Formation of bedforms on a beach profile

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ABSTRACT: Well controlled experiments on bedforms generation on a beach profile have been carried out in a wave flume. The hydrodynamic and sedimentary conditions which have been chosen induce intermediate or reflective beaches, according to Masserlink & Short (1993). An optical technique is used to obtain the morphology of the bed; bedforms such as ripples or bars are accurately captured with this method. The free surface is measured with resistive probes. The tests are performed long enough to get bedforms at the equilibrium state. Present results show that only the Dean number cannot completely depict the beach profiles when there is no tide. A strong interaction between the bedforms and the free surface is displayed.

1 INTRODUCTION

Various forms of beach profile may be found on the earth surface according to the local hydrodynamic and sedimentologic conditions. Masselink & Short (1993) proposed a classification of beach profiles based on the values of the dimensionless fall velocity (Dean number):

$$\Omega = \frac{H_b}{W_s \times T} \quad (1)$$

and of the relative tide range:

$$RTR = TR / H_b \quad (2)$$

where H_b is the breaking wave height, W_s the sediment fall velocity, T the wave period and TR the tide range.This classification exhibits different types of beach profiles; some are characterized by steep slopes (reflective beaches), other by gentle slopes (dissipative beaches) or by pronounced bars. Small scale bedforms known as ripples may be observed on parts of the profiles. However, the physical processes governing the beach profiles are still not well understood. Moreover, the beach profiles are not permanent ; they change according to the wave conditions and the seasons. An equilibrium profile corresponds to a balance between destructive and constructive forces. In nature, it is possible to obtain mean equilibrium profiles by averaging the profiles over a long period. The elevation of the sea level and the increase of the storms frequency which are expected within the framework of the climate change will have significant consequences for the beach profiles. These profiles play an important part in the littoral protection. The sandy bars strongly affect the energy dissipation and the reflection of the incident waves. The existence conditions and the position of these bars are nevertheless poorly known. The aim of the present work is to bring a contribution to the study of the physical processes governing the formation of bed forms on a beach profile from well controlled tests carried out in a wave flume.

2 EXPERIMENTAL SET UP

The experiments were carried out in a wave flume at LOMC (Laboratoire d'Ondes et Milieux Complexes) laboratory, University of Le Havre. This flume has a 10m long, 0.5m high and 0.5m wide section. Regular waves are generated by a piston-type wavemaker. The tested beaches are entirely made of natural sand of median size D_{50}=163µm, and of density s=2.65. At the beginning of every test the beach profile is plane and 5 m long with an initial beach slope of 6%.

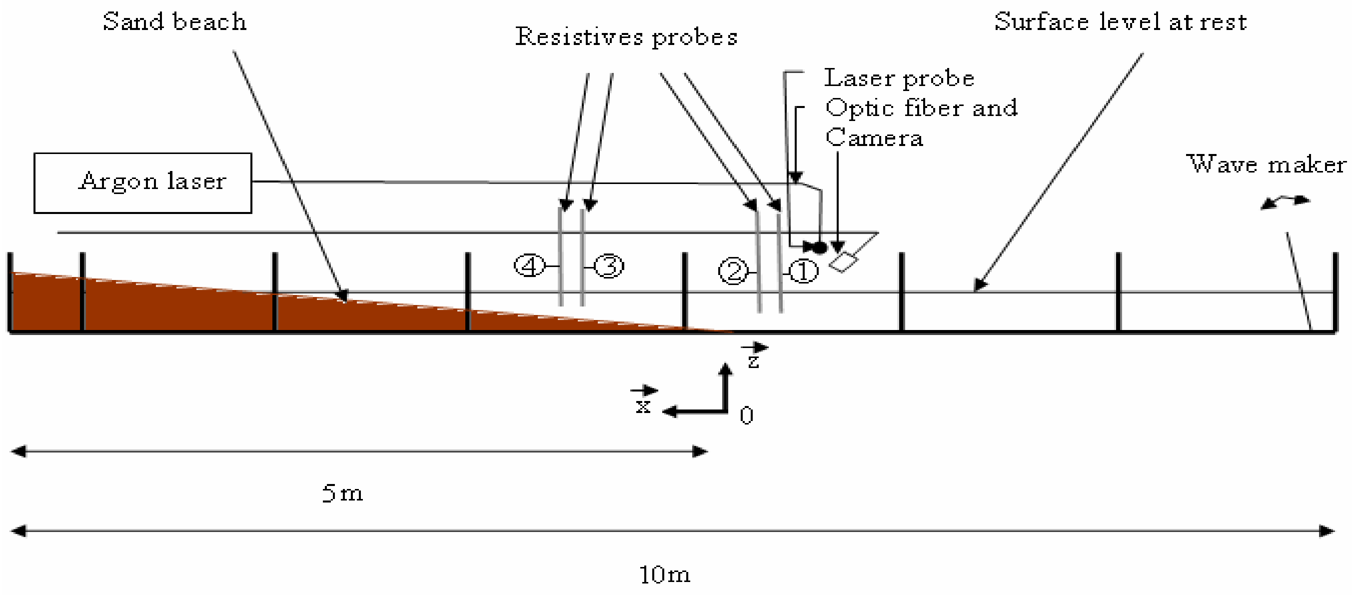

Figure 1. Side view of the flume.

The bathymetry of the beach profile is obtained with an optical method developed by Marin & Ezersky (2007). A pencil camera is immersed under the free surface. It is located sufficiently far from the bed not to disturb the sandy layer. This camera records the trace let by a laser sheet on the bed perpendicularly to the wave propagation. The optical system used to generate this laser sheet and the camera is mounted on a mobile carriage. The displacement of the carriage along the beach allows the video recording of the morphology of the whole profile at a fixed time.

In order to keep the camera immersed during the beach profile capture, the channel is filled up before each bathymetry acquisition. The spatial resolution is 1 mm/pixel in the horizontal and vertical directions.

The free surface elevation is measured with four resistance type wave gauges (Figure 1). Two of them give the characteristics of the incident waves. The two other resistive probes are located in two different sections in the surf zone above the beach profile in order to follow the temporal evolution of the water height.

The control parameters used for this study are the dimensionless fall velocity parameter or Dean number Ω and the Ursell number U_R. The sediment fall velocity is calculated according to the Soulsby formula (1997).

$$W_s = \frac{\nu}{D_{50}} \times ((10.36^2 + 1.049 D_*^3)^{1/2} - 10.36) \qquad (3)$$

where $D_* = [\frac{g \times (s-1)}{\nu^2}]^{1/3} \times D_{50}$ (4)

is the sedimentologic diameter. In this expression, ν is the kinematic viscosity of the water and g the acceleration due to gravity.

The Ursell number is given by:

$$U_R = \frac{gHT^2}{d^2} \qquad (5)$$

where d is the mean water depth.

Taking into account the geometry of the channel, our spatial scale is fixed to 1/100. The average duration of each test is very long in order to reach the bedforms at the equilibrium state.

A typical duration is 40 hours, that is about 400 hours (between 2 and 3 weeks) for real conditions.

The mean water depth is d=0.21m. Our study has been performed under regular waves without tidal effects. The test conditions of the present preliminary tests are given in Table 1.

Table 1. The experimental conditions.

Test number	T (s)	H_b (cm)	Ω	Ur
1	1.1	6.6	3.5	13.9
2	0.9	5.4	3.5	6.3
3	1.2	7.2	3.5	17.9
4	1.3	5.6	2.5	17.2
5	0.9	7.9	4.7	8.2
6	1.3	4.0	1.8	10.6

3 TEMPORAL EVOLUTION OF BEACH PROFILES

In order to obtain a quasi equilibrium state of the beach, the excitation duration is of course long compared to the wave period. Different criteria may be used to estimate the beach equilibrium state. Two different evaluations have been done. First, we consider that a beach has reached an equilibrium state when the mean beach profile velocity V_f tends towards a fixed low value. The V_f velocity is a quadratic velocity defined by:

$$V_f = \left(\frac{1}{L} \int_0^L \left(\frac{\partial Z}{\partial t}\right)^2 dx \right)^{1/2} \qquad (6)$$

where L is the beach length, t is the time, and x and z are the distances measured in the horizontal and vertical directions, respectively. Experimentally, V_f is estimated from consecutive acquired profiles. The excitation duration between consecutive morphological acquisitions varies during a test. It is short at the beginning of the test (8 mm) when the profile undergoes rapid changes and is fixed to 5 hours when the profile evolution becomes more stable. Then, the V_f velocity gives an overall estimation of changes in beach profile during a test.

Another estimation of beach profile evolution with time can be done calculating two distinct velocities which are an accretion velocity V_{i1} and an erosion velocity V_{i2} defined by :

$$V_{i1} = \left(\frac{2}{L} \int_0^{L/2} \left(\frac{\partial Z}{\partial t}\right) dx \right)^{1/2} \qquad (7)$$

$$V_{i2} = \left(\frac{2}{L} \int_{L/2}^{L} \left(\frac{\partial Z}{\partial t}\right) dx \right)^{1/2} \qquad (8)$$

The accretion and erosion of the beach profile can be analyzed in a global way and the equilibrium state can be defined by low values of these two velocities.

On the following Figure 2, we have plotted the mean quadratic velocity V_f as a function of time for different tests.

The velocity V_f decreases rapidly during the five first hours then slowly until V_f reaches a velocity close to 2 mm/hour. This value can be considered as close to zero and the equilibrium beach profile can be estimated exactly from bathymetry acquisitions at 35-40 hours.

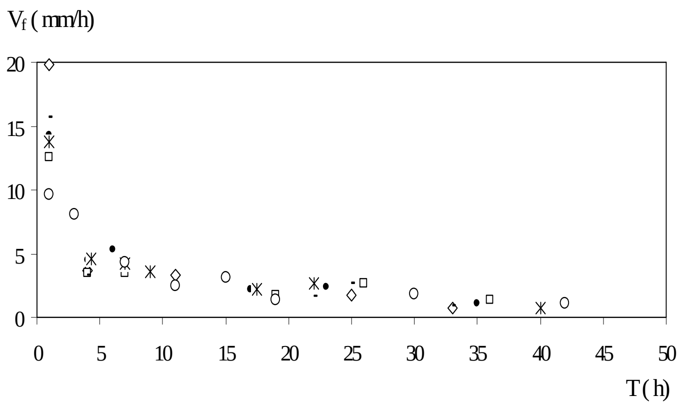

Figure 2. Temporal evolution of the velocity V_f for the following couples (Ω ; Ur) values.

An example of the time evolution of the accretion and erosion velocities for a given test defined by (Ω ; Ur)=(3.5 ; 13.9) is displayed on Figure 3. It can be noticed that these two velocities can evolve differently but they both reach a low value for long times.

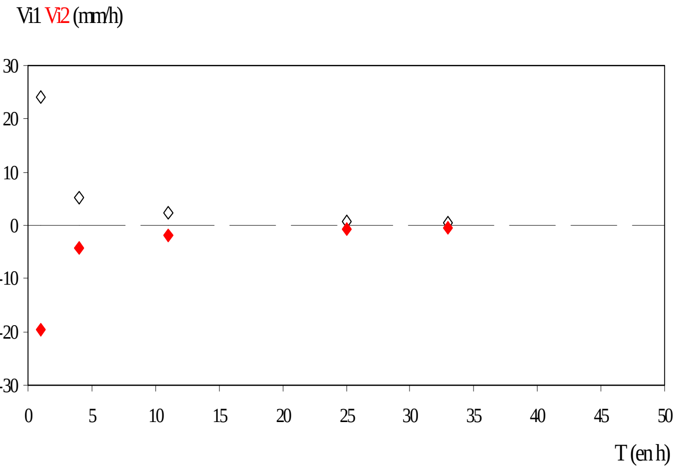

Figure 3. Evolution of the velocities V_{i1} and V_{i2} for Ω =3.5 and Ur = 13.9.

◇ Vi1 ◆ Vi2

The beach profile is shown respectively at t=29 min and t=120min for test 1 on Figures 4a and 4b. Significant changes in the beach shape appear very quickly after waves action. In particular erosion zone appears clearly in the upper part of the beach, and an accretion zone in the lower part. The beach shape at the equilibrium state is shown on Figures 7a for this test.

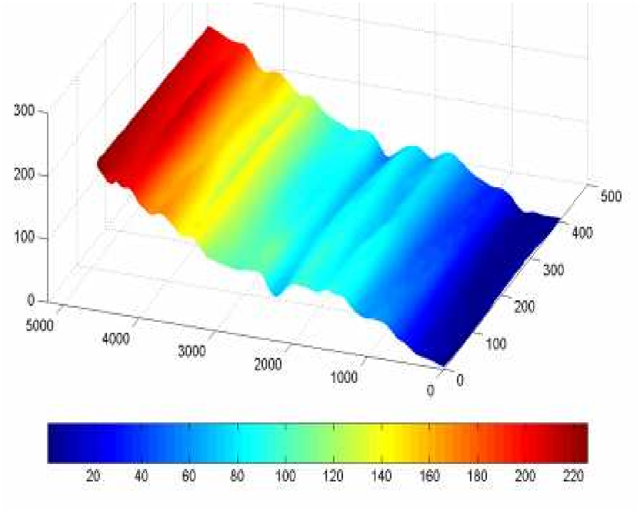

Figure 4a. The beach profile in 3D for Ω =3.5 and Ur = 13.9 at t=29 min.

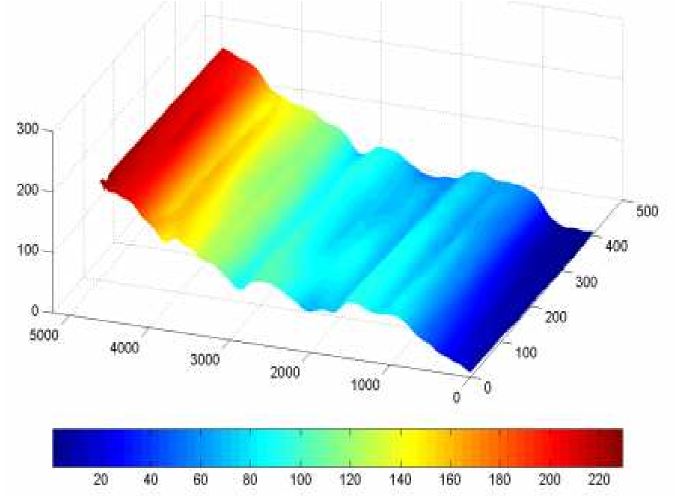

Figure 4b. The beach profile in 3D for Ω =3.5 and Ur = 13.9 at t=120 min.

On Figure 5 is represented the mean beach profile obtained by averaging beach profiles across the width of the channel with the central profile at the equilibrium state for Ω = 3.5. We can observe that the two profiles exhibit minor differences.

This means that, at the beach profile scale, three-dimensional effects do not influence noticeably the mean beach profile. We can also observe the presence of several spatial variations or "bars", and a beach shape in the form of a terrace.

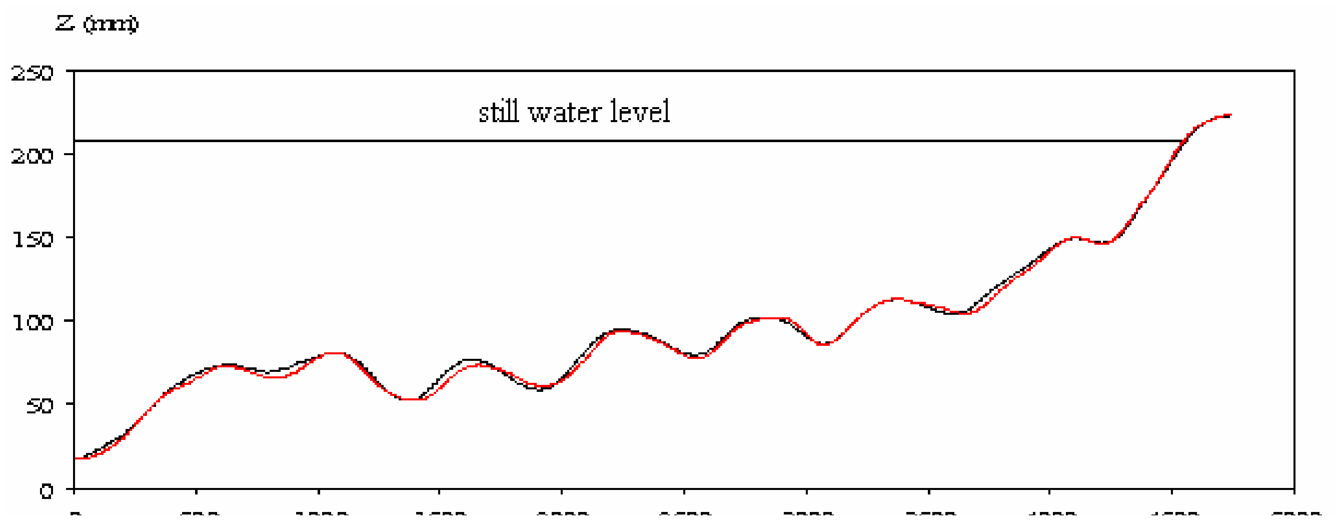

Figure 5. The mean beach profile (in black) and the beach central profile (in red) for Ω = 3.5 and Ur =13.9.

4 THE BEDFORMS AT THE EQUILIBRIUM STATE

The values of Ω have been varied from 1.8 to 4.7 for present tests. The Figure 6 shows the beach profile at the equilibrium state for $\Omega = 1.8$ and Ur=10.6.

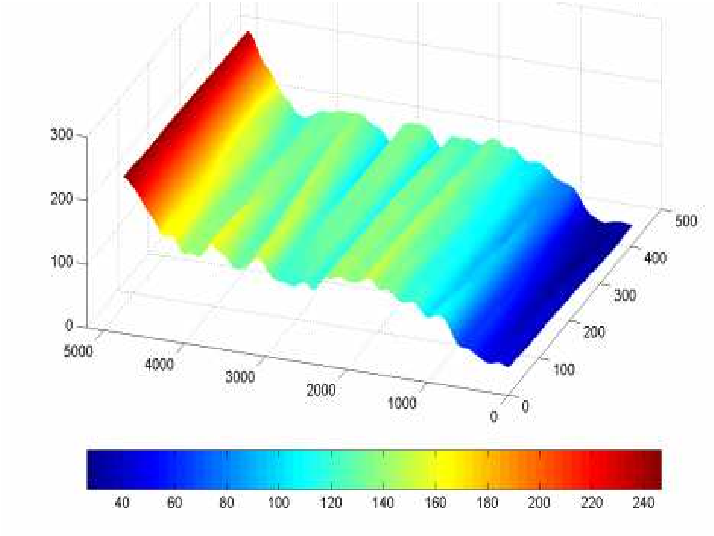

Figure 6. The beach profile in 3D at the equilibrium state for $\Omega = 1.8$ and Ur =10.6.

Following Wright & Short (1993), the beach is reflective for this test since $\Omega < 2$, with a pronounced coarse step at the base of the swash zone, a small terrace, and a more gentle slope in the low part of the beach. This is in agreement with the beach profile obtained in our wave flume.

Tests have also been carried out with a same Dean number, but with different hydrodynamic conditions, changing the wave height and period. Figures 7a and 7b depict the beach profiles obtained at the equilibrium state for $\Omega = 3.5$, for $U_R = 13.9$ and 6.3, respectively.

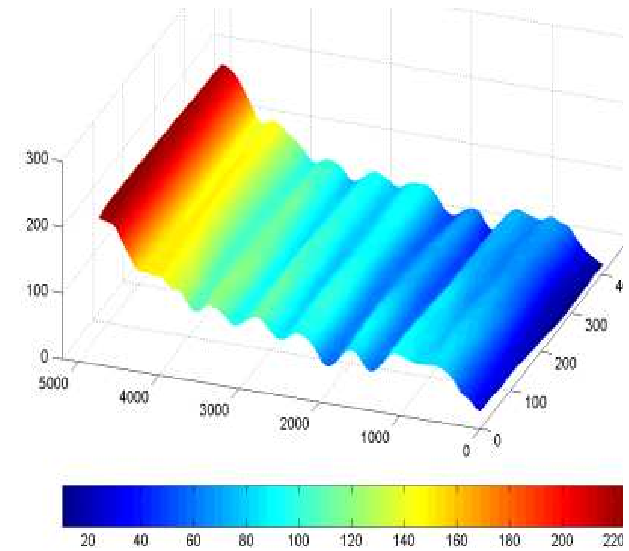

Figure 7a. The beach profile in 3D at the equilibrium state for $\Omega = 3.5$ and Ur = 13.9.

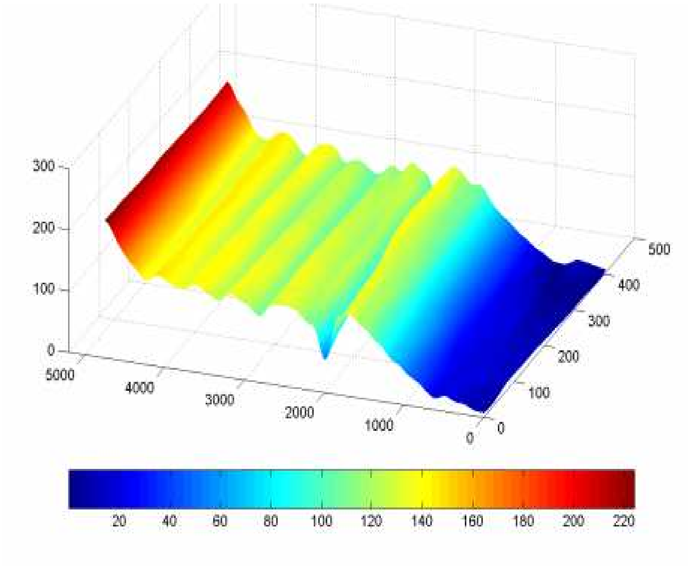

Figure 7b. The beach profile in 3D at the equilibrium state for $\Omega = 3.5$ and Ur = 6.3.

It was observed during the tests that offshore transport increases with the wave period. Furthermore, the equilibrium profiles plotted on Figures 6a & 6b exhibit large differences. Although the two tests were performed with a fixed Dean number, we can see that we don't have the same number of bars generated and that the mean shape of the lower part of the beach differ significantly. This clearly shows that only the Dean number used as a control parameter cannot completely depict the beach profile at the equilibrium state when there is no tidal range.

We observe nevertheless an alternation of bars and channels of evacuation between bars. The existence of a main bar (the first one from the bottom of the beach) is directly linked to the surf zone. The backwash can become important and transports the sediment in the offshore direction. An accumulation of sediment at the breaking point appears. During the offshore transport, this point is displaced generating a movement of the bar or the creation of others bars.

In particular, the plunging breaking waves create vortex having an erosive action on the bottom. Then, a pit is generated and the transport towards offshore of materials is released. This phenomenon contributes to bar formation.

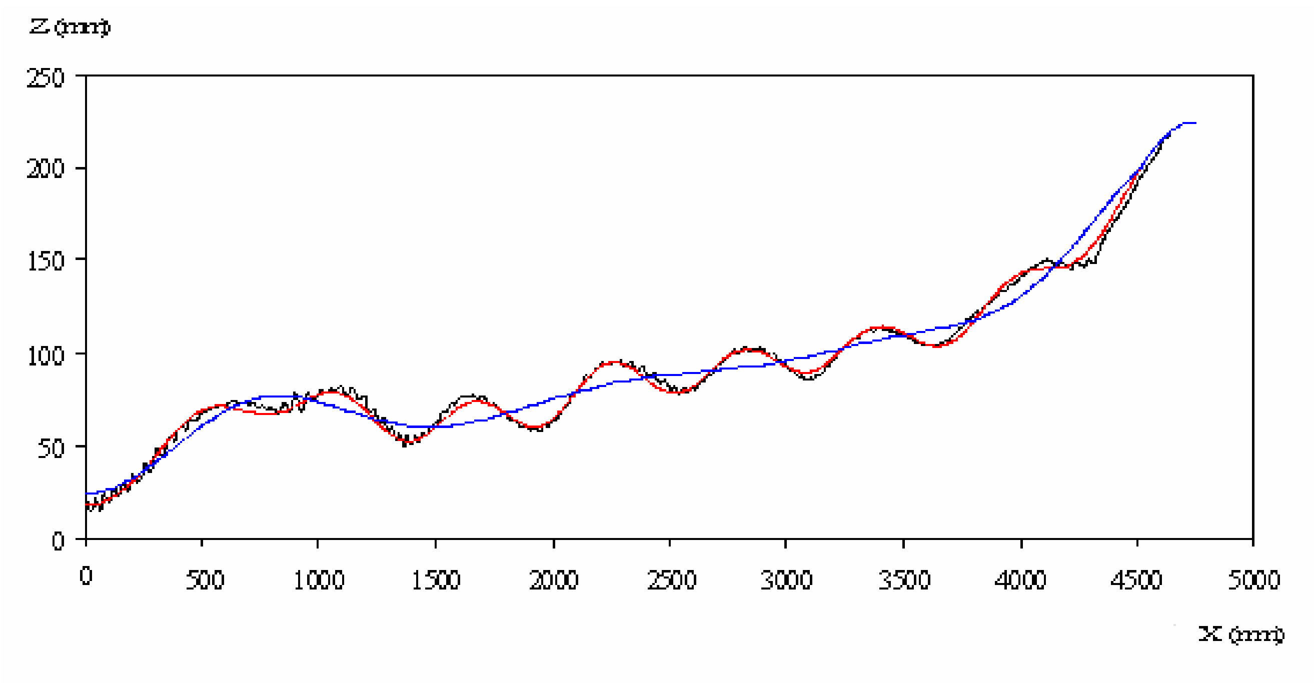

Figure 8. The mean beach profile with and without filtering for Ω =3.5 and Ur = 13.9.
——— no frequency filter ——— ripples filtering ——— ripples and bars filtering

The fine resolution of the experimental technique of bathymetry acquisition makes possible the separation of the three spatial frequency scales present in the beach profile. We can identify the ripples at a small length scale, the bars at an intermediate scale and finally the average profile at the larger scale of the beach. An example of the effect of different frequency filters is presented on Figure 8. This type of treatment will be helpful to determine easily angles of the beach, ripple and bar lengths.

Figures 9a, 9b & 9c exhibit for different instants (t=0, t=19 hours and t=35 hours) the combination of the incident wave and reflected waves from the beach in the first test (Ω=3.5 and Ur=13.9), measured with the probe 1. The time t=0 refers to a first free surface acquisition conducted after a few minutes of waves excitation. We notice in the different spectra, the existence of a range of frequencies lower than the incident wave frequency. It indicates the influence of infragravity waves. Furthermore, Figure 8 shows that there is a strong interaction between the beach and the free surface with an increase of the energy associated to higher frequencies for long excitation periods.

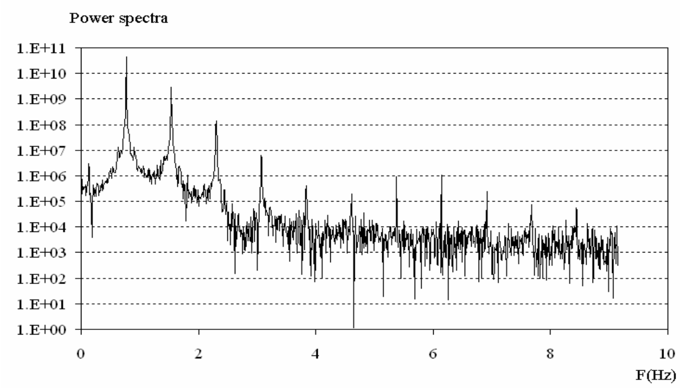

Figure 9a. Evolution with time of power spectra of the free surface for Ω =3.5 and Ur =13.9 at t=0 hour.

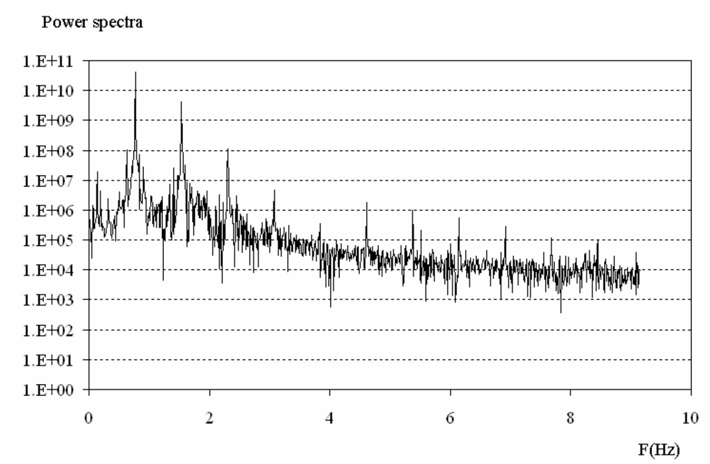

Figure 9b. Evolution with time of power spectra of the free surface for Ω =3.5 and Ur =13.9 at t=19 hours.

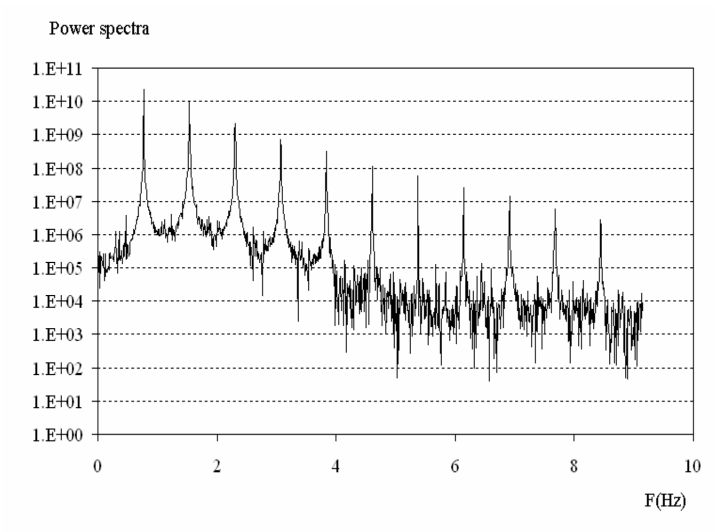

Figure 9c. Evolution with time of power spectra of the free surface for Ω =3.5 ; Ur =13.9 at t=35 hours.

4 CONCLUSION

Tests on bedforms generation on a beach profile have been carried out in a wave flume. An original optical method has been used to obtain the bed morphology, and the free surface was measured with resistive probes. The beach profile was initially flat with a 6/100 slope. The well controlled hydrodynamic conditions have been varied keeping a constant mean water level (no tide) to induce intermediate and reflective beaches according to Masserlink & Short (1993). The action of waves led to the formation of bedforms such as ripples and bars, and to a change of the mean beach profile until an equilibrium state is reached. The effect of the control parameters (Dean number, Ursell number) on the bedforms generation is discussed; it is shown in particular that it is not satisfactory to consider only the Dean number for an accurate description of the bedforms on a beach profile in the case of no tide. A strong interaction between the bedforms and the free surface is depicted.

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