An evaluation of scour measurement devices


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ABSTRACT

Scour, the leading cause of bridge failures, affects hundreds of thousand bridges and costs hundreds of millions of dollars in direct repair costs in the U.S. alone. Furthermore, scouring has also been linked to catastrophic failures that resulted in the loss of human lives. The U.S. Federal Highway Administration has proposed several countermeasures to reduce the impact of bed degradation. One of these countermeasures that is particularly relevant during peak flow periods is the real-time monitoring. Two common scour monitoring techniques are the sonar fathometers and time domain reflectometry. A novel vibration-based monitoring technique, which exploits the nature of turbulence in open channel flows for measuring scour hole depth has recently been proposed.

Through an extensive experimental campaign, the authors evaluate the dependency of the performance of these three monitoring techniques on the channel conditions, such as the water temperature, and salinity or sediment concentration. The experimental results indicate that both the time domain reflectometry and sonar methods are sensitive to the channel temperature and salinity. For the sonar device, such effects can be accounted for by modifying the speed of sound for different temperature and salinity levels. For the time domain reflectometry method, the temperature effects can be accounted for using the above approach, while the presence of salinity degrades the waveform features limiting the device to non-saline environments. Salinity and temperature are shown to have little effect on the novel method. Furthermore, the time domain reflectometry and vibration-based methods are observed to be insensitive to suspended sediment concentrations and turbid flow. Sonar, however, is shown to be sensitive to moving turbid water. In varying topography, sonar is found to record the minimum depth within the beam diameter. Flow misalignments up to 90° have little impact on the vibration-based method.

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1. Introduction

Scour damage to bridges, a widespread and costly threat to transportation infrastructure, can be countered with appropriate monitoring of the riverbed as pointed out in HEC-23. The available monitoring methods however, are sensitive to many environmental and operational conditions in natural channels, such as temperature, turbidity, etc. Thus, understanding the impact of the environmental and operational conditions on the performance of existing scour monitoring methods is essential for successful field deployments.

Scour at bridge piers and abutments typically occurs during high flow periods, such as floods or hurricanes, and has been directly linked to the failure of several bridges. During 1961–1974, of the 86 bridge failures that occurred, 46 were attributed to scour damage [1]. Flooding in the late 1980s and early 1990s in the Northeastern and Midwest U.S. resulted in damage to more than 2500 bridges [2]. More recently, from 1996 to 2001, 68 bridge failures in the U.S. were attributed to scour [3]. Overall, 60% of the reported failures of bridge structures are due to scour damage [4]. Furthermore, approximately 21,000 bridges in the U.S. are scour critical [5] with another approximately 80,000 scour susceptible [5,6].

Floods, often the main source of the increased flows, lead to the development of scour holes and can cost millions of dollars in damage. Floods during the 1980s resulted in damages of $300 million, while in the 1990s individual floods caused as much as $178 million [2,7]. Brice and Blodgett [8] reported that the cost to repair bridge infrastructure is roughly $100 million per scour event. On an aggregate basis, the total annual budget devoted to scour repairs by the US federal government (between Federal Emergency Management Agency and Federal Highway Administration projects) is $20 million [9]. The costs illustrated above, however, only account for the impact to the infrastructure itself and neglect the additional costs to the affiliated population, who depend upon the bridge as a vital part of their transportation system. These additional costs have been estimated to be as much as five times the cost of the actual repairs [9].
While the financial costs can be significant, the loss of a bridge from scour may also cause loss of human life, which has occurred during the Schoharie Creek, Hatchie River, and Arroyo Pasajero River bridge failures. In 1987, the I-90 bridge failed due to a scour hole that formed around a pier footing, resulting in the loss of 10 lives [10]. The U.S. 51 bridge failure over the Hatchie River in Tennessee in 1989 was caused by the scour hole that formed due to migration of the main channel, which went undetected [11], and resulted in the loss of eight lives. Seven lives were lost in 1995 in California when a 3 m deep scour hole formed on the I-5 bridge over the Arroyo Pasajero River [12].

To counter these threats, 32 states have deployed scour monitoring systems. Sonic fathometers are one of the most prominent methods for monitoring scour with 104 fathometers installed on 48 bridges [4]. The performance of these sonar based scour monitoring systems has been reported by Legasse et al. [4], Nassif et al. [13], Hunt [14], Mason and Sheppard [15], DeFalco and Mele [16], Holbeck and McCarthy [17], and Cooper et al. [18]. These reports have documented accurate measurements of scour holes from 0.23 to 1.2 m in depth as well as successful operation during hurricanes. While sonar systems have been used extensively, the environmental conditions in rivers can impact the performance of the device. These conditions include air bubbles entrained in the flow, suspended sediment and turbidity, debris, salinity, and temperature. DeFalco and Mele [16] attributed the cause of 5 m spikes in the measured time histories at two bridges in Italy to the presence of air bubbles and suspended sediment/turbidity in the channel flows. Legasse et al. [4] reported the inability of the system to determine the bed depth with significant air entrainment. Additionally, factors that affect the speed of sound, such as temperature and salinity accounted for a 0.5 m offset in testing on a bridge over an inlet in Florida [4]. Another factor that can have a significant impact on the performance of a sonar system is the presence of debris in the channel. Debris can result in false echoes, leading to inaccurate readings, or direct failure of the device as it physically impacts the hardware or cabling. Cooper et al. [18] reported that debris damage led to the loss of the entire hardware system in field tests in Indiana. Lastly, sonar pulses are emitted as a discrete cone defined by the hardware itself. As the pulse reaches the scour hole, its diameter may be smaller or larger than the hole itself, depending upon the distance between the sonar and bed level. In this case, if the hole is small relative to the beam diameter at the bed, it is possible to have reflected waves returned by the unscoured channel bed, which presents a problem for the determination of scour with sonar devices.

Another scour monitoring technique that has received attention is time domain reflectometry (TDR), which uses electromagnetic (EM) waves to determine the location of water/sediment interface. The TDR system consists of rods buried into the riverbed that act as waveguides for EM pulses. The EM pulses are reflected at various interfaces, such as the water/sediment interface or the air/water interface. TDR devices have been studied extensively in the lab and the investigations have included evaluating the device precision in different bed materials, the impact of suspended sediments in the water, and salinity effects ([19–22]). The TDR device has also been used to monitor the development of scour under ice at the Hwy 16 Bridge in Missouri, where the growth and refill of scour holes of approximately 0.15 m were measured [23,24]. While the method is more robust than sonar for debris, sensitivities of the TDR device to conditions within the channel remain a concern. The effect of salinity levels, which can vary from 0.05 PPT in the upper reaches of a watershed to 17.5 PPT in near coastal waters [25,26] on the performance of TDR measurements are not previously studied. Similarly, the water temperature, which can vary from 7 to 20 °C [25,26], can affect the speed of the EM pulse and lead to inaccuracies in the measurements made with TDR.

To study the variability in the measured scour hole depth due to environmental conditions, an experimental campaign is undertaken to evaluate the performance of sonar fathometer, TDR instrument, and a novel vibration-based monitoring method (discussed in Fisher et al. [27]) under simulated field conditions. The performance of the sonar, TDR, and the vibration-based method are considered under the following environmental conditions, where appropriate:

- Saline conditions, from 0 to 35.5 PPT,
- Water temperatures, from 5 to 40 °C,
- Water with suspended sediments, for turbidities up to 900 NTU, including stratification effects,
- Scour hole size,
- Flow angle.

The objective of these experiments is to provide information on the relative strengths and weaknesses of the aforementioned three devices to facilitate their successful deployment in the field. This study therefore can aid in selecting the optimal device for the anticipated field conditions.

2. Theory and background

2.1. Sonar

A parameter that is fundamental to the operation of the sonar transducer is the speed of sound in water, \( c \), as shown in Eq. (1), where \( D \) is the distance from the sonar transducer to the scour hole and \( t_e \) is the echo time

\[
D = \frac{c t_e}{2}
\]
The speed of the acoustic pulse, which is assumed to be constant in Eq. (1), has been shown to vary with temperature, salinity, and depth ([28–31]). For a typical temperature variation from summer to winter of 30 to 10°C, corresponding errors in a sonar measurement due to the change in the speed of sound are shown in Fig. 1.

The three curves correspond to the equations for the speed of sound, as presented by Mackenzie [31], Kuwahara [28], and Leroy [29], and are given by Eqs. (2)–(4), respectively. In these equations, \(c\) is the speed of sound in m/s, \(T\) is the temperature in degrees Celsius, \(S\) is the salinity in PPT, and \(D\) is the depth in meters. For a temperature change of 20°C, a sonar transducer can have a relative error up to 4% in the distance to the riverbed. This would correspond to an error of 0.15 m for an initial depth of 3.75 m. This is several times larger than the typical resolution of the device and thus, cannot be ignored.

\[
c = 1448.96 + 4.5917 \times 10^{-2}T^2 + 2.374 \times 10^{-4}T^3 + 1.340(S-35) + 1.630 \times 10^{-2}D + 1.675 \times 10^{-7}D^2 - 1.025 \times 10^{-2}T(S-35) - 7.139 \times 10^{-13}TD^3
\]  

(2)

Similarly, the changes in the speed of sound due to salinity must also be considered. Variations in salinity occur in coastal waters subject to tides or for inland waters during rainfall events, where the runoff could contain chemicals and other pollutants that would change the apparent salinity. The impact of changes in the salinity of the channel flow is shown in Fig. 2, and reveals a relative error of approximately 2% in the scour measurements.

In addition to being affected by the temperature and salinity of the water, the ability to make accurate measurements can depend upon the nature of the bed itself. Natural riverbeds typically have a defined transition between the water, \(\rho_0\), and bed sediment densities, \(\rho_2\), with an intermediary density between that of the sediment and the channel flow, \(\rho_1\). This transition is typically

\[
c = 1445 + 4.6647T - 0.0554T^2 + 1.307 \times (S-35) + 0.01815D
\]  

(3)

\[
c = 1492.9 + 3(T-10) - 6 \times 10^{-3}(T-10)^2 - 4 \times 10^{-2}(T-18)^2 + 1.2(1000S-35) - 10^{-2}(T-18)(1000S-35) + D/61
\]  

(4)
defined by an initial step change from the water density to the intermediary density followed by a gradual transition to the final deep bed sediment density [32], as shown in Fig. 3. Robins [33] presented a model for the propagation of sound waves in a fluid of varying density and developed a generalized model for the response of the sound wave as it encounters a density gradient. The reflection coefficient, defined as the ratio of the reflected to incident signals at an interface, can be affected by the stratification of sediments along the sonar pulse. For the general case described above, the result is a complex function of vertical wave number, $k_z$, which is the ratio of signal frequency to speed of sound. The reflection coefficient, as shown in Eq. (5), is a function of the lower bed densities, the water density, the intermediate zone density, the density gradient thickness, $h$, and $k_z$. Robins [33] showed that as the product $k_z h$ approaches zero and infinity, the reflection coefficient approaches values as shown in

$$
R_{k_z h \rightarrow 0} = \frac{\rho_2 - \rho_0}{\rho_2 + \rho_0}
$$

$$
R_{k_z h \rightarrow \infty} = \frac{\rho_1 - \rho_0}{\rho_1 + \rho_0}
$$

The implication of the results shown in Eq. (5) is that at lower $k_z h$, and in turn at lower frequencies, the reflected signal is only a function of the density difference between the final bed sediment density and the flow density and is independent of the intermediate value. Conversely, as the frequency increases Robins' [33] model predicts that the reflection coefficient corresponds to the initial step change between the channel and the riverbed. Stoll and Kan [34] developed a more complex model that accounts for the effects of a porous, viscoelastic, saturated sediment and includes the losses associated with the propagation of sound waves in the sediment structure and the saturated pores. The model includes the effects of porosity, grain size, permeability of the sediment, and internal stresses, and predicts the reflection coefficient as a function of the incidence angle and acoustic signal frequency. Stoll and Kan's [34] results for incidence angles less than 45° to 50° are relatively insensitive to frequency and collapsed to the Robins’ [33] results for low vertical wave number. Above 50°, the model predicts a reflection coefficient that is a function of frequency and rapidly approaches a value of 1.0. The Stoll and Kan's [34] model for varying incidence is useful for scenarios where the sonic waves are not normal to the riverbed. However, for the typical configurations seen in river scour monitoring Robins’ [33] model will suffice.

To explore Robins’ model, the reflection coefficient is plotted in Fig. 4(a, b) as a function of the riverbed sediment density and the intermediary material, respectively. Fig. 4 reveals that for various bed densities, the reflection coefficient varies in the range of approximately 0.2 to 0.3. For the suspended sediment to approach these values, the concentration has to reach 800 g/L. This value is well above the 10 g/L typically found in channels [35]. Thus the wave will pass through the intermediary layer with only a minor reflection occurring at the interface level. This is beneficial if an active bed is present in the channel.

### 2.2. Time domain reflectometry (TDR)

In the field, the salinity, temperature, and the amount of suspended sediment in the channel flow will vary. Each of these parameters has an impact upon the speed of propagation of an EM wave through water. Stogryn [36] developed several empirical equations that describe the impact of salinity and temperature on the apparent dielectric constant, $K_o$, which is the square of the ratio of the speed of light in vacuum to the speed of the EM wave in a particular medium. As the TDR device uses a single EM wave, it is possible to use Stogryn's low frequency results for the static dielectric constant, leading to Eq. (6) through Eq. (9). These relations reveal that the apparent dielectric constant is a function of temperature, $T$, and salt concentration, measured in normality units, $N$. The factors included in Eq. (6) are the relationship of the static dielectric constant with temperature only and an empirical equation to account for the concentration of sodium chloride, $a(N)$. The salinity of the salt water, $S$, can be related to the normality, as shown in Eq. (9)

$$
K_o(T, N) = K_o(T, 0)a(N)
$$

$$
K_o(T, 0) = 87.74 - 4.008T + 9.398 \times 10^{-4}T^2 + 1.410 \times 10^{-6}T^3
$$
This set of equations can be used to assess the impact of the salinity and temperature upon the TDR measurement. To evaluate these effects, a scenario is constructed in which the salinity varied from zero parts per thousand (PPT) to 17.5 PPT, a typical range found in channels near coastal waters [25,26]. In this analysis, the temperature also varied from 0 to 30 °C. In this assessment, the relative error is computed from an apparent dielectric constant of 80.11, which corresponds the value at

\[ a(N) = 1.000 + 0.2551N + 5.151 \times 10^{-2}N^2 - 6.889 \times 10^{-3}N^3 \]  

\[ N = S(1.07 \times 10^{-2} + 1.205 \times 10^{-5}S + 4.058 \times 10^{-8}S^2) \]  

This set of equations can be used to assess the impact of the salinity and temperature upon the TDR measurement. To

![Diagram](image-url)
In addition to the increase in near bed turbulence due to suspended sediment, the impact of the sediment particle on the VTP in the flow may further enhance the measured energy content. Thus in all likelihood, the presence of suspended sediment may improve the difference in the energy content between the VTPs buried in the river bed and the ones in the flow.

To evaluate the impact on the VTP due to changes in the channel salinity or temperature, it is necessary to consider the effect these two parameters may have on the turbulent quantities in the flow. For turbulent open channel flows, velocity fluctuations increase in magnitude with Reynolds number, until the point at which the flow becomes fully turbulent (also called rough turbulent flow). Henderson [43] reported that for \( u_n k_s / \nu \) of greater 100, the flow in open channels is fully turbulent, where \( u_n \) is the shear velocity based on the bed shear stress, \( k_s \) is the surface roughness, and \( \nu \) is the kinematic viscosity of the fluid. For a straight, uniform channel, the \( k_s \) value is approximately 0.3 cm, for a depth of 0.4 m and velocity of 25 cm/s, \( u_n \) is 3.5 cm/s and the corresponding \( u_n k_s / \nu \) is greater than 100. These values represent a very shallow, extremely low velocity natural channel (approaching laboratory conditions). Thus, it is safe to assume that for natural channels of interest for scour monitoring, the flow will be fully turbulent irrespective of temperature and salinity changes. The salinity has minor effect on the kinematic viscosity in rivers (the maximum salinity in near coastal areas is about 17 PPT). The increase in temperature causes reduction in kinematic viscosity. However, in natural channels, the irregular bed and higher bed roughness will dominate and lead to an increase in the values of \( u_n k_s / \nu \).

Lastly, in the ideal case the axis of the disk in the VTPs is aligned with the mean flow direction. It is possible for the mean flow angle relative to the VTP to shift as the channel overflows onto the flood plain. As such, it is necessary to consider the misalignment of the probe.

3. Measurement setup

To investigate the effects of channel conditions on sonar, TDR, and VTP instruments, several experiments are conducted in the Clemson Hydraulics Laboratory (CHL). The following section reviews the experimental setup for each of the devices.

3.1. Sonar experimental setup

The sonar system consists of an Airmar SS510 transducer, with a sampling frequency of 234 KHz, an 8° beam width, and tolerance of 3 cm, connected to a Campbell Scientific CR-800 data logger.

![Fig. 7. Schematic setup for the turbidity stratification test.](image-url)
Data is recorded on a work station via the Campbell Scientific PC200 software package. The temperature and salinity tests for sonar are conducted in a 30.5 cm diameter, 1.83 m high test chamber. During the test, the temperature is varied from 5 to 40 °C, measured with a Type K thermocouple for water depths of up to 156 cm. A uniform temperature distribution is maintained by complete mixing of the water. Salinity is varied from 0 to 35.5 PPT, measured with a Vee Gee SX-1 analog refractometer and a DMA 35 Anton Paar density meter. Depths of up to 131 cm are tested for different salinities within this range.

To investigate the effects of turbidity on the sonar device, experiments are conducted in stationary and dynamic configuration, including the affect of stratified turbidity. The static water turbidity tests are conducted in a 183 cm diameter plastic tank with water depths up to 125 cm and turbidity values from 39 to 520 NTU. The dynamic turbidity tests are conducted in the CHL flume with a depth of 56 cm, for flow velocities from 4 to 12 cm/s. The stratified turbidity flow tests are also conducted in the same flume for depths from 55 to 61 cm, velocity from 5.5 to 12 cm/s, and a stratified turbidity layer of 7 to 17 NTU in the main flow and 300 to 900 NTU in the bottom 5 cm, as shown in Fig. 7. For each of these tests, the turbidity is measured with a Global Water WQ 730 turbidity sensor connected to the GL 500U data logger.

In addition to temperature, salinity, and turbidity effects on sonar, the effect of the bed contour is also investigated. Two series of tests are conducted with cones of 15 and 23 cm in diameter, which are placed underneath the sonar. To create a planar reflecting surface, the cone is partially filled with sand as shown in Fig. 8.

### 3.2. TDR experimental setup

The TDR system used to investigate the effects of temperature, salinity, and turbidity on measurements consists of a probe similar to that used by Yankielun and Zabilansky [19], as shown in Fig. 9. The waveform is generated by the TDR 100, from Campbell Scientific, which is recorded on a work station running the Campbell Scientific PC TDR software. The tests are conducted in a 60 cm diameter barrel, with the lower portion of the TDR probe located in sand with an AFS grain fineness number of 16 and the upper portion completely submerged in the water, as shown in Fig. 9. The temperature tests are conducted at two water depths, 73.5 and 58.5 cm, with temperatures from 7 to 40 °C. During the salinity tests, the concentration varied from 0 to 0.75 PPT, in 0.25 PPT increments, for a water depth of 69 cm. The effect of turbidity on the TDR readings is evaluated by introducing water with dissolved sediment ranging from of 100 NTU to 500 NTU, for a depth of 52.5 cm.

### 3.3. VTP experimental setup

Experiments are conducted to evaluate the effect of suspended sediment and misalignment between the main flow direction and the VTP axis. The VTP is evaluated in the CHL flume, with flow depths of 62 cm, velocities from 7 to 12 cm/s, and turbidities from 0 to 900 NTU in 300 NTU increments. For the flow misalignment tests, the flow velocity is held constant at 27 cm/s while the alignment angle is increased in increments of 15° to 90°.

### 4. Results and discussion

The following sections outline the experimental results for the sonar, TDR and VTP in Sections 4.1–4.3.

#### 4.1. Sonar

The response of sonar to variations in temperature, salinity, turbidity, and uneven topography are presented in this section, where only one factor is varied for each experiment.

![Fig. 8. Schematic setup for the scour hole/beam ratio tests.](image1)

![Fig. 9. Schematic of the TDR setup.](image2)

![Fig. 10. Variation in relative error of sonar with temperature for different water depths.](image3)
4.1.1. Temperature effects

The temperature tests on the sonar device are conducted at water depths of 94.5, 125, and 156 cm. The test revealed that the percent relative error in water depth, relative to the 20 °C sonar reading, diverge from zero as the temperature deviates from the reference value (Fig. 10). The deviation is also larger in colder temperatures than in higher temperature. For the three depths (94.5, 125, and 156 cm), the percent relative errors in the sonar readings range from −3.30% to 3.30%, −4.97% to 1.77% and −5.98% to 2.00%, respectively. There is no specific trend for the three depths except that the variation range increases with increase in water depth. This result suggests that as the channel temperature changes seasonally, the distance to the bed, and any scour depth will artificially vary, simply due to changes in the flow temperature. The experimental results follow the same trend as Eq. (2), the Mackenzie model, predictions (Fig. 10). The deviation between the two results of may be accounted for by the precision of the sonar transducer (+3 cm).

Therefore, to account for this affect, the temperature around the sonar transducer should be measured along with the sonar signal. It must be noted that as the depth of the channel increases, the sonar readings are affected to a greater degree by the temperature since the error is proportional to the distance traveled by the acoustic pulse.

4.1.2. Salinity effects

The salinity tests on sonar are conducted for two water depths (116 and 131 cm). The results obtained from the test, as shown in Table 1, range from 3.51 to 3.81% relative error. These figures are in line with the errors predicted in Section 2 with the Mackenzie model, which reveals that for the same range of salinity, the error could reach up to 3.18%.

The results in Table 1 suggest that if the sonar transducer is located within 131 cm of the bed, the influence of salinity on the measurements is likely to be minor. This presents a tradeoff, however, between the ease of maintenance in the field, which is complicated by installations close to the bed, and measurement error.

4.1.3. Turbidity effects

Turbid waters are commonly encountered in natural rivers. To evaluate the impact of the suspended particles on the sonar readings, three cases are considered. In the first case, still turbid water is evaluated in a tank; in the second case, the combined effect of dynamic, flowing turbid water is evaluated in a flume; and lastly, the effect of turbidity stratification is considered.

For the still turbidity test, the water depth is varied from 94.5 to 128 cm and the concentration is varied from 39 to 525 NTU. The results show that the still turbidity has a negligible effect on the sonar bed measurements.

The combined effects of suspended particles and channel flow are evaluated in a flume for a water depth of 56 cm, the results of which are shown in Figs. 11 and 12. In Fig. 11, the relative percent errors for a 30 s sample mean are plotted for various average velocities and turbidity levels in the channel. Fig. 11 reveals that as the velocity increases, for all turbidities tested, the absolute relative error increases. Additionally, it appears that the level of turbidity has little effect on the measured error. For example, for a turbidity of 402 NTU, the relative error varies from −6.12 to 0.41%, while for 220 NTU the relative error varies from −6.82 to −2.1%. Fig. 11 reveals that the increase in turbidity does not lead to an increase in relative error.

It should be noted in Fig. 11 that for velocities in excess of 9 cm/s, there is a step change in the relative percent. The source of this divergence is revealed in Fig. 12, where for these same higher velocities, the standard deviation in the 30 s time histories increases sharply to a level above the sonar device tolerance. This indicates that for the two highest velocities, the sonar device is not able to locate the bed. Thus, the combined results in Figs. 11 and 12 reveal that as the velocity of a turbid flow increases, the sonar results are marginally affected, up to the point where the sonar can no longer obtain a stable recording. The inability to locate the

Table 1

<table>
<thead>
<tr>
<th>Water depth [cm]</th>
<th>Range of salinity [PPT]</th>
<th>Measured relative error in water depth [%]</th>
<th>Relative error [%] based on Eq. (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>116</td>
<td>0 to 35.5</td>
<td>0 to 3.51</td>
<td>0 to 3.18</td>
</tr>
<tr>
<td>131</td>
<td>0 to 35.5</td>
<td>0 to 3.81</td>
<td>0 to 3.18</td>
</tr>
</tbody>
</table>

Fig. 11. Relative error in the sonar reading for various turbidity concentrations and velocities of the channel flow.
bed is attributed to an increase in the scattering by the particles in the channel due to an increase in the apparent concentration of suspended solids moving beneath the sonar transducer, due to the higher flow velocity.

The results in Figs. 11 and 12 indicate that when the standard deviation of the sonar time history exceeds the device tolerance, the average value from any sonar time history is inaccurate and scour readings should be independently verified with another device. Also, the results suggest that for sites with higher sediment loads during peak flow conditions, another device should be deployed instead of sonar.

In the final turbidity test configuration, the effect of a stratified concentration, layer thickness, and flow velocity are considered. The velocity ranges from 4 to 12 cm/s, the stratified layer thickness varies from 2 to 5 cm, and the concentration in the stratified layer is between 300 and 900 NTU. The flow depth during the tests ranges from 55 to 61 cm. The results of these experiments reveal that for low velocities, and layers of increasing thickness in the depth dimension, the relative error could be as high as 17.5%. For stratified layers of smaller thickness in the depth dimension, this error drops down to 2%, which is of the order of the dimension of the layer.

As with the uniform turbidity tests, it is also important to investigate the standard deviation of the measure signal.

As evident in Fig. 13, the standard deviation of the 30 s time histories for all concentrations is above the sonar device tolerance limit. This indicates that the sonar device is unable to determine the bed level. This result disagrees with Robbins [33] model suggesting that the stratification effects are not well described by considering density alone. Therefore, other effects, such as increased scattering or attenuation by the sediment particles, must also be considered.

In summary, sonar is affected by moving, turbid water. For a uniform turbidity, and for velocities higher than 9 cm/s (for turbidity concentration ranging from 100 to 500 NTU) the sonar device cannot determine the bed level. However, stratified flow, this affect occurs even for low velocities. As such, the findings suggest that sonar devices should not be used independently in highly turbid zones. It is important to monitor the standard deviation of the recorded signal to confirm that the sonar readings are reliable.

### 4.1.4. Topography and beam width effect

Naturally developed scour holes have uneven surfaces. Therefore, it is important to determine the location in the bed topography is registered by sonar pulse. Consider two cases, one in which the sonar beam falls entirely within the scour hole, Case A in Fig. 14, and other one in which the sonar beam completely surrounds the scour hole, Case B. In Case A, the sonar beam reflects along the surfaces from point Q (the minimum depth), to the surface located by point R (the maximum water depth). In Case B, however, the minimum depth corresponds to the unsoured bed level, located by point P. These two conditions are reproduced in the lab, the results of which are shown in Table 2 and 3.

According to Table 2, the measured sonar readings are within the device tolerance limit of point Q for Case A. Similarly, for Case B, Table 3 indicates that the measured sonar results correspond to point P. From these two results it can be concluded that the sonar measurements correspond to the minimum depth encountered by the beam, which does not correspond to the point of maximum scour. Therefore, in the field if the beam is contained within the hole, sonar is expected to underestimate the scour depth. Similarly, if the sonar transducer is located far from the bed, due to installation or maintenance concerns, and if the beam diameter is larger than the scour hole, the presence of scour can be missed entirely.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Experimental results for Case: A.</th>
</tr>
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<tbody>
<tr>
<td>Maximum water depth, R [cm]</td>
<td>Minimum water depth, Q [cm]</td>
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<tr>
<td>85.3</td>
<td>76.7</td>
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<tr>
<td>75.9</td>
<td>68.25</td>
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<td>63.7</td>
<td>57.2</td>
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</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Experimental results for Case: B.</th>
</tr>
</thead>
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<td>Maximum water depth, R [cm]</td>
<td>Minimum water depth, P [cm]</td>
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<td>45.72</td>
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</table>
4.2. Time domain reflectometer (TDR)

The performance of the TDR system in varying channel salinity, temperature, and turbidity are considered in the following sections.

4.2.1. Temperature effects

As discussed previously, the dielectric constant is a function of temperature and decreases with increasing water temperature [36]. Results for the TDR probe under various water temperatures are shown in Fig. 15. The curves in Fig. 15 are the reflected waveforms analyzed using the method outlined by Yankeilun and Zabilansky [19]. Near the start of the waveform, a sharp reflection occurs indicating the start of the probe. This is then followed by a ‘plateau A’ at a reflection coefficient of -0.2, corresponding to the depth of sediment. This plateau then decreases in a step to ‘plateau B’ with a reflection coefficient of approximately -0.4, indicating the presence of water. Finally, at the end of the probe there is a terminal step change. Fig. 15 therefore indicates that as the temperature increases, the waveform shifts such that it gives a decreasing trend of apparent length. Temperature test on TDR system are performed for two water depths (73.5 cm and 58.5 cm). Water depths extracted from TDR waveform are then converted to percent relative error, relative to the dielectric constant at 20°C. Figs. 16 and 17 show the percent relative error in the measured results, for the water depth of 73.5 cm and 58.5 cm, respectively, along with the predictions from Stogryn’s [36] model.

In general, the figures indicate that lower water depths are measured by the TDR as temperature increases above 20°C and that higher depths are measured as the temperature decreases below 20°C. The percent relative error in water depth ranged from -1.36% to 2.18% and -4.98% to 4.78% for 73.5 cm and 58.5 cm of water depth, respectively. As shown in Figs. 16 and 17, the measured values determined by the TDR method are affected by a change in the water temperature. Practically, this suggests that in the winter season, the TDR might overestimate the scour depth while in summer TDR...
might underestimate the scour depth. The temperature dependency of the measurements can be accounted for by measuring temperature as part of the scour monitoring system.

### 4.2.2. Salinity effects

The salinity of the flow can also affect the accuracy of a TDR system [36]. Thus, TDR is tested under various salinity conditions, for which the resulting waveforms are shown in Fig. 18. The TDR waveform, particularly the reflection at the end of the probe, becomes increasingly hard to distinguish as the salinity increases. Above 0.5 PPT, the reflection at the end of the probe is indistinguishable. Thus compared to the sonar, the TDR is sensitive to extremely small salinity. This degradation in performance can be attributed to the decay of the EM wave into the surrounding medium, which becomes more conductive as the salinity increases.

Therefore, deploying a TDR device in a saline environment or to sites that could become brackish (greater than 0.5 PPT) can lead to inconclusive results, due to the loss in the distinct features of the waveform necessary to determine the scour depth.

### 4.2.3. Turbidity effects

The results obtained for the turbidity tests conducted on the TDR system for a water depth of 52 cm are shown in Fig. 19. The effect of turbidity on TDR measurements are determined by calculating the percent relative error in water depths. For turbidities up to 500 NTU, the TDR system is insensitive to the presence of suspended sediments. The offset present in the results in Fig. 19 indicate the precision of the TDR device, 2.2%. The results shown in Fig. 19 imply that the TDR system can be efficiently operated in highly turbid zones.

### 4.3. VTP based method

As discussed in Section 2, the VTP based method has the potential to be affected by the turbidity in the flow, as well as any misalignment between the main flow direction and the VTP axis. The tests to evaluate the performance of the VTP device under various turbidities and flow angles are discussed in the following sections.

#### 4.3.1. Turbidity effects

The impact of dynamic turbidity on the VTP’s turbulent energy content is shown in Fig. 20 for turbidities ranging from 0 to 900 NTU and flow velocities from 7 to 12 cm/s. The results indicate that the registered energy content shows a slight increase with turbidity. The increase in the VTP energy content with flow velocity is expected since \( u' \) increases with the mean flow velocity.

The results shown in Fig. 20 indicate that the VTP’s performance improves with the presence of turbidity in the flow, and thus can be deployed without the need to monitor the channel condition. The energy content of the VTP buried in the bed is not affected by turbidity and flow velocity. Therefore, the VTP method can reliably predict the formation of scour holes in highly turbid zones.

#### 4.3.2. Flow alignment effects

During high flow events, the main flow direction can shift from the nominal flow condition. Therefore, it is necessary to understand how a VTP performs as the flow direction relative to the probe changes. Fig. 21 shows the VTP energy content for three sensors located at different depths within the channel. VTP #6 is located in the sediment and therefore the response should not be a function of the flow angle as confirmed in the results shown in Fig. 21. VTP #5 is located within a scour hole, for which the results reveal that the response is insensitive to flow angle. This is
attributed to the fact that in the scour hole, the flow is separated. Thus, the sensor in a scour hole is subject to velocity fluctuations from the separated flow instead of the turbulent free stream velocity fluctuations. The recorded energy content for VTP #5 is an order of magnitude higher than the VTP in the bed (VTP #6), indicating that the method can be used to determine the water/sediment interface. The energy content recorded by VTP #4 is sensitive to the flow angle, dropping from 0.016 m² s⁻⁴ at 15° to 0.0075 m² s⁻⁴ at 90°. This is expected as the magnitude of the turbulent fluctuations normal to the VTP surface diminishes with increasing misalignment, while it is also important to note that the results are still order of magnitude higher than the VTP located below the bed. The ratio between VTP #4 and VTP #6 at 90° is approximately 75. This suggests that the method can still be used in highly misaligned flows. For the higher flow angles, the separated flow around the probe itself maintains the energy content at a level much higher than the energy content in the sediment.

5. Conclusions

Given that the environmental and operational conditions in natural channels, such as temperature, salinity, and suspended sediment change over time, it is necessary to understand how these parameters can affect any scour monitoring system. An extensive experimental campaign is conducted on two common scour measurement devices: a sonar transducer and a time-domain reflectometry probe. A novel vibration-based method, which exploits the flow turbulence in the channel, is also evaluated.

For the sonar device, changes in the temperature can result in relative errors up to 6% in channel depth. The temperature dependency can be accounted for in the field by measuring the temperature and accounting for the change in the speed of sound. Salinity can lead to relative errors of up to 3%, which can also be accounted for by correcting the scour measurements according to the measured salinity levels. The concentration of suspended particles minimally affects the sonar results in still water. For dynamic turbidity, uniform as well as stratified, the relative error in bed level measurements can be significant, however. The results indicate that measuring the standard deviation of the recorded signal is important to ascertain the validity of the averaged result obtained from the sonar measurements. Lastly, for variable bed topography, the sonar measures the shallowest depth. Therefore, the beam width at the bed with respect to scour hole may significantly affect the accuracy of the scour depth measurements.

For the TDR device, the channel temperature can have a significant effect on the measured depth of a scour hole. The relative errors can be of the order of 5%. This effect, however, can be mitigated by monitoring the channel temperature in addition to the TDR waveform. Salinities greater than 0.5 PPT result in a loss of the distinct features in the TDR waveform necessary to determine scour depth. It is recommended to only install the TDR in freshwater conditions. Turbidity in the channel flow had no measurable effect on the TDR measurements and thus the TDR can be used for monitoring scour in highly turbid zones.

The performance of a VTP is evaluated under turbid flow conditions and varying flow angles. There is no significant change in the energy content recorded by the VTP for varying turbidities. Thus, VTP can be successfully deployed in turbid zones. The energy content recorded by the VTP located in the flow decreased with increasing misalignment between the probe and the main flow direction. Even at 90°, however, the energy content of the VTP in the flow remains an order of magnitude greater than the VTP in the sediment. Thus, VTP can record the location of the water/sediment interface even under significant misaligned conditions expected during peak flow periods.

The work presented in this manuscript has detailed potential environmental and operational sensitivities of three scour monitoring devices by considering the physical principles behind the operation of each device. Additionally, through a series of detailed experiments, these sensitivities have been evaluated in order to assess the impact to scour measurements. Based upon the results presented, it is possible to evaluate potential scour monitoring sites and to select methods that are insensitive to the anticipated channel conditions, resulting in more robust field measurements.

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References


