A Project Report

On

A Review of Bridge Scour Monitoring Techniques and Developments in Piezoelectric Sensor Based Scour Monitoring Technique

Submitted by

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1. Introduction

Bridge scour is defined as the erosion of sediments – such as sand, gravel, and rocks, from surrounding of bridge foundation due to fast flowing water (Kazemian et al., 2023). Bridge scour is the leading cause of bridge failures worldwide. The study conducted by Wardhana and Hadipriono (2003) mentioned that 53% of the failures of bridges between 1989 to 2000 were due to flooding and scour. The economic impact of bridge scour is substantial, with annual flood damage repair costs for highway bridges in the U.S. is estimated to $50 million (Lagasse et al., 1995).

Bridge scour is affected by different factors such as water velocity, water depth, direction of flow, presence of pier or abutment and their shape, properties of sediments, and so on (Deng and Cai, 2009). There are generally three primary types of scours which affects the structural safety of bridge: general scour, contraction scour, and local scour (Sreedhara et al., 2015). General scour is the general removal of sediments from entire section affecting the entire riverbed due to long-term geomorphological changes. Contraction scour occurs due to the reduction in cross-section of the channel, which results in high flow velocity, causing the removal of sediments. Local scour is caused due to the obstruction of river channels by abutments and piers, thereby removing the sediments in the vicinity of the structure (Deng and Cai, 2009).

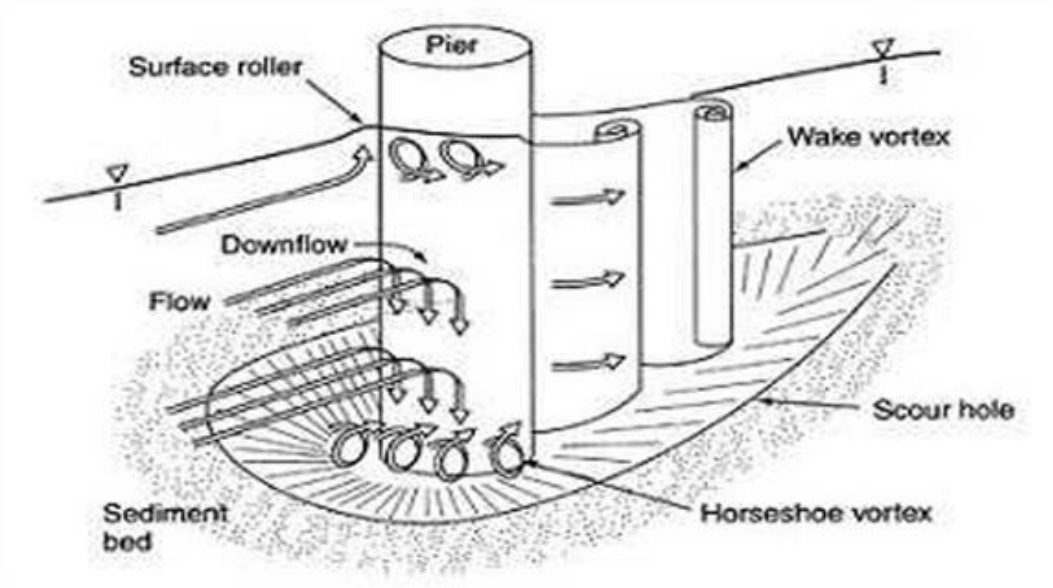

Figure 1: Mechanism of local scour in a circular pier [adapted from Sreedhara et al.,2015]

Local scour accounts for most of the bridge's failure. Figure 1 shows the schematic diagram of flow path near the bridge pier in a scour hole zone. When the water flow encounters a pier, there will be abrupt changes in velocity and pressure. The flow decreases at the top of the per first and creates high pressure zone, causing a downward pressure gradient. This induces a strong downward flow of water casing the initiation of sediment removal. The downward flow rolls up creating vortex flow of horseshoe shape around the base of the pier, which is highly effective in transporting the sediments away from the pier. At the same time, wake vortices are formed downstream due to the separation of flow at the pier sides. These vortices rotate around

the pier in a vertical axis, causing further erosion of the bed materials. The horseshoe vortex is strong compared to wake vortices, but the wake vortex acts like suction system downstream complementing the scouring action of horseshoe vortex (Sreedhara et al., 2015).

2. Overview of Bridge Scour Monitoring Techniques

Bridge Scour monitoring is essential to ensure the structural safety and longevity, which is also economical method to prevent failure of bridges. There are various methods for the quantification of bridge scour. Visual inspection is the traditional method of bridge scour monitoring in which a person measures the bridge scour with basic instrument by diving in the river. However, it comes with major drawbacks such as difficulty in inspection during flood, difficulty in measuring maximum scour depth due to filling of scour holes by sediments after flood, and lack of continuous data to analyze the bridge scour trend (Want et al, 2017). Due to the several drawbacks of visual inspection, several other instrument-based monitoring techniques have been developed which can provide continuous and real-time data, even during high floods.

2.1. Magnetic Sliding Collar

The Magnetic Sliding Collar is the most extensively used robust bridge scour monitoring technique. This technique uses a stainless-steel pile, which is vertically driven into the streambed, containing magnetic collar over it. As the water flow removes the sediment, the magnetic collar shifts downward along the pipe. The stainless-steel pipe contains magnetically sensitive switches, which are placed at regular intervals. As magnetic collar slides down due to the removal of sediment, the switches get activated which gives the signal to the user and user can determine the scour depth (Richardson & Everett, 2002). The schematic diagram of magnetic sliding collar is shown in figure 2.

There have been several instances of use of magnetic sliding collar for bridge scour detection. For instance, the manual magnetic sliding collar which was installed at the South Platte River test site was remained operational for your years, and it withstand debris and ice impact with moderate damage (Richardson & Everett, 2002). Similarly, magnetic sliding collar technology has been used by New Jersey Department of Transportation for long-term monitoring, where the system recorded the scour of 46 Passaic River Bridge and the Matawan Creek Bridge (Nassif et at., 2003). However, the use of magnetic sliding collar is not suitable for every case as it provides limited temporal resolution and cannot function as the scour hole is refilled by the sediments (Briaud et al. 2011).

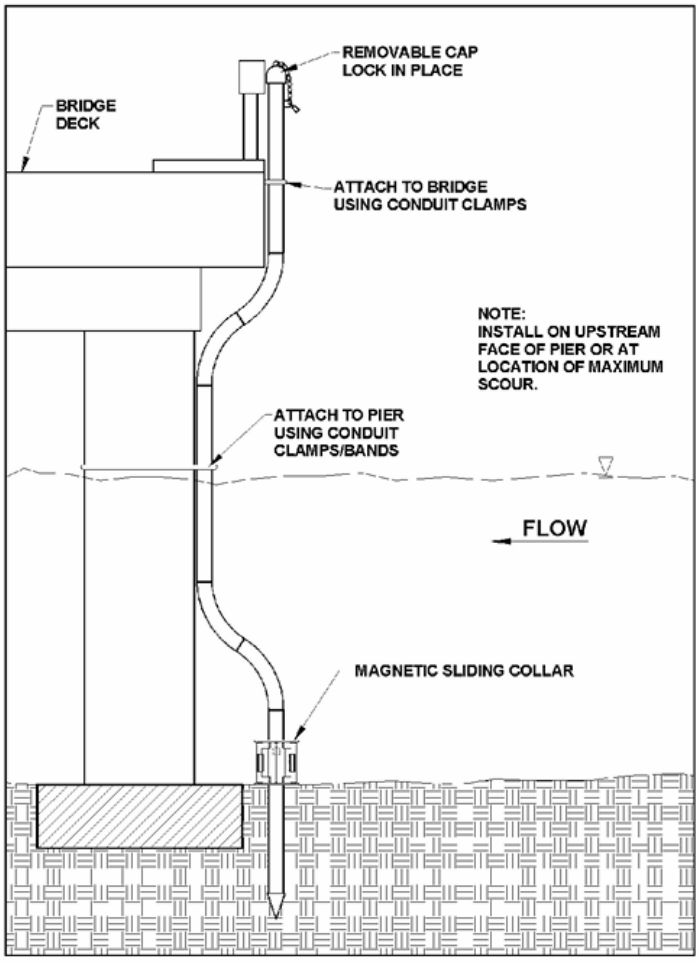

Figure 2: Working mechanism of magnetic sliding collar. [Adapted from Richardson & Everett, 2002]

2.2. Float-out Devices

Float-out devices are the most cost-effective and practical method of local scour detection of bridge piers, particularly when installed at the strategic points of bridge piers and abutments. These devises are typically buried in the riverbed, and they function when the scour reaches to the depth of the installed device, and it floats upward. When the device floats upward, the vertical position of the device is transformed into horizontal position and triggers an internal radio transmitter, which sends binary signal to the data logger (Leuker et al., 2010). A common float out device is 4.5 inches in diameter and 12 inches in length which is show in figure below.

The schematic diagram of float-out devices is shown in Figure 2, which demonstrates the typical installation method near the pier, which is susceptible to scour. These devices are advantageous due to their low power requirements, operational ease, and durability against debris when buried under riprap (Shreedhara, 2015). However, there are certain limitations, such as the device's inability to provide continuous data of scour depth, and neither the maximum scour depth (Leuker et al., 2010). Since, they are single use device so they must be retrieved and reinstalled after it gets activated (Wang et al., 2017). Furthermore, the installation procedure is

costly and complex, as coring and drilling is required. Although, due to their reliability and ease in operation, flout-out devices remain a valuable tool to indicate the critical scour depth of bridge piers (Leuker et al., 2010).

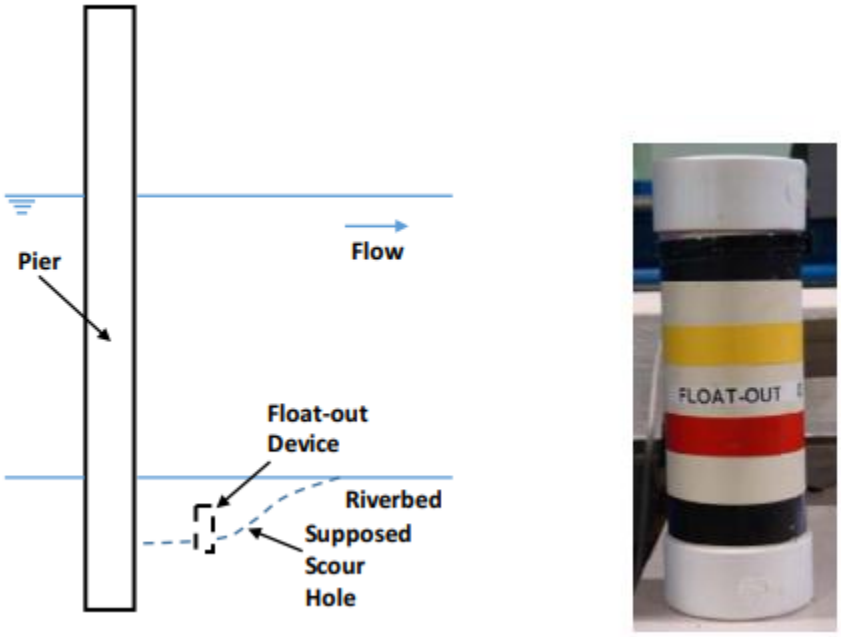

Figure 3: Float-out devices [Adapted from Leuker et al., 2010]

2.3. Smart Rocks

The smart rock method for bridge scour monitoring is robust and durable even under harsh conditions. This method works with the combination of smart magnetic rock, which is embedded inside concrete and contains magnetic label, and magnetic gradient measurement system, which is installed at the bridge pier as shown in figure 4. As the riverbed is scoured, the strategically placed smart rock move with the evolution of scour hole, and the scour depth can be measured by analyzing magnetic gradient measurement (Jiang et al., 2022). The magnetic label inside the smart rock consists of three-gimbal gyroscope, which is built from non-magnetic materials such as Zircona ceramic bearing, high strength plastic and copper screws, and Nd-Fe-B permanent magnet. The permanent magnet is centrally fixed within a three-gimbal gyroscope, which ensures mechanical stability, and the materials of magnetic label and concrete shell provides resistance to internal magnetic interference and protecion under harsh hydraulic conditions (Jiang et al., 2022).

The principle governing this method is based on the assumption that the scour hole forms in the shape of an inverted cone, following the natural angle of repose of bed material and the smart rocks move with the development of the scour hole. In clear-water scour conditions, the smart rock having a diameter of 0.5 m and about 500 kg, can move downslope along the scour cavity due to gravity and hydraulic forces (Richardson & Davis, 2001). Despite its potential benefits, the system faces some limitations under field conditions. The passing vehicle in the bridge, components of the superstructure, and nearby electromagnetic sources introduce some residual magnetic field, which cannot be eliminated by magnetic gradient measurement system.

Furthermore, when the smart rock is moved further downstream during extreme scour events, the increased angle between the magnet and measurement axis can produce localization errors (Jiang et al., 2022).

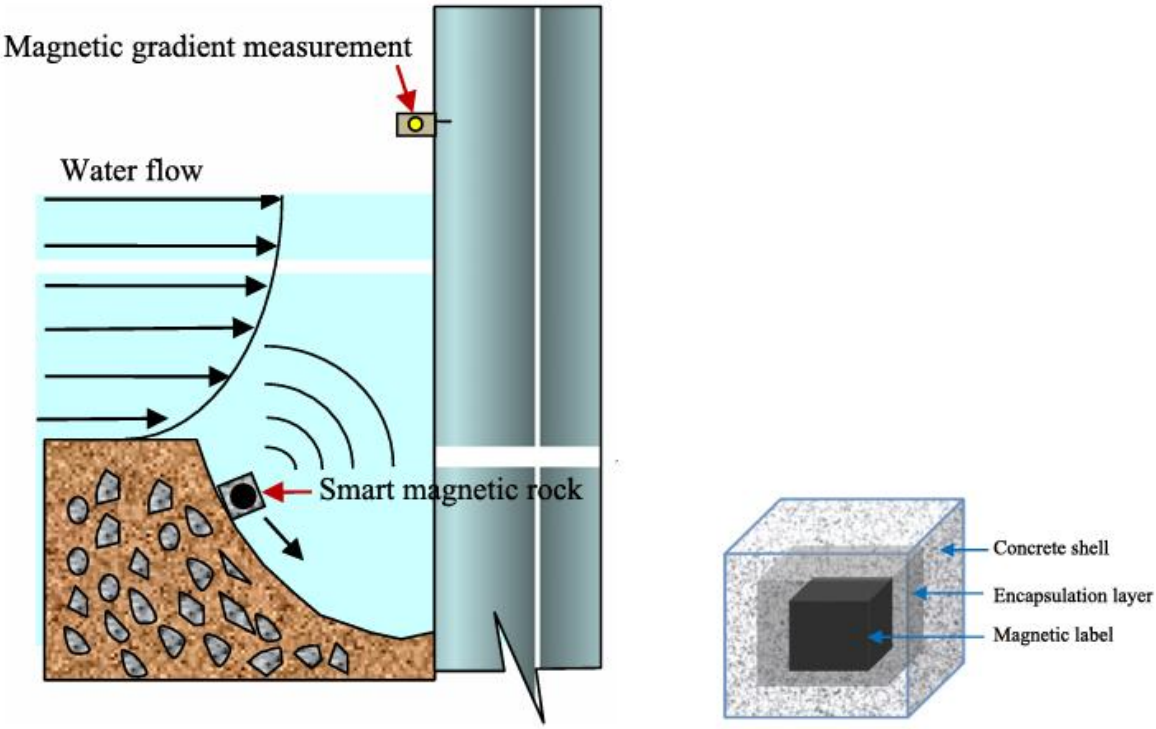

Figure 4: Bridge scour monitoring system using smart magnetic rock [Adapted from Jiang et al. 2022]

2.4. Sonar Sensor

SONAR (Sound Navigation and Ranging) is an acoustic technology which measure scour depth by emitting sound pulses and analyzing the reflected wave from the water-sediment interface. The scour depth can be calculated based on the time delay of reflected signals, and it offers continuous monitoring capabilities. Fathometer is a device, which is installed in bridge pier and uses SONAR technology to find the scour depth. Fathometer has been extensively tested under NCHRP Project 21-3 at locations such as the Johns Pass Bridge in Florida and the South Platte River in Colorado. Fathometer contains solar-powered data loggers, PCC-mounted probes, and fish-finder-type transducers. The performance of these parts is reliable under extreme conditions, for example, in high debris, high turbidity, and tidal environment (Lagasse et al., 1998).

However, there are certain limitations of sonar technology. The accuracy of sonar and fathometer is influenced by flow turbulence, riverbed topography variation, and air entrainment. These devices might miscalculate the scour depth when the beam is reflected from the shallowest point on an uneven bed, and the entrained air interferes with transmitted signals (Wang et al., 2016). Moreover, sonar system is likely to damaged physically by debris when it is not placed carefully (Sreedhara et al., 2015).

2.5. Vibration-Based Scour Monitoring

Vibration-based scour monitoring techniques have been evolved as one of the rising alternatives to traditional scour monitoring techniques. It offers continuous, and real-time data to analyze the condition of scour in bridge piers. There are two categories of vibration-based scour monitoring: vibration-based scour monitoring using rod sensor and vibration-based scour monitoring using structural response.

2.5.1. Vibration-Based Scour Monitoring Using Rod Sensor

In this method, a slender sensing rod is vertically installed into the riverbed near a pier of abutment. The vibration response of rod is then recorded to monitor the bridge scour condition. The rod comprises of instruments like accelerometer, and fiber-optic sensor, which can capture the dynamic response of the rod. The scour depth detection is based on the principle that fundamental natural frequency of vibration is inversely proportional to the vibration of rod (Zarafshan et al., 2011). When the scour erodes the soil around the bridge pier, the unsupported length of the rod installed near bridge pier increases lowering the fundamental natural frequency of vibration (Kazemain et al., 2023). The change in frequency is then calibrated against scour depth by analytical and numerical method. Zarafshan et al. (2011) has demonstrated the use of FBG sensing rod to continuously monitor real time bridge scour. They used a steel rod in which FBG element was bonded. As the free length of the steel rod grew with scour, the FBG recorded the change in vibration signal of the rod, which was converted into fundamental frequency using Fast Fourier Transform (FFT). The system can self-calibrate scour depth by correlating the initial frequency to the drop in frequency due to bridge scour.

There are several advantages of vibration-based scour monitoring using rod sensors. They can continuously monitor the real time bridge scour without manual inspection, even during the flooding condition (Prendergast and Gavin, 2014). Moreover, fiber-optic sensors are resistant to corrosion and electromagnetic interference, which ensures high durability and reliable signal transmission even in long distances. This system is highly sensitive, can detect minor bridge scour, remain functional even after the flood events, and captures both scour and sediment refilling process (Kazemian et al., 2023). However, there are certain limitations of this technology. Each rod can only provide the local bridge scour information, and we need multiple installations of the sensing rod to capture full bridge scour information. The installation of the sensing rod requires driving the rods into the riverbed, which can be challenging in deep and turbulent rivers. The rod is also susceptible to damage by debris impact and strong hydraulic forces. Furthermore, the interpretation of frequency shifts is affected by site soil condition, and calibration should be site specific (Zarafshan et al., 2011).

2.5.2. Vibration-based scour monitoring using structural responses

In this method, bridge itself act as a sensor rather than installing separate sensor. This technique is based on the principle that the effective stiffness of the structure reduces due to the erosion of the supporting around the bridge foundation. The loss in stiffness causes changes in the dynamic properties of the bridge, such as natural frequencies, mode shapes, and damping

ratios (Prendergast and Gavin, 2014). The modal shape of the bridge pier is more sensitive to bridge scour than the modal frequency and it is resistant to external weather condition (Lan et al., 2021). Hashimoto et al. (2020) simulated bridge pile with pile cap, and computed first three mode shapes, which shows that there is asymmetric distortion of the pier with scour while there is symmetric distortion in the pier without scour as shown in figure 5.

There are several advantages of structural vibration-based bridge scour monitoring. This technique does not require any underwater installation, and it is easier and faster to implement on an existing bridge while compared to traditional bridge scour monitoring techniques (Prendergast and Gavin, 2014). The sensors can be installed above the waterline, allowing continuous and remote monitoring. This decreases the risk of water currents and debris damaging the sensors. Moreover, since the dynamic behavior is monitored for the entire bridge, we can capture the scour effects at the multiple piers simultaneously (Kazeimian et al., 2023). However, there are certain limitations of this technique. The magnitude of change in mode shapes and frequency by bridge scour is very low, even less than a few percent, which makes it difficult to distinguish from environmental factors. Moreover, the frequency reduction indicates the overall change in stiffness, and cannot directly locate the specific pier without detailed data analysis (Kazemian et al., 2023).

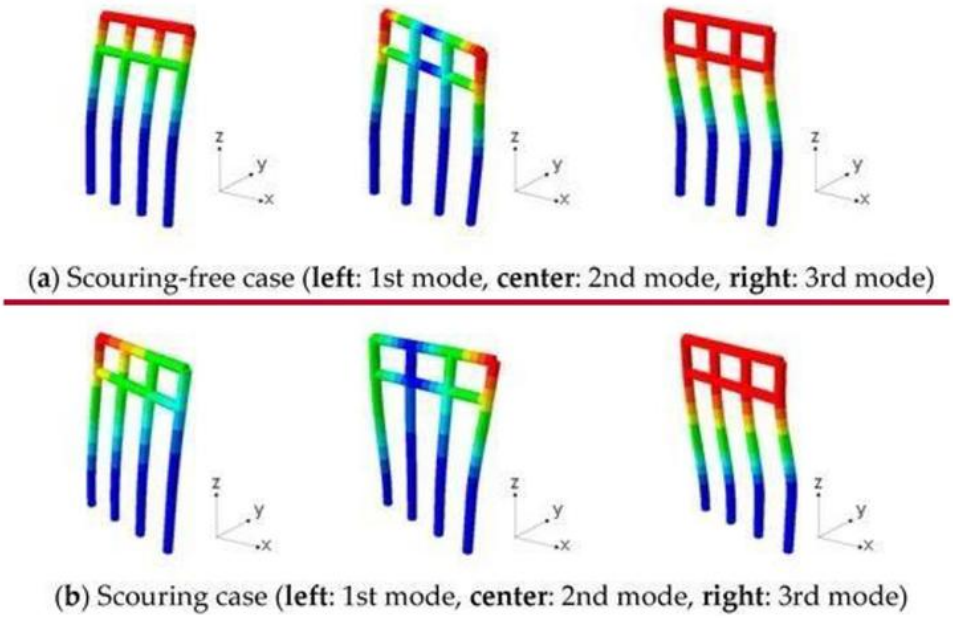

Figure 5: Mode shapes of a simulated bridge pier under scour free and scour cases [Adapted from Hashimoto et al., 2020]

3. Bridge Scour Monitoring Using Piezoelectric Materials:

The ability of piezoelectric materials to convert vibration signal and strain into electric signals make it a suitable technology for bridge scour monitoring. This technology does not need external power sources and can provide continuous real-time scour monitoring data (Funderburk et al., 2022). Piezoelectric materials can detect dynamic effects of flowing water and movement

of sediment around the foundation of bridge through which bridge scour can be detected (Loh et al., 2014). Various studies have been done in past decade to explore different types of piezoelectric-based scour monitoring techniques, which includes piezoelectric rod sensors (wang et al., (2011), Azhari and loh (2016), Funderburk et al., 2019), distributed piezoelectric scour nets (Loh et al., 2014), and piezoelectric energy harvesters (Fitzgerald et al., 2019). Piezoelectric scour sensors are not affected by turbidity, salinity, or temperature of water, and can function during high floods (Funderburk et al., 2022). The following section describes the different types of bridge scour monitoring techniques using piezoelectric sensors.

3.1. Piezoelectric Rod Sensors for Scour Detection

This method is widely studied to detect the local scour of bridge piers. In this method, a thin piezoelectric polymer film, which is constructed usually with polyvinylidene fluoride (PVDF), is embedded in a slender rod. The rod is then driven into the riverbed near to bridge pier. The rod remains buried and not allowed to move by sediments under normal conditions. After the scour progress, the sediment around a pier moves away which exposes a part of the rod, and vibration is induced in the exposed part. This vibration of rod is then converted into electrical signal in the piezoelectric film (Azhari and Loh, 2016; Funderburk et al., 2019).

Several studies have been published which demonstrate the use of rod with piezoelectric sensor embedded rod for bridge scour monitoring. Azhari and Loh (2016) constructed a flexible piezoelectric rod sensor which consists of a continuous PVDF strip that can be driven near the pier. They conducted an experiment in which multiple flexible piezoelectric rods were installed around a bridge pier which is subjected to artificial scour events. The scour events exposed some part of rod which decreases the fundamental frequency of vibration as the exposed length of rod increased. They also experimented sediment refilling process by artificially refilling sediments around a bridge pier model with a piezoelectric rod sensor placed at the side. There was a clear drop in the vibration frequency of the rod. The measured frequencies of the sensor rod were calibrated with the theoretical cantilever beam models, which relates natural frequency to unsupported length. With the help of this calibration, they calculated the exposed length of each rod in real-time which was used to quantify the scour depth evolution over time.

Further studies were done in piezoelectric rod concept. Funderburk et al. (2019) conducted a water flume test in laboratory using several rods with piezoelectric strip (PVDF) and arranged them symmetrically around a bridge pier. They installed each rod using three dimensional-printed footing which stabilizes the rod during testing. They used eight piezoelectric-rod sensors that were distributed around a pier model. This arrangement enabled the researchers to calculate the spatial variation of scour depth and construct the scour hole variation. The piezoelectric rods on the upstream and downstream sides of the pier showed slight variation in responses due to the flow characteristics. There was one challenge in which the rod sensors in a weaker flow area produced lower-amplitude vibration signals which requires advanced signal processing techniques. In response of this, Funderburk et al. (2019) used advanced signal processing techniques, such as Wavelet Packet Transform and Hilbert Transform, to enhance frequency identification.

In their recent research, Funderburk et al. (2022) used piezoelectric rod sensor to monitor vortex-induced vibrations (VIV) of the flow. The purpose of this study was to examine how flow

velocity affects sensor response. In addition to measuring scour depth using change in frequency signal, they used piezoelectric rod sensors to detect the vortex shedding frequency. Through their experiment, they found out that the vortex shedding frequency measured by piezoelectric rod closely matches the result obtained from traditional method. This shows that the rod can be used for dual purposes. They established a relation between flow velocity and vibration response of the rod sensors. Through this relationship, they were able to compensate the flow dependent effects on the vibration response of piezoelectric rod sensors, which helped them to calculate more accurate scour depth value.

3.2. Distributed Piezoelectric Scour Net

Distributed piezoelectric scour net is another innovative technique, which uses a continuous piezoelectric-film sensor placed over a broader area to map scour hole topology. This method is introduced by Loh et al. (2014), where they constructed a continuous piezoelectric sensor sheet by embedding a piezoelectric sensor strip in a thin poly-dimethylsiloxane (PDMS) elastomer substrate. In this method, multiple piezoelectric strips can arrange around a pier across a riverbed. As scour occurs, different portions of each strip become exposed along their length. Each scour net behaves like a cantilever with a varying length, with each portion exposed out of the sediment vibrating freely while the buried portion remains in rest. By calibrating frequency vs. exposed length, scour depth at the location of each strip can be back-calculated (Loh et al. 2014).

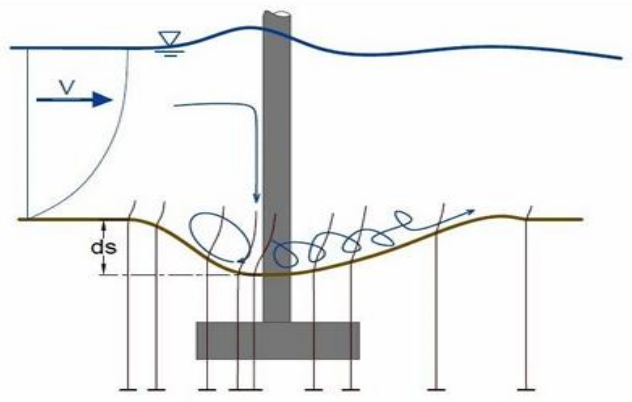

Figure 6: Principle of piezoelectric scour net monitoring system [Adapted from Loh et al., (2014)]

Loh et al. (2014) conducted a laboratory experiment using a network of 11 piezoelectric strips to reconstruct the three-dimensional shape of scour holes. The strips were placed radially around a model pier and tested under the known scour hole profile in dry sand as shown in figure 6. They extracted the frequency response of each strip and converted those response to exposed length, which enabled them to plot a 3D surface of the scour hole which was consistent with the actual hole geometry (figure 7). This experiment proved that a densely distributed piezoelectric sensor network can also capture the shape of scour hole evolution over time. They validated this concept experimentally by testing piezoelectric strip in a water flume with a mobile bed.

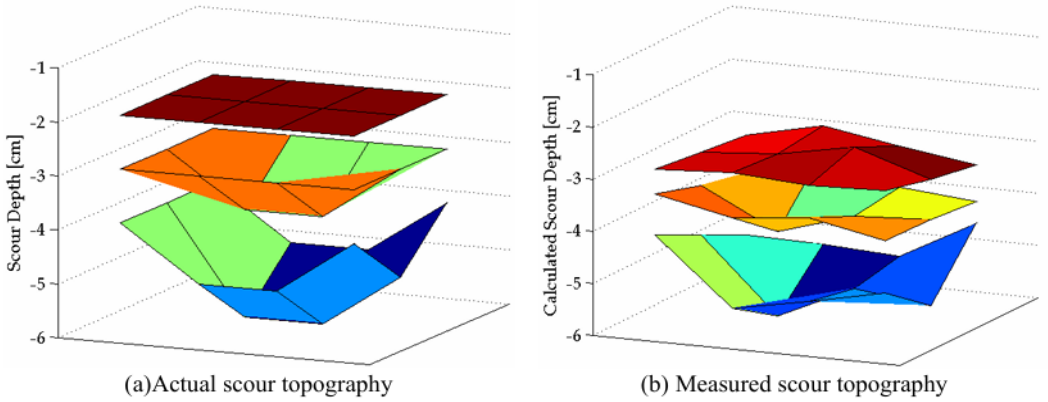

Figure 7: 3D surface modelling of scour depth measured from piezoelectric sensors [Adapted from Loh et al., 2014]

3.3. Piezoelectric Energy Harvesting Devices for Indirect Scour Monitoring

Instead of placing sensors in the riverbed, researchers have also explored the use of piezoelectric energy-harvesting devices attached to the bridge structure to measure bridge scour indirectly. The principle of scour monitoring is that the scour at the foundation will change the boundary conditions and stiffness of the bridge, thereby changing the vibration characteristics of bridge. A piezoelectric sensor can capture the change in dynamic behavior of the bridge and harvest energy from the vibrations (Fitzgerald et al., 2019).

Fitzgerald et al. (2019) developed a vibration-based scour detection methodology using a cantilever-based piezoelectric energy harvesting device (EHD) which was installed on a bridge pier. They constructed a laboratory-scale bridge model with four spans, and bridge scour was simulated by reducing the stiffness of support using springs. A piezoelectric cantilever energy harvesting device was attached to one of the piers as shown in Figure 8, and the voltage generated by the device was recorded for both ambient and vehicular-loading-induced vibrations. The result showed that the voltage spectrum of the energy harvester reflected the shifts in dominant frequencies when the scour damage was introduced. The energy harvester also showed a change in frequency when the harvester was attached to a non-scoured pier. This suggested that the energy harvesting device could potentially monitor scour at multiple supports by observing the frequency response of the bridge.

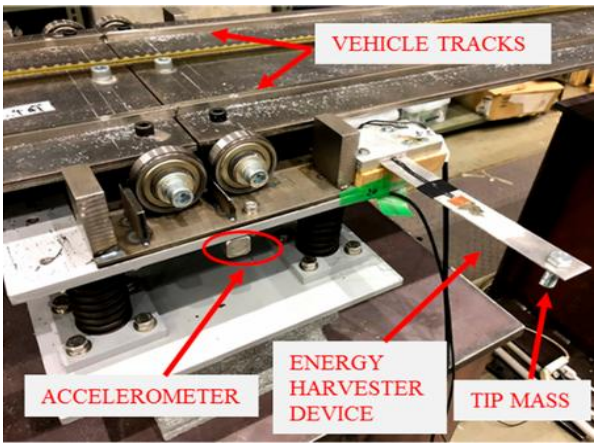

Figure 8: Laboratory installation of piezoelectric energy harvesting device [Adapted from Fitzgerald et al., 2019]

4. Advantages and Limitations of Piezoelectric Scour Monitoring

There are several advantages of piezoelectric-based scour monitoring systems. Most importantly, these sensors are self-sustaining: they do not need external power sources as electrical output can be produced when it is subjected to strain (Funderburk et al., 2022). This feature of piezoelectric materials, when combined with low-power wireless data acquisition system, ensures the reliability of the device during extreme flood events, and power outages, which can be self-sustainable in some cases (Fitgerald et al., 2019). Secondly, piezoelectric sensors can detect mechanical vibrations and pressure fluctuations, which make them highly responsive to the change of dynamic characteristics due to scour (Azhari and Loh, 2016). In contrast to sonar or optical systems, which can be hindered by turbidity, air bubbles, or suspended silt, piezoelectric sensors frequently exhibit superior performance in these conditions, as turbulence enhances the signal of the sensor (Sinha et al., 2022). The capacity of this kind of device for real-time, continuous monitoring allows us to track scouring and refilling procedures (Funderburk et al., 2019). Another advantage of piezoelectric sensors is their low cost and simplicity. PVDF films are inexpensive compared to complex sonar fathometers or fiber-optic sensors They can be installed into different configurations, such as rods, scour nets, or piezoelectric patches (Loh et al., 2014).

However, there are some limitations and challenges of applying piezoelectric scour monitoring techniques. One of the main challenges is the signal interpretation of the sensor is complex and often require careful calibration by considering factors like soil stiffness and flow velocity (Azhari and Loh, 2016). Durability of the sensor is another challenge, as PVDF strips are relatively fragile and long-term exposure to water can lead to the degradation (Funderburk et al., 2014). Additionally, piezoelectric scour sensors have limited sensing radius and can only applied to local scour. To get the full coverage of the bridge site, multiple installations are required which increase the cost, complexity of data handling and installation efforts (Funderburk et al., 2022). Moreover, the field validation of piezoelectric scour monitoring sensor is still lacking. Most of the studies have been conducted inside a laboratory inside controlled environment with limited field application (Funderburk et al., 2022).

5. Future Research Directions for Piezoelectric Sensors in Bridge Scour Monitoring

Piezoelectric sensors have been significantly investigated in laboratory due to its potential for bridge scour monitoring leveraging their self-powering capability, and real-time data acquisition. However, to fully utilize their potential for bridge scour monitoring, several key areas for future research must be addressed.

Enhanced Material Durability and Sensor Design

Although the most used piezoelectric material, polyvinylidene fluoride (PVDF) has shown good performance due to its flexibility and piezoelectric properties, they are susceptible to damage due to its fragility and potential degradation under prolonged exposure to hydraulic forces and sediment abrasion (Funderburk et al., 2014). Improvement of durability and long-term performance of such sensors is needed for full-scale deployment in a riverine environment. Research on more robust piezoelectric materials or protective coatings could be done to enhance mechanical strength while retaining the sensitivity.

Advanced Data Processing and Analysis

Several studies on signal processing techniques have been done to improve the reliability of data obtained from piezoelectric sensors. Funderburk et al. (2022) have applied advanced signal processing techniques, such as Wavelet Packet Transform and Hilbert Transform, to extract the fundamental frequencies from voltage data of piezoelectric sensors. However, there are still several challenges on distinguishing vibration changes due to bridge scour and other influences, such as traffic loads or wind forces. So, developing an algorithm that can filter out the noise and focus on the signal induced by the scour of bridges will be key in improving the sensitivity of piezoelectric sensors.

Optimization of Energy Harvesting from the sensor devices

Piezoelectric energy harvesting devices (EHDs) can perform a dual function: generate power from the ambient environment and act as sensors for scour monitoring of bridges (Fitzgerald et al., 2019). However, constant power cannot be generated using ambient energy sources. Water flow condition fluctuate seasonally which results in inconsistent power supply to piezoelectric sensors. Future studies should focus on optimizing EHD for varying flow condition to ensure a consistent energy output for self-sustainability. Moreover, the integration of solar and thermoelectric energy with piezoelectric sensors has the potential to enhance energy reliability and ensures continuous supply of energy during adverse environmental conditions.

Field Validation and Long-Term deployment:

Although laboratory experiments have been done to demonstrate the effectiveness of piezoelectric sensors in a controlled environments (Azhari and Loh, 2016), their field validation for real scour-monitoring is still lacking. Long-term deployment of piezoelectric sensors at the real bridge site is essential to evaluate durability, sensor performance, and data reliability over long periods of time.

6. Conclusion

A review of recent developments in bridge scour monitoring techniques is presented in this article. It categorizes the scour monitoring techniques into traditional-visual-based methods, sensor-driven technologies, vibration-based monitoring techniques, and emerging piezoelectric sensor-based techniques. The piezoelectric sensor offers a promising solution to conventional systems, which enables real-time, continuous scour monitoring even during high floods. However, there is a challenge of long-term field deployments of sensors due to their durability, and complex data interpretation requirement. Future efforts should focus on optimizing the sensor layouts, improving materials resilience, and field validation.

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