Revue du CAMES - Sciences Appliquées et de l'Ingénieur
Cames 2014 - Published Online 2014 - http://publication.lecames.org/

Vol.1, N° 1, Juin 2014
sai.2014.11001

Geometric relationship of beach cusps with marine hydrodynamics: example of *Cap de Naze* beach, Popenguine (Senegal)

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Reçu mars 2013 – Accepté juin 2014

Abstract
The geometry of beach cusps in the Cap de Naze sandy part of the beach has been investigated. A signal corresponding to beach cusps undulation has been analyzed using Multitaper spectral analysis method. Three periods corresponding to a length of 14, 23 and 35 meters have been highlighted. Comparison with swell geometric parameters shows that the periods of beach cusps are 2.25 to 5.35 times wider. Further parametric studies with varying locality and seasonality are necessary to know all about the observed relationship.

Keywords: beach cups; Cape de Naze; wavelength; period; marine hydrodynamics; swell ; coastal erosion.

1. Introduction

Additionally to its religious and touristic features, the locality of Popenguine (14°33'18''N; 17°06'51''W) is an important geological site. In fact, the only available witness of the Maastrichtian age, forming the base of the Thiès Formation, outcrops in the area and forms the Cap de Naze cliff [1]. The geology of the Cap de Naze has been widely investigated, but most of the studies focused on its biostratigraphy [2]. Meanwhile, the vicinity of the ocean makes the Cap de Naze to be particularly vulnerable to costal erosion; indeed, some parts of the Cap de Naze beach shows sandy formations. The morphology of the sandy parts of the Cap de Naze is directly linked to hydrodynamic parameters. Regular beach cusps are visible in the sandy parts of the Cap de Naze. It has been shown that size and form of beach cusps is linked to marine dynamics [3]. Whether there are several theories to explain the origin of beach cusps, it is well established that their morphology is linked to hydrodynamic parameters [4]. Numerical models for the formation of beach cusps, reviewed by Komar [5], do not take account of all of the processes involved, and therefore have not resolved the problem of their formation [3]. The beach cusps show succession of erosional and depositional parts; it is obvious that a high frequency of beach cusps erosional parts will have negative effects on the sedimentary budget. Therefore, understanding the relation between hydrodynamic parameters and geometry of beach cusps will allow tackling an important aspect of Cap de Naze beach erosion.

The aim of this study is to unravel the geometric relationship between marine hydrodynamics and beach cusps geometry using spectral analysis on a signal corresponding to the undulation of beach cusps as shown on SPOT images.

2. Littoral dynamics

The littoral dynamics is linked to a set of hydrodynamics and sedimentary processes responsible of beach morphology. The main agents of littoral dynamics are winds, tides, marine currents and swells.

Swells stay the main agent of littoral dynamics. In the senegalase Petite Cote, three types of dominant swells are observed according to the season [5].

The geometric parameters of these swells are presented in table 1.

Table 1. Geometric properties of dominant swells (from [9]

Direction	Height	Period	Camber
NW swell (N320 to 20E), observed at 79.3%			
320	1.52	7.35	0.0181
330	1.64	7.29	0.0197
340	1.69	7.17	0.0211
350	1.78	7.08	0.0228
360	1.75	7.00	0.0229
10	1.73	6.96	0.0229
20	1.65	6.99	0.0216
Mean	1.71	7.10	0.0213
SW swell (N180 to 200E), observed at 5.9%			
180	1.41	6.96	0.0187
190	1.46	7.10	0.0186
200	1.49	7.05	0.0192
Mean	1.45	7.02	0.0188
W Swell (N270) observed at 0.9%			
Mean	1.31	6.96	0.0174

Rapid morphologic response are often linked to the action of swells. A common example is the apparition of beach cusps [7]. Beach cusps are regularly spaced ridges and troughs on the beach [3]. They are crescent shaped and present two horns separated by a hollow.

3. Material and method

We investigated a sandy part of Popenguine beach from the islet of Popenguine to the Cap de Naze using high-resolution SPOT image from Google Earth Pro. This part of the coast forms a 200 meters width bay with well-marked beach cusps. A signal is obtained by digitalization of the undulation of the coastline using PlotDigitizer software.

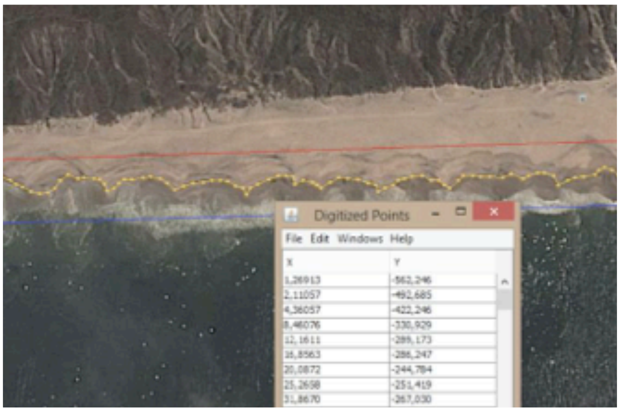


Figure 1. Digitization of beach cusps under PlotDigitizer.

The obtained raw signal corresponding to the variation of the geometry of beach cusps is shown on figure 2.

While digitizing the image, it remains difficult to keep an evenly spaced lag. Therefore, the obtained raw signal has to be resampled at evenly spaced data using Matlab resample function. The sampling step was set to 5 meters.

We noticed also that the obtained signal is not stationary. This is linked to the shape of the studied part of the coast. The trend, linked to the form of the bay was removed using a moving average filtering. The smoothed signal corresponding to the trend was removed from the raw signal. The residue is a stationary signal that can be processed using spectral or wavelet analysis techniques.

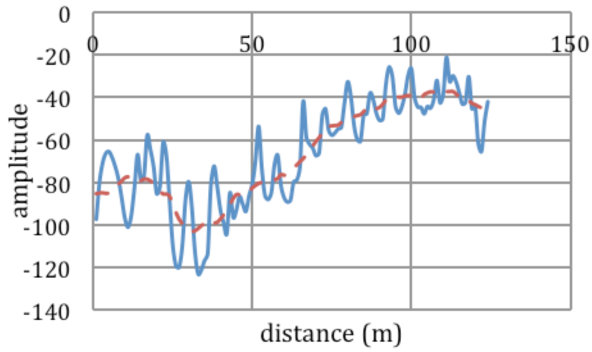


Figure 2. Beach cusps raw signal (continuous line) and trend (dash line) obtained with a 15 meters moving average window

The processing steps, since signal extraction to de-trend signal is summarized in the flow diagram (figure 3).

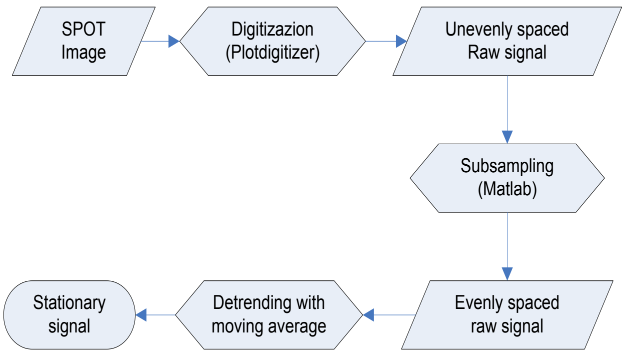


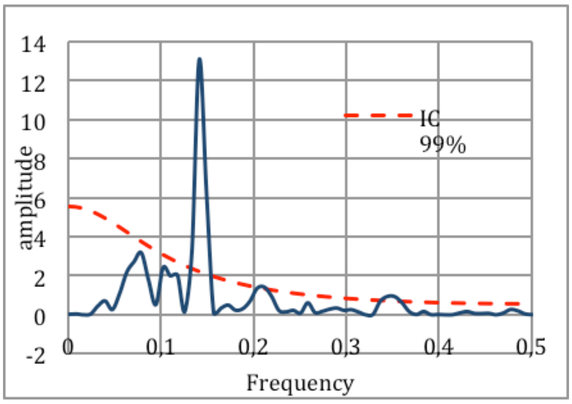
Figure 3. Flow diagram of the beach cusps signal extraction steps

The extracted beach cusps signal, evenly sampled and de-trended is analyzed using Multitaper spectral analysis method (MTM) [8]. In the opposite of the standard fourier analysis methods, MTM gives the confidence level of the obtained peaks and avoid spectral leakage [8]. MTM was performed using 5 eigen tapers, with a resolution of 2. We assumed red noise null hypothesis, robust noise estimation and, log linear fit criterion.

4. Results and discussion

The Multitaper spectral analysis of the signal gives the spectrum shown in figure 4.

Figure 4. Multitaper spectrum of the beach cusps.



The MTM spectrum shows three significant peaks over the 99% confidence level corresponding to the frequencies 0.140, 0.210 and 0.344. Using the relation $T \quad d/f$ where T is the period, f the frequency and the d the unit lag or the step between two data points, we compute the corresponding periods (table 2).

Table 2. Computed periods from MTM spectrum

Frequency	*Computed period*
0.140	35
0.210	23
0.344	14

The existence of these periods has been substantiated using autocorrelation on the beach cusps signal. The autocorrelogram (figure 5) shows a maximum correlation at lags 14, 23 and 35 meters.

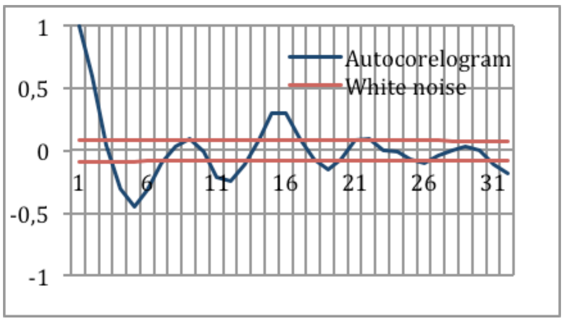


Figure 5. Autocorrelogram of beach cusps

We noticed that for both MTM and autocorrelation, the period of 14 meters is emphasized. The periods of 23 and 35 are less pronounced. To understand the relationship between the periodicity of beach cusps and swells geometry, the obtained periods have been compared to available marine hydrodynamics data [9].

The wavelengths have been computed using geometric properties of dominant swells. By dividing the swell height with the camber we find its wavelength as shown in the table 3.

Table 3. Wavelengths of swells

Direction	Height	Camber	Wavelength
320	1.52	0.0181	84
330	1.64	0.0197	83
340	1.69	0.0211	80
350	1.78	0.0228	78
360	1.75	0.0229	76
10	1.73	0.0229	76
20	1.65	0.0216	76
Mean	**1.71**	**0.0213**	**79**
180	1.41	0.0187	75
190	1.46	0.0186	78
200	1.49	0.0192	78
Mean	**1.45**	**0.0188**	**77**
270	**1.31**	**0.0174**	**75**

The mean wavelengths are respectively 79, 77 and 75 meters for NW, SW and W swells. When we compare the swell wavelengths with the periodicity of beach cusps, we noticed that for a variation from 79 to 75 for the mean wavelength, we have a variation of 35 to 14 meters of the beach cusps periods. In other terms, the swell mean wavelength is 2.25 to 5.35 times wider than the beach cusps.

We noticed also the existence of three periods in the beach cusps and three different wavelengths in the swell geometry. This leads to the possibility to seek, in further investigation, for the link between them in order to define whether the wavelengths act together or separately to shape the beach cusps.

5. Conclusion

Previous study about beach cusps focused on their mobility and evolution through marine season. Our study is in this way an exception in beach cusps morphology understanding. The apparent relationship between swell mean wavelengths and beach cusps periods must be deepened. That can be done performing parametric investigations along coast for various seasons. Such investigations will probably provide more information about the relation between beach cusps and swell hydrodynamics properties.

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