COMPARISON OF THREE TECHNIQUES FOR SCOUR DEPTH MEASUREMENT: PHOTOGRAMMETRY, ECHOSOUNDER PROFILING AND A CALIBRATED PILE

Kate Porter[1] Richard Simons[1] and John Harris[2]

Laboratory studies form an integral part of scour research, yet there is no standard technique for monitoring scour depth development during testing. This paper investigates the advantages and disadvantages of a variety of techniques, and compares results from three methods: photogrammetry, an echosounder, and a calibrated pile. A novel system involving an underwater camera is presented. This produces results in close agreement with the other techniques, and has the advantage of providing accurate measurements over the full scour hole while at the same time enabling qualitative information to be gained from the photographs.

Keywords: Scour; Measurement techniques; Laboratory scale modelling; Echosounder; Photogrammetry

INTRODUCTION

Scour is a topical issue in the marine environment due to the recent development of offshore wind farms in coastal waters. This is an active area of research because it is currently difficult to accurately predict the scour depth that will occur at a structure's foundations in the field. Simplified scale modelling in laboratory flumes can help to advance understanding of the mechanisms for scour and the interactions between the fluid, structure, and sediment. A suitable measurement technique needs to be implemented to monitor the scour depth development during laboratory testing. In practice this is difficult because of the need for the method to be non-intrusive but still operate at the required time and spatial resolutions at the small scale. Consequently, a wide range of measurement systems have been presented in the scour literature. This paper will provide a review of these, highlighting the advantages and disadvantages in reference to their suitability for small scale laboratory testing, before focusing on a comparison of the performance of three of the most promising techniques.

In order to assess the suitability of a measurement technique for scour monitoring in the laboratory, it is first important to consider the required specifications of the scour measurement system:

- The equipment should not interfere with the experiment. For this reason the flow should not be paused or drained, and any equipment placed in the flow should have very small dimensions.
- The system should produce three-dimensional scour hole profiles (full coverage of the scour hole).
- Scour hole profiles should be collected instantaneously, or the points should be measured over a small change in time relative to the rate of scour.
- Measurements should be accurate to at least 1 mm in the horizontal and vertical directions.
- The system should be capable of capturing data at second intervals in the initial stages of scour.
- Vertical resolution of at least 1 mm and horizontal resolution of 1 cm would be suitable in the laboratory flumes specified for this project.

One of the simplest techniques used in the literature is to read the scour depth from a vertical scale attached or marked onto the model pile. This can be monitored by eye or with a camera set up externally to the flume (Roulund et al. 2005), or inside a clear pile (Debnath and Chaudhuri 2011). A more complex version of this method has been developed by Chang et al. (2014) where the system is automated to produce real-time scour depth measurement through an image processing technique. These systems are non-intrusive and inexpensive, and are capable of providing high frequency measurements with good vertical resolution and accuracy. However, they only provide depth measurements adjacent to the pile, so do not necessarily represent the deepest point in the scour hole. Furthermore, they do not provide information about the evolution of the scour hole shape, volume or extent. It should be noted that it is likely to be impractical to place a camera inside the pile in small scale tests due to the dimensions of the pile compared to the camera equipment.

Sumer and Fredsøe (2001) extended the use of scales to obtain maps of the scour hole by placing measurement pins at different locations in the bed. Alternatively a point gauge can be moved to different locations in sequence to build a 3D profile (Lanca et al. 2013). However, both of these systems are rather intrusive. Although some less intrusive versions of point gauges have been designed (Simons et al. 2007, Ballio and Radice 2003) it takes a considerable amount of time to obtain a scour

[1] Department of Civil, Environmental and Geomatic Engineering, University College London, Gower Street, London, WC1E 6BT, UK
[2] HR Wallingford, Howbery Park, Wallingford, Oxfordshire, OX10 8BA, UK

hole profile with any of these devices, so dynamic profiling is not possible especially during the initial stage of the scour process.

Echosounder and laser distance sensors have been used for scour depth measurement in the laboratory (Coleman et al. 2003, Sheppard and Miller 2006, Stahlmann and Schlurmann 2010). Like the point gauge methods these have to be traversed to different locations to collect a 3D profile. However, they are generally able to scan the bed more rapidly than point gauges, so that quasi-dynamic measurements may be possible. Another advantage of these devices is that they can be much less intrusive to the experiment as they are not required to be in close proximity to the bed. However, the dimensions of the sensors are often large relative to the pile, so in several studies the flow is paused or the water is drained before measurements are collected (Jensen et al. 2006, Margheritini et al. 2006, Hartvig et al. 2010). It must also be noted that laser and echosounder systems are considerably more expensive than the basic options. While laser sensors can provide reasonably precise measurements (to the nearest mm), the precision of echosounder measurements is reduced because of the spreading of the beam as it travels away from the sensor. This means that at each measurement point an area of the bed is averaged as an approximation to a point measurement. The size of the beam footprint is inversely proportional to the frequency and diameter of the sensor. As a small sensor diameter is required to reduce interference with the flow in small scale laboratory testing, a high frequency sensor must be used so that the beam footprint will be small enough to provide adequate spatial resolution. Larger suspended particles such as sand grains can affect echosounder measurements (McGovern et al. 2012) and both echosounder and laser sensors can be subject to spurious reflections from the sand bed or the pile (Hartvig et al. 2010, Dingler et al. 1977).

Another technique that has been employed in the laboratory in a variety of set-ups is photogrammetry. 2D measurements in the form of line profiles through the scour hole have been obtained from photographs of a laser light sheet intersecting the bed (Younkin and Hill 2009). The complexity of camera calibration is reduced by using a 2D technique, and only one camera is needed. The advantage of this system is that it can be non-intrusive if the cameras are position outside of the flume, and a line profile is captured instantaneously so that fully dynamic measurements are possible. However, the light sheet must be traversed across the scour hole to obtain full spatial coverage (Huang et al. 2010), which also increases the complexity of the calibration.

A minimum of two cameras are needed to make 3D reconstruction of the scour hole possible. However, many of the techniques require the flow to be paused or drained (Umeda et al. 2008, Rosier et al. 2004, Raaijmakers et al. 2012). Dynamic measurements have been obtained by Baglio et al. (2001) where the cameras were set up outside of the flume. However, this system does not account for lens distortions or for refraction of light through the air-glass-water interfaces, reducing the accuracy of the results. A similar system was implemented in a recent study by Sumer et al. (2013) which did include corrections for lens distortions but refraction through the flume wall was still not modelled correctly. In these systems measurement points in the scour hole are identified using a grid of dots produced by a diffractive laser (Sumer et al. 2013, Baglio et al. 2001), or by using feature matching software (Raaijmakers et al. 2012). Foti et al. (2011) noted that sand surfaces are not ideal for feature matching and this can result in a reduction in the accuracy of the solution.

From the literature review the 3D photogrammetry technique showed the most potential for fulfilling all of the stated requirements for measuring scour in the laboratory. However, this type of system has not yet been fully established, as the dynamic measurement systems have not yet included a correction for refraction. Therefore, this technique requires development and testing before it can be utilised. Verification can be provided through comparison with another technique. In this study an echosounder was chosen as it offers a reasonable compromise to the measurement requirements while being of suitable dimensions and cost for this project. The pile was also calibrated with a vertical scale to provide a baseline for the comparison.

This paper details the methodology and development of these three techniques and provides a comparison between them to give a detailed analysis of their strengths and weaknesses and applicability to scour depth measurement in the laboratory.

METHODOLOGY

The investigation of techniques for scour depth measurement was conducted as part of a larger project studying marine scour. Scour tests were conducted in two laboratory flumes of different dimensions. Details of the experiment set-up and test program can be found in Porter et al. (2012) and Porter et al. (2014). A range of hydrodynamic conditions (currents, waves, tidal flow) and several pile diameters were used in the test program which presented some restrictions in terms of the set-up of the measurement system. For this reason it was not possible to place equipment inside the pile and the impact that equipment would have on the flow needed to be carefully considered.

The vertical scale on the pile was marked onto the outside of the pile in concentric circles using a lathe, at 5 mm intervals. The vertical resolution was chosen to improve visibility of the scale in the flume. The vertical scale is shown in Fig. 1.

Figure 1. Calibrated pile in the small flume

The second technique employed a 1 MHz echosounder (Ultralab UWS model) made by General Acoustics. This device was chosen because it has a small sensor diameter and narrow beam angle. The diameter of the sensor is 30 mm, and only the face of the sensor needs to be submerged in the water to take a depth measurement (i.e. submerged by less than 2 mm). The sensor has a beam angle of less than 3 degrees. Higher resolution sensors came at the cost of a larger sensor size.

The echosounder was fixed to a motorized traverse sitting above the larger flume. In the smaller flume it was traversed manually by sliding its support against a scale running parallel with the flume wall. Fig. 2 shows the set-up in each flume. In both cases the centre of the sensor could not be placed closer than 2 cm to the edge of the pile, because of the dimensions of the bracket that the sensor was mounted on.

The measurement procedure was different in the two flumes due to the configuration of the equipment. In the small flume, 2D profiles were measured along the centreline of the scour hole in the stream-wise direction. The echosounder was traversed upstream and downstream of the pile in 1 cm intervals. The sensor was left at each position for approximately 30 seconds and the maximum depth reading was recorded over this time; spurious reflections such as those from suspended sand grains were ignored. In this set-up the beam footprint on the initial flat-bed level was about 8 mm in diameter (water depth = 16 cm).

In the larger flume, the echosounder was connected to a data logger so that depth readings were recorded directly to a computer. The echosounder had to be calibrated to convert the output voltage reading to depth. This was achieved by recording measurements over a set of blocks of known heights positioned in the flume beneath the echosounder. A linear relationship between voltage and depth made the calibration straightforward. The echosounder was traversed in a variety of patterns, depending on the rate of scouring. The echosounder recorded 10 depth readings at each position in the profile (the frequency of measurements was 10 Hz) and following the approach in the smaller flume, the maximum depth at each location was used in the analysis. A 3D profile was collected in approximately 20 minutes. To reduce the profiling time during the initial stages of a test 2D profiles were taken along the centreline of the scour hole. In the later stages of testing 3D profiles of the bed were obtained. As the traverse and echosounder systems were not operated from the same computer, the two systems had to be synchronised manually. Importantly, as the water depth in this flume was 45 cm, the beam footprint diameter on the initial flat bed was close to 24 mm, so that there was a significant loss of resolution in this flume compared to the smaller scale tests.

Figure 2. Echosounder sensor and system set-up in the large and small flumes

A photogrammetry system similar in set-up to Baglio et al (2001) was tested initially. Two cameras were positioned outside of the flume. A grid of dots was projected onto the bed to mark out the measurement points. Digital projectors provided a cheaper alternative to the diffractive laser used by Baglio et al. (2001). The two cameras were synchronized using a trigger box. The lighting, camera and projector positioning, and camera settings (aperture, focal length, etc.) were chosen so as to obtain the best possible coverage of the scour hole, and best image quality. The image processing and photogrammetry computations were completed using a software package, VMS (Robson and Shortis, 2012). This software uses the bundle adjustment method which provides an explicit solution to the colinearity equation, Eq. 1. In this equation the 2D coordinates of the measurement points in the images, $\mathbf{x_a}$, are linked to the 3D coordinates of the measurement points in the object space, $\mathbf{X_A}$, through the parameters for the position ($\mathbf{X_0}$) and orientation ($\mathbf{R^t}$) of the camera. Cooper and Robson (1996) provide a comprehensive treatment of this topic.

$$\mathbf{X_A = X_0 - \mu\ R^t\ x_a} \qquad (1)$$

As the colinearity equation is based on the pin-hole camera model, it assumes that light rays travel in a straight line through the camera from the point on the object to the image plane. As light will actually be refracted through a real camera due to the configuration of the lens, a correction is applied to the colinearity equation to account for this. The lens distortions have been shown to be closely approximated by a polynomial function, which is added to the solution obtained from the colinearity equation as an error term.

With a minimum of 4 known coordinates in the object space (for calibration) and a minimum of two images taken from different positions, the colinearity equation can be solved. The bundle adjustment uses a least squares iterative approach to obtain a robust solution by simultaneously computing a number of measurement points from a set of images.

A specially designed calibration cube with dots of known coordinates along its bars was used prior to the experiments to provide the points of known coordinates in the object space. With the cameras left in the same position and with the same focal settings, the camera intrinsic and extrinsic parameters were first calculated using the calibration cube (i.e. camera properties such as lens distortions and focal length, as well as the location and orientation of each camera). These parameters provided enough information to compute unknown coordinates of points in the scour hole during the experiments.

The VMS software does not include an explicit solution for refraction of light through the flume wall and water, so initially an implicit solution for refraction was sought using the software. This method attempted to incorporate the refractions into the camera calibration procedure in the same way that the camera lens distortions and other internal parameters are modelled. The results of this method were generally unsuccessful due to the nature of the distortions (large in magnitude and asymmetric due to the angles of the cameras relative to the flume wall). This indicated that in the given flume settings a full solution for refraction would be necessary. Refraction can be modelled explicitly using a ray tracing algorithm (Kotowski 1988). However, this is known to be computationally demanding because a solution must be obtained iteratively.

Alternatively, the effect of refraction can be reduced by changing the set-up of the cameras. Refraction planes close to the camera lens or parallel with the image plane are more likely to be modelled successfully in the bundle adjustment so that a real refraction model is not necessary (Agrawal et al. 2012) and the VMS software can still be used to provide accurate solutions. Therefore, a new set-up involving underwater cameras was implemented. To demonstrate the feasibility of measurements involving underwater cameras, a series of photographs were taken of the scour hole with one camera, while the flow was paused. This did not cause undue disruption to the tests as the measurements were only collected when the flow was paused for other reasons, such as during tidal flows at the point of flow reversal, and overnight for health and safety reasons. This system compromised in terms of the time resolution of measurements, but matched all of the other requirements. Fig. 3 shows the set-up of the underwater system. Dots were projected onto the bed to identify the measurement points in a similar manner to the initial set-up. However, a matrix of dots of known coordinates was marked onto the pile before it was placed in the flume (see Fig. 3) so that the scour hole measurements and calibration data were captured simultaneously. This system had the advantage of producing very robust network solutions as each image contained a large number of measurement points, and each solution included a number of photographs (at least 15) from a range of orientations.

Once the bundle adjustment solution had been computed using VMS, coordinate transformations had to be applied to the output data to align the axes to the convention in the flume so that the z axis was vertical, the x axis pointed downstream, and the y axis was aligned with the cross-stream. The origin was positioned at the initial bed level at the centre of the pile. The coordinate transformations were applied to the data in Matlab, and then the final bed profile was produced by fitting an interpolated surface to the computed measurement points.

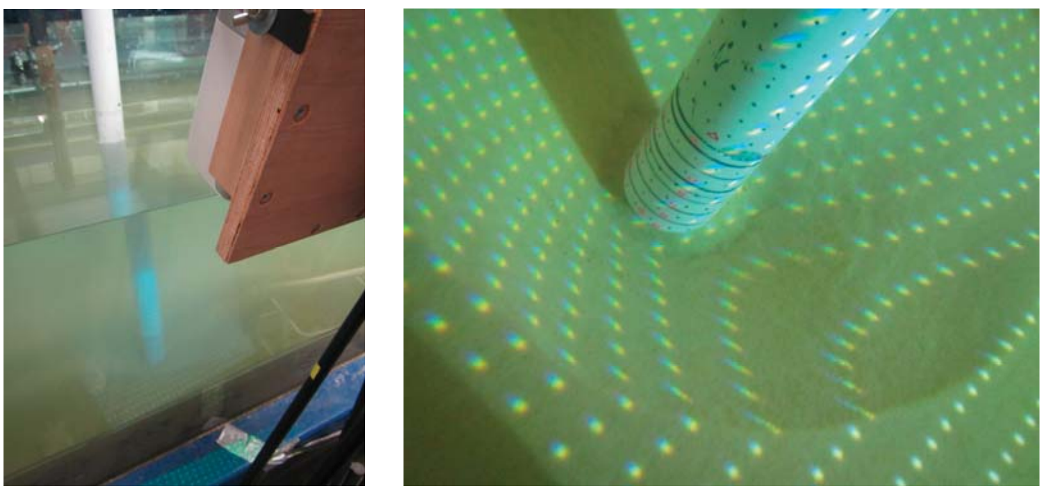

Figure 3. Photogrammetry set-up with projector outside of the flume, light markers on the bed and targets on the pile

RESULTS

The results obtained with the photogrammetry system will be presented and discussed in a qualitative way, before comparisons are made with the echosounder and pile scale measurements. Two and three dimensional measurements will be considered using data from both the small and larger scale flumes.

Initial assessment of photogrammetry results

Fig. 4a shows the final results generated by the computation and processing completed in VMS and Matlab for one set of photographs. The figure shows a plan view of the scour hole, in which an interpolated surface has been fitted to the computed coordinates of the projected light dots on the sand bed (white dots in Fig. 4a). The computed coordinates of the target dots that were marked on to the pile are also included (black dots in Fig. 4a). One of the original photographs used in the computation is shown for comparison (Fig. 4b). It is clear that, qualitatively at least, the features in the photograph are correctly represented in the photogrammetry solution. However, the strength of the solution is dependent on the coverage of dots on the bed. In the shadow zone behind the pile, and also at the nearside of the pile where the bed slopes away from the projectors the solution is based on a sparse number of measurement points and the accuracy of the interpolated solution will be reduced in these areas.

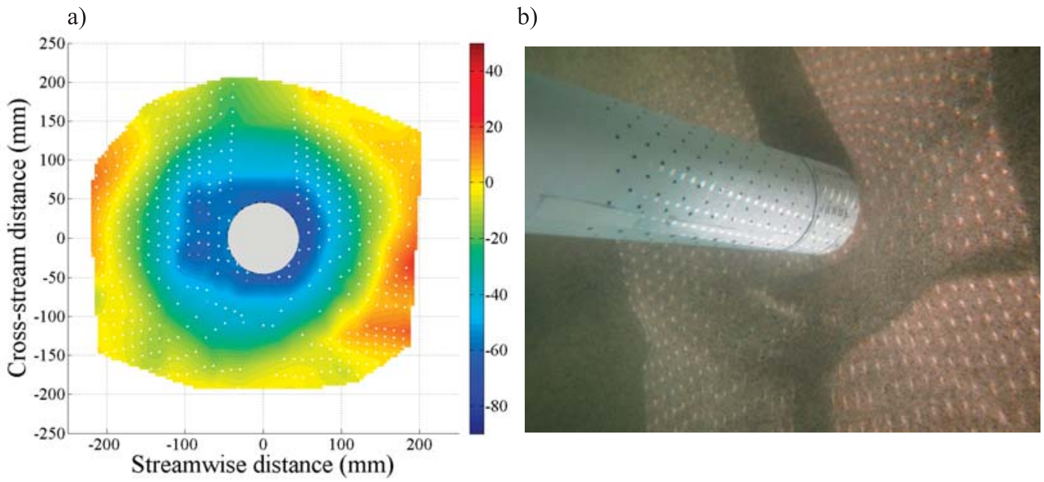

Figure 4. a) Plan view of a 3D profile of a scour hole using the photogrammetry technique b) Photograph of the scour hole used in the photogrammetry computation

2D comparison of techniques in the small flume

A quantitative assessment of the performance of the photogrammetry system was obtained through comparison with measurements from the echosounder and the scale marked on to the pile. A first comparison was made using the measurements collected in the smaller flume at the same point in time during a test.

As the echosounder was set up to produce two dimensional scour hole profiles in this flume, 2D profiles from the photogrammetry data had to be obtained for the comparison. Points at 1 cm intervals along the centerline of the scour hole were picked from the interpolated 3D solution, allowing direct comparison with the echosounder profile.

The comparison is shown in Fig. 5. It should be noted that due to the set-up constraints at the small scale, dots could not be projected in close proximity to the pile and both the photogrammetry and echosounder data have to be extrapolated to enable comparison with the pile scale. The echosounder and photogrammetry profiles compare reasonably well with the pile scale measurements in Fig. 5, but a more robust comparison will be provided when considering the larger scale flume where the data did not need to be extrapolated (see the following section). In general the agreement between the echosounder and photogrammetry data is good in Fig. 5. However, there is a greater discrepancy between the measurements on the downstream side of the pile. This may be explained by a small difference in the cross-stream positioning between the echosounder and photogrammetry profiles such as the echosounder sensor being a little off vertical, or not perfectly centred relative to the pile. This would be more noticeable at the downstream side where the deposition zone slopes off sharply in the cross-stream direction directly behind the pile.

The most significant discrepancy between the echosounder and photogrammetry data is at the upstream side of the pile, at the transition between the flat bed and the start of the scour hole slope. This can be explained by the limitations of the echosounder measurements caused by the diameter of the beam footprint. As the echosounder is positioned parallel to the flat bed, it will receive a stronger echo from the flat bed than a sloping section. Therefore, as it is traversed across this transition, it will continue to register and output the flat bed height for as long as the flat bed is in range of the beam footprint. This was confirmed in the flume by moving the echosounder in small increments over the transition region. The echosounder recorded the flat bed level until a large step change in depth was indicated, which was clearly not representative of the true bed shape.

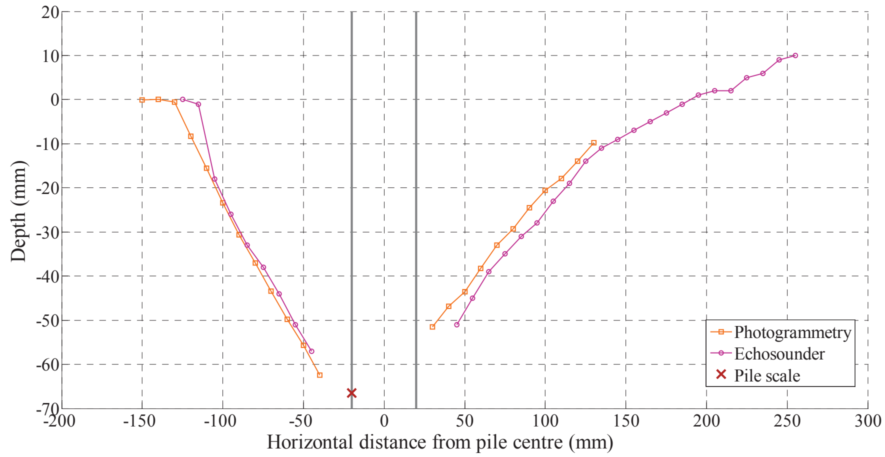

Figure 5. Comparison of photogrammetry, echosounder and pile scale measurements of a scour hole in the small flume

2D comparison of techniques in the larger flume

The results discussed in the previous section indicated that the discrepancies in the measurements were linked to issues with the echosounder system. Therefore, a second comparison focusing on the photogrammetry and calibrated pile is presented to provide confidence in the results. In the larger flume, dots were projected in close proximity to the pile, so a direct comparison could be made between these two techniques. Three interpolated profiles collected at different points in time during a test are shown in Fig. 6 which were obtained from the 3D photogrammetry solutions (in the same way as in the previous section). Each of these is compared with the pile scale reading at the corresponding time during the test. The agreement is excellent in each case. The very small discrepancy between the measurements is due to the interpolation method in the photogrammetry solution. Where the measurement points coincide with actual measurement points the agreement is improved.

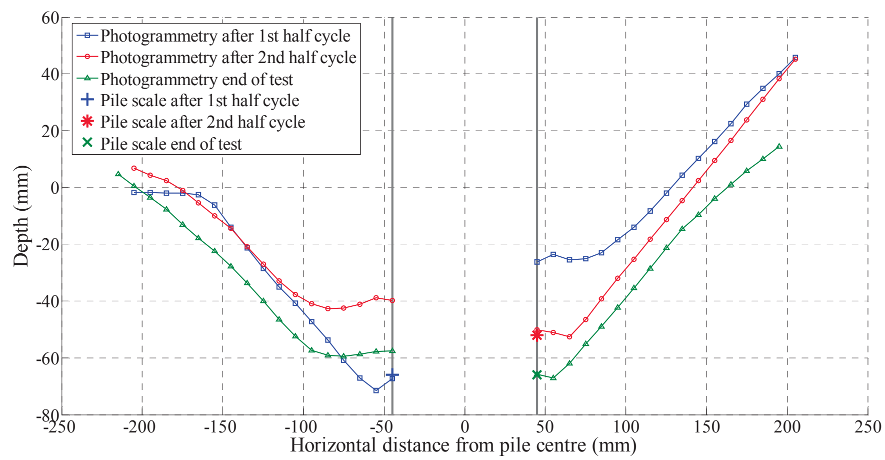

Figure 6. Comparison of streamwise photogrammetry scour hole profiles in the large flume with the corresponding measurements from the calibrated pile

3D comparison of techniques at the larger scale

Another comparison of interest is the performance of the systems at 3D bed profiling in the larger scale flume. Side elevations and plan views of the same scour hole are shown in Fig. 7 and Fig. 8 respectively where Fig. 7a and Fig. 8a show the results from the echosounder, and Fig. 7b and Fig. 8b show the results from the photogrammetry. The echosounder data is presented in a similar way to the photogrammetry data so that the origin and orientation of the axes is consistent, and an interpolated surface has been fitted to the measurement points. It should be noted that the proximity of the echosounder to the pile is further restricted in this set-up at the far side of the pile due to the construction of the bracket, so the interpolated solution is less reliable in the vicinity of the pile. In Fig. 7 and 8 it is observed that in general the differences between the measurements from the two systems are considerable. This can be related to the larger beam footprint of the echosounder in this flume, and the shorter measurement time at each position, so that the loss of accuracy with the echosounder has become significant across large areas of the scour hole.

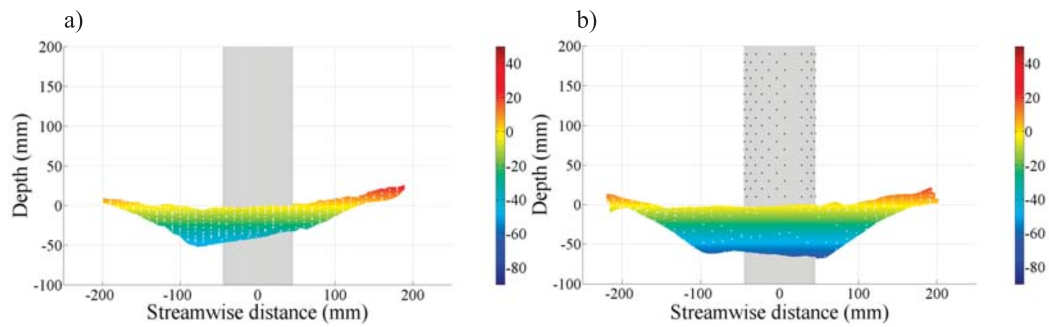

Figure 7. a) Side elevation of 3D echosounder profile b) Side elevation of 3D photogrammetry profile

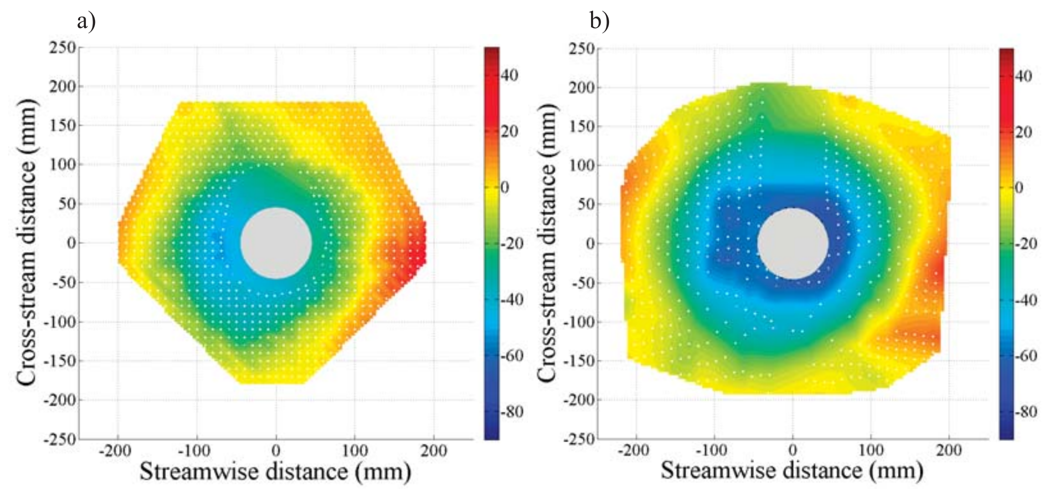

Figure 8. a) Plan view of 3D echosounder profile b) Plan view of 3D photogrammetry profile

An identity plot of the echosounder and photogrammetry measurements in the larger and smaller flumes is given in Fig. 9. The significant scatter in the data at the large scale demonstrates the extent of the reduction in accuracy regarding the echosounder measurements with a difference of as much as 3-4 cm between the two techniques. The echosounder consistently underestimates the scour depth. Interestingly, the best agreement between the two devices is found close to the initial bed level (at zero in Fig. 9). This result indicates that the echosounder is producing more accurate measurements on the flat bed, which is to be expected as the beam footprint will have a smaller area, and the strength of the reflected signal will be more uniform. As discussed earlier, the agreement between the 2D profiles at the small scale is shown to be very reasonable.

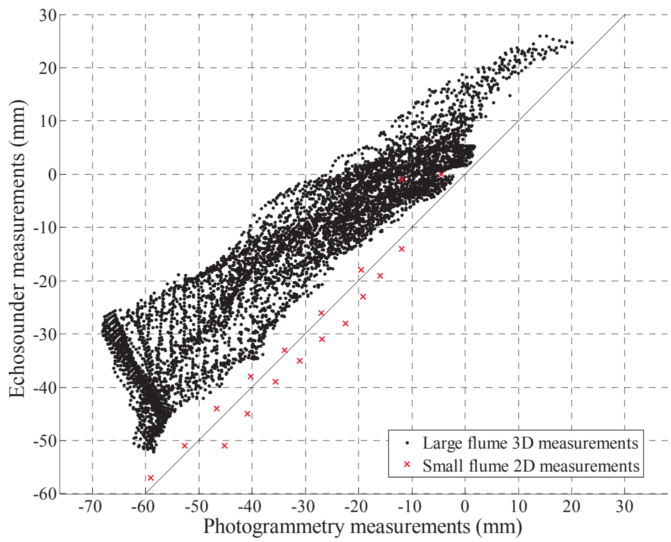

Figure 9. Identity plot of photogrammety and echosounder measurements in the small and large flumes

Evaluation of techniques

For comparative purposes, the specifications of each technique have been detailed in Table 1, allowing the strengths and weaknesses of each technique to be analysed.

The echosounder performed poorly in terms of accuracy due to the large size of the beam footprint relative to the scale of the tests, especially at the larger scale. Sharp changes in bed slope were not correctly modelled in either flume. However, this technique does enable the scour depth development to be monitored in test at a variety of locations, and at the small scale the results were generally acceptable. It should be noted that this was the most expensive of the three techniques in terms of equipment cost.

The Photogrammetry technique provided the most extensive spatial coverage of the scour hole and it was possible to measure points very close to the pile, which could not be covered with the echosounder. This technique had the highest precision of the three systems, and the measurement procedure was fast and straightforward. However, post-test processing of the data was time consuming, as many of the measurement points had to be identified manually in the images. The photogrammetry technique performed poorly regarding the time resolution of measurements as the data could only be collected when the experiment was paused.

Despite being the simplest technique, the pile scale out-performed the other techniques in the remaining categories in Table 1 especially with regards to the temporal resolution of measurements. Also, it is an easy system to set-up and is inexpensive. The shortcomings of this technique are that it cannot provide 3D coverage of the scour hole, and the coarse resolution of the scale resulted in a reduction in measurement accuracy. However, this technique was imperative to collecting scour depth time histories through the tests.

The different strengths and weaknesses of the three systems meant that by using a combination of techniques the pertinent information could be collected enabling the scour process to be monitored comprehensively in this project.

Table 1. Evaluation of measurement techniques

	Calibrated pile	Echosounder	Photogrammetry
Spatial resolution	Adjacent to pile only	Location can be varied but measurements not possible within 2 cm of the pile	Coverage of full scour hole including close to the pile, but shadow zone behind pile and at near wall due to position of projectors
Temporal resolution	O(s) (Excellent - especially with a video camera)	Best results when maximum depth reading taken over a 30 second period, but actual resolution is 0.1 s. Takes time to build a 2D or 3D profile of points i.e. simultaneous measurements of multiple locations is not possible	Flow paused for measurements
Accuracy	5 mm scale, measurements estimated by eye to the nearest 1 mm	Loss of accuracy on sharp changes of slope. Measurements can be affected by suspended sediment	Sub mm precision is possible but depends on projected dot size, camera specifications and distance from image to object
Set-up and measurement procedure	Straightforward set-up and direct measurements	In manual mode, measurements are direct. In recording mode, data must be calibrated. Requires mounting system and method of traversing the sensor.	Set-up is complex as projectors must be mounted and positioned correctly, lighting controlled, and targets must be precisely marked onto pile. Measurement collection is straightforward and quick.
Data processing	No processing needed	No processing needed for manual measurements. Processing is fairly straightforward for recorded mode, with linear calibration, but coupling with a traverse path is complex.	Lengthy processing due to labelling measurement points on multiple photographs. Coordinate transformations needed between VMS and Matlab.
Intrusiveness	Non-intrusive	Echosounder sensor face (30 mm diameter) submerged by approx. 2 mm, but more than this under wave crests.	Camera submerged in the water, but at a distance from the bed and with no flow
Expense	Low cost	O(£10,000) for the Echosounder system. Extra for traverse, data logger	O(£1000) for the camera and projector. More for additional projectors, tripods etc.

Future work

The main limitation of the underwater photogrammetry system is that it is not possible to collect measurements while the flow is running. Future developments of the system should attempt to overcome this aspect so that this technique could be implemented as a stand alone system without the need for comparative techniques. One way to do this would be to include a ray tracing algorithm in the computation and position the cameras outside of the flume. However, as discussed earlier there is no direct solution to the ray tracing problem so an iterative approach would have to be adopted.

Alternatively, the underwater cameras system could be developed further by sourcing small cameras with the capability to be synchronised. An investigation would be needed to determine a feasible location for the cameras to ensure they have the required view of the scour hole, while at the same time not interfering with the flow. The small submergence depth of the echosounder sensor had a negligible impact at the scale of tests discussed in this paper. Therefore, if the cameras could be positioned in a similar way, or were of much smaller diameter, this would be an acceptable solution.

Another improvement that could be made to the photogrammetry technique would be to reduce the data processing time. The time consuming aspect of the method is identifying the measurement points in the photographs. Feature matching techniques could be investigated, although as was discussed earlier this is difficult with some types of sand beds. Instead, the projected dots could be modified to make them more easily distinguishable in the images. A unique pattern, or colour coded dots could be implemented which would firstly help the user to correctly identify the markers, but secondly could be used to improve the automatic detection of the dots through additional coding in the software.

CONCLUSIONS

This paper has identified a gap in the literature in terms of a comprehensive measurement technique for monitoring scour depth in the laboratory. Photogrammetry was identified as a promising technique but required development to solve the refraction issue. A novel underwater camera measurement system was presented. The main conclusions of the paper are:

- The photogrammetry results were shown to be in agreement with standard techniques at two different scales and considering both 2D and 3D measurements.
- The photogrammetry system was shown to be superior to the echosounder device as the accuracy of the echosounder measurements was significantly reduced on sloping sections and in the larger scale flume due to the size of the beam footprint.
- Echosounder measurements of scour holes in the laboratory should be treated with caution especially where an echosounder with similar or lower specifications has been applied at a comparable scale to this study.
- Photogrammetry produces accurate, high resolution 3D scour hole profiles. This allows additional information about the scour hole development to be analysed including the scour extent, volume and slope angles, while the photographs can provide further qualitative insights into the scour process.

ACKNOWLEDGEMENTS

This research project is funded by the EPSRC and HR Wallingford.

REFERENCES

Agrawal, A., S. Ramalingam, Y. Taguchi, and V. Chari. 2012. A theory of multi-layer flat refractive geometry, *IEEE Conference on Computer Vision and Pattern Recognition,* 3346-3353.

Baglio, S., C. Faraci, E. Foti, and R. Musumeci. 2001. Measurements of the 3-D scour process around a pile in an oscillating flow through a stereo vision approach, *Measurement,* 30, 145-160.

Ballio, F., and A. Radice. 2003 A non-touch sensor for local scour measurements, *Journal of Hydraulic Research,* 41(1), 105-108.

Chang, W.-Y., J.-S. Lai, T.-Y. Yu, F. Lin, L.-C. Lee, W.-F. Tsai, and C.-H. Loh. 2014. Pier scour monitoring system by bed-level image tracking, *International Journal of Sediment Research,* 29, 269-277.

Coleman, S.E., C.S. Lauchlan, and B.W. Melville. 2003. Clear-water scour development at bridge abutments, *Journal of Hydraulic Research,* 41(5), 521-531.

Cooper, M.A.R., and S. Robson. 1996. Theory of close range photogrammetry. In Atkinson, K.B. (ed.), *Close range photogrammetry and machine vision*: 9-51. Whittles Publishing, Caithness.

Debnath, K., and S. Chaudhuri. 2011. Effect of suspended sediment concentration on local scour around cylinder for clay-sand mixed sediment beds, *Engineering Geology,* 117, 236-245.

Dingler, J.R., J.C. Boylis, and R.L. Lowe. 1977. A high-frequency sonar for profiling small-scale subaqueous bedforms, *Marine Geology,* 24, 279-288.

Foti, E., I.C. Rabionet, A. Marini, R.E. Musumeci, and A. Sanchez-Arcilla. 2011. Experimental investigations of the bed evolution in wave flumes: performance of 2D and 3D optical systems, *Coastal Engineering,* 58(7), 606-622.

Hartvig, P.A., J.M. Thomsen, P. Frigaard, and T.L. Andersen. 2010. Experimental study of the development of scour and backfilling, *Coastal Engineering Journal,* 52(2), 157-194.

Huang, M.Y.F., A.Y.L. Huang, and H. Capart. 2010. Joint mapping of bed elevation and flow depth in microscale morphodynamics experiments, *Experiments in Fluids,* 49, 1121-1134.

Jensen, M.S., B.J. Larsen, P.B. Frigaard, L. DeVos, E. D. Christensen, E.Asp Hensen, T.Solberg, B. H. Hjertager, and S. Bove. 2006. Offshore wind turbines situated in areas with strong currents, Offshore Center Danmark.

Kotowski, R., 1988. Phototriangulation in multi-media photogrammetry, *International Archives of Photogrammetry and Remote Sensing,* XXVII, Part B5, 324-334.

Lanca, R., C. Fael, R. Maia, J. Pego, and A. Cardoso. 2013. Clear-water scour at comparatively large cylindrical piers, *Journal of Hydraulic Engineering,* 139(11), 1117-1125.

Margheritini, L., P. Frigaard, L. Martinelli, and A. Lamberti. 2006. Scour around monopole foundations for off-shore wind turbines, *Proceedings of the 1st International Conference on the Application of Physical Modelling to Port and Coastal Protection – Coastlab06,* Porto, Portugal.

McGovern, D.J., S. Ilic, A.M. Folkard, S.J. McLelland, and B.J. Murphy. 2012. Evolution of local scour around a collared monopole through tidal cycles, *33rd International Conference on Coastal Engineering,* Santander, Spain.

Porter, K.E., R.R. Simons, and J.M. Harris. 2014. Laboratory investigation of scour development through a spring-neap tidal cycle, *7th International Conference on Scour and Erosion,* Perth, Australia (forthcoming).

Porter, K, R. Simons, J. Harris, and T.F. Ferradosa. 2012. Scour development in complex sediment beds, *33rd International Conference on Coastal Engineering,* Santander, Spain.

Raaijmakers, T., F. Liefhebber, B. Hofland, and P. Meys. 2012. Mapping of 3D-bathymetries and structures using stereophotography through an air-water-interface, *4th International Conference on the Application of Physical Modelling to Port and Coastal Protection - Coastlab12,* Ghent, Belgium, 390-399.

Robson, S., and M.R. Shortis. 2012. Vision Measurement System (version 8.5) [Computer program] Geometric Software P/L, 15 Maranoa Crescent, Coburg, 3058, Australia, www.geomsoft.com.

Rosier, B., J.-L. Boillat, and A. Schleiss. 2004. Mapping of bed morphology for lateral overflow using digital photogrammetry, *2nd International Conference on Scour and Erosion,* Singapore.

Roulund, A., B.M. Sumer, J. Fredsøe, and J. Michelsen. 2005. Numerical and experimental investigation of flow and scour around a circular pile, *Journal of Fluid Mechanics,* 534, 351-401.

Sheppard, D. and W., Jr. Miller. 2006. Live-bed local pier scour experiments. *Journal of Hydraulic Engineering,* 132(7), 635-642.

Simons, R. J. Weller, and R. Whitehouse. 2007. Scour development around truncated cylindrical structures. *5th International Conference on Coastal Structures,* Venice, Italy, 1881-1890.

Stahlmann, A., and T. Schlurmann. 2010. Physical modelling of scour around tripod foundation structures for offshore wind energy converters, *32nd International Conference on Coastal Engineering,* Shanghai, China.

Sumer, B.M., T.U. Petersen, L. Locatelli, J. Fredsøe, R.E. Musumeci, and E. Foti. 2013. Backfilling of a scour hole around a pile in waves and current, *Journal of Waterway, Port, Coastal, and Ocean Engineering,* 139(1), 9-23.

Sumer, B.M., and J. Fredsøe. 2001. Scour around Pile in Combined Waves and Current, *Journal of Hydraulic Engineering,* 127(5), 403-411.

Umeda, S., T. Yamazaki, and H. Ishida. 2008. Time evolution of scour and deposition around a cylindrical pier in steady flow, *4th International Conference on Scour and Erosion,* Tokyo, Japan.

Younkin, B.D., and D.F. Hill. 2009. Rapid profiling of an evolving bed form using planar laser sheet illumination, *Journal of Hydraulic Engineering,* 135(10), 852-856.