

On the role of fine-sand dune dynamics in controlling water depth changes in Rio Parapeti, Serrania Borebigua (Southern sub-Andean zone of Bolivia)

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Abstract

The role of the fine-dune sand dynamics in controlling the natural regeneration of the upper layer of a riverbed used for filtration is studied at the Choreti test reach of Rio Parapeti, in the Southern sub-Andean zone of Bolivia. Local production of drinking water relies on Riverbed Filtration, the delivery of which depends on the river water depth and the riverbed permeability. There is a strong, natural, declamation process of the upper layer maintained by dune bed-forms migrating downstream. It is thus essential to understand and represent local water depth changes as a function of the incoming discharge. We show the vortex-drag model can be used to correctly calculate the stream velocity in natural environment. Then we study the sand dunes characteristic (wavelength and celerity) in the Rio Parapeti. Because of the shallow-flow configuration the dominant dune length can be easily extracted from satellite images taken at various dates. We also show that it is more than likely that dune movement can be followed by the simple deployment of a pressure probe into the water under stable discharge condition, even if further data and investigation are necessary to confirm this.

1. INTRODUCTION

The role of the fine-dune sand dynamics in controlling the natural regeneration of the upper layer of a riverbed used for filtration is studied at the Choreti test reach (20°1'0" N 63°31'60" E) of Rio Parapeti, in the Southern sub-Andean zone of Bolivia. The site is located at 800m elevation, mid-slope from the Central Cordillera towards the Chaco plain (Baby et al. 2009). The subtropical climate is characterised by two distinct seasons. During the summer is a heavy rainy season from November to April (Ministerio de saneamiento basico 2005) accompanied by melting ice from the Andean mountains, while winter is dry. From this results a high variation in the discharge value of the Rio Parapeti (Table 1).

	Min	Max	Average
Discharge Q (m ³ /s)	5.2	940	90

Table : Daily data of Rio Parapeti discharge 1975-1984 at the San Antonio site, 550 m elevation, at the bottom of sub-Andean foothills (Guyot et al. 1994)

The subandean ground is composed by the late Cenozoic sedimentary strata of sandstone, in this case the Yecua and Tariquia formations of late Miocene (Hulka et al. 2006, Hulka & Heubeck 2010). This explains the particularly small granulometry found for streambed particles in Choreti, with a median grain size of 250µm of non-cohesive, very homogeneous, silica sand. Size-distribution analysis indicates that sand particles sizing between 210µm and 290µm constitute more than 55% of the active layer of local riverbed deposits. For this reason rio Parapeti in Choreti forms a remarkable field investigation site to study alluvial adaptations and consequences for bedform roughness. The combination of small granulometry and high discharge during the rainy season explains the highly dynamic riverbed present at the Choreti site. Even if the river is around 90 m wide, it is a shallow river with a mean depth of only 1 m even if in extreme events, it can goes up to 4-5m (Camacho 2004).

Local production of drinking water relies on Riverbed Filtration (RBeF). The system, which derives from the well-known riverbank filtration used in Europe since last century (Stuyfzand *et al.* 2006), consists in extracting water from a lateral well directly connected to an infiltration gallery installed perpendicularly

The production of such a system is mainly dependent of the river water depth (D) and the riverbed permeability. But the system eventually starts to clog with infiltration of small particles into lower layers and biological development (Schalchli 1992, Stoquart 2009, Craddock 2012). This causes the productivity to decrease in time and water quality is mainly dependent on the upper sand-bed layer. Indeed, there is a strong, natural, declamation process of the upper filtration layer maintained by dune bed-forms migrating downstream. This renewal avoids the upper layer to clog and preserve its capability to clean infiltrating water. It is thus important to understand and represent local water depth changes as a function of the incoming discharge. Water depth is controlled by alluvial hydraulic roughness and by sand-bed adaptive morphology (Simons & Richardson 1961). Our observations take place during the rainy season thus high stream power conditions were present all the time. In a fine non-cohesive sand particles system like this one, the riverbed is highly dynamic and adapts itself quickly to the stream velocity (U) changes. Basically, the system can be separated, as a function of ambient specific stream power (W/m^2), into two different regimes which are lower alluvial regime, associated to fully developed dunes (FDD) and upper alluvial regime with In-phase waves (IPW) (Simons & Richardson 1961). IPW presence is easily identifiable on the spot (see Fig.3) because of the characteristic undular water surface deformations.

1.1 The control factor m and stream velocity determination

FDD flow is characterised by a phase opposition between water surface and sand wave profiles. The water flow is accelerated due to the topographic forcing on the back of the dune (Fig. 1) until the crest where it loses contact at the separation edge. At this moment an eddy is formed which creates a strong velocity gradient between the recirculation zone and

under the riverbed. The filtering layers at that location of the riverbed are formed by top-down increasing sand and gravel beds laid there for the purpose (Camacho 2004).

the overlying free stream. Kelvin-Helmholtz instabilities therefore develop at the shear layer (Muller and Gyr 1982, 1986). These instabilities reach the back of the next dune, generating a secondary perturbation in the form of a vortex, or kolk-boil, that in a sufficiently shallow stream can be observed at the water surface (Best 2005, Barua & Rahman 1998).

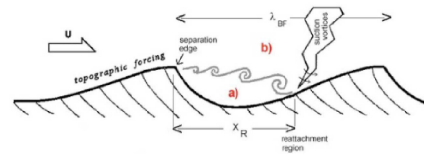


Figure : Attached/detached flow model. The movable-bed resistance problem can be seen as a combinaison of (a) topographically-forced attached flow, and (b) instabilities in the separated shear layer which originates at the bedform crest

Levi (1983) introduced the universal Strouhal law (Eq. 1.1) to describe the frequency of vortex shedding as Strouhal did for aeolian tones.

$$f_{detached} = \frac{1}{2\pi} \frac{U}{x_r} \quad (1.1)$$

where $f_{detached}$ = frequency of perturbation (s^{-1}), U = stream velocity (m/s) and x_r = characteristic length (m). Later, Verbanck (2008) introduces the « control factor m » from Kiya's theoretical development into the universal Strouhal law to take into account the different harmonic modes. m value of one corresponds to the fundamental mode described initially by Levi (with IPW) and m value of two corresponds to the second harmonic with the presence of FDD (Verbanck 2008, Huybrechts *et al* 2011). This gives us the equation:

$$f_{detached} = \frac{1}{T_{kolk-boil}} = \frac{mU}{2\pi D} \quad (1.2)$$

where $T_{\text{kolk-boil}}$ = kolk-boil period (s), D = water depth (m) and m = control factor.

Verbanck pursues the development by formulating the vortex-drag equation which is a combination of both the detached effect (universal Strouhal law) and the attached effect. The local topography of the dune forces the flow to accelerate. This creates a gravity wave which tries to plan the water surface. The propagation of this wave (neglecting surface tension) is described by Airy's law.

$$c = \sqrt{\frac{g \lambda_{bf} \tanh \frac{2\pi D}{\lambda_{bf}}}{2\pi}} \quad (1.3)$$

where c = gravity wave celerity (m/s), g = gravitational constant (m/s^2) and λ_{bf} = dune wavelength (m).

The two phenomena participate in the dissipation of energy. The attached phenomenon is the most efficient way to evacuate the excess water and thus tends to reduce the energy loss of the stream, while the detached phenomenon consumes energy for maintaining the vortex turbulences. Verbanck assumes then these two effects can be reunited into a single formulation of the energy gradient:

$$S = \beta \left(\frac{\frac{mU}{2\pi D}}{\sqrt{\frac{g \lambda_{bf} \tanh \frac{2\pi D}{\lambda_{bf}}}{2\pi}}} \right)^\alpha \quad (1.4)$$

where S = surface water slope and α, β = coefficients. An empirical analysis was conducted to give value to the coefficients, which leads us to the vortex-drag equation used in this work.

$$U = \frac{2\pi}{m} \sqrt{\frac{g \lambda_{bf} \tanh \frac{2\pi D}{\lambda_{bf}}}{2\pi}} S^{0.3} \quad (1.5)$$

1.2 Field measurements

Field measurements were performed for several years on the spot in Choreti (2009-2012) during the rainy season. Measures of water depth were recorded daily

by both limnimeter and pressure probe OTD Diver Schlumberger (Fig. 2).

Water velocity was recorded by General Oceanics 2030 currentmeter with standard 2030-R mechanical rotor. We arbitrarily took the measure in the middle of the stream with two measures at respectively 20 and 80 % of the water depth in appreciation of the vertical logarithmic velocity profile.

The alluvial regime is easily recognizable in this river. Upper alluvial regime is represented by IPW (Fig. 3) and lower alluvial regime by FDD. As we explained earlier, kolk-boils are visible when there are FDD and thus we could measure the time between each of them determining $T_{\text{kolk-boils}}$.



Figure : Installation of the limnimeter in the Rio Parapeti. The pressure probe is inserted into the pole.



Figure : IPW formation at Choreti test reach, Bolivia (Photo credit: F.Craddock).

Because of high particles concentrations and thus water opacity, dunes lengths were not directly visually discernable on the spot. But we show that satellite images can be used to determine their length

relatively precisely. Thanks to the shallow-stream, dunes migration were visible with only the installation of a pressure sensor into a protecting pole (Fig. 2). The study of the water surface slope has been done between two bridges separated by a curvilinear distance 1.8km from each other. The determination of the reference piezometric level at the two points has been done by a theoretical development due to a lack a precision of our GPS.

2. RESULTS

2.1 On the determination of stream flow velocity by the vortex-drag model

The vortex-drag equation needs four terms to be applied. The control factor “m”, dunes length, water depth and water slope.

2.1.1 The control factor m

There are different ways to determine the value of the control factor m. It can be based on water surface slope or kolk-boil frequency.

First of all, we try to confirm the link between the kolk-boil period and the expected value of control factor $m = 2$. The determination of kolk-boil period has been done by visual observation on the spot. Equation (1.2) is used to calculate the m value associated with these kolk-boils (Table 2).

	5/4/10	17/03/11	18/03/11
Observed period (s)	4.0	2.6	4.0
m with $T_{detached}$	1.92	2.35	2.27
Q (m ³ /s)	49	116	122

Tableau : Field observations of the time elapsed between two consecutive kolk-boils appearing at the water surface. The second line is the m value calculated with Equ. 1.2. The discharge, obtained using the local Choret hydrometric rating curve (Stoquart 2009), is represented at the third line.

As we can see, the m value is close to the expected value of $m=2$ for the three observations. This means that we can allow us to attribute a “visual” value for the parameter $m = 2$ when we observed FDD. And when we observed IPW, the control factor value is $m=1$ (Huybrechts *et al.* 2011a). We can also see that m value of 2 can be found for contrasted values of discharge.

2.1.2 Water surface slope

First of all we determine the absolute level difference between our two (upstream-downstream) measurement points. As explained before, m equals 2 when kolk-boils are present. Therefore, we base this study on the 18/3/2011 where kolk-boils were visible and calculate the water surface slope with the equation (1.5). This gives us a standard slope value that we used to determine comparatively the water surface slope for all the other days. The surface water slope on the 18/3/2011 was $S = 0.00022$.

We also used these values of S to determine the daily control factor m that we compare with the values obtained with the flow resistance prediction rule proposed by Huybrechts *et al.* 2011b (Fig. 4). We can see we have an acceptable agreement between the two estimation methods.

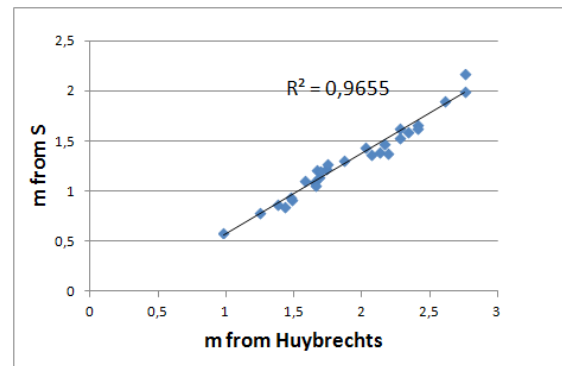


Figure : Comparison of the control factor m calculated with the method of Huybrechts (abscissa) and calculated with the measured surface water slope (equation (1.5)) (ordinate).

Huybrechts' method gives slightly higher values of m than the ones extracted from the local experimental water slope. However, it seems that it is Huybrechts who over-estimates the control factor m value because the stream power calculated with his values are too

big to describe what has been observed ($P_{w_{mean}} = 11.5 \text{ W/m}^2$). Indeed, it would mean that upper alluvial regime has been there every single day which, from field observations, is known not to be true. Therefore, we will work with our measured values.

2.1.3 Dune wavelengths

Due to local constraints no detailed bathymetry survey was possible. The information about dominant dunes length (λ_{bf}) was thus extracted from available satellite images. Three satellite images were used to have a mean value of dunes length (See example at Fig. 5). The value we kept in this work is $\lambda_{bf}=6.7\text{m}$.



Figure : September 2007, we count 11 sand waves on 76 m, thus $\lambda_{bf} = 6.9\text{m}$. Source: Google earth®.

This result is in good agreement with the proposition of Julien and Klaassen (1995) who predict $\lambda_{bf} \approx 6.5D$. Indeed, the flow depth measured in the Rio Parapeti at the Choreti site is around 1.0 m deep which corresponds then to $\lambda_{bf}=6.5\text{m}$. The equation of Liang (2003) also gives us the same magnitude of sand waves length.

	Satellite image (m)	Liang 2003 (m)	Julien & Klaassen 1995 (m)
14/4/09	6.7 ± 0.5	1.40	3.84
26/3/11	6.7 ± 0.5	2.95	4.81
1/04/11	6.7 ± 0.5	4.95	7.99

Table : Dune wavelength estimates

2.1.4 The vortex-drag model

Finally, we use the vortex-drag equation to determine the water velocity, taking into account the measured water depth, measured water surface slope, visual control factor “m” (thus $m=1$ when IPW or 2 when FDD) and the dunes length (satellite images). We plot

it with the velocity obtained with the currentmeter (Fig. 6). The calculated velocity correctly follows the variation of the stream velocity. This encourages us to pursue our further work relying on this equation.

This means also that when there are FDD, we can use the same equation to approximate the water slope of a river by measuring the stream velocity, the dunes length and the water depth only in one point. One way to get better results would be to improve the determination of the control factor m (not only $m=1$ or 2) to be closer to the measured velocity as well as the measured water surface slope.

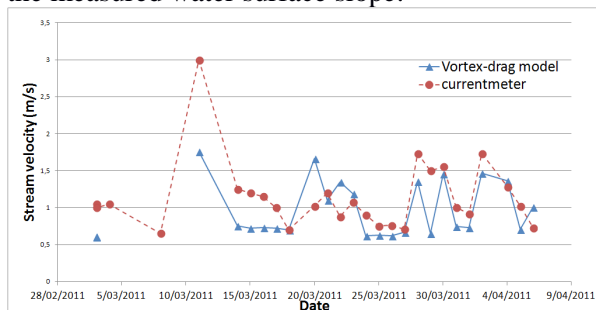


Figure : Comparison of the stream velocity determined by the vortex-drag model with the experimental data at the Choreti test reach in 2011.

2.2 On the determination of sand dunes celerity

As is well explained in the literature, the passage of a FDD in a shallow stream is associated with a phase opposition of the water surface (Simons & Richardson 1961). Where the dune crest exactly stands, the observed water level will be lower due to the topographical forcing effect mentioned before. Therefore, we argue that the dunes movement can be followed by the simple deployment of a (fixed-altitude) pressure probe into water during stable-discharge conditions (no rainfall nor tributary discharge). As an example, the 1-minute water level record in the Choreti test reach on April 1st, 2011 is represented in Fig. 7. We can see that the dune took about 4.5 hours to pass the sensor. As perceived by the Eulerian pressure sensing, the rapid raising of the water level at 15:10 (but also from 11:20 to 11:40) corresponds to the moment when the dune crest suddenly disappears underneath the probe. That is why all our water level records, here exemplified by Fig. 7, provide a transposed (top to bottom) representation which is exactly the reverse of the expected dune longitudinal shape. Besides, as shown

by a FFT analysis, the available records indirectly suggest that ripples (or mini-dunes) are actually migrating on the back of the big dunes. Their wavelength is about 20 times shorter than the reference 6.7m scale characteristic of the large-sized dunes evoked so far (those which are sufficiently large to be discernable by satellite imagery). Indeed, as shown in Fig. 7, we can count 21 ripples passing under the probe on the back of one big dune. AGD

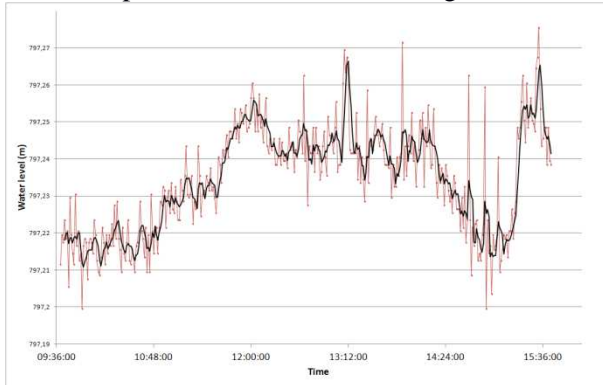


Figure : 1-min record of the water level evolution obtained with the (fixed-altitude) immersed pressure probe. Choret test reach, 1 April 2011. The black line is the moving average with a period of 6 minutes.

To confirm these observations for the large dunes, we will compare the dune celerity determined with the pressure probe with the celerity determined by different authors.

Several authors have proposed a method (Pushkarev 1936, Kondratiev 1962, Simons et al. 1965, Thomas 1967, Kondap & Garde 1973, Orgis 1974, Fedele 1995) to predict the dune celerity. Strasser (2008) made a comparative study on those equations and showed that the correlations of Kondap & Garde, Pushkarev, Orgis and Fedele give good agreement on both laboratory (Guy et al. 1966) and river data (Rhine, Waal and Dommel). However, Pushkarev, Orgis and Fedele primarily consider coarser (gravel) grain-sizes and thus do not provide satisfactory predictions for fine-size (sand) granulometry (Fig. 8 and Table 4) (data from Guy *et al.* 1966, Termes 1986 and Driegen 1986). Therefore, despite the fact that granulometry is not explicitly represented in the relation, we will use the one of Kondap and Garde to evaluate the dune celerity in the Choret site (Equ.2.2).

$$\frac{c_w}{\sqrt{gD}} = 0.021 Fr^4 \quad (2.2)$$

where c_w = sand wave celerity (m/s) and Fr = Froude number.

Fedele	Orgis	Kondra -tiev	Simons	Kondap
0.14	0.39	0.27	0.52	0.49
12.3	60.9	48.0	67.4	1.75

Table : R-square and AGD value for the different equations with the experimental data (Guy et al. 1966, Driegen 1986 and Termes 1986). The Average Geometric Deviation proposed by Zanke (AGD) (Huybrechts et al. 2011b) describes the discrepancy between the predicted and measured data. (AGD = 1 corresponds to a perfect match).

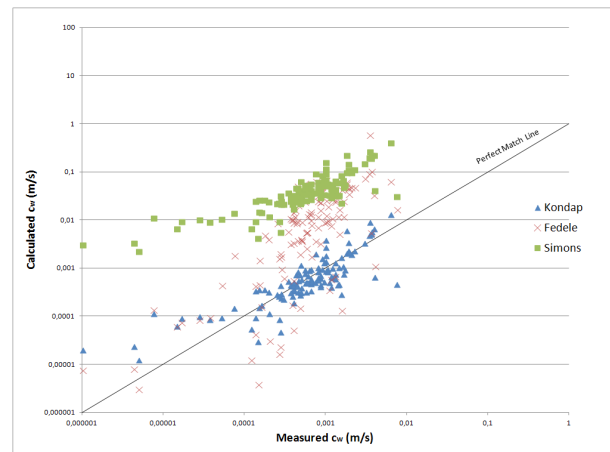


Figure : Comparison of the calculated sand dunes celerity by different authors (Kondap, Fedele and Simons) and the experimental data (Guy et al. 1966, Driegen 1986 and Termes 1986).

The sand wave celerity at the Choret site is simply obtained by dividing the dune length extracted from satellite images (Table 3), by the time necessary for the dune to pass under the (water-column measuring) Schlumberger sensor. The results are given in Table 5.

Date	Choret test reach (m/h)	Kondap & Garde (m/h)
14/4/09	1.01	0.45
26/3/11	4.48	1.27
1/04/11	1.34	1.26

Table : Comparison of the measured dunes celerity with the celerity calculated by the equation of Kondap & Garde.

As we can see, there is an acceptable relationship between sand wave celerities. This tends to confirm our hypothesis that records such as the one in Fig. 7 (we have many of them) indeed correspond to the indirect visualisation of the sand wave (the dune) migrating under the pressure probe. Further investigations and more data are needed to confirm this hypothesis in the future.

3. CONCLUSION

We study the applicability of the vortex-drag equation on the Choreti test reach of Rio Parapeti, Camiri (Bolivia). In the shallow-water condition prevailing here, Fully Developed Dunes are associated with marked kolk-boils periodicity appearing at the water surface. We show that field observation of kolk-boil periods leads us to the expected value of the control factor (m equal 2). Then we make use of the vortex-drag equation to study the stream velocity change taking into account bedforms configuration (m , wavelength λ_{bf}), water depth and water surface slope (S). The results show a satisfactory description of the stream velocity changes. This means that, reversely, the same equation could be used to correctly assess the water surface slope over fluvial dune fields by simply measuring the stream velocity, water depth and dunes length. A universal method to predict the value of control factor m as a function of local stream circumstances (and increasing stream power) would thus be most welcome.

We also show that the sand wave celerity can be followed by the simple deployment of a (fixed-altitude) pressure probe within the right conditions. Indeed, we obtain the dune celerity with the determination of the time needed for the dune to pass the probe and the sand wavelength determined by satellite images (confirmed by the equation of Julien & Klaassen, 1995, and Liang, 2003). The comparison of this celerity with the one obtained by the equation of Kondap and Garde (1973) shows that it is reasonable to argue that it is actually a sand wave passing under the probe. This is also indicated by the recurrence of this observation in our database. Further investigation and data collection are needed to

continue the study of the Riverbed filtration at the Choreti test reach.

4. NOTATION

c	Gravity wave celerity (m/s)
D	Water depth (m)
d_{50}	median grain size (m)
$f_{detached}$	vortex shedding frequency (s^{-1})
Fr	Froude number (-)
g	Gravitational constant (m/s^2)
λ_{bf}	Dune length (m)
m	Control factor m (-)
P_w	Specific stream power (W/m^2)
Q	Discharge (m^3/s)
S	Water surface slope (-)
$T_{kolk-boil}$	Kolk-boil period (s)
U	Stream velocity (m/s)
c_w	Sand wave celerity (m/s)
x_r	Length of separation zone (m)

	D (m)	U (m/s)	Q (m^3/s)	S
Average	0.88	0.82	90	0.00023
	λ_b	H_{bf} (m)	c_w (m/s)	d_{50} (m)
Average	f_r (m)	0.25	1-4 m/h	$250 \cdot 10^{-6}$

Table : Average hydraulic characteristics of rio Parapeti at the Choreti test reach. H_{bf} value has been estimated with the equation of Flemming (2000) and Julien & Klaassen (1995).

5. ACKNOWLEDGMENTS

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