Experimental study of the erosion in a sand bed caused by wakes behind tidal energy extraction devices

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Abstract – This work deals with an experimental fluid dynamic study of wakes generated by submerged sails used in devices of tidal energy extraction. The main aim is to study the environmental effect that these wakes could have in the sediment re-suspension from a sandy bottom located at a given distance from the sail. To that end, a 2 cm chord sail, consisting of a rectangular flat plate, is located in the center of a sediment channel of 64 mm width, whose bottom has been filled with sand of 0.3 mm mean diameter. We have characterized the effect of the sail on a sandy bottom for different angles of attack between the sail and the uniform stream flowing through the channel and different distances from the sail to the bottom for a given Reynolds number.

1. Introduction

Interest in renewable energy has increased continually over the last decades. Energy extraction using tidal current energy devices offers a sustainable alternative to conventional sources and a predictable alternative to other renewable energy technologies [1].

The airfoils and sails used in some devices to extract energy from tidal river and currents affect the marine and fluvial environments causing re-suspension of bottom sediments. Accordingly, it is important to take into consideration their potential impact on the surrounding marine and coastal environments once they are being used as a tidal energy capture device. In addition, there are many other marine and fluvial engineering devices that can also produce severe erosion on the sand bed, such as the wakes from maneuvering ship's propeller [2], and, even, on rock masses, such as the erosion phenomena downstream of spillways in large dams [3].

In this work we present an experimental fluid dynamic study of the erosion on a sand bed, and the characterization of corresponding scour, generated by wakes behind sails typically used in devices of tidal energy extraction. To that end, we have used a sediment channel where we are able to characterize the effect of the presence of a sail on a sandy bottom for different angles of attack between the sail and the uniform stream flowing through the channel, and for different distances from the sail to the bottom.

A number of different techniques are available for measuring sediment scours. Some of the current available techniques to reconstruct the scour real magnitude are, for instance, stereo photography, infrared beam, ultrasonic, depth profilers, laser 3D-scanning devices, …. (see [4] and [5], among others).

As it has been said previously, the main aim of this work is to study the environmental effect that wakes behind sails could have in the sediment re-suspension from a sandy bottom located at a given distance below the sail. To that end, a 2 cm chord sail, consisting of a rectangular flat plate, is located in the center of the channel of 64 mm width, whose bottom has been filled with sand of 0.3 mm mean diameter. For quantitative measurement of the scour pattern created on the sand bed, once it becomes steady, a digital camera, mounted on a side of the channel, is used to take photos of the scour illuminated by a laser sheet. These images are later digitally processed to get from them the dimensional profile of the scour. Its illumination was carried out by means of a 40 mW green laser with a wavelength of 532 nm. Similar techniques to the one used here have been previously used in [6], to characterize aeolian sand ripples, or in [5], to measure the scour created by impinging swirling jets.

The analysis of the scour properties for different values of the parameter under consideration are used to evaluate the environmental impact caused by the presence of the above mentioned devices.

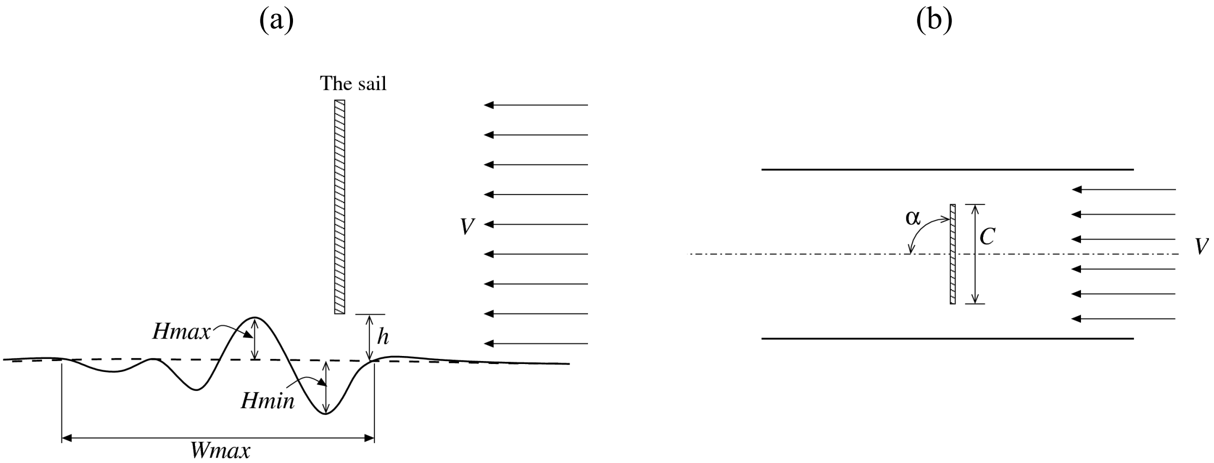


Figure 1. Sketch of the experiment. (a) Side view: the dash line is the unperturbed sandy bottom and the solid line the profile of the scour after the erosion with its main properties indicated. (b) Top view: the angle of attack and the chord are indicated. *V* is the mean velocity of the flow.

2. Experimental setup

The experiments have been carried out in a sediment channel where the sail is located at a known distance *h* above the sand (see Figure 1 with an sketch of the experiment). The measurement of the erosion on the sandy bottom around the sail is done by means of a Z-laser (with a wavelength λ=532 nm) used to illuminate the scour profile. The illuminated profile is then captured by a digital camera placed on the side of the sediment channel and, finally, the image taken is digitally processed to get the dimensions of the created scour. Figure 2 shows the different instruments and devices of the experimental setup and whose principal characteristics are described below. A sketch of the experimental setup is depicted in Figure 2 with a description of its different elements in Table 1.

Figure 2: Photograph of the experimental setup.

2.1 Sediment channel

It consists in a channel of rectangular section (64 mm x 2.5 m) with transparent walls, made by folded transparent pieces of methacrylate, and assembled on two supports, with a system to control the inclination of the channel (which is used to set the channel horizontally). Its different elements can be seen if Figure 3 and described in Table 1. The flow rate through the channel can be selected by means of a valve placed in the Basic Hydraulic Feed System (FME00/B).

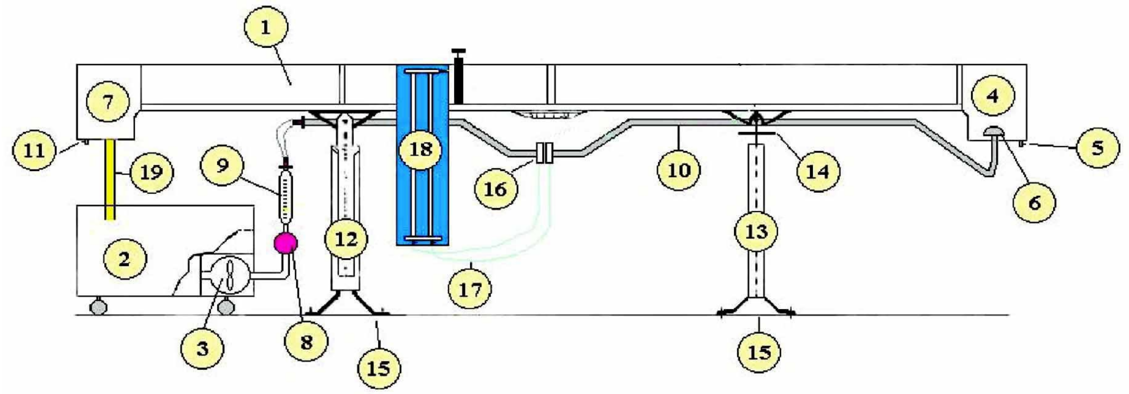


Figure 3: Sketch of Sediment channel.

Element #	Description
1	Channel of rectangular section with transparent walls.
2	Storage tank.
3	Impulsion pump.
4	Input storage.
5	Flush valve.

6	Reassuring input flow.
7	Catch basin.
8	Flow control valve.
9	Flowmeter.
10	Tubing.
11	Flush valve.
12	Support.
13	Support.
14	Wheel to control the inclination of the channel.
15	Ground anchorages.
16	Orifice plate flowmeter.
17	Connecting tubes between the orifice plate and manometer tubes Panel.
18	Manometric tubes panel and hand pump.
19	Discharge pipe to the storage tank.

Table 1. Description of the elements of the setup.

2.2 The sail

The sail used was a flat plate with a 2 cm chord and a rotation angle between 0º to 360º (see Figure 4).

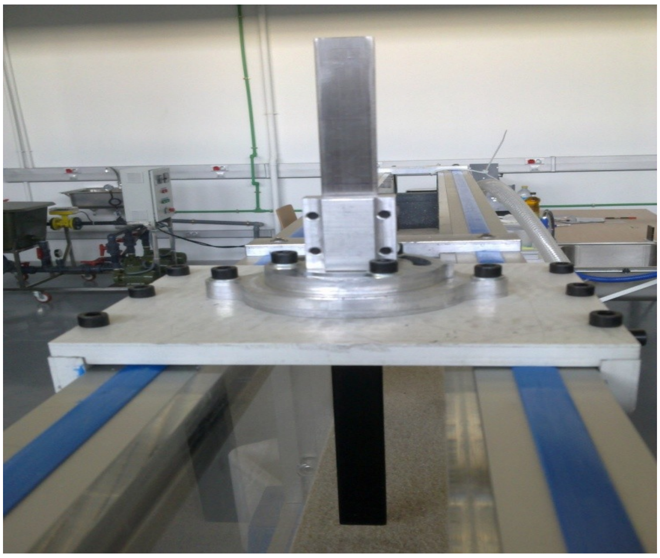


Figure 4: The sail (in black) and its support at the top of the channel of sediment.

2.3 Z-laser

For the visualization of the erosion around the sail, a Z-laser was used with the following characteristics:

- Output power: 40 m W;
- Wavelength: 532 nm; and

- Dimensions: Ø 40 x 280 mm (11 in).

2.4 The camera

To take the photos of the illuminated scour, a camera was used with the following characteristics:

- Video camera Sony Handycam 60 GB, Model: DCR-SR37E;
- Video signal: PAL color, Specification 1.080/50i,
- Hard Disk: 60 G bytes; and
- Images per second: 25.

3. Quantitative measurements of the scour in a sandy bottom

The experimental procedure consists of several steps which can be summarized as follows:

1. An image of a target (containing an array of white concave points) inside the sediment channel with the water at rest is taken by the camera;
2. After that, the target is removed, and the sail is put in the channel at a distance *h* above the sand bed and with an angle of attack α with respect to the water flow (see Figure 1);
3. Then, the pump is started and a flow rate *Q* is selected. It works until the scour is created in the sand bed;
4. Next and once the sand bed is stabilized, the pump is switched off, the sail removed and a new picture of the scour illuminated by the laser sheet is taken; and
5. Finally, the image processing is carried out and the real magnitude of the scour is obtained.

The target contains an array of white concave points with a distance between centers of 2.5 mm. Since the real dimensions of the target and the distance between points are known, the distorted image taken in #1 (due to refraction and the misalignment between the camera and the laser sheet) will be used later to get the coefficients of a bilinear transformation between the original and distorted target (see Figure 5). Also, the ratio pixel/mm is obtained at this step. The transformation obtained will allow us to reconstruct the real magnitude not only of the target but also of the illuminated scour created. Figure 6 shows an example of the transformation once it is applied to the illuminated scour: (a) is the distorted image of the scour pattern, as captured by the camera, and (b) is the transformed image, corresponding to its actual shape. In this case h=1 mm, α=90º and Q=0.0014 m^3/s, which corresponds to a Reynolds number based on the sail chord of about 4500.

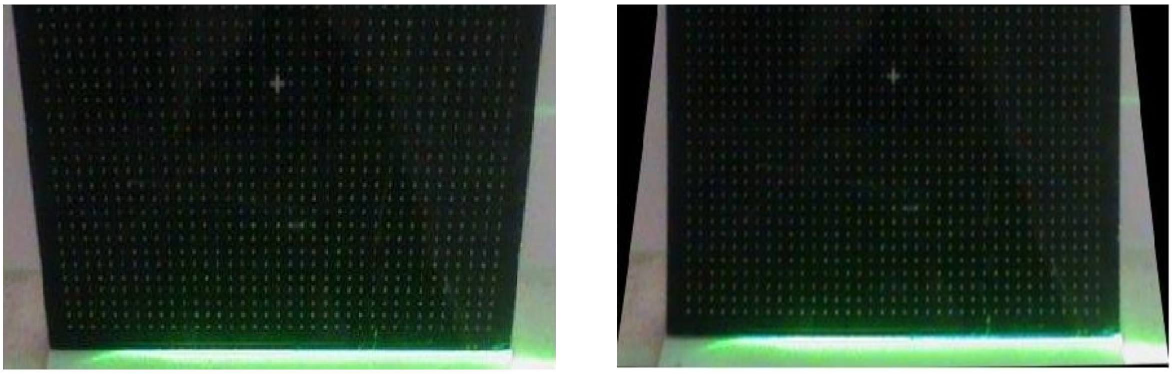
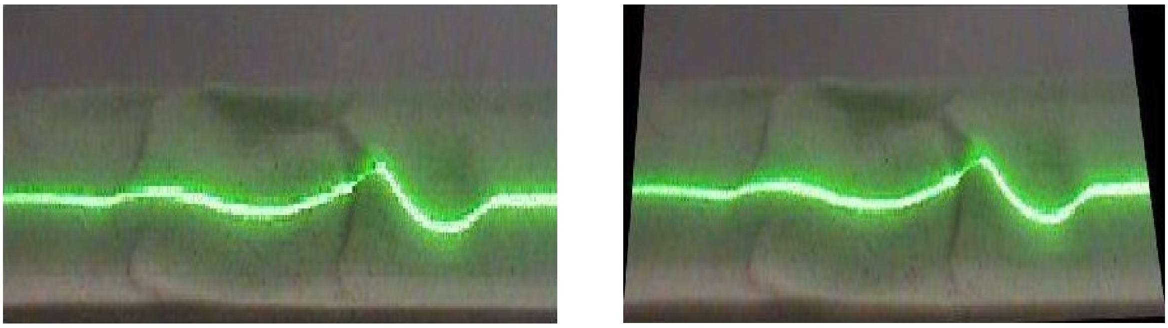


Figure 5: Image of the target before (left) and after (right) the transformation is carried out.



(a) (b)

Figure 6: Images of scour illuminated with laser sheet, (a) before, (b) after transformation resulting from calibration.

Once the scour profile is transformed to its real magnitude, a threshold segmentation technique is used to select only the illuminated pixels of the image and with the known ratio pixel/mm, the real dimensions of the scour can be obtained. This can be seen in Figure 7, where the scour dimensions are shown (in mm) after the image processing is carried out.

4. Results

As it has been discussed previously, the results presented here are those obtained after the illuminated images taken of the scour are digitally processed using Matlab. We have considered three angles of attacks (α=90º, 70º y 50º), four distances h from the sail to the bottom, h/C=0.05, 0.1, 0.15 y 0.2, where C is the sail chord, and a flow rate of 0.0014 m^3/s, being water the working fluid. From these values, and considering laboratory conditions, the Reynolds number based on the sail chord is of about 4500.

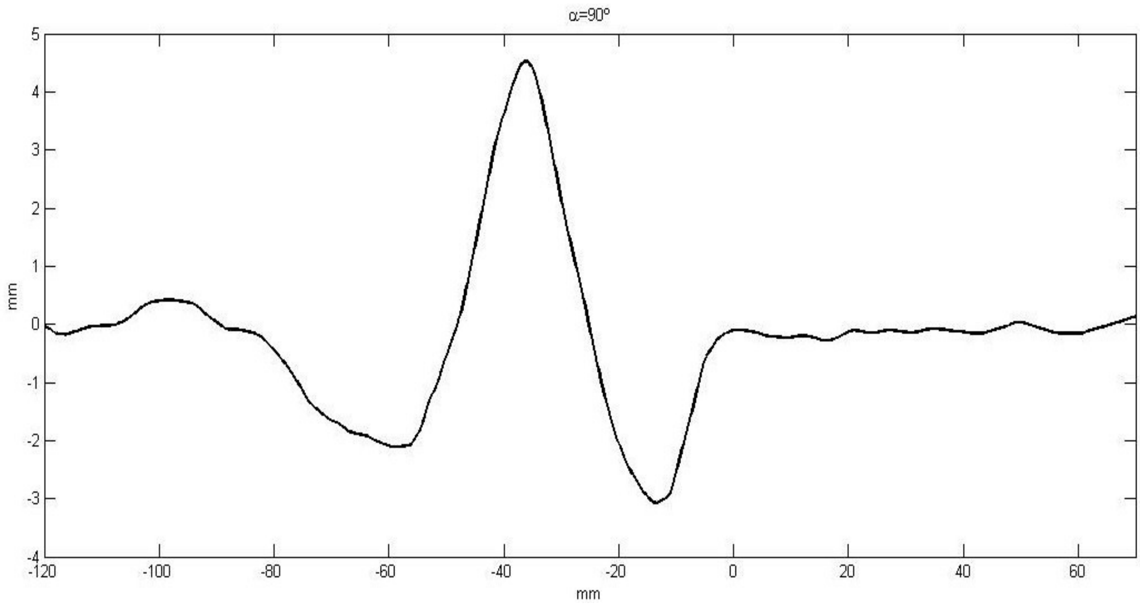


Figure 7: Dimensional digitalized profile of the scour. The flow is from right to left (*h*=1mm, α=90º and Re=4500).

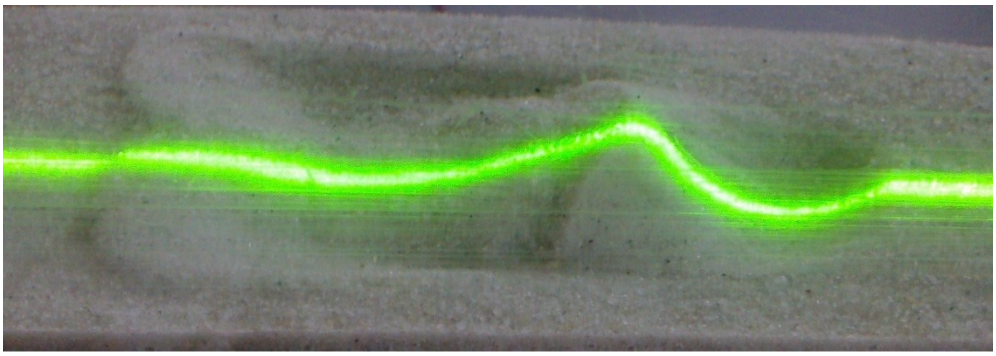


Figure 8: Image showing the scour with its central profile illuminated by the laser sheet along the middle of the channel for α=90ºand *h*/*C*=0.05.The flow is from right to left.

To compare all the results, we have fixed the laser sheet passing through the middle of the channel for all experiments, as shown in Figure 8, where the illuminated scour created when α=90º and *h*/*C*=0.05 is shown. This image can help us to understand the process: taking into account that the flow is from right to left, with the sail located just above the first minimum in the sand bed, the fluid flows around the sail being the flow under the sail the responsible of making the first and pronounced "crater". Next, some of the eroded sediments are deposited just downstream the sail, giving place to a "hill", behind which the erosion continues until a certain distance downstream where the decaying wake is not able to suspend more sediments. It is also remarkable the erosion created at both sides of the scour pattern (where the scour is actually deeper than anywhere else). This is due to the couple of intense vortices emerging from the two lateral borders of the sail which, as can be seen in Figure 8 have high erosion capacity. Furthermore, as one can see for this case with α=90º, the pattern created is symmetrical with respect to the laser sheet or channel symmetry line (remember the laser is passing through the middle of both the sail and channel), a fact that will not happen with other angles of attack for which the scour seems to rotate with the sail losing its symmetry with respect to the channel, as it will be shown below.

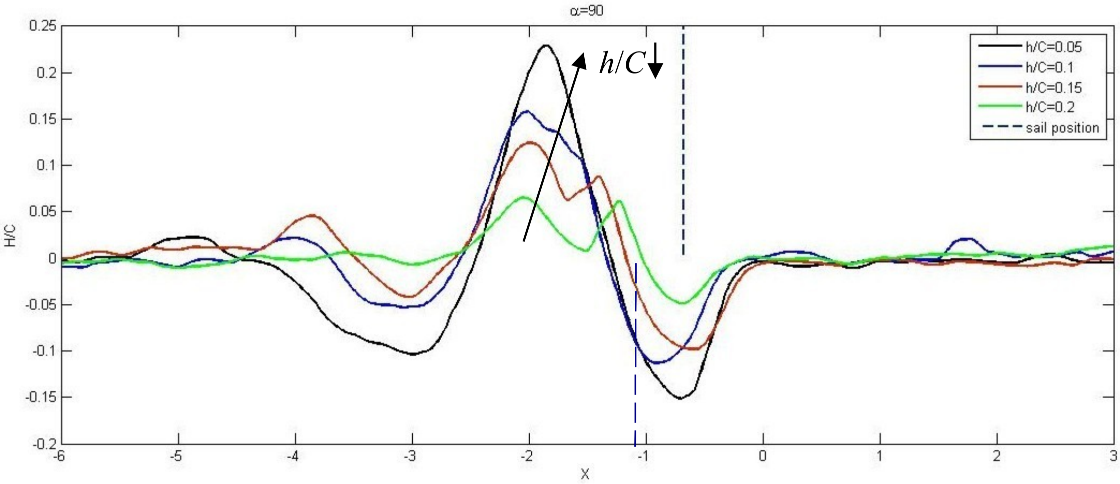


Figure 9: Non-dimensional profile of the scour for h/C=0.05, 0.1, 0.15 and 0.2 with an angle of attack α=90º. The x-axis has also been made non-dimensional with the sail chord C. The flow is from right to left. The vertical dash line corresponds to the position of the sail.

We report in what follows the non-dimensional scour profiles, as well as their most relevant features, once the images have been digitally processed.

Figures 9, 10 and 11 show the non-dimensional profiles of the scour H/C for different distances h/C between the sail and the bottom, and the three angles of attack, α=90º, 70º and 50º, respectively. Some preliminary conclusions can be drawn from their analysis: On the one hand, one can observe that the scours generated when the angle is 90º are much deeper and wider than scours generated with lower angles; that is, the higher the angle of attack, the deeper and wider the scour created. And, on the other hand, as the distance to the bed decreases both the depth and width of the scour on the sand bed increase; that is, the lower the distance from the sail to the bed, the deeper and wider the scour created. It must be remarked that these profiles are obtained along the middle of the channel, and only when α=90º they coincide with the symmetry line of the scour.

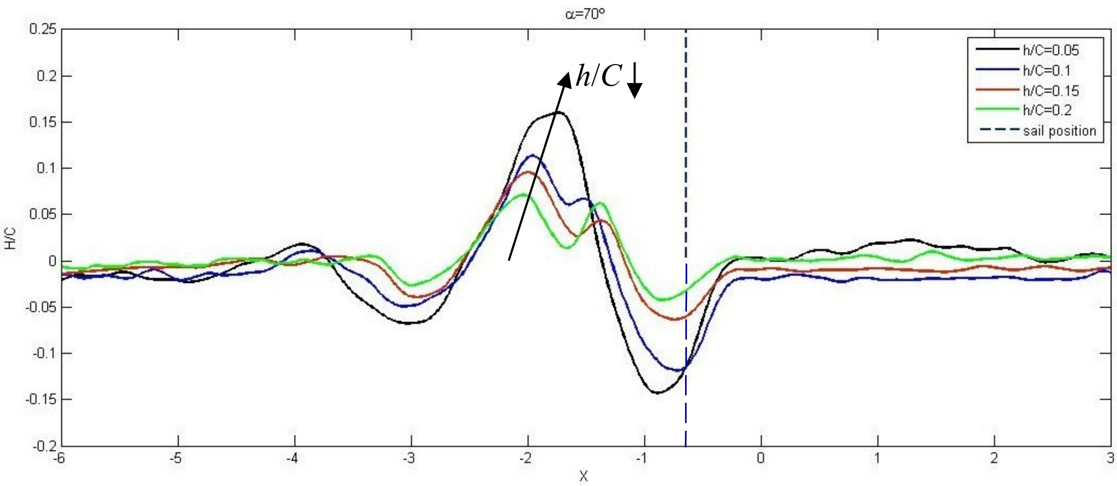


Figure 10: As in Figure 9, but for α=70º.

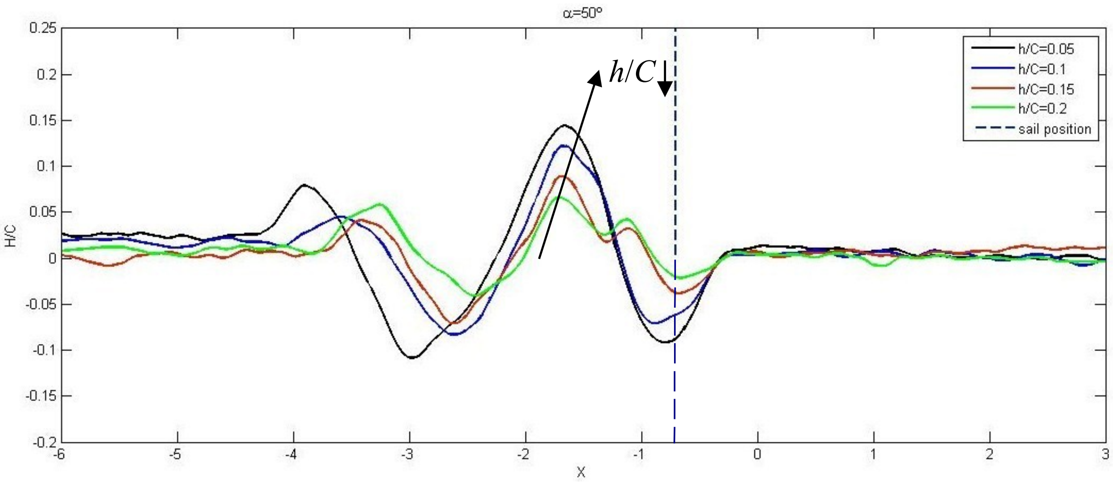


Figure 11: As in Figure 9, but for α=50º.

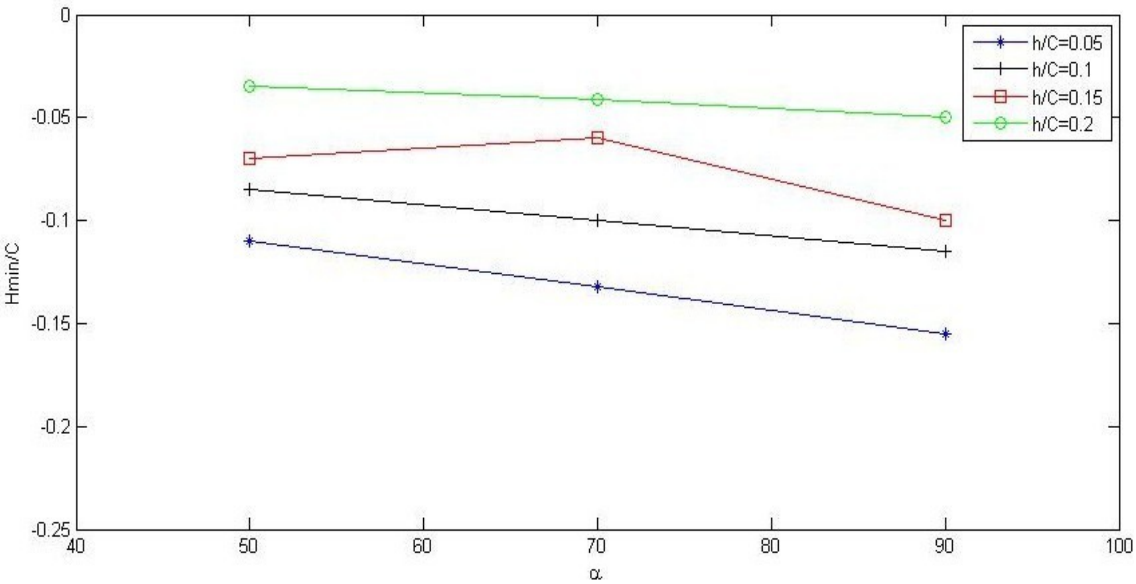


Figure 12: *Hmin*/*C* versus the angle of attack α for the values of *h*/*C* indicated.

When the angles of attack are α=90º (Figure 9) and 70º (Figure 10), the maximum depth along the middle of the channel is directly below the sail; i.e., it coincides with the first minimum of the measured profiles. However, when α=50º, the maximum depth is located downstream the sail and it coincides with the second minimum of the profile. This is due to the rotation of the sail having as a result a change in the main direction along which the scour develops. This direction seems to be almost perpendicular to the sail, which means that the second minimum observed in Figure 11 is due to the lateral vortices generated by the sail, responsible of the highest erosion and deepest scour in the middle of the channel (deeper than the erosion just under the sail).

To characterize the different profiles of the scours, three parameters have been used (see Figure 1): the maximum depth of the scour (*Hmin*); the maximum height of the elevation due to the re-deposition of sediments (*Hmax*); and the maximum width of the scour (*Wmax*). All these magnitudes can be extracted from Figures 9-11, and they are summarized in Figures 12, 13 and 14, where their non-dimensional evolution are shown as a function of the angle of attack and for the different distances *h*/*C* used. It is observed that all the mentioned parameters, *Hmin*, *Hmax*, and *Wmax*, increase (in absolute value) when the distance to the bed decreases and the angle of attack increases. As it was said previously, special care must be taken when the angle of attack is 50º, because in that case *Hmin* depicted in Figure 15 is not the absolute minimum for all values of *h*/*C*.

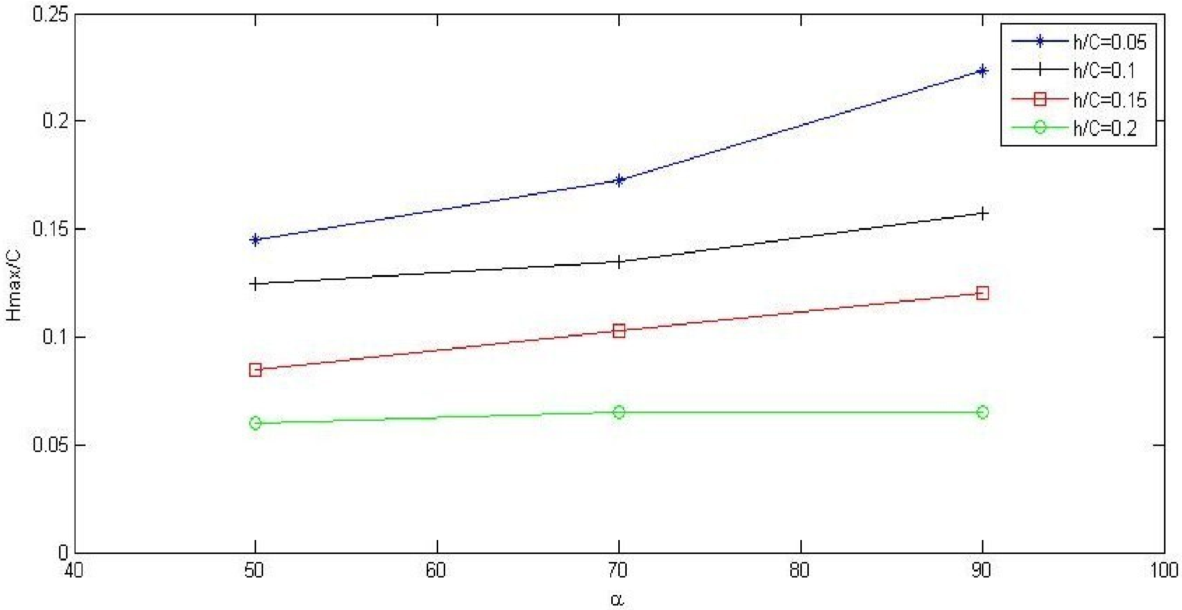


Figure 13: As in Figure 12 but for *Hmax*/*C*.

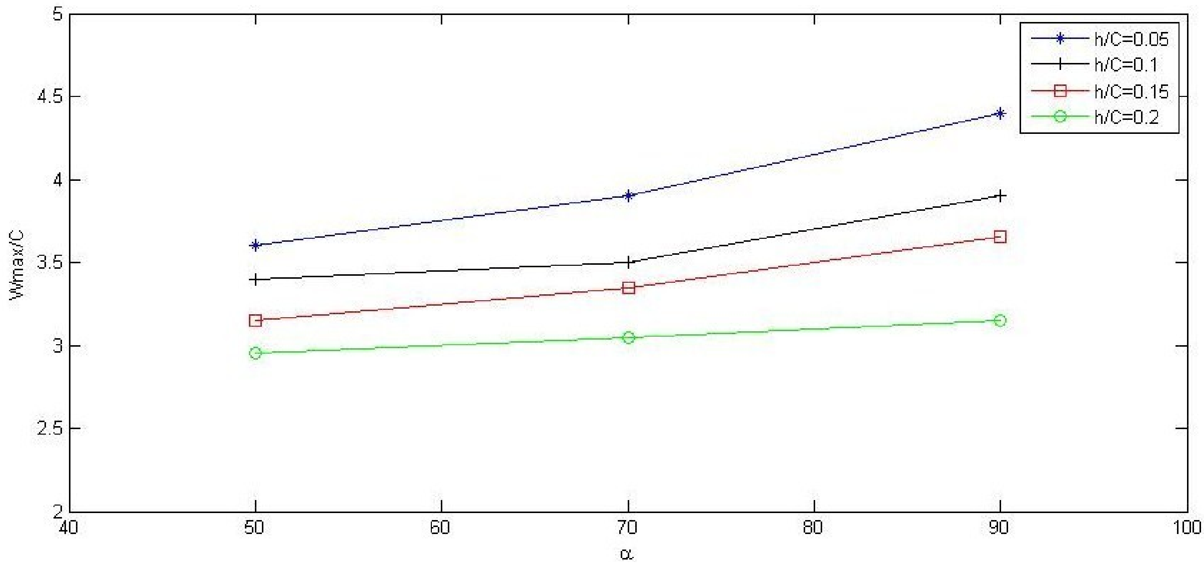


Figure 14: As in Figure 12 but for *Wmax*/*C*.

5. Conclusions

From an environmental point of view, it is obvious that the higher the distance between the sail and the bottom, the lesser the effect on the last one. However, sometimes due to either working conditions or physical limitations, the sail have to be as close to the sandy bottom as possible. It is then when its effect on the bottom can be important and the angle of attack crucial on the final erosion created. In that sense, the results obtained show that, along the middle of the channel, the higher the angle of attack, the deeper and wider the scour on the sand bed. Nevertheless, this affirmation could be different if the whole pattern were analyzed since, in that case, the erosion due to the interaction between the leading/trailing end vortices and the sand bed could be the highest on the bottom. To answer this question, a 3D map of the scour must be obtained, being this task the authors' future work.

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