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Using a novel mylar film technique to measure the efficacy of scour mitigation methods for offshore wind turbines

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ABSTRACT

In recent years research on scour around subsurface structures in the offshore wind environment has gained momentum due to the accelerated demand for renewable energy. This study looks at the use of collars to modify the downflow, the main driver of scour, and reduce the horseshoe and lee-wake vortices, thus reducing local scour depths. For measurement of scour in this study, acoustically transparent Mylar film was applied to the surface of the collar, enabling continuous recording of the scour processes beneath the collar, whilst simultaneously preventing the water and sediment passing through the collar. This enables measurement of scour development throughout the experiments until an equilibrium bed state was developed. Three different collar diameters were investigated at five different heights from the bed with data showing that the larger collars closer to the bed have a higher potential to mitigate local scour depths.

INTRODUCTION

The rapid expansion of the offshore wind industry has caused an increase in demand to assess the impact of sub-surface structures, such as monopile foundations used in the offshore wind industry, on the seabed (Al-Hammadi and Simons, 2020). A number of environmental issues arise due to hydraulic flows when monopiles are installed on the seabed and one of the main issues has been identified as bed scour (De Vos 2008; Whitehouse et al. 2011; Matutano et al., 2013; Kallehave et al., 2015; Harris et al., 2016). To reduce sea bed erosion and ensure the structural stability of monopiles, it is often necessary to mitigate against scour processes thereby reducing environmental impacts and increasing structural integrity for offshore wind installations (Den Boon et al., 2004; Matutano et al., 2013; Prendergast et al., 2015; Tang et al., 2022).

The fundamentals of scour need to be understood in order to develop appropriate interventions for scour management and mitigation. The key flow characteristics related to scour development observed around a cylindrical pile are described by Sumer and Fredsøe (2002) as the downflow, the horseshoe vortex and lee-wake vortices. These flow characteristics induce higher bed shear stress and turbulence intensity around and downstream from the structure, resulting in a higher sediment transport capacity, leading to an increase in bed scour (Wang et al., 2020). One approach to reducing scour around cylindrical structures is to weaken the downflow and thus the formation of the horseshoe vortex (Zarrati et al., 2006; Masjedi et al., 2010; Sonneville et al., 2010; Mashahir et al., 2010; Bestawy et al., 2020). Zarrati et al. (2006) explain how a collar at any height will separate the flow into two; above and below the collar. For the region above the collar, it acts as an interference to the downflow. In the region below the collar, the downflow decreases in intensity leading to a reduction in the strength of the horseshoe vortex (Zarrati et al., 2006).

There have been a number of experimental investigations to evaluate the effectiveness of collars for scour mitigation (e.g. Kumar et al., 1999; Zarrati et al., 2006; Mashahir et al., 2010; Masjedi et al., 2010; Amini et al., 2012; Karimaei Tabarestani et al., 2015; Bestawy et al., 2020). Most of these do not consider continuous monitoring of scour development beneath the collar without using fish eye or 360°cameras which can be difficult to use when there is high suspended sediment transport (Raaijmakers and Rudolph, 2008; Sonneville et al., 2010).

This study provides guidance on the use of a novel acoustic transparent Mylar film method to continuously monitor scour development of collars with varying diameters and heights from the bed. The results demonstrated the effectiveness of different collar configurations for the reduction of bed scour.

METHODS

Experimental Setup

The experiments were conducted in the Cohen Building flume at the University of Hull from May to October 2022. The 12 m long, 0.5 m wide recirculating flume had a water depth of 0.16 m. The bed depth of the experiments was 0.15m and used a well-sorted sediment with a d_{50} 0.85 mm, to minimise the chance of the sediment acting in a cohesive nature.

A pile with an external diameter of 0.05 m is used in this study which is no greater than 10% of the flow width, thereby minimising side wall effects (e.g. Chiew and Melville, 1987). The pile was installed by suspending it from a clamp above, allowing it to be easily removed and repositioned at the same location with different collar diameters and elevations. For every run, the pile was positioned centrally across the width of the flume and 6.9 m from the flume entrance. To avoid any vibration of the monopile, it was located securely in the sediment bed and clamped rigidly for each experiment.

Three different collar diameters were investigated, 3dp, 2.5dp and 2dp (where dp is the pile diameter, see Figure 1). Collars larger than 3dp may be more effective but are considered to be impractical for deployment in the field (Zarrati et al., 2006). All collars were 2 mm thick. The flow was measured for each collar configuration at five different elevations above the bed, 0.5dp, 0.25dp, 0.1dp, 0dp (bed Level) and -0.1dp to allow comparison with earlier research (Ettema, 1980; Kumar et al., 1999; Zarrati et al., 2006; Masjedi et al., 2010). In total 15 different collar configurations were assessed.

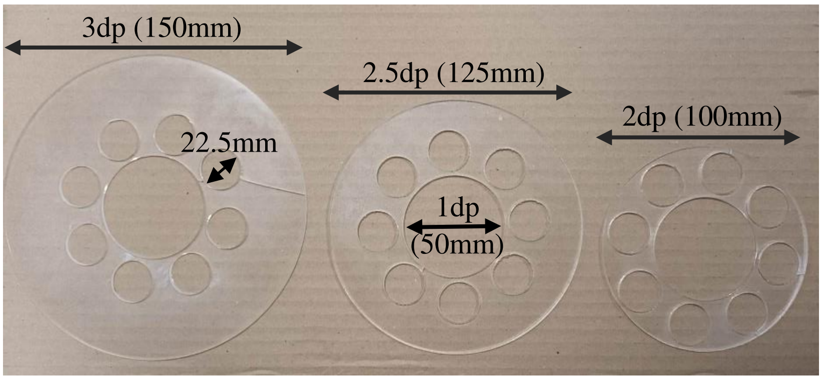


Figure 1: Three different collar designs with varying diameters, 3dp, 2.5dp and 2dp.

Bed elevation and scour development were measured using an array of three Ultrasonic Velocity Profilers (UVP) and 11 Ultrasonic Ranging Sensors (URS (Figure 2). The Metflow ® UVP uses acoustic pulses to calculate water depth by measuring the travel time of a sound pulse to reach the bed and for the received echo to return (Neill and Hashemi, 2018) enabling bed elevation measurements at a frequency of 2MHz. The UVP also measures velocity which is not reported here. To enable UVP acoustic pulses to penetrate the collar holes equivalent to the UVP beam diameter were made in the collar at 45° intervals 15 mm from the pile wall (holes in collars shown in Figure 1). To avoid flow through the holes, both sides of the collar were covered with acoustically transparent Mylar ® film (75 µm), enabling acoustic signals from the UVP to continue to pass through and measure the flow and bed. The Seatek URS were deployed to track scour depth elsewhere in the flume. The UVP and URS transducers are 8 mm and 13 mm in diameter, respectively and the transceiver head was located 10 mm below the water surface to reduce disturbance of the flow and avoid air entrainment. Acoustic Doppler Velocimetry (ADV) sensors were positioned upstream and downstream of the pile to measure 3D flow velocities. Water surface elevations were recorded using five UltraLab Advanced Water Level Sensors, with an accuracy of +/- 1 mm (General Acoustics, 2015), installed along the length of the flume at 3.3m, 4.85m, 6.4m, 7.95m and 9.5m from the entrance (Figure 2).

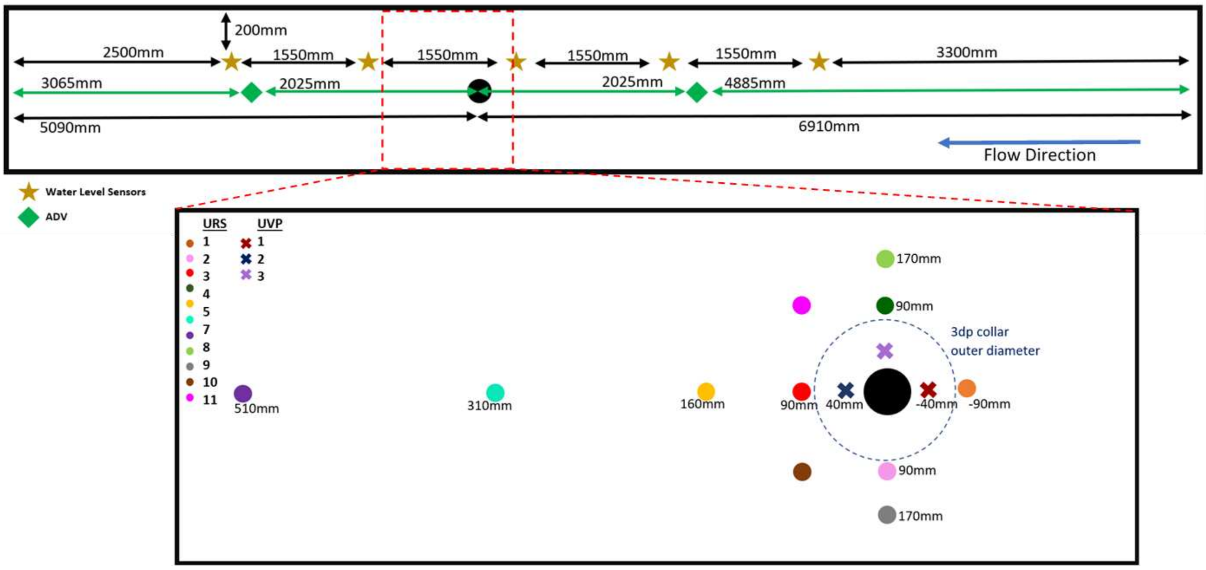


Figure 2: Flume layout and setup, measurements from pile centre

Experimental Procedure

Before starting each experiment, the sand bed was levelled along the length of the test section and the collar was adjusted to the desired elevation above the sediment bed. The flow was then ramped up to a fixed rate.

In this study, two flow regimes were investigated with average bulk flow velocities of 0.30ms^{-1} and 0.41 ms^{-1} associated with two scour regimes; clear water and live bed, respectively. For the low-velocity (clear water) flows, the rate of scour decreased over time with an equilibrium scour depth being achieved within 18000 seconds or 5 hours (Figure 3). For the high-velocity (live-bed) flow, scour was more rapid to reach a maximum depth before fluctuating in a cyclical pattern and the bed was allowed to evolve for a period of 10800 seconds or 3 hours (Figure 3). These results are similar to the trends set out by Richardson and Davis, 2001.

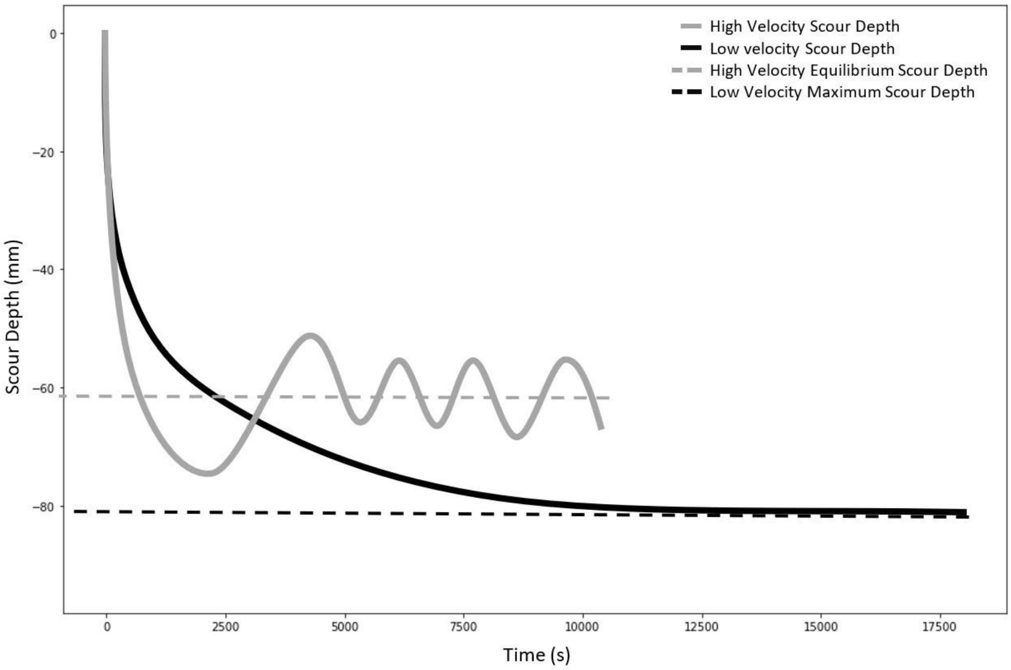


Figure 3: Time evolution of scour depth S (without collars) for high velocity and low velocity flows

Throughout the testing period, the scour depth recordings taken by the UVP and URS probes were measured every 15 seconds. Unlike previous research, the rate of recordings did not change throughout the testing period (Masjedi et al., 2010; Bestawy et al., 2020). At the completion of each testing period the flow was turned off.

The average variance in depth from the highest level to the lowest level recorded for each low-velocity run was less than 1.4% of the total water depth, and the average variance from the highest level to the lowest level for high-velocity experiments was less than 2.9% of the total water depth. The average slope angle of the low-velocity run was smaller than -0.0041° degrees and the slope angle of the high-velocity runs was smaller than -0.00091° degrees. These small variances and slope angles give confidence in the results of the experiments.

Angle of repose experiments carried out, at the pile with no collar, showed that the observed slopes were in the order of 27°- 31°which formed scour hole slopes of 1:2. These slope angles are in line with Raaijmakers and Rudolph (2008) who found side slopes of 30°-35°and Whitehouse et al. (2006) who found side slopes of 30°- 32°.

RESULTS & DISCUSSION

Figure 4 shows the time evolution of normalised scours depth (S/dp) at the low-velocity flow regime with the different collar configurations. Each graph shows the data from one UVP probe of one collar width at the five different heights as well as the results from “no collar” as a comparison. The scour depth value shown on the graph is the averaged data from one time step to the next. From Figure 4 it is clear that collars closer to the bed produce the greatest reduction in scour. The collars positioned further away from the bed at 0.25dp and 0.5dp are the least successful in scour mitigation. When comparing the collar diameters, Figure

4 shows that smaller collars are less effective at reducing scour, and that the largest collar (3dp in diameter) is most effective at scour mitigation.

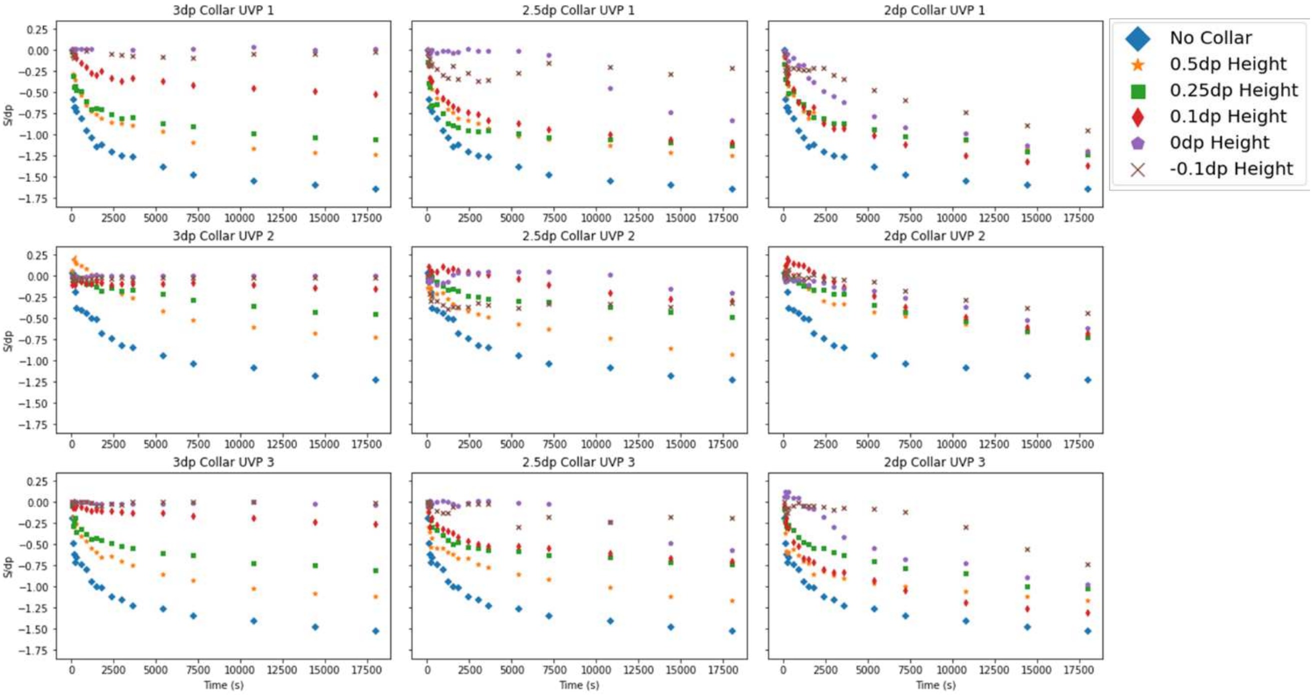


Figure 4: Comparison of normalised scour depth (S/dp) for different collar diameters and heights from the bed as averages over a time period of 5hrs at the low flow rate

Figure 5 shows the temporal development of normalised scours depth for the high-velocity, live-bed flow regime. These results show that the smaller collar (2dp) has the least impact on scour compared to the no mitigation experiments. Figure 5 also shows that the 2.5dp collar at heights 0.5dp and 0.25dp above the bed increases bed scour, creating larger scour holes than with no mitigation for all three locations where bed elevation were measured. All collars positioned closer to the bed (-0.1dp, 0dp and 0.1dp) are more effective at scour mitigation regardless of the collar size. And, as with the low-velocity flow rate, the 3dp collars are the most effective for reducing bed scour.

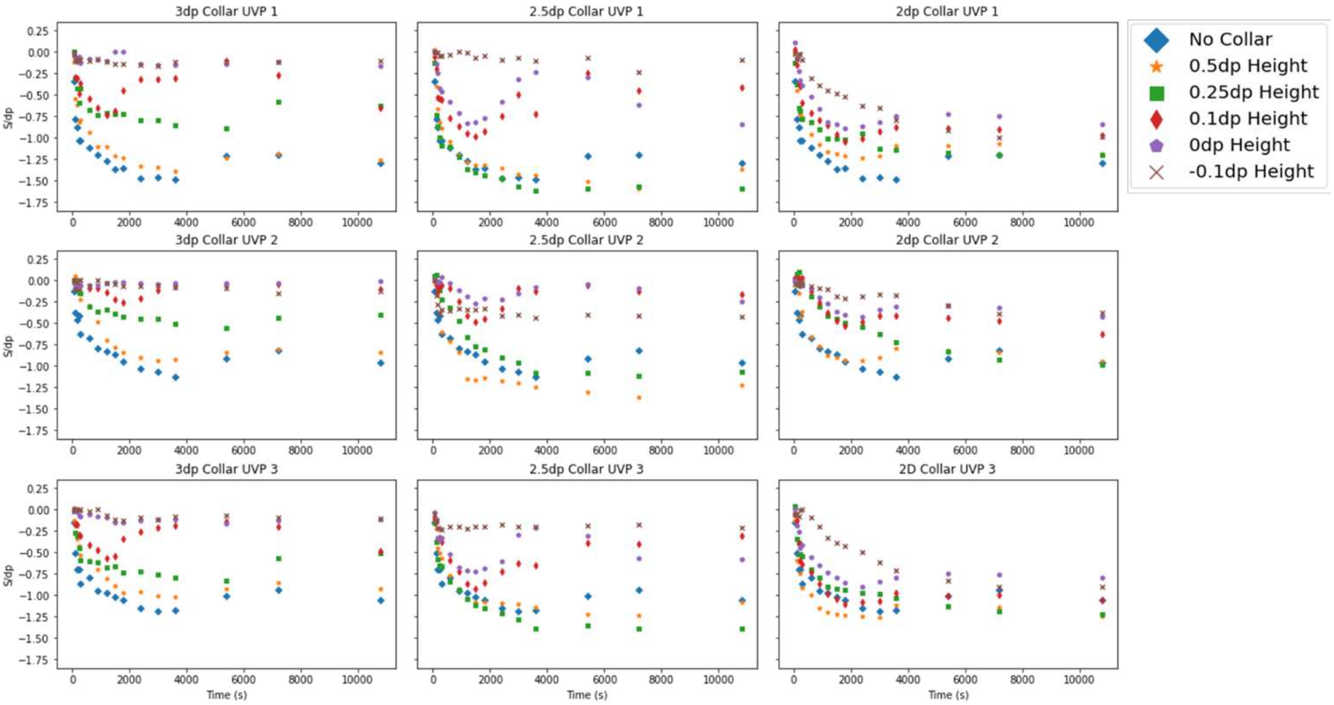


Figure 5: Comparison of normalised scour depth (S/dp) for collar diameters and heights from the bed as averages over a time period of 3hrs at the high flow rate

Figure 6 shows the scour depths recorded from the 7 sensors (URS1 -90mm, UVP 1 -40mm, pile wall upstream -25mm, pile centre 0mm, pile wall downstream +25mm, UVP2 +40mm, URS3 +90mm, URS5 +160mm, URS7 +310mm, URS8 +510mm) installed down the longitudinal axis of the flume, upstream and downstream of the pile for the 3dp collar at different heights from the bed. The results here further support that the closer to the bed the more effective the larger collar is at scour mitigation. These graphs also indicate the amount of deposition downstream. The collar configurations where more scour occurs cause higher deposition downstream. As well as the increase in scour this may cause issues in the field with cable overheating if excessive sediment deposition is present. When the 3dp collar is placed at 0.1dp height the scour mostly occurs upstream of the pile whereas when placed below the bed the scour mostly occurs in the lee of the pile. Further research could be carried out for longer testing periods to gain a better understanding of deposition downstream.

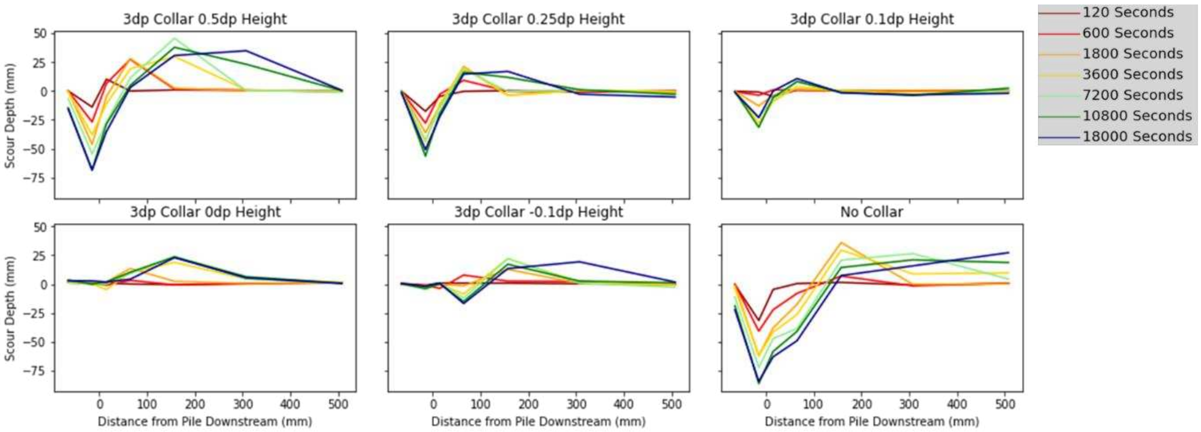


Figure 6: Longitudinal scour depths for the low velocity flow rate over the 5 hr time period, where 0mm is the pile centre

Scoring Matrix

A scoring matrix was devised to compare the effectiveness of each collar configuration, using both the UVP and URS data (14 measurements in total for each configuration). Higher weighting (5) was given to measurements closer to the pile, with the weighting decreasing to 1 for measurements furthest from the pile (Figure 7), with the pattern of the scoring matrix around the pile based on the observed scour development without collars. Higher weighting was also given closer to the pile as higher scour levels in these areas lead to an increase in vibration frequency of the monopile. The maximum scour depth for each configuration was established for four different time periods, 0 - 30 minutes defined as the first stage of initial scour development, and 30 - 60 minutes assumed to be the second stage of scour development. Maximum scour depth of 1 hr to 2 hrs and 2 hrs to 3/5 hrs were also used.

The maximum scour depth was chosen rather than the average to account for the worst case scour depths. Deposition values were excluded from the matrix. These values of maximum scour depth were then multiplied by the location weighting value described above. For each experiment, a total score was calculated with a lower score representing better mitigation against bed scour, and ultimately a (theoretical) score of zero associated with total protection, i.e. no scour.

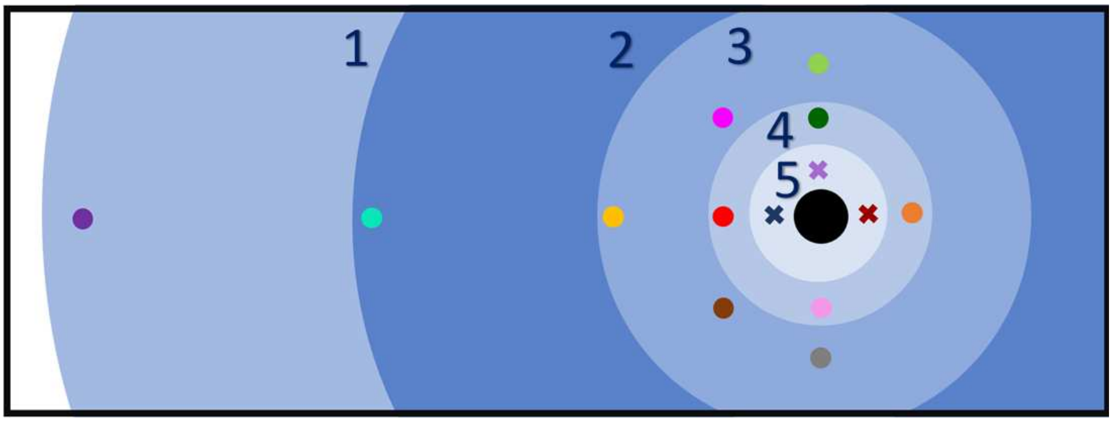
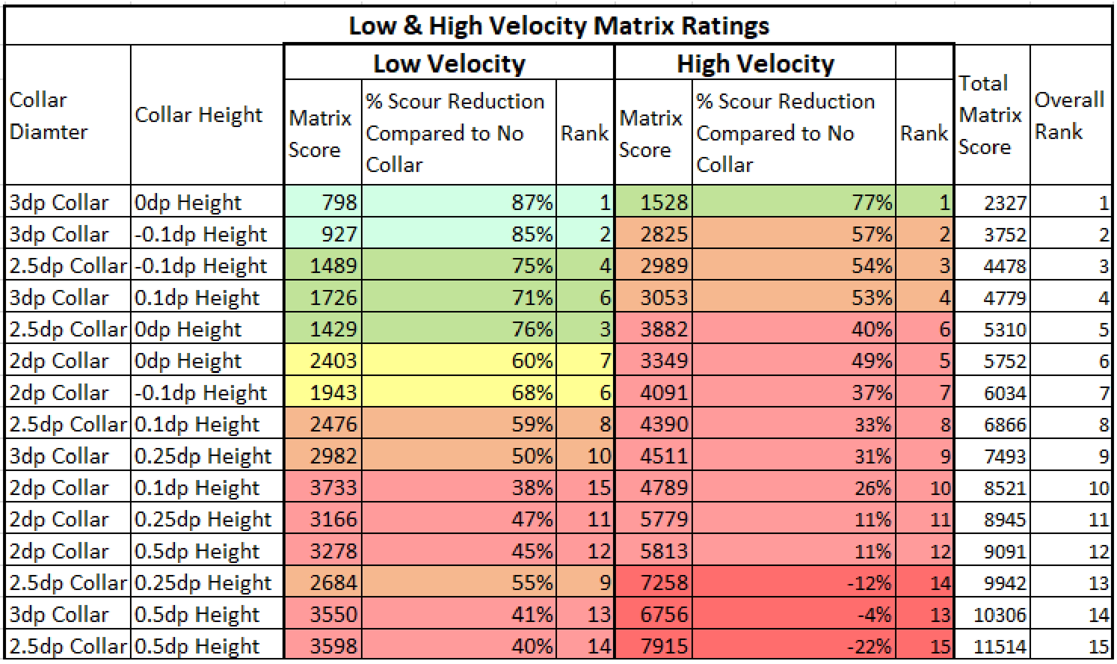


Figure 7: Scoring matrix within the flume overlaying the sensor layout (see Figure 2 for definition of sensors).

The results for the low and high velocity scoring matrices are shown in Figure 8 which shows that the 3dp collar at heights of 0dp and -0.1dp are the most suitable for scour mitigation. The results show they reduced the scour by more than 80% compared to when no collar was used. The 2.5dp collars also at 0dp and -0.1dp as well as the 3dp collar at 0.1dp may also be suitable and reduce the maximum scour depth by over 70%. The 3dp and 2.5dp collars at a height of 0.5dp and the 2dp collar at a height of 0.1dp have the least impact on scour mitigation, however, they are still capable of mitigating scour by 40%-50%. This suggests that the larger and closer to the bed the collars, the more successful at scour mitigation.

The results for the high-velocity experiments suggest that the 3dp collar at a height of 0dp is the most successful collar configuration for this flow regime, mitigating scour by 77%. The 3dp at heights of -0.1dp and 0.1dp as well as the 2.5dp collar at a height of -0.1dp have a 50% to 60% scour reduction rate. The least suitable collar configurations at this flow rate are the 3dp collar at 0.5dp height and the 2.5dp collars at a height of 0.25dp and 0.5dp - these collar configurations increase the amount of scour produced compared to when no mitigation method is used and therefore should be disregarded. The results from the high flow rate matrix again suggest that the larger the collar and the closer to the bed the more successful the collar at scour mitigation. Conversely, the smaller the collar or the further away from the bed any collar size the less successful.

When looking at both the low and high flow rate matrix results together (Figure 8) it is clear to see that the 3dp collar at a height of 0dp and -0.1dp are the most effective at scour mitigation as they rank 1st and 2nd for both low and high flow rates. The 2.5dp collar at heights of -0.1dp and 0dp as well as the 3dp collar at a height of 0.1dp are similarly effective in scour mitigation. Collars placed below the bed are shown to be effective for scour mitigation. However, collars at this level may cause issues during installation and may not be practical for real-world deployment. Hence, the most suitable collar configuration for scour mitigation gathered from these data are the 3dp collar at 0dp and 0.1dp height and the 2.5dp collar at 0.1dp and 0dp height.



Low & High Velocity Matrix Ratings										
		Low Velocity			High Velocity					
Collar Diamter	Collar Height	Matrix Score	% Scour Reduction Compared to No Collar	Rank	Matrix Score	% Scour Reduction Compared to No Collar	Rank	Total Matrix Score	Overall Rank
3dp Collar	0dp Height	798	87%	1	1528	77%	1	2327	1
3dp Collar	-0.1dp Height	927	85%	2	2825	57%	2	3752	2
2.5dp Collar	-0.1dp Height	1489	75%	4	2989	54%	3	4478	3
3dp Collar	0.1dp Height	1726	71%	6	3053	53%	4	4779	4
2.5dp Collar	0dp Height	1429	76%	3	3882	40%	6	5310	5
2dp Collar	0dp Height	2403	60%	7	3349	49%	5	5752	6
2dp Collar	-0.1dp Height	1943	68%	6	4091	37%	7	6034	7
2.5dp Collar	0.1dp Height	2476	59%	8	4390	33%	8	6866	8
3dp Collar	0.25dp Height	2982	50%	10	4511	31%	9	7493	9
2dp Collar	0.1dp Height	3733	38%	15	4789	26%	10	8521	10
2dp Collar	0.25dp Height	3166	47%	11	5779	11%	11	8945	11
2dp Collar	0.5dp Height	3278	45%	12	5813	11%	12	9091	12
2.5dp Collar	0.25dp Height	2684	55%	9	7258	-12%	14	9942	13
3dp Collar	0.5dp Height	3550	41%	13	6756	-4%	13	10306	14
2.5dp Collar	0.5dp Height	3598	40%	14	7915	-22%	15	11514	15

Figure 8: Scoring matrix results for all experiments, ranked as most to least suitable.

Comparisons

A comparison of these results with other previous studies shows similar findings. Masjedi et al. (2010) show there is a reduction of scour of 78% with a 3dp collar and a reduction of 73% with a 2.5dp collar both at bed level. Consideration should be taken into account when comparing results as the threshold of motion, flume size and shape, and collar width and material may all impact the comparison. These results further support previous studies which indicate that the larger the collar and the closer to the bed the more effective the collar as scour mitigation (Kumar et al., 1999; Zarrati et al., 2006; Mashahir et al., 2010; Masjedi et al., 2010; Amini et al., 2012; Karimaei Tabarestani et al., 2015; Bestawy et al., 2020). Tanaka and Yano (1967) explain that the efficacy of the collars increases at a lower elevation to the bed as less flow can penetrate underneath it.

CONCLUSION

Because continuous testing of scour development beneath the collar had not yet been achieved without the use of a fish eye or 360°cameras the method of using an acoustic transparent Mylar film technique described herein was developed. This technique proved to be successful in delivering valuable data to measure the processes in scour hole development around a cylindrical pile. This monitoring technique was implemented for three different collar diameters positioned at five different heights from the bed. UVP readings were taken to determine the bed depth through the collar, providing an accurate time series of scour depths and bed changes. Alongside this novel technique, the most suitable collar configurations for scour mitigation could also be predicted. The experiments carried out allowed the following conclusions to be drawn:

- The high flow rate experiments reached the maximum scour quicker than the low flow rate experiments.
- Larger collars at a lower height were able to mitigate scour more effectively than smaller collars, and collars at a greater height from the bed.
- The most suitable collar for scour mitigation under low and high flow rates was the largest 3dp collar placed at bed level.
- All collars situated at a height of 0.5dp regardless of their diameter had a similar impact on the scour hole development.
- The use of the Mylar film as a novel technique was shown to be suitable for continuously measuring scour depth beneath the collar.

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