge computer where the object detection algorithm is deployed. When debris or sediment buildup is detected, the system would send alerts, allowing for swift removal or further investigation before the situation worsens.

2.4. Thermal Imaging for Submerged Scour Detection

Thermal imaging offers an alternative method for detecting scour beneath the water’s surface, where visual inspection may be limited by water clarity or depth. Thermal cameras can detect temperature variations caused by sediment displacement, allowing for the identification of scouring even when it is not visible to the naked eye. By mounting thermal cameras on drones or fixed points near the bridge, it is possible to monitor submerged scour areas that would otherwise go unnoticed.

The use of thermal imaging is particularly beneficial in environments with high water turbidity, where traditional underwater cameras or sonar may struggle to provide accurate data. This approach adds an extra layer of detection, enhancing the robustness of scour monitoring systems. Moreover, thermal cameras can operate in low-light or night-time conditions, offering 24/7 monitoring capabilities.

A practical application would involve equipping drones with thermal cameras, particularly in regions where submerged scour is a concern. These drones could fly over bridge sites, capturing thermal data that is processed in real-time using computer vision algorithms to detect any significant temperature anomalies. This system would provide immediate feedback, triggering alerts if scouring is detected, and enabling timely intervention.

2.5. AI-Driven Predictive Modeling for Scour Risk Assessment

AI-driven predictive modelling, when combined with computer vision data, can offer dynamic risk assessments for future scour events. By analysing historical data from previous scouring incidents—such as water flow rates, sediment composition, and visual records — AI models can predict the likelihood of future scour based on current environmental conditions. Integrating predictive models with real-time visual data from computer vision systems provides a forward-looking approach to scour management, allowing for more proactive measures to be taken.

The benefits of this approach include the ability to assess risk continuously, reducing reliance on reactive maintenance. Instead of waiting for scour damage to become visible, predictive modelling can forecast when and where scour is most likely to occur, enabling early interventions. This forward-looking capability is particularly valuable in regions prone to sudden environmental changes, such as flash floods or heavy rainfall.

In practice, AI-driven predictive modelling would be integrated into existing monitoring systems. Data collected from computer vision algorithms—such as image segmentation or 3D reconstruction—would feed into AI models that assess risk based on historical trends. Maintenance teams would receive regular risk reports, helping them prioritise interventions before damage occurs.

3. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Despite the promising potential of CV in bridge pier scour detection and monitoring, several limitations and challenges must be addressed to realize its full benefits. Understanding these barriers is crucial to improving CV systems and ensuring their reliable application in real-world scenarios.

- **Environmental Variability:** One of the primary challenges in using computer vision for scour detection is the variability in environmental conditions. Water turbidity, sediment suspension, lighting, and weather conditions such as rain or fog can significantly degrade image quality, impacting the performance of CV algorithms. Underwater visibility can also be compromised due to murky water, limiting the effectiveness of traditional image and video-based methods.
- **Data Collection and Quality:** High-quality, consistent data collection is vital for effective CV-based scour monitoring. However, gathering sufficient training data for AI models, especially in dynamic environments like rivers or coastal areas, can be a challenge. Variations in camera positioning, frame rate, and sensor calibration further complicate data consistency, leading to discrepancies in the analysis.
- **Limited Field of View (FoV) and Occlusion:** The FoV of cameras is often restricted, limiting the area that can be monitored. This becomes particularly problematic for large bridge structures where scour may occur in hard-to-reach or unseen areas. Furthermore, occlusion due to debris, vegetation, or structural components can obstruct the view of critical zones, leading to incomplete assessments.
- **Scour Progression and Complexity:** Scour is a highly dynamic and complex process, influenced by a variety of hydrodynamic and geological factors. Capturing the nuanced progression of scour over time with CV alone can be difficult, especially when subtle changes in the riverbed or pier foundation are not immediately visible on the surface. This complexity often requires multi-sensor integration to comprehensively understand the scour process.
- **Algorithm Robustness and Generalization:** While CV models can be trained on historical data, their ability to generalise to new, unseen scenarios remains a challenge. Water flow characteristics, soil properties, and pier designs vary widely between sites, requiring models to adapt to diverse conditions. Overfitting to specific datasets may lead to poor performance when the system is applied to different environments.
- **Hardware and Infrastructure Constraints:** CV systems often require high-resolution

cameras, GPUs, and robust computational infrastructure to process large volumes of visual data in real time. For remote bridge locations, the cost and logistics of installing and maintaining such systems can be prohibitive. Ensuring continuous power supply, network connectivity, and protection from harsh weather conditions adds to the complexity of field deployment.

To address these challenges, the following are a few recommendations which can be adopted and explored for future research.

- **Integration with Multi-Sensor Systems:** To overcome the limitations posed by environmental variability and occlusion, integrating computer vision with other sensing technologies such as sonar, LiDAR, and accelerometers can provide a more comprehensive understanding of scour. Combining visual data with real-time depth measurements and hydrodynamic monitoring can improve the robustness and reliability of the system.
- **Use of Advanced Preprocessing Techniques:** Advanced image enhancement and filtering techniques, such as dehazing and contrast adjustment, can help mitigate issues related to poor visibility and low lighting. Additionally, integrating underwater imaging technologies such as structured light or acoustic cameras can enhance the system's ability to operate in turbid water conditions.
- **Adoption of AI and Machine Learning for Adaptability:** AI-based approaches, particularly deep learning models, can be trained to detect patterns in scour progression that are not easily discernible by human operators. Transfer learning techniques can help adapt models trained in one environment to new sites with similar characteristics, improving the generalizability of the system. Continuous updates and retraining with new data can further enhance the adaptability of the models.
- **Real-Time Monitoring and Automation:** Developing real-time CV systems for scour monitoring can significantly reduce the time between data collection and analysis, enabling proactive responses to critical scour events. Drones or autonomous surface vehicles equipped with cameras can periodically capture images of bridge piers, automating the data collection process and providing an aerial or underwater perspective that would otherwise be difficult to access.
- **Improved Field Deployment Strategies:** Designing cost-effective and low-power hardware solutions is key to ensuring the feasibility of CV-based scour monitoring in remote or resource-constrained environments. Solar-powered systems with low-power cameras and edge computing devices can be explored as alternatives to traditional energy-intensive setups. Additionally, wireless communication technologies such as IoT-enabled devices can facilitate real-time data transmission to centralised monitoring stations.
- **Collaboration between Researchers and Practitioners:** Close collaboration between CV researchers, civil engineers, and hydrologists is essential for developing solutions tailored to the unique challenges posed by bridge scour. Field validation through pilot studies and partnerships with local authorities will help identify real-world limitations and fine-tune CV systems for practical use in large-scale scour monitoring projects.

4. CONCLUSIONS

Bridge pier scour remains a significant challenge for the safety and longevity of bridge structures, exacerbated by complex hydrodynamic interactions and the unpredictable nature of environmental conditions. Traditional methods of scour detection, though effective in certain cases, face limitations in terms of accessibility, cost, and reliability, particularly in remote or hazardous locations. The advent of computer vision technologies, offering real-time, non-intrusive monitoring capabilities, presents a promising alternative to conventional scour assessment techniques. This paper has explored the various prospects of applying computer vision technologies, such as image segmentation, 3D reconstruction, object detection, and thermal imaging, to detect and monitor bridge pier scour. These techniques, combined with AI-driven predictive modelling, have the potential to transform scour management practices by enhancing real-time detection, reducing reliance on manual inspections, and improving overall accuracy. Additionally, the use of drones and automated systems provides further advantages in terms of scalability and operational efficiency. However, challenges remain in ensuring the robustness of these systems, particularly in dynamic and variable environmental conditions. Issues such as occlusion, water turbidity, and limited data availability continue to pose obstacles for reliable scour monitoring using computer vision alone. Therefore, the integration of multi-sensor systems and advanced AI techniques, as well as addressing the hardware and infrastructure constraints of field deployment, will be essential for realising the full potential of these technologies.

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