A novel vibration-based monitoring technique for bridge pier and abutment scour

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Abstract
Scouring degrades the overall health of a bridge by removing the bed material surrounding the piers and abutments. If undetected, scour may lead to the catastrophic failure of a bridge resulting in hundreds of millions in repair costs. The loss of a bridge due to undetected scour formations can also hinder emergency evacuations since riverbed scouring typically occurs in peak flow periods such as hurricane or flood events. To take requisite precautions against such catastrophic events, a monitoring system that can reliably detect scour formation, without being adversely affected by the environmental conditions, is essential. This article presents a novel scour monitoring technique that exploits the differences between the low-frequency ambient excitations exerted on a thin, flexible plate located in the flow versus the same device located in the sediment. The underlying principle is that a flexible plate excited by the turbulent flow vibrates at significantly higher amplitudes compared to an identical plate surrounded by sediment. To validate this principle, a simplified numerical model is developed to guide the design of the scaled laboratory device; next, a prototype model is built in the laboratory and tested in an indoor flume. The energy content of the sensor in the flow is measured to be one to two orders of magnitude greater than the sensor in sediment. The findings obtained at various flow conditions indicate that this technique can supply reliable information on the water/sediment interface, and thus scour and refill processes. Experimental results also demonstrate that the presence of a scour hole further improves the ability to detect the interface location. Additionally, the results show that maximum slope of the sensor energy content as a function of the sensor depth can be used as a feature to estimate the water/sediment interface.

Keywords
Condition monitoring, infrastructure management, vibration testing, structural dynamics, single degree of freedom, turbulence, open channel

Introduction
Scouring occurs when high-velocity flows erode the riverbed, removing the material surrounding the bridge piers and abutments, which ultimately affects the stability of the bridge foundation. Scour damage to these structural components can potentially result in the failure of the entire bridge. Bridge repair and restoration, from all types of damage, account for 19% of the federal emergency funds allocated for highway repairs. Between the 1960s and 1990s, of the 1000 bridge failures in the United States, 60% were attributed to scour. The financial cost associated with repairing scour damage to bridge structural elements was estimated to be US$100m per scour event from 1964 to 1972. Rapid riverbed scouring typically develops during high flow periods such as floods and hurricanes. Since bridges are often key infrastructure elements for the evacuation of the public or transportation of relief supplies, any structural failure of a bridge due to scour has an impact beyond the losses associated with the collapse of the bridge itself. Therefore, safeguarding bridges from failure due to scour, which can be achieved through real-time monitoring of scour development in riverbeds, is of critical importance.
During the last decade, various projects have been undertaken to evaluate the existing scour monitoring techniques, the majority of which have involved the investigation of sonar fathometers and other riverbed mounted sensors. Sonar fathometers, mounted on the bridge piers or abutments, use acoustic signals to record the distance to the riverbed.4 In previous experiments, fathometers have been used in the field to monitor both the maximum scour and subsequent refill during an event.4,5 These field studies, however, were typically hampered by various environmental and operational conditions, specifically channel debris, which for bridges in Indiana7 and New Mexico,6 interrupted the signal reflected from the river bottom. Debris can also directly impact the sonar unit or cabling, resulting in a loss of the unit and/or signal altogether.5 Aside from debris, turbulent water can further hinder the operational environment of sonar devices. Holnbeck and McCarthy7 reported that of the four sonar units installed on each pier of the I-90 bridge over the Blackfoot River in Montana, only one provided operational data due to highly turbulent water and air entrainment through the bridge section. Temperature and salinity in the channel also significantly affect sonar results. Lagasse et al.6 reported that for John’s Pass Bridge in Florida, it was necessary to adjust the measured signal by approximately 0.5 m on average to account for the temperature and salinity effects. Another commonly used instrument in scour observation is the magnetic sliding collar (MSC), a device consisting of a rod driven into the riverbed with a collar that rests on the bed surface and slides down the rod during a scour event.6 As the scour hole refills, however, the magnetic collar is buried under the refill material and becomes incapable of recording any refill of the scour hole.6 As with sonar systems, MSC devices are also vulnerable to debris impacting the device that in turn damages the monitoring unit.5,6 It is also possible for sediment in the riverbed to foul the space between the collar and rod and prevent the collar from moving during a scour event.6

The time-domain reflectometry (TDR) method, which uses electromagnetic (EM) pulses transmitted through pipes buried in the riverbed, is another rod-based method used for scour observation.8 Here, the elimination of debris and jamming problems associated with sonar and MSC techniques permits the gathering of information regarding the refill of the scour hole. TDR, however, is susceptible to temperature and salinity changes. Even though Yu and Yu9,10 reported that varying salinity levels from 0 to 750 ppm did not adversely affect the performance of the TDR method, these ranges are unsuitable for use in near coastal waters. In estuarine environments, for instance, the temperature can vary by 20°C or more, and the specific conductance, a measure of the salinity, can vary from a yearly average of approximately 100 μS cm\(^{-1}\) to a maximum of 25,000 μS cm\(^{-1}\) (approximately 50–17,500 ppm),11,12 well above the range tested in the laboratory.

As shown in the relevant literature, available scour monitoring techniques (e.g. sonar fathometers, TDR, and MSC) are susceptible to environmental and flow conditions, including temperature, salinity, turbidity, air entrainment, and debris. Furthermore, MSC devices can only record the maximum scour depth and cannot record refill. In this article, the authors propose a novel technique that is more resilient to environmental and flow conditions and is capable of measuring both scour development and refill.

In the proposed method, several dynamic sensors mounted on thin, flexible plates, referred to as vibration-based turbulent pressure sensors (VTPs), are distributed along the length of a sealed pipe that is driven into the riverbed near the pier or abutment. The VTPs in the river are subjected to the natural turbulence of the river flow and are excited by the associated time varying dynamic pressure. The VTPs in the flow vibrate at amplitude levels detectable by modern vibration transducers. Conversely, a VTP in the sediment, which is not exposed to the turbulence, vibrates at lower amplitudes than those experienced by the VTPs in the flow. The time history of the vibrations of each sensor can be recorded by an accelerometer mounted on the inside surface of the plate. The captured signals can then be processed to quantify the mean squared acceleration response in the time domain, which is related to the signal energy content. By monitoring the energy content associated with several VTPs distributed throughout the depth of the pier or abutment, it is possible to correlate the changes in vibration response to the changes in the bed level. Determining the changes in the bed level allows the assessment of not only scour development but also the refill process.

The VTP mechanism is robust against many of the environmental conditions that plague existing scour monitoring devices. Debris in the channel causes false echoes in a sonar system; however, the VTP method is unaffected by debris since it measures the water/sediment interface directly. Turbidity, which hinders the performance of sonar fathometers, has a favorable effect on the performance of the VTP as the method depends upon the turbulent dynamic pressure in the channel. By the same argument, as salinity has a minimal influence on turbulent dynamic pressure, the VTP mechanism is theoretically immune to the changes in the salinity in the channel water, which has adverse affects on the TDR method. Finally, given the anticipated temperature range in natural rivers, which can affect both the TDR-based and sonar-based methods, the response of the VTP method is likely to remain unchanged as any variation in the vibration characteristics of the thin flexible
plates associated with temperature variations will be minor since it is possible to select materials with a low coefficient of thermal expansion.

Starting in section “Numerical proof of concept,” the underlying principle behind the VTP device is discussed along with the practical aspects regarding the development of a prototype VTP system. The laboratory experimental campaign is discussed in section “Experimental setup” with the results reviewed in section “Results and discussions.” Pertinent conclusions drawn from the laboratory experiments in preparation for field implementation of the VTP method are discussed in section “Conclusions” along with an overview of future study.

**Numerical proof of concept**

A simplified numerical proof-of-concept model is built based upon the principles of dynamics for a plate subjected to an applied pressure distribution. It will be established that a single-degree-of-freedom (SDOF) system provides an adequate means for estimating the dynamic response of the proposed VTP to the varying pressure caused by turbulence in the channel flow. It is useful to define the response of the VTP in the frequency domain since models for the response of a SDOF system are readily available. In addition, the turbulent dynamic pressure in the channel is also described well in the frequency domain. By combining these models, it will be possible to predict the response of the VTP to the pressure associated with the turbulent fluctuation in the channel.

**Modeling of open-channel turbulent flow**

Several features of the nature of turbulence within open channels lend themselves to being exploited by the VTP method. In particular, the distribution of the turbulent fluctuations in the mean flow direction, $\sqrt{u'^2}$, peaks near the riverbed in the wall region, at $y^+$ of 15. The parameter $y^+$ is equal to the product of the vertical position in the channel, $y$, and the friction velocity, $U_f$, divided by the kinematic viscosity of the fluid, $v$. Additionally, for open-channel flows, once the flow is fully developed, the power spectral density of the turbulent velocity fluctuations, $\Phi_{UU}(f)$, is stationary. The power spectral density is related to the correlation function, $R_s(r)$, as shown in equation (1), for two turbulent velocity measurements, $u'(x)$ and $u'(x+r)$, spaced a distance $r$ apart. Taylor’s hypothesis of frozen turbulence makes it possible to convert the spectra, $\Phi_{UU}(k)$, from wave number space, $k$, to frequency space, $f$, as shown in Nezu and Nakagawa. In addition, since $R_s(r)$ can be determined from measurements of the velocities in open-channel flows, it is possible to develop experimental representations of the power spectrum, through the use of the Fourier transform. The resulting power spectrum can be nondimensionalized for the range of flow conditions typically found in open channels; thus, various attempts have been made to develop models that matched the experimentally measured spectra.

\[
R_s(r) = \frac{u'(x) \cdot u'(x+r)}{u'^2} = \int \Phi_{UU}(k) \cos(k \cdot r) dk
\]

\[
\Phi_{UU}(k) = \frac{2}{\pi} R_s(r) \cos(k \cdot r) dr
\]  

(1)

One such model was developed by Von Kármán for isotropic turbulence at high Reynolds number and is valid from the production to the inertial subrange of the turbulent energy spectrum. Another model was developed by Heisenberg and is shown in equation (2), which is valid from the inertial subrange to the point of viscous dissipation. These two models are used to predict the magnitude of the turbulent pressure impinging on the VTP. The reader is directed to Nakagawa et al., Nezu and Nakagawa, and Von Kármán for further details on the development of these models.

\[
\frac{\overline{u'^2} \Phi_{UU}(f)}{U^2} = \frac{4L_X}{U} \left( 1 + \left( \frac{f}{f_c} \right)^2 \right)^{-5/6}
\]  

(2)

\[
\frac{\overline{u'^2} \Phi_{UU}(f)}{U^2} = \left( \frac{2\pi}{U} \right)^{-2/3} C_{ke}^{2/3} f^{-5/3} \left( 1 + \gamma' \left( \frac{2\pi f}{U} \eta \right) \right)^{-4/3}
\]  

(3)

These models depend upon the mean eddy macroscale, $L_X$; the characteristic frequency, $f_c$; the dissipation rate of turbulent energy, $\varepsilon$; the mean flow velocity, $U$; the mean of the squared turbulence level, $\sqrt{u'^2}$; the constants $\gamma'$ and $C_{ke}$; and, finally, the Kolmogorov length scale, $\eta$. The mean eddy macroscale, shown in equation (4), is a function of vertical position in the channel, the channel depth, $h$, and an empirically determined constant, $B_1$, which varies from 1 to 1.14

\[
\frac{L_X}{h} = B_1 \left( \frac{y}{h} \right)^{1/2} \text{ for } y/h < 0.6
\]

\[
\frac{L_X}{h} = 0.77B_1 \text{ for } y/h > 0.6
\]  

(4)

The additional parameters in equation (2) can be determined from the universal function for the turbulence intensity in open channels, which for the mean flow direction is shown in equation (5). Equation (5), in turn, is dependent upon the friction velocity, the
friction Reynolds number, \( Re = hU_0 / v \), \( y^+ \) defined previously, and various empirical constants, \( D_U = 2.3 \), \( B = 10 \), and \( C_1 = 0.3 \)

\[
\frac{\sqrt{u'^2}}{U_s} = D_U \exp\left(\frac{-y^+}{Re_s}\right) \Gamma(y^+) + C_1 y^+ \left(1 - \Gamma(y^+)\right)
\]

\[
\Gamma(y^+) = 1 - \exp\left(\frac{-y^+}{B}\right)
\] (5)

The dissipation rate for isotropic turbulence can be modeled, as shown in equation (6).\(^{13}\) Finally, the micro-length scales (\( \eta \) and \( \omega \)) can be correlated to the macro-length scales via the relations in equations (7) and (8),\(^{14}\) with \( Re_L = \sqrt{u'^2 L_X / v} \) and \( K \) as given in equation (8)\(^{14}\)

\[
\varepsilon = \frac{15 u'^2}{\lambda^2}
\] (6)

\[
\frac{L_X}{\lambda} = \left(\frac{K}{15}\right)^{1/2} Re_L^{1/2}
\] (7)

\[
\frac{L_X}{\eta} = K^{1/4} Re_L^{3/4}
\] (8)

\[
K = 0.691 + \frac{3.98}{\sqrt{Re_L}}
\] (9)

Given the spectra for the turbulent velocity fluctuations, the corresponding spectra for the associated pressure on the flexible plates are constructed as the product of the velocity spectra and the flow density, \( \rho \), as shown in equation (10)

\[
\Phi_{PP}(f) = \frac{1}{2} \rho u'^2 \Phi_{UU}(f)
\] (10)

**Modeling of VTP dynamic response**

Given the nature of the turbulent dynamic pressure in the channel, it is necessary to describe the response of a plate to this dynamic forcing function. Following the method developed by Blevins,\(^{16}\) it can be shown that the response of a plate, \( w_i \), for each mode \( i \), to the dynamic turbulent pressure, \( P_i \), is governed by equation (11), where \( \zeta_i \) is the modal damping factor and \( J_i \) is the joint acceptance between the mode shape and the pressure distribution

\[
\frac{1}{\omega_i^2} \ddot{w}_i + \frac{2 \zeta_i}{\omega_i} \dot{w}_i + w_i = J_i P_i
\] (11)

The joint acceptance governs the manner in which the modal displacement response of the plate corresponds to the spatially varied pressure distribution for a given mode. Under the condition that the mode shape and the pressure distribution are aligned, the joint acceptance is 1,\(^{16}\) and the solution to equation (10) for a sinusoidal pressure distribution becomes the classical harmonic excitation response of a SDOF system. Given that the turbulence in open channels is stationary and random, the autospectral density of the displacement response of the VTP, \( \Phi_{XX}(\omega) \), can then be computed from the mean square of the classical harmonic excitation response to the autospectral density of the pressure distribution, as shown in equation (12). What remains is then to describe the means square response of the VTP and couple that response function with the previously discussed turbulent pressure spectrum (equation 10)

\[
\Phi_{XX}(\omega) = |H(\omega)|^2 \Phi_{PP}(\omega)
\] (12)

The steady-state response function \( |H(\omega)|^2 \) can be described from the modal damping and the natural frequency, \( \omega_N \), of the SDOF system, as shown in equation (13)\(^{16,17}\)

\[
|H(\omega)|^2 = \frac{1}{\left(1 + \left(\frac{\omega}{\omega_N}\right)^2\right)^2 + \left(2 \zeta \frac{\omega}{\omega_N}\right)^2}
\] (13)

A closed-form solution for the first natural frequency of a circular plate fixed at its circumference is given by equation (14)\(^{18}\)

\[
\omega_N = \frac{10.22}{r^2} \frac{E t^3}{12 \rho t (1 - \nu^2)}
\] (14)

where \( r \) is the radius of the disk, \( E \) is Young’s modulus, \( \nu \) is Poisson’s ratio, \( \rho \) is the density, and \( t \) is the plate thickness.

**Numerical model results**

The SDOF model and the input forcing function, discussed previously, are used to model the response of the VTP to the dynamic excitation from turbulent flow. The flow case considered has a mean flow speed of 0.3 m s\(^{-1}\) and a depth of 3 m with a VTP located at \( y / h \) of 0.1, a representative case for natural channels.

The displacement response spectra from the VTP model are shown in Figure 1, along with the velocity and acceleration spectra, computed from derivatives of equation (11). The turbulent spectrum of the forcing function (due to turbulent pressure) is also shown in Figure 1, including both the production and inertial subranges. The spectrum exhibits a broad peak at low frequencies, less than 0.1 Hz, associated with the large eddy structures in the flow. The inertial subrange encompasses approximately 0.1–40 Hz, at which point the declination in the amplitude of the input spectrum is observed. This reduction is associated with the
transition to the viscous subrange. Accordingly, an ideal VTP would be sensitive to the turbulent pressure within the frequency range of 0.1–40 Hz.

The first natural frequency for a representative circular plate made from neoprene rubber, calculated using equation (14), can be seen in all three response spectra for the VTP at approximately 250 Hz. The magnitude of the acceleration, velocity, and displacement spectra, shown in Figure 1, reveal the frequency ranges appropriate to various sensor types that could be used in recording the response of the VTP. In the low, near direct current (DC), frequency range less than 10 Hz, the results indicate that a position sensor would be optimal. However, in the range of 10–400 Hz, Figure 1 indicates that an accelerometer would be better suited to measure the response. Accelerometers with sensitivities over the frequency range of 10–400 Hz are commonly available. Therefore, for the initial prototype, these accelerometers are selected for the development of the scaled prototype model.

During operation of the VTP, the variation in the energy content of the flexible plates throughout the depth of the pier or abutment must be monitored: a low energy content corresponds to sediment, while a high energy content corresponds to channel flow. Using the spectra shown in Figure 1, it is also possible to compute the mean value of the acceleration autospectrum of the vibration response over the frequency range of interest. The response spectra computed for various geometric and material configurations can then be used to evaluate the hypothesis behind the operation of the VTP device and to determine the optimal configuration for the prototype.

Based upon the numerical model results, an optimal VTP would respond to low-frequency turbulent pressure fluctuations at a level detectable by commercially available accelerometers. The VTP prototype must be designed considering the competing constraints of maximizing the energy content response while keeping the dimensions of the plate small such that the spacing between VTPs is kept to a minimum.

For the VTP prototype, both metallic and nonmetallic materials are considered, including stainless steel (304 Grade), aluminum, (6061-T6), brass, and three plastics, polyvinyl chloride (PVC), low-density polyethylene (LDPE), and a neoprene rubber (durometer of 30 A). Plates of 3.2 mm thickness with both circular and square geometric forms are considered. The simplified numerical model is used to analyze the response, with an appropriate change in equation (14) for the square geometry. The energy content response computed for various VTP plate areas is plotted in Figure 2.

For the metallic materials, the circular VTP consistently has the higher energy content over the square VTP for a given area and material. For the largest VTP, with an area of 0.073 m², the circular aluminum, brass, and stainless steel VTPs have a mean response level of 9%, 13%, and 10% greater than the square VTP. For each geometric shape, the brass VTP responds, on average, at a level of 14% above that of the aluminum VTP and 18% above that of the stainless steel.
steel VTP. Therefore, for the metallic VTPs, the circular VTP is the preferred configuration, with the optimum metallic material being brass.

For the nonmetallic materials, the optimal geometric configuration depends upon the VTP area. For instance, for the LDPE, the circular VTP at lower areas responds as much as 14% more than the square VTP, for the same area. However, as the area of the VTP increases, this trend shifts. For the LDPE VTP, this transition occurs at areas above 0.03 m², while for the PVC and neoprene VTPs this occurs at 0.008 and 0.005 m², respectively. Within a particular case, the optimal material also is a function of area. At lower VTP sizes (0.002–0.008 m²), the neoprene VTP responds on average 19% more than the PVC VTP. For the 0.01 m² case, however, the PVC response peaks 68% higher than the neoprene area of the same case and size. Then, from 0.02 to 0.07 m², the LDPE response peaks and is several orders of magnitude larger than that of the PVC or neoprene VTPs. Thus, for the nonmetallic VTPs, the optimal geometry and material choice are a function of area. For smaller VTPs, a circular neoprene VTP is optimal. For larger VTPs, an LDPE, square VTP is optimal.

When considering an optimal VTP configuration for evaluating the hypothesis behind the operation of the VTP devices, it is important to balance the desire to maximize the response level in the turbulent flow with the size of the plate. Therefore, a size limit of 0.01 m² is imposed to keep the spacing in line with the resolution of an MSC device. Based on this limit, it can be concluded that a circular VTP made from neoprene is optimal.

**Experimental setup**

According to the materials and geometric form selected in the previous section, a prototype is constructed with eight neoprene VTPs of 0.0254 m radius. The VTPs are spaced approximately 0.10 m apart, on center, in a 0.10-m-diameter PVC support pipe. A schematic of the prototype assembly is shown in Figure 3. The assembly consists of a compression pipe coupling mounted in the support pipe with a toroidal disk sandwiched between the compression coupling components. The flexible plate is fixed to the toroidal disk, as shown in Figure 3. Overall, the size of the VTP and the support pipe are small in comparison with the physical dimensions for a pier, which are typically 0.5–1 m or more in width. For such a device in a typical field case, the equilibrium scour depth predicted with the Neill equation¹⁹ is approximately 1.4 m, while the pipe would only result in a 0.3 m hole, well within the original scour depth. As such, the presence of the VTP is anticipated to have a limited affect on the flow around the pier and any subsequent scouring of the riverbed.

The support pipe is buried below the sediment, with several sensors exposed to the flow and several sensors below the water/sediment interface. The experiments are conducted in the Clemson Hydraulic Laboratory in a 1.2 × 1.2 m square cross section, 18 m long flume. The flume is equipped with a recess for scour measurements, in which the support pipe and VTPs are located. The support pipe is fixed to the flume frame, as shown in Figure 4. The riverbed is simulated with quartz sand of a d₅₀ of 1.5 mm. A sand bed represents a worst case evaluation of the VTP method since the pressure waves impinging on the bed from the turbulent flow will have a greater depth of penetration in the quartz sand bed. Since the dissipation of a wave will be greatest in a clay or silt bed,²⁰ the turbulent pressures incident on the sand bed will propagate furthest into the sand bed, leading to the highest possible response from a VTP in the sediment. The flow rates are varied from 0.028 to 0.14 m³ s⁻¹, which is measured with an FMG3101 magnetic flow meter.

To measure the acceleration of the VTP plate, a B&K 4507 B 006 uniaxial transducer, with a sensitivity of approximately 51 mV m⁻¹ s⁻², is mounted in the center of the flexible plate inside each VTP. These accelerometers are connected to a B&K LAN-XI 3050A-060 data acquisition system. A sampling frequency of 25.6 kHz yields a converged root mean square (RMS) value of the acceleration response for a given flow condition and is thus selected as the measurement frequency for the experiments. The measurements are recorded for 10 s each with 10 repeat measurements for each flow condition. The mean squared value is computed for each

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VTP from the measured signals, which is proportional to the energy of the time-domain acceleration. The mean squared value will be referred to as the VTP energy content for the remainder of this article. The experimental setup is shown in Figure 4.

Results and discussions

The experiments are conducted with three objectives: (1) to supply a proof-of-concept, (2) to evaluate the performance of the VTP system in a scour hole, and (3) to determine the precision of the VTPs.

Verification of the hypothesis behind VTP

During this phase of testing, the following four VTPs are submerged in the flume: two positioned in the sediment (VTPs 7 and 8) and two positioned in the flow (VTPs 5 and 6). VTPs 1–4 in this test are above the water free surface. VTP 8 is situated at the lowest position (0.16 m below the sediment bed) while VTP 5 is situated at the highest position (0.14 m above the sediment bed). The results of the tests are shown in Figures 5 and 6.

In Figure 5, the energy content response is calculated for four different flow rates ranging from 0.060 to 0.14 cm and plotted against the distance from the sediment interface. The mean and standard deviation of the ten 10-s measurements are plotted to present the central tendency and the variability of the measurements. In Figure 5, the VTP within the flow and adjacent to the bed measures the peak energy content. The energy content decreases with increasing distance from the sediment surface, which is in agreement with the expected profile of the flow turbulence across the depth of the channel [13].

On the other hand, the VTP response in the sediment is one to two orders of magnitude lower than the measured acceleration in the flow. This difference between the energy content levels of VTPs in the channel and sediment is well above the uncertainty bounds of the sensors in the flow; therefore, proving that the low-frequency vibration response of the VTP can be used to distinguish between channel flow and sediment.

In Figure 6, the mean square of the time-domain response of VTP 5, located in the channel flow, is compared against that of VTP 8, located in the sediment, for varying flow rates. For each flow rate, the average for each of the ten 10-s measurements is plotted. For all flow rates, the average difference between the VTPs in the flow and the sediment is 0.028 m² s⁻⁴. Depending upon the flow rate, the minimum difference between the two signals is one order of magnitude, while the largest difference increases to two orders of magnitude. Figure 6 shows a general trend where the measured energy content increases with flow rate, an observation consistent with expectations since the amplitude of the pressure fluctuations due to turbulence increases with the mean flow speed, and therefore with flow rate. Even at low flow rates, however, the difference between the sensors mean square response in the flow and sediment is detectable. Thus, as the flow rate, and therefore the flow velocity increases, the difference in energy content levels for VTPs located in the flow versus the sediment increases, aiding in the observation of the water/sediment interface, as shown in Figure 6. It should be noted, however, that for the highest flow rate, the energy content level drops slightly from the value at a flow rate of 0.135 cm. This is attributed to the averaging time of 10 s, which may not fully capture all of the large eddies in the flow. Future field tests should
investigate longer averaging times to avoid this complication.

Additionally, Figure 6 highlights the potential impact that additional vibration sources can have on this novel scour monitoring method. The energy content of the VTPs in the sediment, which are dominated by noise vibration sources, is an order of magnitude below the responses from the VTPs located in the flow, which are also subject to the same noise sources but are dominated by the vibrations due to the turbulent flow.

Assessing scour hole performance

The nature of the turbulence in a scour hole varies in magnitude and spatial distribution from that found in the channel flow, making it necessary to verify the performance of the VTPs in a scour hole. For this purpose, the response of the VTP located in a manually developed 0.056 m scour hole is measured (Figure 7). The experiments are conducted where VTP 1 is partially submerged, VTPs 2–4 fully submerged, VTP 5 partially visible in the unscoured bed, and VTPs 6–8 fully in the sediment, as shown in Figure 4. The energy content, computed as the mean square of the time-domain response, is computed for each VTP, and the mean and standard deviation are plotted against position relative to the bed in Figure 7.

Figure 7 indicates that VTP 5, which is fully uncovered by the scour hole development, is subject to an excitation level due to the turbulence in the scour hole itself that is greater than the excitation in the main flow. This is expected, however, since the turbulence intensity should be higher in the scour hole due to the
Thus, the presence of the scour hole itself improves the VTP approach’s ability to detect the water/sediment interface.

Precision assessment

The precision of the VTP scour detection is investigated with several experimentally controlled scour holes ranging in depth from approximately 0.04 to 0.14 m. During these experiments, VTP 1 is partially submerged, VTPs 2–4 are fully submerged, VTPs 5–8 are buried in the sediment, and VTPs 5 and 6 are visible due to the various scour holes. The slope of the VTP energy content is computed along the depth, with the maximum gradient used as the determining point for the sediment interface. The depth of the scour hole is determined as the average height between the two VTPs surrounding the point of maximum gradient. Figure 8 presents six profiles for the cases varying from no scour to the 0.14 m deep scour hole, along with the slope of the profiles. Figure 8 reveals that for the 0.056–0.14 m deep scour

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**Figure 7.** Turbulent energy content of prototype VTPs in unscoured and 0.056-m scoured channel beds. The mean values are denoted by the points, while the dotted lines represent the standard deviation of the measured results around the mean value. VTP: vibration-based turbulent pressure sensors.

**Figure 8.** Energy content of prototype VTPs in scour holes of various sizes. The mean profile is plotted alongside the slope of the mean profile, scaled by a factor of 1/10. The VTP and the independently measured scour hole depths are indicated for each experiment: (a) no scour, (b) 0.0385 m scour, (c) 0.056 m scour, (d) 0.0825 m scour, (e) 0.1235 m scour, and (f) 0.142 m scour. VTP: vibration-based turbulent pressure sensors.
holes, the point of maximum slope corresponds to the interface location.

The results for the 0 and 0.038 m deep scour holes are shown in Figure 8, where the point of maximum slope is above the channel bed. Since it is only possible to locate the interface as the mid-height of the two VTP positions around the point of maximum slope, the VTP indicated water/sediment interface is 0.03 m above the original bed level. Additionally, in the 0.038 m deep scour hole case, VTP 5 responds at a level between its adjacent VTPs. In this case, VTP 5 is not fully exposed by the scour hole, indicating that a critical depth of scour around the VTP is required to observe enough of the turbulent flow to obtain an accurate measure of the water/sediment interface. As the scour hole deepens and uncovers more surface area of the VTP, the response increases, yielding a more accurate water/sediment interface location.

During the development of the scour hole shown in Figure 8, the 0.14 m scour event occurred prior to the 0.12 m event; thus, the 0.12 m results represent a refilling scour hole scenario. For the 0.012 m case, VTP 6 is partially exposed for approximately 50% of its diameter. Correspondingly, the energy content of VTP 6 (0.0016 m² s⁻⁴) is between the values for the adjacent VTPs, 0.011 m² s⁻⁴ for VTP 5 in the flow, and 0.0005 m² s⁻⁴ for VTP 7 in the sediment. As the refill process proceeds, however, the response of VTP 6 continues to drop, resulting in a determination of the interface location during refill.

The scour depth detected by the VTPs is then compared against the independently measured scour depth to assess the precision with which the VTP can determine the water/sediment interface (Figure 9). Ideally, this comparison would yield a straight line with a slope of 1:1. The results shown in Figure 9, however, highlight the coarse nature of the VTP spacing. Error bars plotted for each of the VTP interface locations represent ±0.5 of the spacing. Since the point of scour is determined by the average of the two VTPs above/below the point of maximum slope, having a larger number of closely spaced VTPs would decrease the spacing between detection points. This would lead to an improved precision in determining the scour hole location.

Figure 9 also illustrates that for the 0.12 m scour hole, where VTP 6 is uncovered for approximately 50% of its depth, the VTP determined scour depth, even considering the uncertainty bars, predicts a value below that of the independently measured depth. This result, in conjunction with the result from the 0.038 m scour case, where VTP 5 was uncovered for approximately 88% of its surface yet still indicated a scour position between VTPs 4 and 5 instead of VTPs 5 and 6, indicates that there is a minimum amount of VTP surface that must be uncovered by scour to register the presence of the turbulent flow. This result is attributed to the nature of the dynamic force due to turbulence impinging on the VTP surface. Since the magnitude of this force is a function of the exposed area, for a partially exposed VTP, the energy content is lower than for a fully exposed VTP. As the scour location is determined by the point of maximum slope, an energy content level between a partially exposed VTP and one in the sediment does not result in a significant change in the slope, leading to an inaccurate reading. Conservatively, this minimum exposure can be taken as the entire surface of the VTP area. Further testing, however, is necessary for the final field version of the VTP device to verify this result.

The results presented show that the VTPs are capable of distinguishing whether the surrounding material is sediment or flowing water in a channel. The results also show that the method is feasible in the presence of a scour hole, in which the turbulence levels result in a dynamic pressure that is higher in magnitude than in the main, unscoured channel. Also, the precision of the method is shown to be within the VTP spacing, which can be improved by reducing the spacing of the VTP units through further refinement of the device.

**Conclusions**

Since scour damage to bridge piers and abutments accounts for the majority of bridge failures within the United States, and given that the cost of these repairs can extend into the hundreds of millions of dollars, it is...
of critical importance to develop a robust real-time monitoring system that can detect the development and presence of scour. A survey of the related literature has shown that many of the traditional measurement methods are sensitive to the environmental conditions within rivers such as water temperature, salinity, and debris in the channel.

Since measuring scour is of critical importance, and given that traditional devices are susceptible to many of the conditions in natural channels, a novel method is proposed that can determine scour depth in real time and is also insensitive to many of the conditions that cause other monitoring methods to fail. The proposed methodology consists of a series of vibration-based turbulent pressure sensors, referred to as VTPs, mounted along the length of a support pipe that is buried in the channel bed. The VTPs consist of an accelerometer attached to a thin plate, which is exposed to the channel. The mean squared acceleration response of the plate is computed in the time domain and used to determine whether the material surrounding the VTP is water or sediment. Since the device is sensitive to the dynamic pressure in the flow associated with turbulent fluctuations, a VTP with high energy content indicates the presence of flowing water in the channel. A VTP in the sediment, however, is not subject to the same dynamic pressure as a device in the flow. Therefore, by measuring the profile of the energy content for multiple VTPs mounted along a bridge pier or abutment, it is possible to determine the location of the water/sediment interface.

Based upon the experimental results presented, the evidence demonstrates that the energy content of the VTPs located in the sediment is one to two orders of magnitude lower than that of the VTPs located in the channel flow. Therefore, the original hypothesis that it is possible to exploit the difference between the mean excitation level in the sediment and those in the flow to measure the water/sediment interface is demonstrated to be an effective means of monitoring the riverbed for scour. Additionally, the measurement results show that the slope of the energy content profile relative to depth is a reliable means of determining the location of the water/sediment interface, located by the point of maximum slope.

The presence of a scour hole is also shown to have little impact on the ability of the VTP method to determine the location of the water/sediment interface. The experimental results, however, reveal that the percentage of the VTP surface that is exposed to the flow affects the VTP response and thus the determination of the water/sediment interface. Even considering this result, however, the precision of the VTPs is shown to be better than 0.10 m, which is more accurate than the MSC device (which has a precision of 0.15 m) but is below that of a sonar/fathometer (which is accurate to within 0.03 m).

The precision of the device is dependent upon the resolution of the sensors, and thus the VTP size. With further refinement of the sensors, the precision of the system can be improved. Additionally, further testing is needed to identify the critical amount of VTP surface exposure to the turbulent flow required to improve the identification of the presence of turbulent flow surrounding the VTP.

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**References**