OPTICAL TECHNIQUES FOR MEASURING SWASH ZONE MORPHODYNAMICS

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The use of different optical systems based on computer vision approach, for measuring swash zone morphological changes, is here proposed. In particular, such techniques are able to achieve quite accurate 2D and 3D reconstruction of the sandy bottom in dynamic conditions under regular waves. They are considered truly non-invasive, since there is no interaction of the hardware with the water motion. The optical techniques have been applied both at small and at large scale facilities for the investigation on the seabed interaction with the fluid motion within the swash zone. The performances of well-established more traditional measurement instruments have been compared with the proposed optical instruments both at small and large scales. In both cases satisfactory results have been gathered during the present experimental campaign.

Keywords: computer vision; morphological changes; swash zone.

INTRODUCTION

A significant progress has been made over the past decade in the understanding of sediment transport processes within the swash zone, which is a complex and highly dynamic region because of the intermittent presence of the water caused by the shoreline motion. Few of the mechanisms which have received attention in recent studies are: the differences between the hydrodynamic characteristics of the uprush and backwash motion; the influence of infiltration and exfiltration phenomena; the relevance of swash zone processes in sediment transport processes (see reviews by Butt and Russell, 2000; Elfrink and Baldock, 2002; Masselink and Puleo, 2006; Brocchini and Baldock, 2008). However, a lot remains to be done in this field. Indeed, for example, there is still a lack of knowledge on the effects of single swash events on the morphology changes of the sandy bottom, since intra-wave analysis cannot be easily performed. This is mainly due to the fact that observations of the morphology evolution of the swash zone have been limited by the available technology (Miles et al. 2006, Masselink et al., 2009).

As a matter of fact, the swash zone is an area where it is difficult to install measurement instruments (Hughes et al., 1997), because of the high turbulence and suspension levels, and also because of the rapid changes of the bed level either leading to burial of instruments or scouring below them, which may cause their actual location to be too far from the bed (Masselink et al., 2009). According to Masselink and Puleo (2006), in the field high-resolution (spatial and temporal) measurements of the beachface morphology, obtained either manually (Duncan, 1964; Eliot and Clarke, 1986; Masselink et al., 1997, Kulkarni et al. 2004) or by remote sensing techniques (Holland and Puleo., 2001) can be used to derive net sediment transport rates in the swash zone. Moreover instruments such as the widely adopted sediment traps (James and Brenninkmeyer, 1977; Hardisty et al., 1984; Masselink and Hughes, 1998; Jackson et al., 2004) and pump samplers (Kroon, 1991) allow to measure the bulk sediment load and give information on event-scale sediment transport rates, for example, the transport over an uprush/backwash cycle. However, many of the aforementioned instruments interact with the water motion while are located inside the investigated area.

Although field campaign are very useful in order to provide a comprehensive picture of the phenomena, only laboratory experiments can specifically address the investigation of the basic processes which control the beachface dynamics.

In hydraulic laboratories, nowadays, swash zone morphology is usually recovered by traditional mechanical instruments, such as rods or wheel bed profilers, or more advanced 3D laser scanner. All these instruments cannot work in a dynamic fashion and often data have to be acquired in dry condition, which means not only that the experiments have to be stopped, but also that the wave tank have to be dried before recovering the bottom. Obviously, these procedures strongly limits the possibility to perform dynamic analyses of swash zone morphology, not considering the fact that the presence of the rods or the movement of the mechanical bed profilers can also slightly modify the bed shape.

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The aim of this work is to present optical measurements techniques based on computer vision approaches, which allow to acquire data about the sandy bottom morphology in a noninvasive and dynamic manner. In particular, in the present paper 2D and 3D measurement methodologies have been developed and applied to the investigation of swash zone morphodynamics. One of the key point of the proposed techniques is that, aiming at materialize onto the sandy bottom the reference measurement points or sections different structured light patterns have been on purposely projected onto the sandy bottom. As specified, the proposed techniques have been developed to overcome the limit of the available instrumentation, in particular they can be used in wet conditions, i.e. without stopping the experiments and without drying the wave tank. Some preliminary applications to the analysis of the scour around a vertical cylinder due to wave motion were initially performed by Faraci et al. (2000) and by Baglio et al. (2001) in small scale facilities O(20 cm x 20 cm). However, since large scale experiments should be preferred in order to reduce scale effects, in the present work the proposed techniques have been applied to the investigation of the bottom evolution within the swash zone both in a small and in a large scale wave flume. In this way, the measurement accuracy of such methodologies has been evaluated both at small scale, measurement area O(20 cm x 20 cm), and at large scale, measurement area O(1 m x 1 m).

In the following sections, a description of the theoretical background of the measurement methodologies is presented; then the main technical improvements to such optical techniques for extending their application at large scale are discussed, and the adopted experimental apparatus and procedure are described; thus the experimental results are analyzed and finally some final remarks on the present work are drawn.

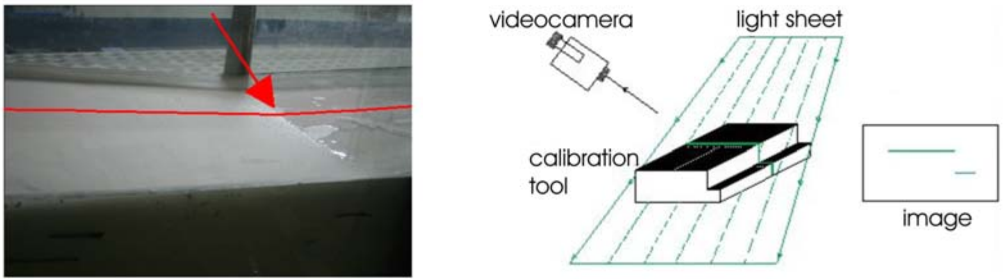
COMPUTER VISION TECHNIQUES FOR MEASURING SANDY BOTTOM EVOLUTION

Computer vision techniques have been developed in the field of robotics, both to improve the automation of industrial processes and to allow the self-motion of robots through the recognition of paths free of obstacles to be performed. The basic idea behind such an approach is to simulate the human vision capability, by implementing the following three steps: (i) image formation; (ii) image acquisition and (iii) image analysis.

Aim of the present work is to apply computer vision techniques as measurement instruments of the sandy bottom evolution under the action of waves and currents, since they allow the bed morphology to be continuously and non-invasively recovered. The question is whether or not their accuracy is sufficient and comparable to that of more traditional instruments nowadays adopted in hydraulic laboratory.

During the last decades, two different optical measurement systems for morphodynamic investigations have been developed at the University of Catania, which allow both two-dimensional and three-dimensional measurements. For brevity sake, in the following they will be referred to as UCAT's 2D technique and UCAT's 3D technique.

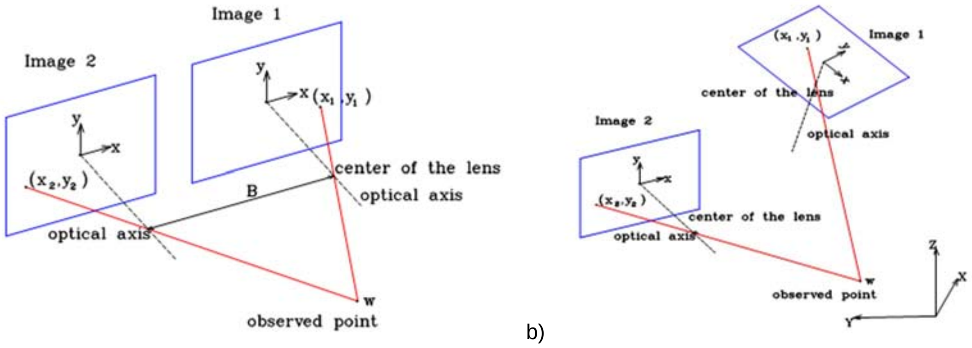
In particular, the UCAT's 2D technique was initially presented by Faraci et al. (2000) to investigate the evolution of the scour around a vertical pile. By using the information gathered on a single image of the investigated bottom, the methodology developed by Faraci et al. (2000) is able to obtain metric information along a specific section of the bottom itself. In order to accomplish the image formation step, a laser source coupled with a cylindrical lens projects a light sheet onto the sandy bottom. In Figure 1a an example of the projected light sheet in the correspondence of the swash zone is reported. The image acquisition is performed by using a commercial CCD video-camera. Finally the image interpretation and analysis is performed by means of a calibration process, which allows to translate the pixel dimensions on the image in real word dimensions. In particular, the laser sheet is projected onto an object having known dimensions. Moreover the shape and the dimensions of the calibration tool have to be also comparable to those of the investigated phenomena. In this way it is possible to determine the transfer function between the dimensions along the light line on the image and the real dimensions. Figure 1b reports a sketch which summarizes the calibration procedure.



a) b)

Figure 1. UCAT's 2D technique: a) example of the projection of the laser sheet onto the sandy bottom in the correspondence of the swash zone; b) sketch of the image calibration procedure by means of the image of a a calibration tool (object having known dimensions).

The UCAT's 3D methodology has been initially introduced by Baglio et al. (2001) in order to obtain three-dimensional measurements of the sandy bottom evolution for the same test case as the one of Faraci et al. (2000), i.e. the scour around a vertical cylinder. Usually 3D techniques follow the traditional stereoscopic hypothesis, i.e. equal and parallel image planes, same focal length, aligned optical axes. Aiming at developing a more flexible measurement methodology, Baglio et al. (2001) implemented a new algorithm which allows to remove the limiting hypotheses of the classical stereoscopy. Such improvements are extremely suitable, since in laboratory environments several obstacles and obstructions to the view can be present, due for example to the structure of the wave tank or to the presence of other measurement instruments. Therefore the possibility to observe the phenomenon by complying with a rigid positioning of the cameras may be severely limited. In order to highlight the differences between the classical approach and the one proposed by Baglio et al. (2001), which is the one developed in the present work, Figure 2 depicts the sketches of the two different settings, along with the definition of the main optical variables.



a) b)

Figure 2. Stereoscopic approach: a) sketch of the traditional stereoscopic setting; b) sketch of the setting of the cameras by adopting the UCAT's 3D technique.

The technique makes use of two different commercial CCD video-cameras. Since the sandy bottom is deprived of any reference point, in order to visualize on the images the location of the bed, also in this case structured light is adopted. Such points are obtained by using a diffractive lens which decomposes the single laser beam into a regular grid of light points. Such points are useful not only to analyze the bed evolution but also for the matching process during image processing.

It should be stressed that the coherence of the laser beam allows uncertainties related to the position of the measuring section, in the 2D case, or of the measurement points, in the 3D case, to be reduced. In particular, Figure 3 shows the two light patterns used respectively for the 2D and the 3D measurement methodologies adopted in the present work, namely a light sheet and an regular grid of points.

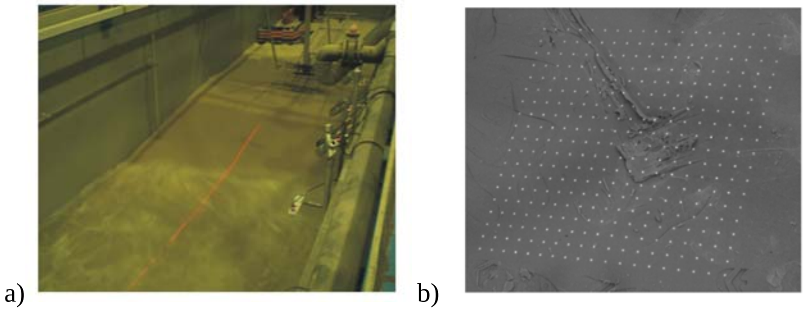


Figure 3. Structured light patterns adopted for visualizing the measuring points onto the sandy bottom: a) laser sheet adopted for the 2D UCAT's technique; b) laser grid adopted for the 3D UCAT's technique.

Previous applications of the above described optical methodologies have been performed so far only in small scale facilities, where the investigated area was about 20 cm x 20 cm. Aim of the present work is to extend the possibility to use such techniques also in large scale facilities, where the physical processes are not biased by the presence of scale effects and the advantages related to the overcoming of some of the limits of the traditional measurement instruments are much more important.

Moreover, an additional 3D technique has been applied during the experimental campaign, along with the two techniques described above. Such a technique is based on the use of a stereo-head camera, usually adopted in robotic applications. The stereo-head is produced by Videre Design and it is made up of two identical USB cameras mounted on a steel frame, in such a way that the traditional stereoscopic hypotheses, schematized in Figure 2a, can be fulfilled. The calibration procedure of the cameras is performed through a software based on the well-known Tsai's method (Tsai, 1985). Such a calibration software is furnished by the camera's manufacturer along with a software for the stereo matching of the images and the algorithm for three-dimensional reconstruction. The cameras are able to perform both still and movie three-dimensional reconstructions, by providing the outcome both as 3D graphical representation and as 3D numerical coordinates. In the following, such a technique will be referred to as traditional stereoscopic technique.

As mentioned, during the present experimental campaign, the three optical systems presented above have been applied to the investigation of swash zone morphodynamics. The performances of such methodologies, in particular their measurement accuracy, have been compared with traditional mechanical instruments, usually applied in hydraulic laboratories, both in small scale and in large scale facilities. It is worth pointing out that the transfer of the proposed methodologies from the small scale to the large one is not trivial and a number of problems had to be considered and solved, as described in the following sections.

Main technical improvements to the optical techniques for extension to large scale applications

When considering the application of optical systems for measuring the bottom morphology in a dynamic fashion, several aspects have to be carefully taken into account, such as the water quality, perspective effects and image quality. Such aspects can be easily controlled in a small wave tank, but not in a huge wave flume such as the one present at the Technical University of Catalunya, where a large part of the experimental work has been carried out.

Indeed, for example, in order to have readable images the water within the tank must be clear, with no turbidity and suspended materials. Besides, the image quality depends also on several other factors such as the characteristics of the laser generator (power, length scale, etc.), the technology adopted for generating the light pattern to be projected onto the bottom (rotating mirror, cylindrical or diffractive lens), the characteristics of the adopted camera, and the environment light. Moreover, the location of the investigated area onto the sandy bottom may be also constrained by the location of side glass windows along the wave flume. Finally, the positioning of the camera may be problematic, due to perspective effects which may affect the measurements. Therefore the calibration process is a key-point, and dimension and shape of the calibration tool have to be carefully designed.

As mentioned, previous studies were conducted at small scale by applying the described optical techniques for the analysis of phenomena such as the scour around a pile, the geometry of ripple evolution and the analysis of sandpit morphological changes (see Baglio et al. 1998, Faraci et al. 2000, Baglio et al. 2001, Faraci and Foti, 2000, Cavallaro et al. 2008).

During the present investigation, a preliminary re-assessment of the measurement accuracy of the 2D and of the 3D techniques has been carried out by considering the same test case., i.e. the measurement of a PVC small scale bed-form profile (ripple length equal to 9.00 cm and ripple height equal to 1.40 cm). The measurement have been gathered in the presence of a wave motion above the bed. Therefore, both the cameras and the laser projector have been located below trough level. Figure 4 shows the rough images of the wavy bottom used to obtain the 2D and the 3D measurements of the ripple shape and geometrical characteristics. Both measurement methodologies showed an accuracy of O(0.05 cm), both along the horizontal and the vertical dimensions.

Figure 4. Accuracy analysis carried out at small scale over a PVC rippled bed: a) image acquired for the UCAT's 2D technique; b) left image acquired for the UCAT's 3D technique; c) right image acquired for the UCAT's 3D technique.

Going to large scale experiments, the image quality of the 3D proposed technique has been improved in several ways. For example the Gaussian lens previously adopted at small scale showed to provide blurred images with light dots characterized by non-uniform intensities, i.e. lighter at the center and weaker at the edges, with a number of spurious points. Another weak point of the first grid was that the grid pattern had too large blank spaces, giving a pour spatial resolution at large scale (see Figure 5a). In order to have cleaner images a new non-Gaussian lens has been adopted, characterized by the same power intensity of all the 19x19 points of the grid, whose distribution in this case is also less sparse (see Figure 5b).

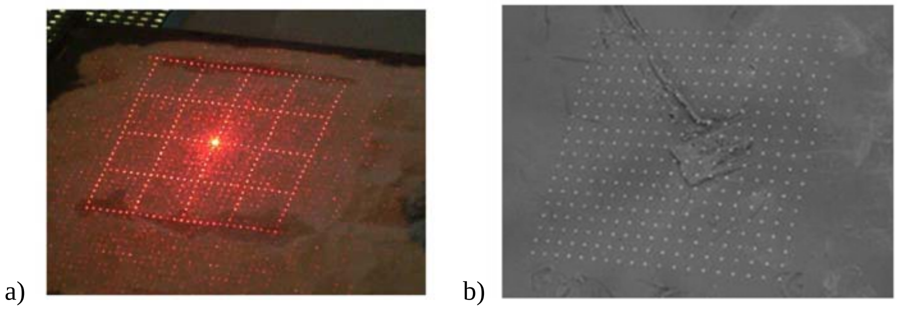
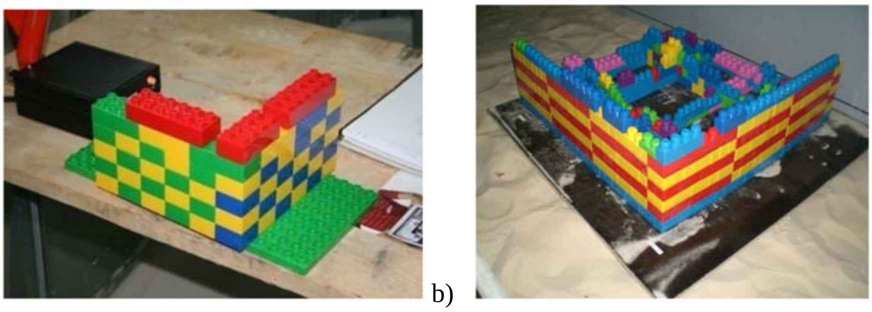


Figure 5. Images of the grid laser projection: a) projection with a non-Gaussian distribution lens adopted in the small scale facility; b) projection with a Gaussian distribution lens adopted in large scale facility.

Concerning the calibration procedure a preliminary error analysis has been conducted at large scale over the investigated area, in order both to determine the best camera set-up along the flume and also the optimal dimension and shape of the calibration tool (Figure 6). It should be mentioned that a new system was adopted for building up the calibration tool. Indeed, following Nielsen (2007), the calibration tool both at large and small scale (see Figure 6) has been constructed by using industrially shaped colourful plastic blocks. Such a system proved to be an easy and cheap way to build a tool with regular and well controlled dimensions and variable size and shape, depending on the kind of experiment to be performed.

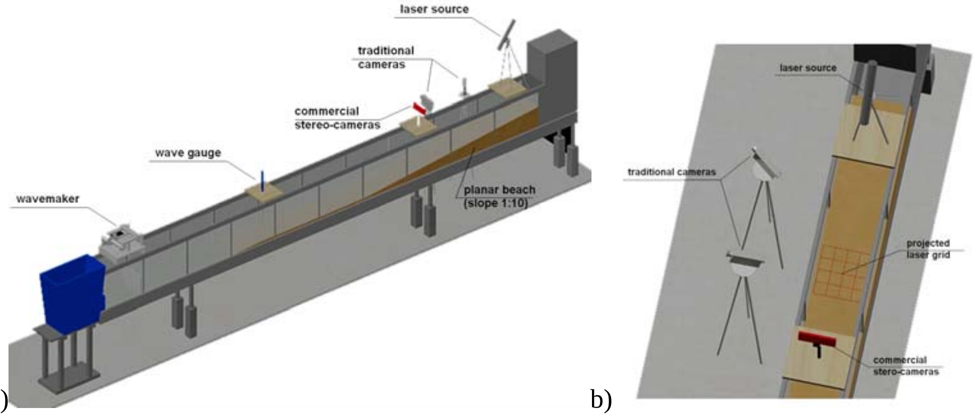


a) b)

Figure 6. Calibration tool used for the UCAT's 3D technique adopted: a) at small scale; b) at large scale.

EXPERIMENTAL APPARATUS AND PROCEDURE

Small scale experiments on the morphodynamics of the swash zone have been performed at the Hydraulic Laboratory of the Department of Civil and Environmental Engineering of the University of Catania (Italy). The adopted wave flume is showed in Figure 7a. The flume is 9.0 m long, 0.5 m wide and 0.7 m high. A beach made up of well-sorted natural quartz sand (d_{50}=0.24 mm) with an initial slope 1:10 is located at the far end of the flume. Such a flume has lateral glass walls, which allow images of the investigated zone to be acquired from outside of the flume. Figure 7b shows a closer view of the location of the optical equipment in the correspondence of the swash zone. The investigated area is about 25 cm x 25 cm large.



a) b)

Figure 7. Sketch of the wave flume adopted at the Hydraulics Laboratory of the University of Catania for the small scale investigation of swash zone morphodynamics: a) overall view (9.0 m long, 0.5 m wide, 0.7 m high); b) location of the optical devices for performing the dynamic measurements of the sandy bottom.

With reference to the 3D measurement methodologies applied here, the adopted optical equipment is shown in Figure 8. In particular the two commercial cameras adopted for the 3D UCAT's technique were located on the left side of the flume (see Figure 8a), the stereo-head camera was positioned above the center of the wave flume (see Figure 8b) and the laser source coupled with the diffractive lens has been placed in front of the latter one, always above the center of the flume (see Figure 8c). The set-up for the 2D technique was quite similar, but obviously only one camera was adopted in that case.

The large scale experiments have been carried out within the large wave flume at the UPC (Universitat Politècnica de Catalunya of Barcelona, Spain). The wave flume is 100 m long, 3 m wide and 5 m deep. Such a big dimensions allow to perform experiments which are scale 1:2 with respect to prototype. The flume is equipped with a recirculating system which allows to have a very clear filtered water. A sandy bottom made up of natural quartz sand (d_{50}=0.25 mm) is present within the flume for movable bed experiments. During the present experimental campaign no mechanical adjustment of the initial beach slope has been performed, thus experiments started from the configuration of the beach present in the flume at the time of the tests. A sketch of the flume is reported in Figure 9a, while in Figure 9b a sketch of the location of the optical equipment in the correspondence of the swash zone is presented. As reported in the previous section, an accurate preliminary analysis has been carried out in order to determine the best placement of the cameras and of the laser with respect to the sandy bottom.

Figure 8. Optical equipment adopted at small scale for the 3D optical measurement of the sandy bottom within the swash zone: a) commercial CCD cameras used UCAT's 3D technique; b) stereo-head camera used for the traditional stereoscopic technique; c) laser generator coupled to a diffractive lens.

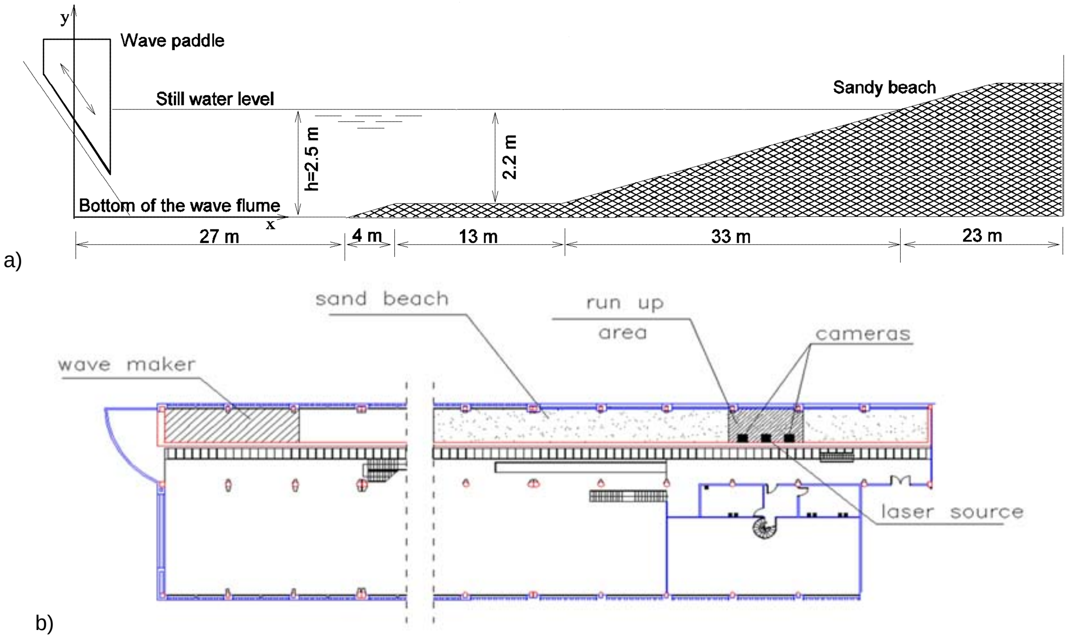


Figure 9. Wave flume at UPC for large scale test (dimensions: length equal to 100 m, width of 3 m and height of 5 m): a) longitudinal profile; b) top-view of the set-up of the optical instruments adopted during the experimental campaign at large scale.

Both at small and large scale, the experimental procedure is constituted by the following phases:

- preliminary operations (bottom preparation, location of the cameras and of the other instruments, etc.)
- calibration of the different optical techniques;
- initial bottom profile survey also by means of traditional measurement instruments (graduated bar at small scale and wheel bed profiler at large scale);
- wave motion generation and swash zone evolution acquisition by means of the optical probes, without stopping the experiments);
- final bottom profile survey also by means of traditional measurement instruments (graduated bar at small scale and wheel bed profiler at large scale);
- images elaboration and reconstruction.

More in details, the preliminary operations consist mainly in the preparation of the sandy bottom (only at smalle scale), the projection of the structured light grid onto the sandy bottom, the placement of the specific equipment related to the different optical systems adopted, the synchronization of the cameras (only for the 3D UCAT’s technique) and finally the positioning and calibration of other hydraulic instruments, such as resistance type wave gauge. In particular, since during the present experiments we are more interested into the analysis of the swash zone morphodynamics, the structured light grid has been projected over a section above the still water level, where the most relevant morphological changes occur.

Concerning the calibration of the optical systems, when applying the UCAT's 2D technique, a picture representing the laser sheet projected onto the calibration tool, having dimensions similar to those of the investigated phenomenon, is obtained as shown in Figure 10. Once the pixel dimensions of the calibration tool are determined through an image processing, the transfer function between pixel dimensions and metric dimension is obtained by applying a simple linear algorithm.

Figure 10. Calibration of the UCAT' s 2D technique: image of the laser sheet projected onto the calibration tool.

Following Baglio et al. (2001), the UCAT's 3D technique calibration procedure consists into acquiring the pixel coordinates of at least 6 points of a three-dimensional object. In this way the camera models of the two cameras is determined, then the stereo matching is performed to obtain the metric three-dimensional coordinates of the observed object. In order to validate the quality of the calibration a three-dimensional reconstruction of the coordinates of all the calibration tool point is reported in Figure 11c.

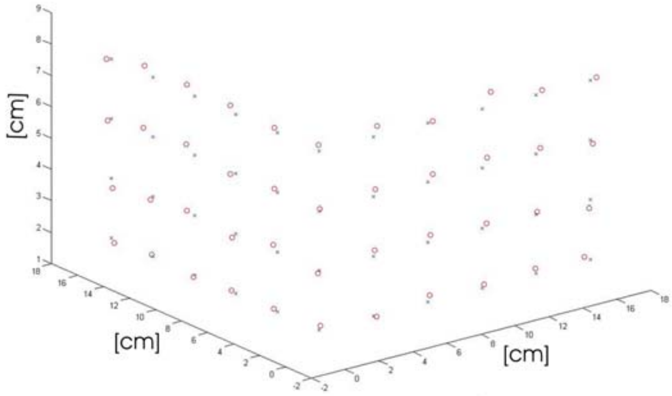


Figure 11. Calibration of the UCAT' s 3D technique: reconstruction of the caliber in real world coordinates (cm).

The calibration process of the traditional stereoscopic technique is carried out by using the software *smallv* which is furnished by the manufacturer of the stereo head-camera. In this case at least five pictures, taken from different angulations, of the well know Tsai's caliber (Tsai, 1985) have to be taken from both camera. In Figure 12 a sequence of the images gathered during the calibration process by the left camera is presented.

The initial and the final profile morphological survey have been conducted by using the proposed optical techniques and also by means of mechanical systems, usually adopted in hydraulic laboratories. In particular, during the present experiments a graduated bar and a wheel bed profiler have been adopted at small scale and large scale respectively. These surveys are also useful for comparison with data acquired by the adopted optical measurement equipments, since they allow accuracy of the proposed techniques to be further estimated.

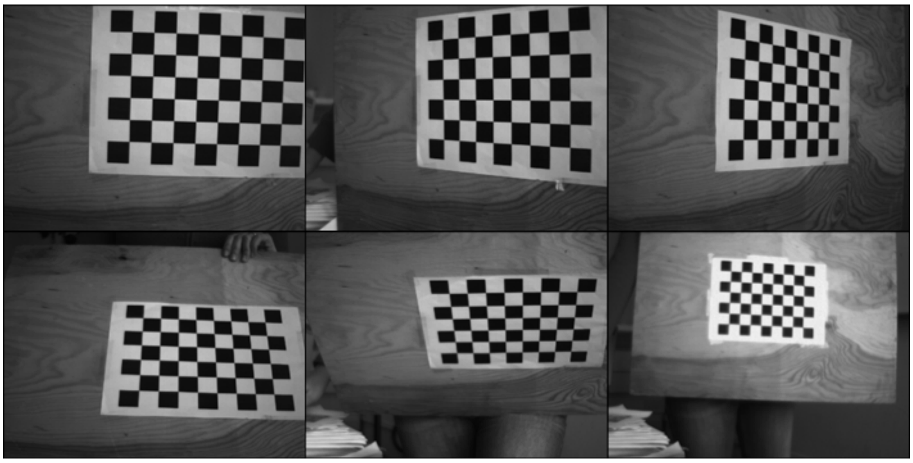
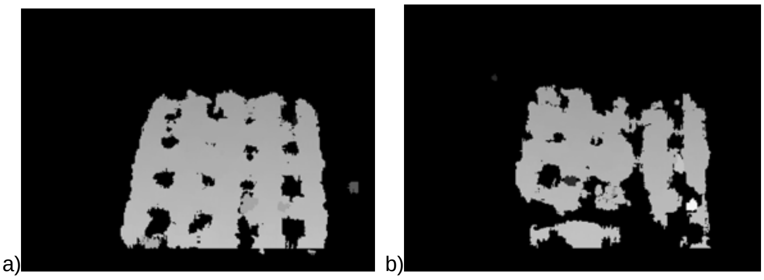


Figure 12.Calibration of the traditional stereoscopic technique: sequence of images gathered by the left camera of the stereo-head equipment.

Once the wave generator is switched on, the optical systems start to record the morphodynamics changes of the sandy bottom within the swash zone. By using the proposed optical measurement methodologies, there is no need to either stop the experiments or empty the wave flume. Such a procedure is not only faster, particularly when running long term evolution experiments, but it also allows to avoid spurious phenomena, such as unwanted sedimentation of suspended sediment transport.

After image acquisition, image processing starts in order to get the 2D and/or 3D reconstruction of the observed phenomenon. In particular, for both the UCAT's techniques, based on the 2D and on the 3D approach, the elaboration process, i.e. the recovering of the pixel coordinates onto the images is not fully automatic, while for the traditional stereoscopic technique the matching process strongly related to the quality of the obtained disparity images, such as those shown in Figure 13.



a) b)

Figure 13 Map of disparity of a small scale experiments: a) at the initial condition t=0; b) at the final condition t=30 min.

EXPERIMENTAL RESULTS

At small scale, the wave forcing is represented by a train of regular monochromatic waves. The adopted control hydrodynamic parameters are shown in Table 1, where *h* is the water depth, *H* the wave height, *T* the wave period and *n* the number of waves.

Table 1. Adopted control hydrodynamic parameters during the small scale experimental campaign.

Exp. no	*h*	*H*	*T*	*n*
	[cm]	[cm]	[s]	[-]
1	20	4.28	1.7	1060
2	20	2.25	1.43	1260
3	20	2.5	1.3	1385
4	20	2.58	1.28	1400

As mentioned the results obtained by means of the proposed optical systems have been compared with those obtained by using a graduated high-precision bar (errors of order of 0.5 mm). All the small scale experiments follow in the field of the typical accretive conditions, characteristic of low-steepness waves.

Since aim of the present work is not to perform a comprehensive and detailed analysis of swash zone phenomena, but to validate the possibility to use optical systems as alternative measuring instruments for bed shape dynamic mapping, the sampling frequency as been kept low, in order to reduce the number of images to be analyzed. In particular, in the present case, the sandy bottom evolution has been investigated by considering time steps of five minutes, but it is quite straightforward to have sampling frequencies as large as 30 Hz or even higher, in case an high-speed camera is adopted.

With reference to the 2D UCAT’s approach, a sequence of images representing the laser sheet projected onto the sandy bottom is shown in Figure 14. Figure 15 shows the profile of the investigated area recovered at each time step by the 2D non invasive technique. Such a profile has been compared with the profiles gathered by means of a graduated bar both at the beginning and at the end of the experiment. The results point out a very good agreement between the 2D UCAT's optical technique and the traditional mechanical system with max errors of ± 0.5 mm in the estimation of the berm height. Moreover, the 2D UCAT’s technique allows to have information also on the intermediate stages, allowing to investigate in details the dynamics which leads to the berm formation.

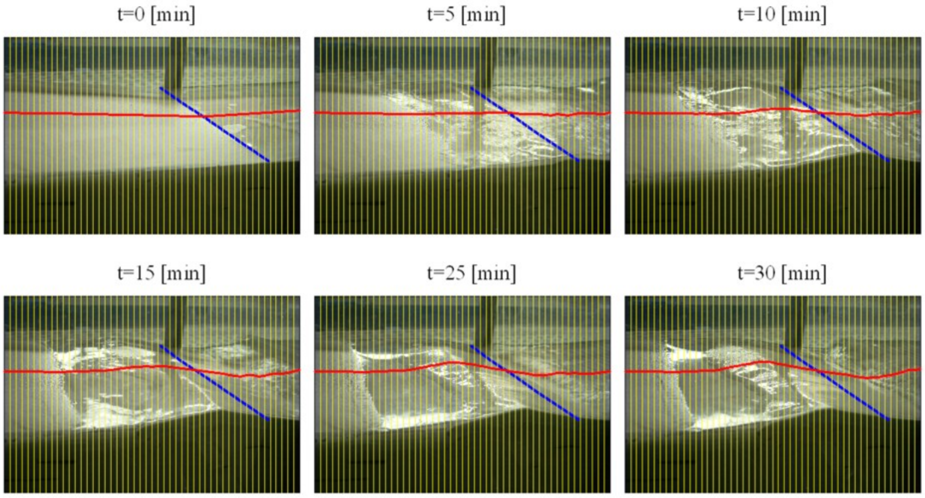


Figure 14. Sequence of images obtained by means of the 2D UCAT's technique at time steps of 5 minutes, representing the laser sheet projection onto the sandy bottom within the swash zone.

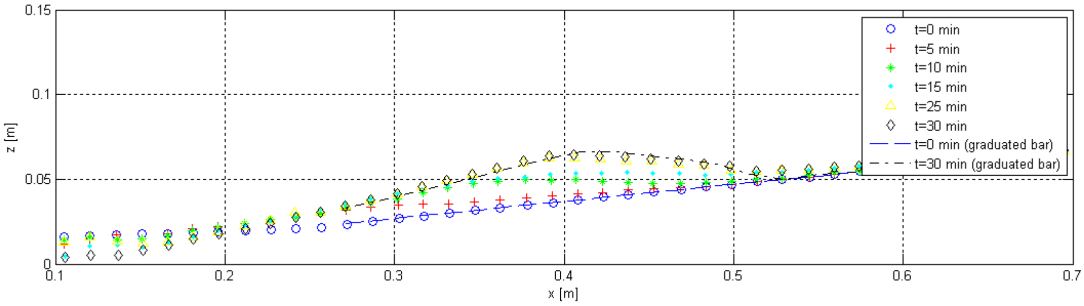


Figure 15. Small scale experiments: measurements of the morphological evolution of the swash zone obtained by means of the 2D UCAT's technique and of the mechanical system (exp. no. 4).

Regarding the results obtained by the means of the two proposed 3D techniques, for consistency sake, also in this case the morphological changes of the sandy bottom have been investigated at time steps of 5 minutes. In particular, the reconstruction as obtained by the traditional stereoscopic technique compared with the initial and final profiles acquired by the mechanical system is shown in Figure 16. In this case, the max error in the estimation of the berm height is of ± 0.3 cm.

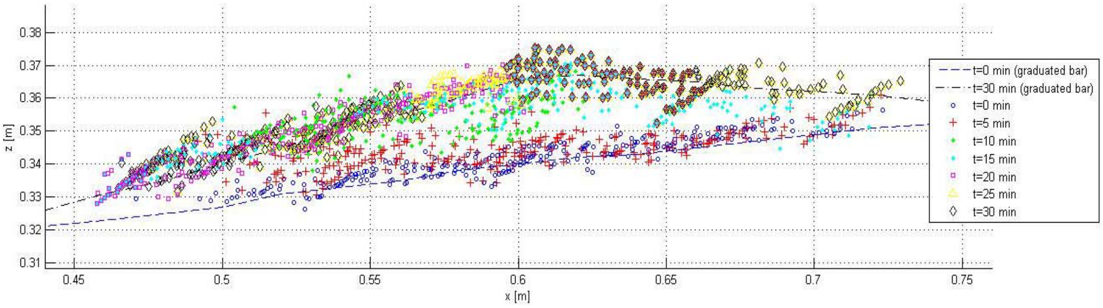


Figure 16. Small scale experiments: measurements of the morphological evolution of the swash zone obtained by means of the 3D traditional stereoscopic technique and of the mechanical system (exp. no. 3).

The 3D reconstruction gathered by the 3D UCAT's technique compared, also in this case, with the initial and final profiles measured by the mechanical system is presented in Figure 17. A maximum error of ± 0.1 cm in the estimation of the berm height has been obtained, indicating a higher accuracy of this system when compared with the traditional stereoscopic technique. However a distortion effect is observed in the far field of the reconstruction, due to reflection effects related to the position of the commercial camera below the glass wall of the wave flume.

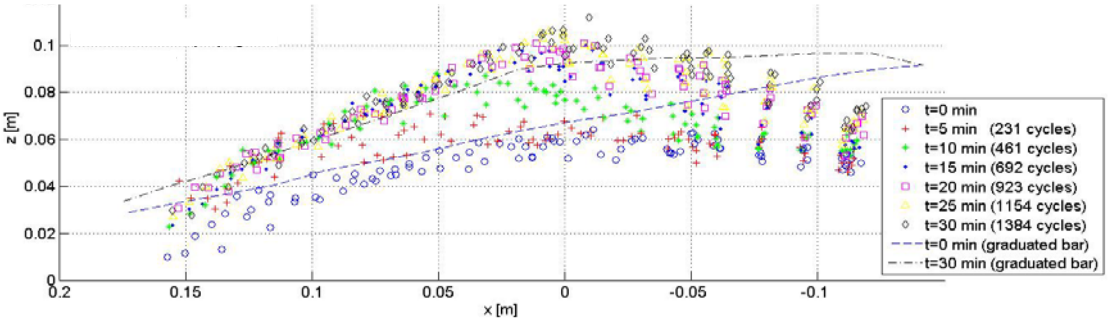


Figure 17. Small scale experiments: measurements of the morphological evolution of the swash zone obtained by means of the 3D UCAT's technique and of the mechanical system (exp. no.3).

The control hydrodynamic parameters adopted at the large scale are shown in Table 2. The present tests have the same hydrodynamic characteristics of some tests of Scandura et al. (2010). Indeed, the regular waves have been generated at the wave maker adopting Stokes linear wave theory, however, as discussed in Scandura et al. (2010) the wave profile deviates from linear theory at some distance from the wavemaker.

From the morphodynamic viewpoint, experiments no. 1 and no.2 represent an erosive condition while experiment no. 3 represents an accretive condition. It should be noted that no mechanical re-shaping of the sandy bottom was performed after the end of each test. Therefore the final configuration of a test represents the initial condition for the following one.

Table 2. Adopted control hydrodynamic parameters during the large scale experimental campaign.

Exp. no	*h*	*H*	*T*	*n*
	[m]	[m]	[s]	[-]
1	2.5	0.6	4.25	600
2	2.5	0.6	5.5	600
3	2.5	0.3	5.5	600

The reconstruction of the investigated area acquired by the traditional stereoscopic technique has been compared with the measurement of a wheel bed profiler, as shown by Figure 18, where the reconstruction of each initial and final stage of a single train of regular waves is reported. In this case, it is possible to recognize how this technique is able to reproduce a large amount of points for each reconstruction, but often they do not appear uniformly or even consistently distributed.

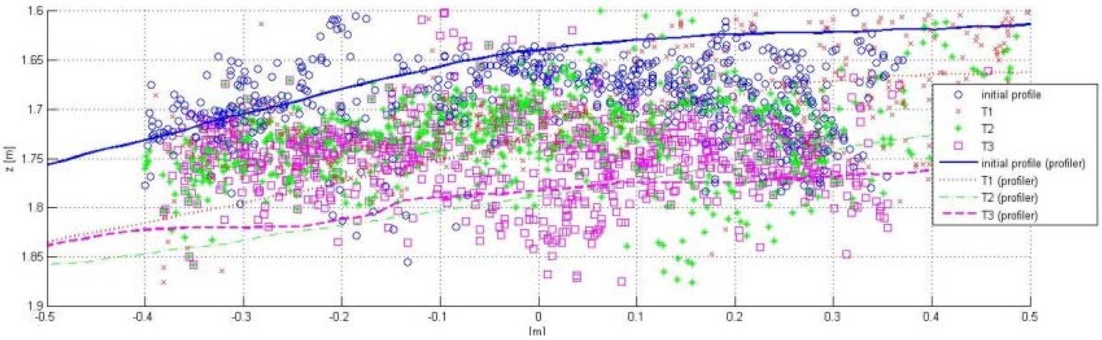


Figure 18. Large scale experiments: measurements of the morphological evolution of the swash zone obtained by means of the 3D traditional stereoscopic technique and of the wheel bed profiler.

Instead, Figure 19 shows both the reconstruction obtained by means of the 3D UCAT's technique against the profiles acquired by the wheel bed profiler. As opposite to the previous case, here it is possible to recognize as the 3D reconstruction agrees fairly well with the profiles measured by the wheel bed profiler.

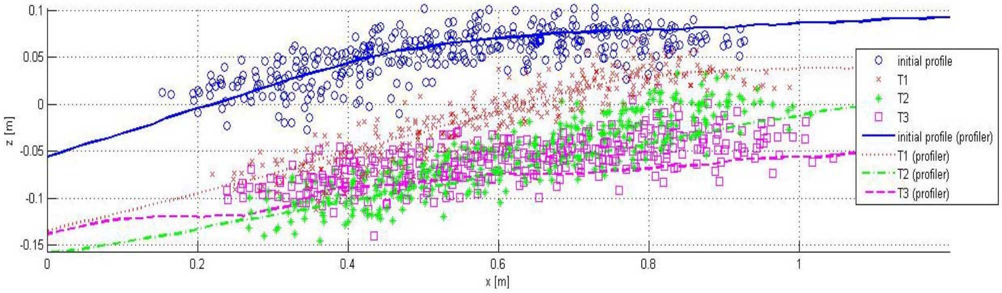


Figure 19. Measurements of swash zone morphological evolution obtained by means of the 3D UCAT's technique and wheel bed profiler in large scale experimental campaign.

In order to determine the accuracy of such techniques, an error analysis has been carried out. In particular, it turned out that by applying the 3D UCAT's approach the maximum error is halved with respect to the traditional stereo method, being at max of about 5 % of the overall linear extension of the investigated area. The greatest errors are obtained in the far field (x=0.8 m) confirming the tendency to the distortion of the proposed measurement strategy in the region farthest from the cameras.

Finally it is worth to point out that, at large scale, since the amount of lateral glass windows was limited, it was not possible to obtain a satisfactory setup for the 2D technique, whose results were affected by relevant perspective error. On the other side, the results of the 3D techniques showed a good agreement with those obtained by the wheel-bed profiler.

FINAL REMARKS

In the present work, different optical techniques for bed shape mapping have been developed to perform measurements of the swash zone morphodynamics, both at small and at large scale facilities. Optical methodologies are suitable as measurement techniques, because they are truly non invasive, thus the disturbing interaction of the measurement instrument with the water motion or with the sandy bottom is thoroughly avoided. A non invasive technique is particularly suitable for the investigation of highly dynamic zones, such as the swash zone, which is interested by the alternate presence of water.

Different kinds of optical systems have been adopted during the present experimental campaign in order to determine the uncertainties related to the use of the optical equipments as compared with that of more established mechanical instruments, such as graduated bars and wheel-bed profilers. In particular, in the present work a 2D approach and two 3D approaches have been implemented and a performance assessment of the techniques has been carried out in different scale facilities.

The extension of the experimental campaign to the large scale facility has been done in order to understand the flow-sediment-morphology interaction in a fully turbulent condition. In particular, some improvements have been applied in order to make more accurate the techniques implemented and also to overcome some difficulties connected to their application at a large scale.

The results obtained by using a traditional mechanical instruments, such as micrometer and wheel bed profiler, have been compared with those obtained by using computer vision techniques.

At small scale, the results of 2D UCAT's technique show a very high accuracy, with max error ± 0.5 mm, while the 3D results show that the traditional stereoscopic camera slightly underestimates the beach face steepening, of about 10% over the vertical. On the other hand, the results obtained by the 3D UCAT's technique, which have smaller errors (5%), are affected by some distortion, particularly in the final part of the profile.

At large scale, the proposed 3D approach seems to behave better, since the maximum error is halved with respect to the traditional stereo method, being of about 5% instead of 10% of the overall linear extension of the investigated area.

Finally the UCAT's techniques provide generally reasonable results in comparison to traditional mechanical instruments.

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