

The development of automated spatial and temporal measurement system for lab-scale local scour

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ABSTRACT: The spatial and temporal measurements of local scour around bridge piers provide the quantification of local scouring process. Most studies on a laboratory scale faced difficulties in obtaining a holistic local spatial variability around bridge pier, especially for continuous small time interval. Long experimental period, which could take up to few days, does not permit a consistent time interval spatial scour measurement due in particular to the physical constraints that exist under laboratory conditions. This study proposed an automated, cost-effective system which is capable of detecting changes in both spatial and temporal local scour. The system allows measurement to be made by using data recorder at an adjustable distance (± 0.1 mm) and angle ($\pm 0.1^\circ$) from the original position, which is programmed and controlled with an Arduino, which is an open source microcontroller with multiple capability of controlling electrical components such as motors and sensors. When the data recorder is in position, data is automatically captured and sequentially saved at a particular spatial interval. In this study, a web camera was used as a data recorder to capture images in the azimuthal plane for a one-hour interval. Images were captured for 30 seconds per measurement per position. The system was set up to monitor and measure the temporal and spatial local scour continuously in an 80-hour experiment. Results show that the location of maximum scour depth varied for different time intervals, and migrated from downstream to upstream of the pier. The rate of scour decreased as duration of experiment was increased. The system was able to provide a holistic view of both spatial and temporal variability in the development of local scour on a laboratory scale.

1 INTRODUCTION

Bridge scour is one of the major causes of bridge failures throughout the world. It is a major determinant of the total cost of construction and maintenance (Diab 2011). Investigation of bridge failure in the United States between 1989 to 2000 shows that 53% of the failures were caused by flooding and scouring (Wardhana and Hadipriono 2003). Investigations were conducted to investigate the problems and improve bridge quality. Similar investigation in the United States showed that between 2000 and 2012 almost 50% of all bridge failure was caused by flooding and scouring (Taricska 2014). Estimation of optimization shows that the cost of bridges could be optimized by up to 40 % when an accurate scour depth is taken into account (Dumas and Krolack 2002). Therefore hydraulic issues remains as the major cause of bridge failure, and further investigations and researches need to be done in this area.

Previous studies conducted on scouring around piers focused on point measurements of scour depth in front of a circular pier in alluvial sand beds (Chiew 1984; Melville 1975; Singh and Maiti 2012).

The spatial investigations of scour holes are very seldom conducted. Knowledge of the geometric features of scour holes provides useful information in determining the size of bridge foundations and in determining the of appropriate scour countermeasures (Diab 2011). The data obtained from a short experimental period of 10 to 12 hours could be less than 50% of the equilibrium scour depth (Melville and Chiew 1999). As such, it is necessary and crucial to run an experiment for several days in order to obtain a holistic scouring profile.

Special and expensive tools are required to measure temporal and spatial scouring, and the measurement process is time consuming. These are some of the reasons why researches are often restricted to one-point measurement studies, and this is especially true with limited research budget. Such limitations have led the authors to ponder upon using high accuracy, cost-effective tools. The open source Arduino microcontroller was seen as an attractive choice.

1.1 Why Arduino?

Arduino is an open-source microcontroller, which means that it could be easily obtained at a very low price (approximately US\$10) while all programming softwares are available for free. It is a flexible device which could be used to control various electrical components such as sensors and motors through digital and analogue input and output. It can be easily controlled and programmed through the use of a computer. It could also be used as a standalone controller to control electrical components without being connected to a computer. It could be connected to a computer via Wi-Fi or even a mobile network system to make the data recording easier and safe.

Arduino is a user friendly, open source device; there are plenty of examples regarding its use and the source of code for programming is available online, if required. Arduino uses standard serial interface and is able to communicate directly with a computer. It is available in different sizes with varying numbers of input and output, which could be adjusted according to the requirements and needs of a project. Figure 1 shows the Arduino MEGA used in this project. The analogue and digital input and output could be seen in the board.

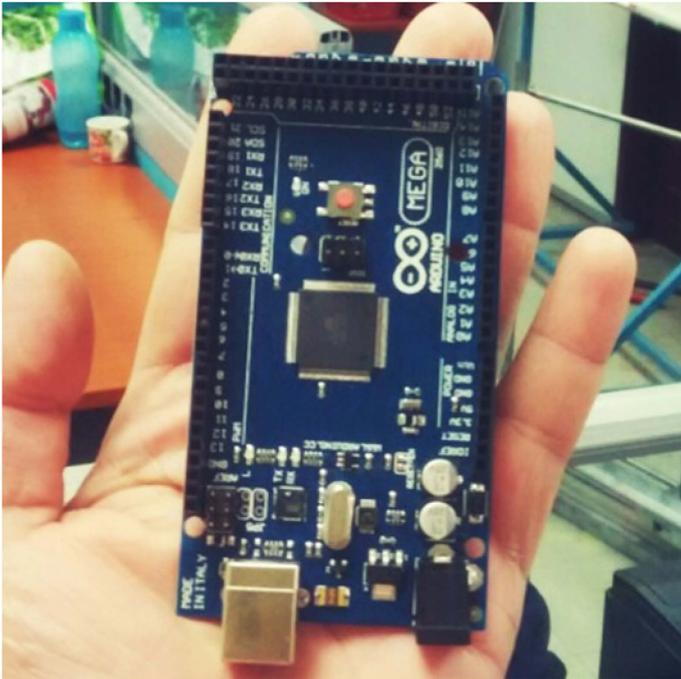


Figure 1. Arduino MEGA microcontroller

2 METHODOLOGY AND EXPERIMENTAL SETUP

The general objective of this research is to examine the efficiency of low cost automated spatial-temporal measurement system for a lab-scale local scour. In order to achieve this objective an automated measuring system was installed in an 8 m long, 1

m wide and 1 m deep tilting flume kept at the constant slope of 0.001, which is located in the coastal lab of Universiti Kebangsaan Malaysia.

A 0.35 m-deep and 2 m-long sediment recess was installed 3 m downstream of the flume entrance. A false floor 0.35 m high was fixed both upstream and downstream of the sediment recess to ensure that the bed is level and that the flow is uniform. Artificial fine sand with $d_{50}=152.7 \mu\text{m}$, $\sigma_g = 1.73$ (standard deviation d_{84}/d_{16}) was used as sediment bed material.

A 0.1 m diameter water resistant full scale cylindrical pier, which was made from Perspex, was fixed in the middle of sediment recess as shown in Figure 2. Since Perspex is water proof, it protects the electrical instrument within the pier, such as the camera used as a measurement device. The sediment recess was filled with 35 cm-thick sand.

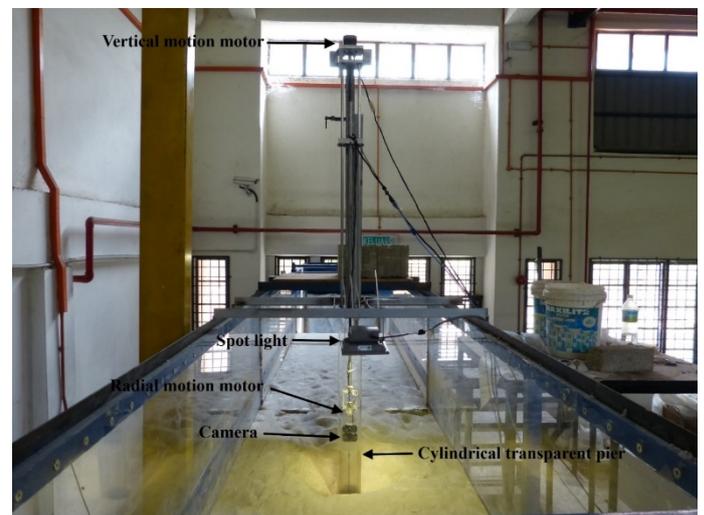


Figure 2. Experimental setup.

An ADV velocimeter was installed on the traverse, with adjustable positioning, upstream of the pier, to measure the velocity profile. Velocity was estimated by measuring the mean velocity at $0.2 y$ and $0.8 y$ and averaging them to a similar previous studies (Debnath and Chaudhuri 2011; Ting et al. 2001), where y is the depth of water.

A submersible pump recirculates water throughout the experiment with a discharge of up to $0.14 \text{ m}^3\text{s}^{-1}$. The velocity and depth of water were fixed at 21 cm/s and 30 cm respectively throughout the experiment.

The camera is connected to an automated traverse system fully controlled by Arduino which allows it to be adjusted at different elevation ($\pm 1 \text{ cm}$) and angles ($\pm 1^\circ$) using two step motors, as shown in Figure 2. The addition of a laser sensor allows the system to make dual measurement. Figure 3 shows the schematic position of the camera inside the pier. As can be seen in the figure, the upstream nose of the pier is set at $\alpha = 0^\circ$, where α is the radial position around the pier.

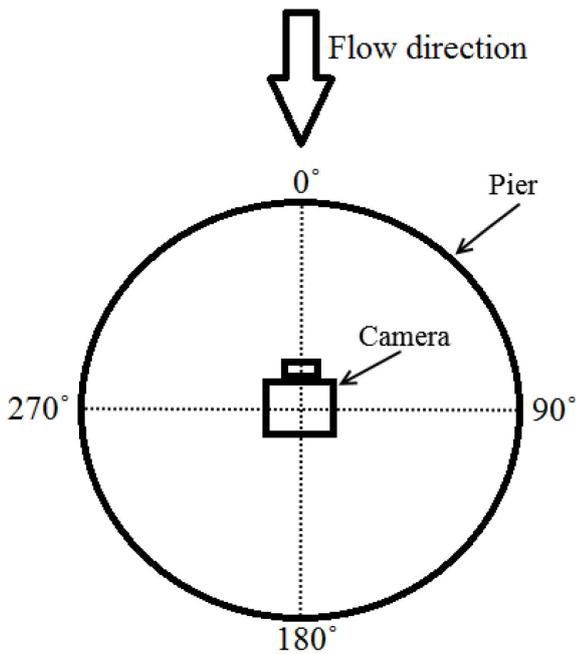


Figure 3. Schematic diagram of the position of the camera inside the pier

In this study, the scale was set at 1 cm vertical and 45° radial to improve the accuracy of profile measurement.

The vertical and radial changes were obtained through the movement of two stepper motors. The stepper motors are connected to the step motor drivers located in the central control unit, as shown in Figure 4. The Arduino sends instructions to the drivers and the drivers then send the instructions to the step motors to move the camera to the desired locations.

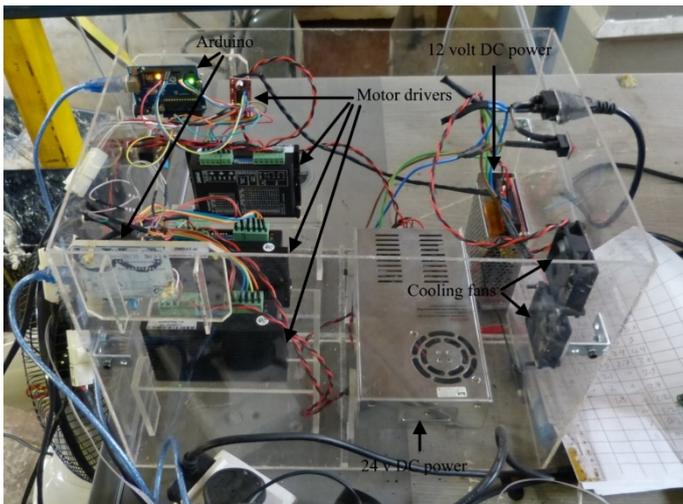


Figure 4. Central Control Unit.

Figure 5 is a flow diagram which clearly illustrates the four step-sequence of the system. In the first step a coded programme is uploaded into a computer. This programme gives instruction to the Arduino which then send the instruction to the motor drivers at specific locations (namely, the positioning

of the camera). After the camera has been positioned, the Arduino sends feedback of the current camera position to the computer through the serial port, denoted here as Step 2. In the third step the computer instructs the camera to capture an image. In the final step, the camera sends the feedback of image captured, which is automatically saved and recorded in a specified folder.

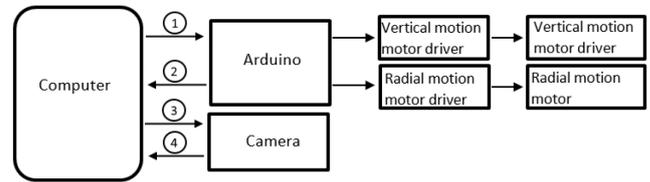


Figure 5. Flow diagram of the system. The arrow pointing to the right (\rightarrow) denotes instruction while the arrow pointing to the left (\leftarrow) denotes feedback. The number inside the circles indicate the steps in the system

3 RESULT AND DISCUSSION

The laboratory experiment was run continuously for 80 hours. The experiment was terminated after no scour similar to those observed in previous studies was observed for at least five consecutive hours (Debnath and Chaudhuri 2010). Figure 6 shows the panoramic photo made from the photographs captured at varying time intervals, namely $t = 1, 2, 3, 4$ and 5 hours, and at varying angles of between $\alpha = 0^\circ$ to $\alpha = 360^\circ$. In this experiment the system was set to take photographs with a step of 45° in radial direction and a step of 3 cm in vertical direction. The photographs covered 360° radial direction and 36 cm vertical direction. It took approximately three minutes to take a set of photos. The initial sediment depth was set at 35 cm.

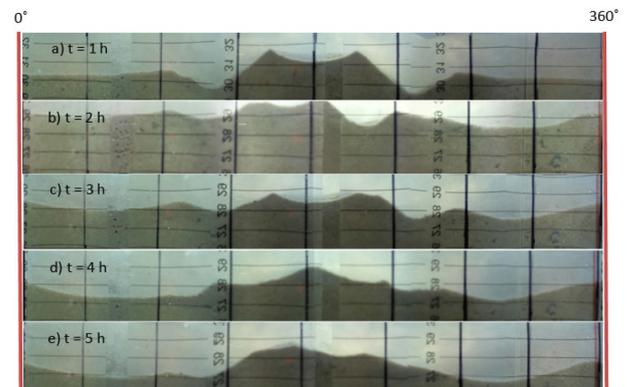


Figure 6. Panoramic photos of scour at different angles between 0° to 360°. a) after 1 hour, b) after 2 hours, c) after 3 hours, d) after 4 hours, e) after 5 hours.

In Figure 6a the scour around the cylindrical pier is presented at a one hour-interval. The radial profile around the pier between $\alpha = 0^\circ$ to 360° can be seen.

The maximum and minimum scours and the specific location can be inferred from this figure. The maximum scour is almost 5.4 cm and is located at the angle of $\alpha = 235^\circ$, whereas the minimum scour is almost 3.2 and is found at the angle of $\alpha = 152^\circ$. The scour radial profile looks almost symmetrical at its midplane.

For any given time interval defined for the system, the radial profile can be accurately derived from the photographs, as shown in Figure 6a to 6e. An analysis of the scaled photographs shown in Figure 6a to 6e using the image processing technique produced a radial profile of the scouring at different intervals.

Figure 7 presents the data derived from panoramic photos in Figure 6 using the ImageJ software for a step of 15° angle and a time interval of 1 to 5 hours. Here $\alpha/\alpha_{max} = 0$ to 0.25 and $\alpha/\alpha_{max} = 0.75$ to 1 upstream of the pier while the $\alpha/\alpha_{max} = 0.25$ to 0.75 is downstream of the pier. In this experiment the minimum scour happened downstream of the pier at between $\alpha/\alpha_{max} = 0.375$ and 0.625. In the beginning of the experiment the maximum scour occurred downstream but it then (after 3 hours) moved laterally upstream. Scour radial profile looks more symmetrical upstream compared to the downstream profile. It shows that significant scouring was observed in the first hour of the experiment ($y_s/b = 0.32-0.54$), while the development of scour depth is lower ($y_s/b = 0.11-0.2$) in the second hour. The development of the scour depth at the fifth hour of the experiment is approximately 0.4 cm. This indicates that the scour rate gradually decreased as with time during the experimental period.

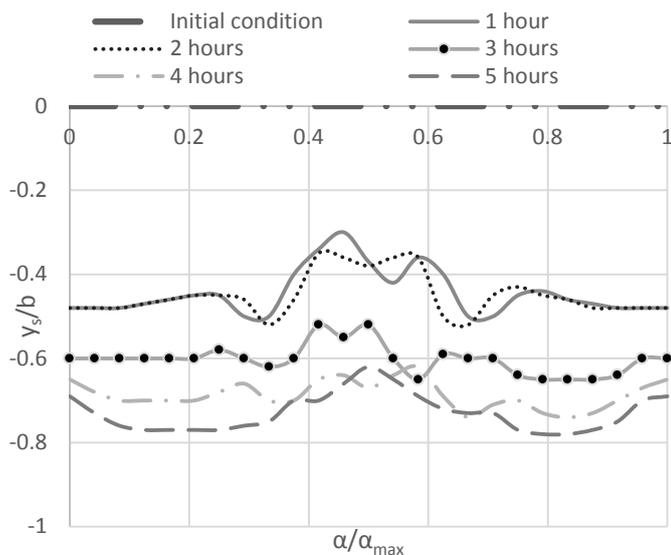


Figure 7. Local scour radial profile at different angles for 1-5 hour time interval, where y_s is the local scour depth, b is bridge width, α is the angle and α_{max} is the maximum angle, namely 360° .

The development of scour seemed to increase steadily upstream of the pier. During the first 7 hours the rate of scour was high (maximum 5.4 cm/h for the first hour and 0.3 cm/h for the seventh hour), and then it began to decrease (approximately 0.03 cm/h average for the last 10 hours of the experiment) as shown in Figure 8a.

However a different behavior was observed downstream. The pattern of scour development seemed to change with time. Scour depth increased inconsistently with some fluctuations, especially at $\alpha/\alpha_{max} = 0.375$. The scour increased during the first 10 hours at $\alpha/\alpha_{max} = 0.375$, and then decreased in the second 20 hours of the experiment, and increased again during the third 10 hours. Such behavior was observed during other interval time and radial position downstream, as shown in Figure 8b.

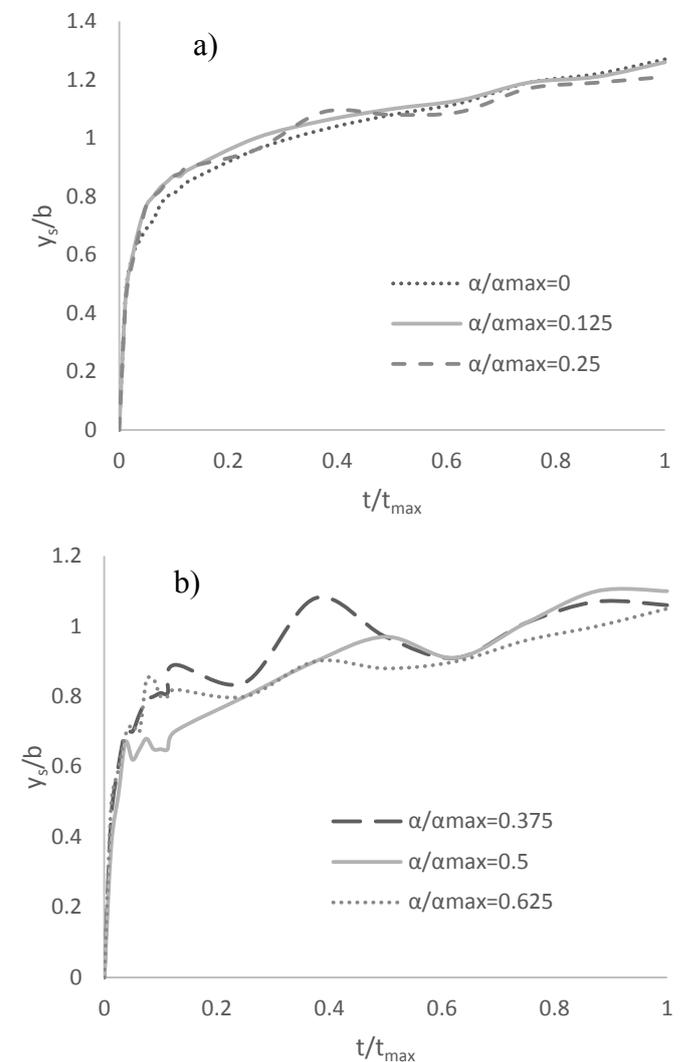


Figure 8. Comparison of dimensionless local scour depth as a function of time. a) upstream, and b) downstream of the pier

We examined the maximum and minimum scour depth independent of the radial position, as shown in Figure 9. For $t/t_{max} = 0.088-0.113$, the scour depth increased at a high rate up to 5.4 cm/h, and subsequently decreased and reached 0.03 cm/h at $t/t_{max} = 0.875-1$.

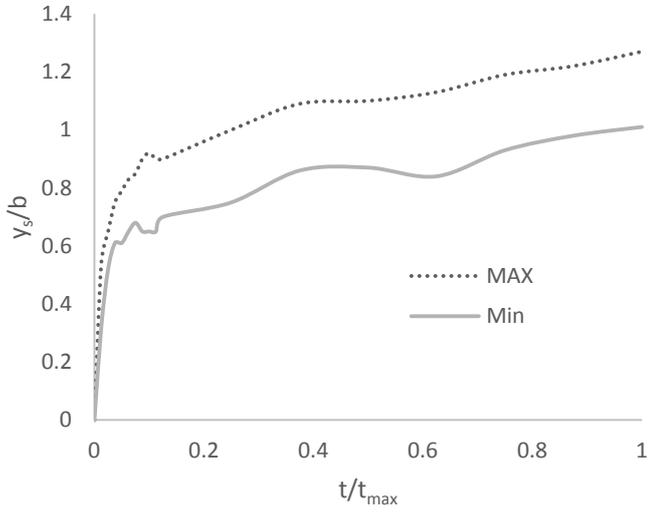


Figure 9. Comparison of maximum and minimum local scour depth as a function of time

As can be seen in Figures 8a and 8b, the scour rate seemed to be more consistent upstream. This could be the reason why the maximum amount of scour depth in Figure 9 looks more steady than the minimum, since the maximum scour normally occurred upstream and the minimum scour always occurred downstream in this experiment. Degradation seemed to occur only upstream of the pier whereas both aggradation and degradation occurred simultaneously downstream of the pier. We believe this could be the reason why the upstream scour development showed a more consistent trend.

No scour development was observed at $t/t_{max}=0.925$. At $t/t_{max}=1$, the maximum scour depth was observed upstream ($\alpha/\alpha_{max}=0$) at approximately $y_s/b=1.27$ while the minimum scour depth was observed downstream ($\alpha/\alpha_{max}=0.597$) at approximately $y_s/b=1.01$. At $t/t_{max}=0.0875$ the difference between maximum and minimum scour depth is almost constant at approximately 2.5 cm.

In order to validate the experimental setup and the results, equation (1) was used to calculate the equilibrium scour.

$$y_{se} = K_s b \quad (1)$$

where y_{se} is the equilibrium scour depth, $K_s=1.5$ for circular pier, and b is the pier width. By substituting 10 cm for pier width, the equilibrium scour depth is 15 cm. The related temporal scour is calculated using equation (2),

$$y_s = y_{se}(1 - \exp(-0.028T^{1/3})) \quad (2)$$

where y_s is the temporal scour depth and T is dimensionless time. Dimensionless time (T) was calculated using equation (3),

$$T = \frac{ut}{b} \quad (3)$$

where u is the mean velocity, t is time, and b is pier width.

The observed data fell closely to the calculated data while the calculated data seemed to overestimate the local scour, as shown in Figure 10.

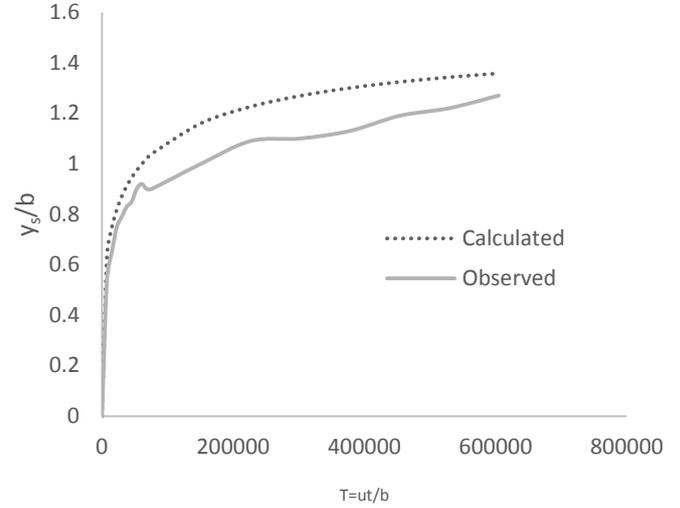


Figure 10. Comparison of observed and calculated local scour depth as a function of dimensionless time (T).

4 CONCLUSION

The automated system to monitor and measure the spatial and temporal local scour has been successfully tested. The observed results proved the ability of an automated system to measure spatial and temporal scour development. The system was able to determine the maximum and minimum scour depth regardless of the radial position around the pier.

The main advantage of the Arduino is its ease of implementation as a low cost microcontroller, with the added advantage of it being user friendly, open source device with a wide range of online source and programming codes; it could be used even in research with limited budget. It transforms a simple device such as a low cost web camera into a rather accurate measuring device for making the required measurement in laboratories.

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