THE LENGTH-SCALE OF DUNES IN FREE SURFACE FLOWS: MEASUREMENTS IN THE SAPUCAÍ RIVER

Ivan Felipe Silva dos Santos, ivanfelipedeice@hotmail.com
Instituto de Recursos Naturais – Universidade Federal de Itajubá

Erick de Moraes Franklin, erick@unifei.edu.br
Instituto de Engenharia Mecânica – Universidade Federal de Itajubá

Ana Paula Moni Silva, anamoni@unifei.edu.br
Instituto de Recursos Naturais – Universidade Federal de Itajubá

Abstract. *The transport of granular matter by a fluid flow is frequently found in nature and in industry. When the shear stresses exerted by the fluid flow on a granular bed are bounded to some limits, a mobile granular layer known as bed-load takes place in which the grains stay in contact with the fixed part of the granular bed. Under these conditions, an initially flat granular bed may be unstable, generating ripples and dunes, such as those observed in deserts, in rivers, but also in pipelines conveying sand. In nature, some examples affecting human activities are the aeolian and the aquatic dunes. The aquatic ripples and dunes observed on the bed of some rivers create a supplementary friction between the bed and the water, affecting the water depth and being related to flood problems. In cases where their size is comparable to the water depth, water flows can experiment strong depth variations, seriously affecting navigation. This paper presents an experimental study about dune formation in rivers. Field measurements were made in the Sapucaí river (Minas Gerais State, Brazil), and they are confronted in this paper to analytical theories. The bedforms and the water discharge rates were measured simultaneously with an ADCP (Acoustic Doppler Current Profiler) device, in different days and seasons, and the experimental results show the length-scale of the dunes on the river bed. The results are then compared to the wavelength predicted by some linear and nonlinear stability analyses of bed patterns in free surface flows.*

Keywords*: Turbulent flow, free surface, bed-load, instability, dunes*

1. INTRODUCTION

The transport of solid particles entrained by a fluid flow is frequently found in nature and in industry. It is present, for example, in the erosion of river banks, in the displacement of desert dunes and in hydrocarbon pipelines conveying sand. When shear stresses exerted by the fluid flow on the granular bed are able to move some grains, but are relatively small compared to the grains weight, the flow is not able to transport grains as a suspension. Instead, a mobile layer of grains known as bed-load takes place in which the grains stay in contact with the fixed part of the granular bed. The thickness of this mobile layer is a few grain diameters (Bagnold, 1941; Raudkivi, 1976).

An initially flat granular bed may become unstable and give rise to bedforms when submitted to a fluid flow. These forms, initially two-dimensional, may grow and generate patterns such as ripples or dunes. In nature, some examples affecting human activities are the aeolian and the aquatic dunes. The aquatic ripples and dunes observed on the bed of some rivers create a supplementary friction between the bed and the water, affecting the water depth and being related to flood problems. In cases where their size is comparable to the water depth, water flows can experiment strong depth variations, seriously affecting navigation (Engelund and Fredsoe, 1982). In industry, examples are mostly related to closed-conduit flows conveying grains, such as hydrocarbon pipelines conveying sand. In such cases, the bedforms generate supplementary pressure loss, but also pressure and flow rate transients (Kuru et al., 1995; Franklin, 2008).

The stability of a granular bed is given by the balance between local grains erosion and deposition. If there is erosion at the crests of the granular bed, the amplitude of initial bed undulations decreases and the bed is stable. On the contrary, the bed is unstable. If there is neither erosion nor deposition at the crests, there is neutral stability. The regions of erosion and deposition can be found from the mass conservation of grains. The mass conservation implies that there is erosion in regions where the gradient of the flow rate of grains is positive and deposition where it is negative, so that the phase lag between the flow rate of grains and the bedform is a stability criterion. If the maximum of the flow rate of grains is upstream a crest, there must be deposition at the crest and the bed is unstable, otherwise the bed is stable. To answer the stability question, the mechanisms creating a phase lag between the shape of the granular bed and the flow rate of grains need to be known.

In a recent article (Franklin, 2010a), the mechanisms of this instability were explained and a linear stability analysis was presented, in the specific case of granular beds sheared by turbulent boundary-layers of liquids, without free surface effects. It was seen that the basic mechanisms are three: the fluid flow perturbation by the shape of the bed, which is known to be the unstable mechanism (Jackson et al., 1975; Hunt et al., 1988; Weng et al., 1991), the relaxation effects related to the transport of grains and the gravity effects, which are the stable mechanisms (Valance and Langlois (2005) and Charru (2006) in the case of viscous flows, Franklin (2010a) in the case of turbulent flows). The linear stability analysis of Franklin (2010a) showed that the length-scale of the initial bedforms varies with the fluid flow conditions.

Franklin (2010b) presented a nonlinear stability analysis in the same scope of Franklin (2010a). The approach used was the weakly nonlinear analysis (Landau and Lifchitz, 1994; Schmid and Henningson, 2001; Drazin and Reid, 2004; Charru, 2007), useful whenever a dominant mode can be proved to exist. This means that the modes resonating with this dominant one will grow much faster than the others, which can be neglected. The analysis is then made on a bounded number of modes. Franklin (2010b) showed that after the initial exponential growth (linear phase), the granular bed instabilities saturate, i.e., they attenuate their growth rate and maintain the same wavelength.

In both articles, Franklin (2010a) and Franklin (2010b), the results of the analyses were compared to some experimental data concerning ripples in closed-conduit flows (which is a case where free surface effects are absent). In particular, the dependence of the bedform wavelength on the fluid flow conditions and the saturation of the bedform amplitude were confirmed by experimental results. Nevertheless, the analysis of Franklin (2010a) and Franklin (2010b) are not complete in order to describe the bed instabilities in cases where free surface effects are expected, such as the large wavelength bedforms (dunes) observed in river flows.

Franklin (2010c) presented a simplified analysis, based on Franklin (2010a) and Franklin (2010b), of the instabilities on a granular bed in the presence of free surface effects. The main purpose was to understand the size of ripples and dunes observed in nature. The analysis of Franklin (2010c) determines the asymptotic behavior of the wavelength and celerity of bedforms observed in free surface flows, such as the ripples and dunes observed in rivers and in open-channel flows.

This paper presents some experimental results of bedform morphology and water flow discharge, collected in the Sapucaí river. These measurements were performed with an ADCP (Acoustic Doppler Current Profiler) device, in different days and seasons. The experimental data is then confronted to theoretical results, in particular the asymptotic behavior predicted by Franklin (2010c).

The next section presents a summary of the asymptotic analysis of Franklin (2010c). The following section describes the experimental devices and procedures as well as the location where the field tests were performed. It is then followed by the experimental results and the conclusion sections.

2. RIPPLES AND DUNES IN RIVERS: ASYMPTOTIC BEHAVIOR

In Franklin (2010a) and Franklin (2010b), the effects related to the presence of a free surface were not considered. However, in many cases of practical and environmental interest, the presence of a free surface must be taken into account. One example is the presence of dunes in rivers whose depth is of the same order of the dune wavelength. In this case, free surface effects affect the fluid flow near the bed. It is known from measurements in the field that in such cases there are at least two characteristic wavelengths, one scaling with the grains diameter and with an inner layer close to the bed (but not with the flow depth, as they are too small), and another scaling with the fluid flow depth.

In the last decades, many stability analyses have been done in order to understand the wavelength and the celerity of dunes in rivers (Kennedy, 1963; Reynolds, 1964; Engelund, 1970; Richards, 1980; Engelund and Fredsoe, 1982; Coleman and Fenton, 2000). The great majority of these works found that the wavelength of the initial instabilities scales with the liquid depth, i.e., there would be a primary instability affected by free surface effects. This primary instability should be strong enough to allow the direct growth of bedforms whose length scales with the liquid depth.

Richards (1980) performed a linear stability analysis that showed the presence of two unstable modes: one scaling with the liquid depth (dune mode) and the other scaling with the grains diameter, but independent of the free surface (ripple mode). He proposed that both modes would emerge as a primary instability.

Recently, Fourrière et al. (2010) presented a linear stability analysis for bedforms in rivers, in turbulent regime. In their analysis, they found that the ripple mode (without free surface effects) has a growth rate many times greater than the dune mode (with free surface effects). Also, they found a wavelength range where the growth rate is strongly negative, corresponding to wavelengths in the order of magnitude of the liquid depth. They called this range “resonance region”. Any bedform in this wavelength range has a strong negative growth rate.

Fourrière et al. (2010) showed that the time scale for the growth of dunes as a primary linear instability is greater than that for the appearance of dunes by the coalescence of ripples (which have a much faster growth rate and evolution). As a consequence, dunes observed in rivers are the product of a secondary instability resulting from the coalescence of ripples. These dunes grow until reaching a length-scale in the resonance range, where their growth is stopped by free surface effects. In summary, they found that ripples appear as a primary linear instability that eventually saturates (but they do not prove the saturation), and that dunes appear as a secondary instability resulting from the coalescence of ripples (unstable mechanism) and the free surface effects in the resonance range (stable mechanism).

Franklin (2010c) was devoted to the understanding of the bedforms observed in fluid flows with a free surface, such as the flows in open-channels and rivers. We know from previous works that in such cases there are at least two characteristic wavelengths, one scaling with the grains diameter and with an inner layer close to the bed (ripple mode), and another scaling with the fluid flow depth (dune mode). The ripple mode isn’t affected by free surface effects, so that Franklin (2010c) proposes that the stability analyses made in Franklin (2010a) and Franklin (2010b) are valid for this case: we can predict the initial instabilities and saturation with the presented models. For the dune mode, Franklin (2010c) proposes that it is a secondary instability resulting from the competition of ripples coalescence and free surface effects.

With these considerations, Franklin (2010c) proposed that the dune mode is determined by a resonance mechanism between the bed and the free surface, so that the mathematical treatment to find the dune mode consists basically in combining the free surface effects with the models of Franklin (2010a) and Franklin (2010b). The reasoning employed by Franklin (2010c) was based on Fourrière et al. (2010): in free surface flows, as dunes grow by ripples coalescence, their length become comparable to the liquid depth. In the beginning, this affects the free surface in a subcritical regime and excites gravity waves in the free surface in anti-phase with the dunes (180^0 out-of-phase). If they keep growing, they would eventually reach a supercritical regime, for which the excited surface waves are in phase with the dunes (0^0 out-of-phase). But the dunes have their growth rate stopped in a region close to the transition from subcritical to supercritical: in this region, the excited surface waves are out-of-phase by nearly 90^0 lagging the dunes, resulting in erosion in the crests. This region, called "resonance region" by Fourrière et al. (2010), dictates the characteristic length of dunes.

Franklin (2010c) employed a very simple approach to model the free surface effects, in order to obtain the scales of length and celerity of the dune mode. This approach consisted in approximating the fluid flow far from the bed as a potential flow. With this approximation the behavior of the free surface may be estimated by applying the mass conservation and the Bernoulli equations to a potential liquid flow. Eqs. (1) to (4) are the asymptotic behaviors predicted by Franklin (2010c). In these equations, the subscript *0* corresponds to the fluid flow over a flat bed (zeroth order), and the main variables are defined in Fig. 1. The main results of Franklin (2010c) are summarized below.

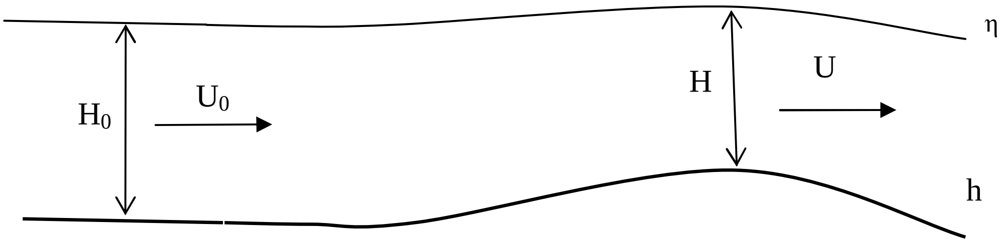

Figure 1. Definition of the free surface η, the dune height h, the liquid depth H and the fluid velocity U. The subscript *0* corresponds to the fluid flow over a flat bed.

- Case I: subcritical flow

In this case, $0<Fr<1$, which implies that $\eta<0$ and $U>U_0$, where $Fr = U_0 / \sqrt{gH_0}$ is the Froude number: the ratio between the mean flow velocity and the celerity of surface gravity waves. This means that the free surface above the bedform is a trough, and that the mean velocity is accelerated in the crest region. The surface gravity waves are 180^0 out-of-phase with respect to the bedforms. The maximum of the fluid velocity is around the crest, with an upstream out-of-phase component that this simplified model is not capable to obtain (so that the fluid flow is an unstable mechanism). Also, in this case $C_0>0$, so that the bedforms have a downstream celerity. From these characteristics, we can conclude that those forms are dunes (Engelund and Fredsoe , 1982).

- Case II: supercritical flow

In this case, $Fr>1$, which implies that $\eta>0$ and $U<U_0$. This means that the free surface above the bedform is a bump, and that the mean velocity is decelerated in the bedform crest region. The surface gravity waves are 0^0 out-of-phase with respect to the bedforms The minimum of the fluid velocity is around the crest. Also, in this case $C_0<0$, so that the bedforms have an upstream celerity. From those characteristics, we can conclude that those forms are the usually called anti-dunes (Engelund and Fredsoe , 1982).

- Case III: transition

In this case, $Fr \approx 1$. In this region, the excited surface waves are out-of-phase by nearly 90^0 lagging the dunes. This means that the maximum flow velocities are shifted downstream the bedform crests, implying erosion on the crests and stability (the fluid flow is a stable mechanism in this case). This condition bounds the length-scale of dunes by means of the surface waves and bedform interaction, and for this reason it is called a resonance region.

Franklin (2010c) considered that dunes are a secondary instability, i.e., they are generated from the coalescence of ripples. In this case, as the dunes grow up the local values of *Fr* increase and tend to $Fr\approx1$. When $Fr\approx1$, the fluid flow becomes a stable mechanism, limiting then the size of dunes.

From this, Franklin (2010c) proposes that the wavelength λ_{dune} and the celerity of dunes C_{dune}, in the presence of a free surface, have the following scales

$$\lambda_{dune} \sim H_0 \tag{1}$$

$$C_{dune} \sim -\frac{3C_1U_0^3}{H_0}\frac{1}{Fr^2-1} \tag{2}$$

where C_1 is a constant. These scales agree with some experimental results. For example, from experimental data, Allen (1970) and Yalin (1977) propose that $\lambda_{dune} = 2\pi H_0$. Raudkivi (1976) claims that experimental results lead to $\lambda_{dune} = 4H_0$ to $8H_0$.

Fourrière et al. (2010) argue that larger bedforms may appear from the coalescence of dunes. These forms are called mega-dunes and, as the dunes, scale with the water depth (although with a higher order of magnitude).

For the ripples, the scales are given by Franklin (2010a) and Franklin (2010b):

$$\lambda_{ripple} \sim L_{sat} \tag{3}$$

$$C_{ripples} \sim -\frac{Q_{sat}}{L_{sat}} \tag{4}$$

where $L_{sat} \sim L_d = d\left(u_* U_S^{-1}\right)$ is a distance called "saturation length", *d* is the mean grain diameter, u_* is the friction velocity (square root of the division of the shear stress by the fluid density) and U_s is the typical settling velocity of a grain. This distance is a characteristic length due to saturation effects (Franklin, 2010a). Q_{sat} is the saturated volumetric flow rate of grains by unit of width over a flat surface (basic state).

3. MEASUREMENTS IN THE FIELD: EXPERIMENTAL PROCEDURES

3.1. The Sapucaí River

The sources of the Sapucaí river are located in Campos do Jordão (São Paulo State, Brazil), at a height of about *1700 m* (Mantiqueira montains), and it ends at the Rio Grande river, in Paraguaçu (Minas Gerais State, Brazil), at a height of about *780 m*. The Sapucaí river crosses two Brazilian States (São Paulo and Minas Gerais) and has a total length of *333 km* (Moni Silva, 2007).

The field experiments were performed at Itajubá (Minas Gerais State), whose location is: south latitude *22°:25':36,55''* and west longitude *45°:27':33,42''*. In this region, the river has a slope of about *0.60 m/km* and the bed is composed mainly of fine sand.

3.2. Instrumentation

In order to measure the bed morphology and the water flow discharge, an ADCP (Acoustic Doppler Current Profiler) device was employed. This equipment allows, by acoustic Doppler effects, the measurement of the water velocity and of the bed morphology, in accordance with a pre-determined grid (in a plane). If the plane is transversal to the water stream, the ADCP measures the mean velocities in each cell of the plane grid and the transversal area traversed by the water flow, so that the water discharge rate can be computed.

If the plane is longitudinal to the water stream, the ADCP can map the existence of transversal dunes along the flow (but the water discharge has no practical meaning in this case).

The ADCP device is composed of:

- a transducer, with usually three or four sensors, each sensor transmitting and receiving acoustic beams;
- a computer, which controls the transducer functioning and stores the raw data;
- electronic cables and connectors;
- a software, responsible for the transducer control, the data storage and the processing of the raw data.

To collect the data in a plane, the ADCP transducer must be displaced over the water surface, along a line, while it measures the water velocities and the bed vertical distance below it. In order to displace the ADCP transducer over long distances, a boat is usually employed.

The device employed in these tests was an ADCP from Teledyne RD Instruments. It was composed of:

- the WorkHorse Rio Grande transducer, containing four sensors and emitting/receiving at a frequency of 1200 Hz;
- the softwares WinRiverII (tests performed in July 2010) and WinRiverI (tests performed in December 2010);
- a portable computer;
- a boat, employed to tow the transducer.

3.3. Procedures

All the tests were made in the same location: the Santa Rosa station, belonging to COPASA (Companhia de Saneamento de Minas Gerais), in the city of Itajubá, so that the tests presented here correspond to the same river location, in different days.

For each experiment, the same procedure was employed:

(a) we performed a transversal measurement with the ADCP, which gave us the discharge rate of the Sapucaí river at the test location;

(b) we performed a longitudinal measurement with the ADCP, in order to obtain the longitudinal variation of the river bed.

(c) we collected a sample of bed material for analyses;

(d) the ADCP data was processed with its software (WinRiverII or WinRiverI);

(e) the data was post-processed with MatLab.

The next section presents some of the collected data and the main results that can be drawn from them.

4. RESULTS

4.1. July 28th 2010

The first bed morphology tests were performed on July 28th 2010 at the COPASA Santa Rosa station. The acquisition done in this particular day was performed using the WinRiverII software, and the cells size was *0.5 m* for both the longitudinal and the transversal measurements (in order to obtain the water discharge rate).

For these tests, the transversal ADCP measurements provided a water discharge rate of $Q = 11.1\ m^3/s$ and a transversal area of $A = 26.6\ m^2$, which gives a mean velocity of $U = Q/A = 0.42\ m/s$. The maximum depth in this particular transversal line is $H_{trans} = 1.9\ m$, so that $Fr \approx 0.1$ and the flow is subcritical and anti-dunes are not expected to be present. The flow is turbulent, for reference: $Re_{Htrans} \approx 8.10^5$, where $Re_{Htrans} = U.H_{trans}/\nu$ and ν is the cinematic viscosity of the fluid.

We present and discuss next the longitudinal measurements of the bed morphology, as they concern directly the presence of ripples, dunes, anti-dunes and mega-dunes. Figure 2 presents the river bed profile measured this particular day at the Santa Rosa station, where *Z* is the water depth (measured from the water surface) and *X* is its longitudinal position. The longitudinal position *X* is measured from the transversal line and is from downstream to upstream.

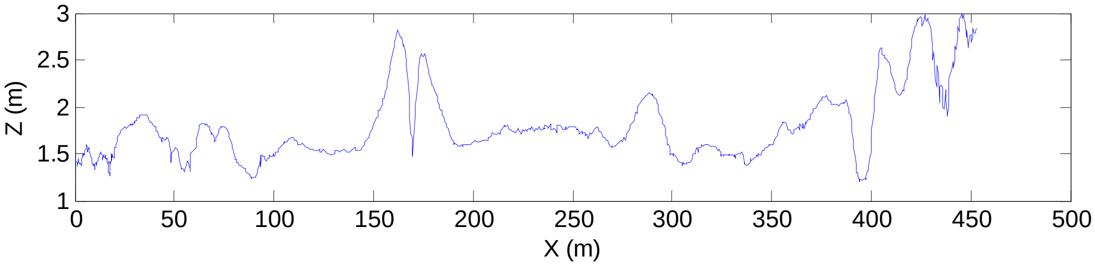

Figure 2. Water depth *Z* as a function of the longitudinal position *X*.

From Fig. 2 it is clear the existence of bedforms in the Sapucaí river, with the coexistence of small and large wavelength forms. At a first glance, one would tend to infer the smallest bedforms to ripples, the largest bedforms to mega-dunes and the intermediate bedforms to dunes. However, analyzing Fig. 2 in more detail, it can be observed that the smallest wavelengths are on the same order of the spatial resolution given by the ADCP device, i. e., *0.5 m*, so that it would be erroneous to associate these wavelengths to the wavelength of ripples.

Obtain the characteristic wavelengths directly from Fig. 2 is difficult and can lead to errors related to our particular perception of the signal. So, in order to obtain the wavelengths present in the signal (here the water depth, directly related to the bedform), we transformed the signal to the Fourier space (as usually done in signal processing): we took the Fast Fourier Transform (FFT) of the entire signal and plotted its Power (the Fourier transform multiplied by its convolution) as a function of the linear wavenumber $k = 1/\lambda$. Figure 3a presents the Power of the signal as a function of the dimensional wavenumber. From this figure, it is clear that three or four large wavelength bedforms (small wavenumber) are well defined in the signal, and that the small wavelength ripples (large wavenumber) cannot be clearly detected, due to the resolution of the ADCP sampling. The small wavelength ripples are in fact treated by the FFT as noise, due to the small sampling resolution. Some intermediate bedforms are also detected, but their Power is weak, also due to the small sampling resolution.

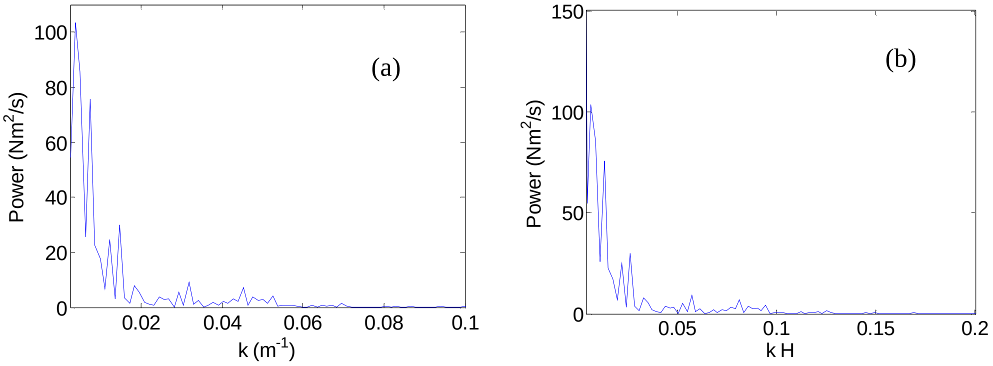

Figure 3. (a) Power as a function of the wavenumber *k* and (b) Power as a function of the dimensionless wavenumber *kH*.

Figure 3b presents the Power of the signal as a function of the dimensionless wavenumber kH, where H is the mean water depth in the longitudinal direction. From Fig. 3b we can measure the position of the peaks (where the signal is stronger) in depth units, allowing us to directly associate the bedforms wavenumber (or wavelength) to the water depth. In Fig. 3b, the first four peaks (from the left) correspond to $kH = 0.007$; $kH = 0.013$; $kH = 0.022$ and $kH = 0.026$, respectively. These peaks then correspond to bedforms whose wavelengths are a hundred times the water depth, characterizing the mega-dunes (formed from the coalescence of dunes).

Next, one can identify three peaks of lower Power (due to the spatial resolution of the sampling), corresponding to $kH = 0.057$; $kH = 0.081$ and $kH = 0.094$. These peaks correspond to bedforms whose wavelengths are one order of magnitude greater than the water depth, corresponding then to dunes. As said before, the spatial sampling resolution given by the ADCP is not sufficient to detect the presence of ripples.

4.2. December 14th 2010

The second bed morphology tests were performed on December 14th 2010 at the same location: the COPASA Santa Rosa station. The acquisition done in this particular day was performed using the WinRiverI software, and the cells size was of about *0.5 m* for the transversal measurements (in order to obtain the water discharge rate) and of about *1 m* for the longitudinal measurements.

For these tests, the transversal ADCP measurements provided a water discharge rate of $Q = 20.6\ m^3/s$ and a transversal area of $A = 32.4\ m^2$, which gives a mean velocity of $U = Q/A = 0.64\ m/s$. The maximum depth in this particular transversal line is $H_{trans} = 2.1\ m$, so that $Fr \approx 0,1$ and the flow is subcritical and anti-dunes are not expected to be present. The flow is turbulent, for reference: $Re_{Htrans} \approx 10^6$.

As done for the other tests, we present and discuss next the longitudinal measurements of the bed morphology, as they concern directly the presence of ripples, dunes, anti-dunes and mega-dunes. Figure 4 presents the river bed profile measured this particular day at the Santa Rosa station, where Z is the water depth (measured from the water surface) and X is its longitudinal position. The longitudinal position X is measured from the transversal line and is from downstream to upstream.

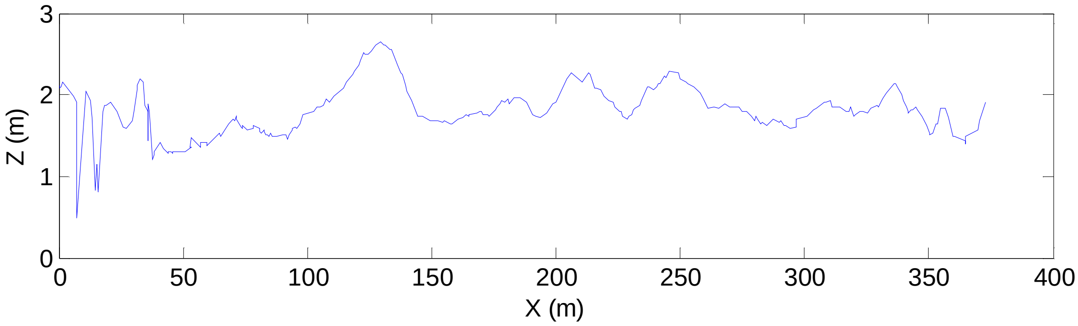

Figure 4. Water depth *Z* as a function of the longitudinal position *X*.

As in the case of Fig. 2, Fig. 4 shows the presence of bedforms in the Sapucaí river, with the coexistence of small and large wavelength forms. However, the smallest wavelength present in Fig. 2 cannot be seen in Fig. 4, and the explanation for this is the smaller sampling resolution given by the ADCP in the December tests, i. e., *1 m*. Also, from this smaller resolution, one can expect more difficulties to identify the wavelengths corresponding to dunes. In order to identify the characteristic wavelengths present in the bed, we proceed as before and we computed the Power of the signal in the Fourier space.

Figure 5a presents the Power of the signal as a function of the dimensional wavenumber. From this figure, it is clear that two or three large wavelength bedforms (small wavenumber) are well defined in the signal, and that the small wavelength ripples (large wavenumber) cannot be detected, due to the resolution of the ADCP sampling. Some intermediate bedforms are also detected, but their Power is weaker, also due to the small sampling resolution.

Figure 5b presents the Power of the signal as a function of the dimensionless wavenumber *kH*. From Fig. 3b we can measure the position of the peaks (where the signal is stronger) in depth units, allowing us to directly associate the bedforms wavenumber (or wavelength) to the water depth. In Fig. 3b, the first three peaks (from the left) correspond to $kH = 0.018$; $kH = 0.032$; and $kH = 0.046$, respectively. These peaks correspond then to bedforms with wavelengths a hundred times the water depth, characterizing the mega-dunes (formed from the coalescence of dunes).

Next, one can identify two peaks of lower power (due to the spatial resolution of the sampling), corresponding to $kH = 0.060$; and $kH = 0.071$. These peaks correspond to bedforms whose wavelengths are one order of magnitude greater than the water depth, corresponding then to dunes. As said before, the sampling resolution given by the ADCP is not sufficient to detect the presence of ripples.

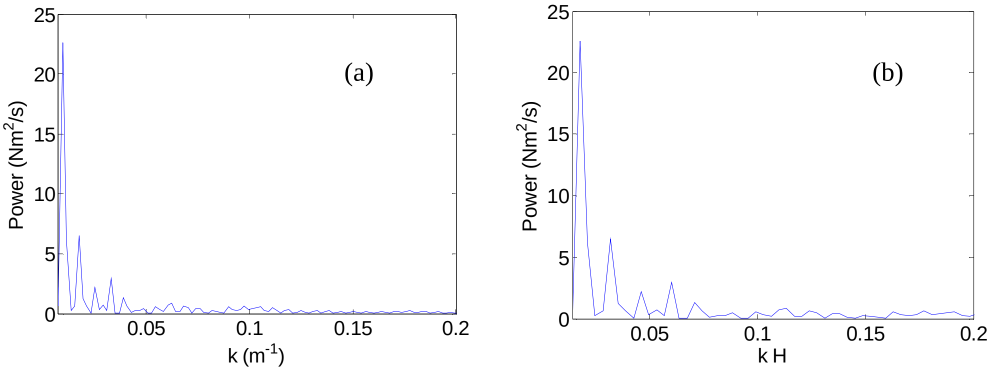

Figure 5. (a) Power as a function of the wavenumber *k* and (b) Power as a function of the dimensionless wavenumber *kH*.

4.3. Discussion

The experimental results were able to show the existence of bedforms in the Sapucaí river, and the measured bedforms scale with the water flow depth. We can distinguish two distinct bedform sizes: one with a wavelength of about ten times the water depth *H* and the other with a wavelength of about a hundred times the water depth *H*.

The presence of a wavelength of about ten times the water depth *H* strongly supports the physical argument proposed by Fourrière et al. (2010) and Franklin (2010c) that dunes are secondary nonlinear instabilities formed by the coalescence of ripples and whose length-scales are given by a stable mechanism due to free surface effects. Also, the scales obtained by the mathematical treatment proposed by Franklin (2010c) are corroborated by the experimental results. In cases where the water stream is subcritical, these forms are called dunes.

The presence of a wavelength of about a hundred times the water depth *H* means larger bedforms, whose wavelength is an order of magnitude greater than the wavelength of dunes. Fourrière et al. (2010) propose that, after dune formation, another nonlinear instability takes place with the coalescence of dunes, forming even larger bedforms. These forms are called mega-dunes. The ADCP measurements in the Sapucaí river showed then the presence of both dunes and mega-dunes.

Finally, due to the small sampling resolution of the ADCP, ripples cannot be clearly detected in the experimental data. For this reason, we were not able to compare the scales proposed in the literature with the Sapucaí ripples.

5. CONCLUSION

The transport of granular matter by a fluid flow is frequently found in nature and in industry. When the shear stresses exerted by the fluid flow on a granular bed are bounded to some limits, a mobile granular layer known as bed-load takes place in which the grains stay in contact with the fixed part of the granular bed. Under these conditions, an initially flat granular bed may be unstable, generating ripples and dunes, such as those observed in deserts, in river beds but also in pipelines conveying sand.

It is known from observations in rivers and in open-channels that two different kinds of bedforms may coexist. Those forms have different wavelengths, one scaling with the grains diameter and with an inner layer close to the bed (but not with the flow depth), called ripple, and another scaling with the fluid flow depth, called dune (this category includes the mega-dunes and the anti-dunes). Many previous works were made in an attempt to understand the generation and evolution of these forms, but until now there is not a consensus about it.

This paper presents experimental results obtained in the field, concerning the morphology of sand beds in free surface turbulent streams. The tests were made in the Sapucaí river, in the city of Itajubá (Minas Gerais State, Brazil), with the use of an ADCP (Acoustic Doppler Current Profiler) device. The obtained data concern the water discharge rate and the longitudinal variation of the bed.

The experimental data showed the existence of bedforms whose wavelength scales with the flow depth:

- bedforms whose wavelength is one order of magnitude greater than the water depth;
- bedforms whose wavelength is two orders of magnitude greater than the water depth.

The scaling of the bedforms wavelength with the water depth comes from a stable mechanism related to free surface effects, and that occur in the transition from subcritical to supercritical regimes, known as “resonance region” (Fourrière et al., 2010; Franklin, 2010c). As soon as these forms appear, their wavelength is about ten times the water depth and, if the water stream is in subcritical regime, they are called dunes.

Concerning the bedforms whose wavelength is a hundred times the water depth, it has been argued that they originate from the coalescence of dunes (Fourrière et al., 2010). These larger forms are usually called mega-dunes.

Due to the small sampling resolution of the ADCP, ripples could not be clearly detected in the experimental data. For this reason, we were not able to compare the experimental data with the scales proposed for ripples in the literature.

In summary, the field measurements showed the presence of bedforms in the Sapucaí river. Although we suppose that ripples exist in the bed, they could not be detected (due to the small sampling resolution of the ADCP device used). The experimental data showed the presence of dunes and mega-dunes in the Sapucaí river, whose scales agree with those predicted in literature (Franklin, 2010c; Fourrière et al., 2010). This agreement corroborates the recent theoretical efforts to understand the formation and evolution of bedforms in rivers and open-channel flows.

6. ACKNOWLEDGEMENTS

The authors are grateful to the IRN-UNIFEI for the help with the ADCP device and the boat, to COPASA for the assistance provided with the Santa Rosa station, and to CNPq for the scholarship granted to Ivan Felipe Silva dos Santos.

7. REFERENCES

Allen, J.R.L., 1970, “Physical processes of sedimentation”, Ed. Allen & Unwin, London, United Kingdon, 248p.

Andreotti, B., Claudin, P. and Douady, S., 2002, “Selection of dune shapes and velocities. part 2: a two-dimensional model”, Eur. Phys. J. B, Vol. 28, pp. 341 - 352.

Bagnold, R.A., 1941, “The physics of blown sand and desert dunes”, Ed. Chapman and Hall, London, United Kingdom, 320 p.

Charru, F., Mouilleron-Arnould, H. and Eiff, O., 2004, “Erosion and deposition of particles on a bed sheared by a viscous flow”, J. Fluid Mech., Vol. 519 pp. 55 - 80.

Charru, F., 2006, “Selection of the ripple length on a granular bed sheared by a liquid flow”, Physics of Fluids, Vol. 18 (121508).

Charru, F., 2007, “Instabilités hydrodynamiques”, Ed. EDP Sciences, Les Ulis, France, 386 p.

Coleman, S., Fedele, J. and Garcia, M.H., 2003, “Closed-conduit bedform initiation and development”, J. Hydraul. Eng., Vol. 129, No. 12, pp. 956 - 965.

Coleman, S.E. and Fenton, J.D., 2000, “Potential-flow instability theory and alluvial stream bed forms”, J. Fluid Mech., Vol. 418 pp. 101 - 117.

Drazin, P.G. and Reid, W.R., 2004, “Hydrodynamic stability”, Ed. Cambridge University Press, Cambridge, United Kingdom, 605 p.

Engelund, F., 1970, “Instability of erodible beds”, J. Fluid Mech., Vol. 42, pp. 225 - 244.

Engelund, F. and Fredsoe, J., 1982, “Sediment ripples and dunes”, Ann. Rev. Fluid Mech., Vol. 14, pp. 13 - 37.

Franklin, E.M., 2010a, “Initial instabilities of a granular bed sheared by a turbulent liquid flow: length-scale determination”, J. Braz. Soc. Mech. Sci. Eng., Vol. 32, pp. 460-467.

Franklin, E.M., 2010b, “Non-linear instabilities on a granular bed sheared by a turbulent liquid flow”, J. Braz. Soc. Mech. Sci. Eng., accepted.

Franklin, E.M., 2010c, “Linear and nonlinear instabilities of a granular bed: determination of the scales of ripples and dunes in rivers”, Applied Mathematical Modelling, submitted.

Franklin, E.M., 2008, “Dynamique de dunes isolées dans un écoulement cisaillé”, (in french), Ph.D. Thesis, Université de Toulouse, Toulouse, France, 166 p.

Franklin, E.M. and Charru, F., 2007, “Dune migration in a closed-conduit flow”, Proceedings of the 6th International Conference on Multiphase Flow, Leipzig, Germany.

Franklin, E.M. and Charru, F., 2009, “Morphology and displacement of dunes in a closed-conduit flow”, Powder Technology, Vol. 190, pp. 247 - 251.

Fourrière, A., Claudin, P. and Andreotti, B., 2010, “Bedforms in a turbulent stream: formation of ripples by primary linear instability and of dunes by nonlinear pattern coarsening”, J. Fluid Mech., Vol. 649 pp. 287 - 328.

Hunt, J. C. R., Leibovich, S. and Richards, K., 1988, “Turbulent shear flows over low Hills”, Quart. J. R. Met. Soc., Vol. 114, pp. 1435 - 1470.

Jackson, P.S. and Hunt, J. C. R., 1975, “ Turbulent wind flow over a low hill”, Quart. J. R. Met. Soc., Vol. 101, pp. 929 - 955.

Kennedy, J. F., 1963, “The mechanics of dunes and antidunes in erodible-bed channels”, J. Fluid Mech., Vol. 16, pp. 521 - 544.

Kuru, W. C., Leighton, D. T. and McCready M. J., 1995, “Formation of waves on a horizontal erodible bed of particles”, Int. J. Multiphase Flow, Vol. 21, No.6, pp. 1123 -1140.

Landau, L.D. and Lifchitz, E.M., 1994, “Physique théorique: mécanique des fluides”, Ed. Ellipses (traduction française), Poitiers, France, 752 p.

Moni Silva, A.P., 2007, “Elaboração de manchas de inundação para o município de Itajubá, utilizando SIG”, MSc. Thesis, Universidade Federal de Itajubá, Itajubá, Brasil.

Raudkivi, A.J., 1976, “Loose boundary hydraulics”, Ed. Pergamon, Oxford, United Kingdom, 397p.

Reynolds, A.J., 1964, “Waves on the erodible bed of an open channel”, J. Fluid Mech., Vol. 22 pp. 113 - 133.

Richards, K.J., 1980, “The formation of ripples and dunes on an erodible bed”, J. Fluid Mech., Vol. 99, pp. 597 - 618

Schmid, P.J. and Henningson, D.S., 2001, “Stability and transition in shear flows”, Ed. Springer, New York, United States of America, 556 p.

Valance, A. and Langlois, V., 2005, “Ripple formation over a sand bed submitted to a laminar shear flow”, Eur. Phys. J. B, Vol. 43, pp. 283 - 294.

Weng, W. S., Hunt, J. C. R., Carruthers, D. J. , Warren, A., Wiggs, G. F. S., Livingstone, I. , and Castro, I., 1991, “Air flow and sand transport over sand-dunes”, Acta Mechanica, pp. 1 – 21.

Yalin, M.S., 1977, “Mechanics of sediment transport”, Ed. Pergamon Press, Oxford, United Kingdon, 298p.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.