Growth of cuspate spits

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ABSTRACT

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The present work concerns cuspate spits, slightly symmetric geomorphic features growing along the shoreline in shallow waters. We develop a new working out for the dynamics of cuspate spits. Our development lies on classical paradigms such as a conservation law to the shoreface scale, and an explicit formula for the alongshore sediment transport. We derive a non-linear diffusion equation and a fully explicit solution for the growth of cuspate spits. From this general expression, we found interesting applications to quantify shoreline dynamics in the presence of cuspate spits. In particular, we point out a simple method for the datation of a cuspate spit given a limited number of input parameters. Furthermore, we develop a method to quantify the mean alongshore diffusivity along a shoreline perturbed by well-defined cuspate spits of known sizes. Finally, we introduce a formal relationship between the geometric characteristics (amplitude, length) of cuspate spits, which recall the self-similarity of these geomorphic features.

ADDITIONAL INDEX WORDS: *nearshore, sand spit, Pelnard-Considère, non-linear diffusion equation*

INTRODUCTION

A wide range of large-scale long-standing geomorphic features occur in shallow water environments, from tens of metres of water depth to the shoreline, either in the open sea or in continental settings. Ripples, megaripples, dunes and sandwaves develop in rhythmic or isolated patterns metre to kilometre long (Bruun, 1954; Bakker, 1968; Lonsdale and Malfait, 1974; McBride and Moslow, 1991; Reynaud et al., 1999; Lykousis, 2001; Todd, 2005; Raynal et al., 2009; Bouchette et al., 2010; Raynal et al., 2010). Sandbanks are a part of this family of bedforms, and include members such as mega-dunes, bars and ridges (Dyer and Huntley, 1999). Some sandbanks, termed shoreface-connected ridges and headland-associated banks, correspond to features that develop seaward from high points connected to the coast (McBride and Moslow, 1991; Dronkers, 2005). They are progading down-drift, and they usually extend down to deep waters. Obviously, these local shoreline perturbations are associated to accumulation of sand.

Zenkovitch (1959) first described cuspate spits (Fig. 1) as a limited category of shore-connected features that result from symmetrical wind/ wave forcings and/ or peculiar initial shore configuration (Bird, 1994; Coco and Murray, 2007). Asthon et al. (2001) and Asthon and Murray (2006) proned that cuspate spits, flying spits and other shoreline features derive from instabilities inherent in the relationship between alongshore sediment transport and local shoreline orientation. They exhibited a comprehensive weakly non-linear theory for cuspate and spit dynamics, and gave a striking numerical solutions to the problem.

The present work focuses on cuspate spits, also termed foreland spits, cuspate foreland or v-notches (Gilbert, 1885; Gulliver, 1896; Fisher, 1955; Zenkovitch, 1959), which are slightly symmetric shoreline-connected features that grow along the shoreline of shallow water environments. Basically, cuspates belong to the class of self-similar pattern i.e. as the time proceeds, shoreline varies while remains always geometrically similar to itself. From this point, we develop a new working out for the dynamics of cuspate forelands. We derive a non linear diffusion equation and an explicit solution for the dynamics of foreland spits. The final objective of this paper is to use the model developed with our approach to quantify mean growth velocity of cuspate spits, to contribute to the determination of their age or the mean longshore diffusivity at their origin. The paper also aims at providing additional ideas on the underlying physics of cuspate spits.

First, we recall the mechanical context driving the edification of custape spits, specifying what has been discussed already in the literature, and what we promote here. Then we present the main steps for the development and the proof of our mathematical model. Last, we adapt our cuspate model to various simple applied circumstances and we initiate a more formal discussion on the physics at the origin of cuspate spits.

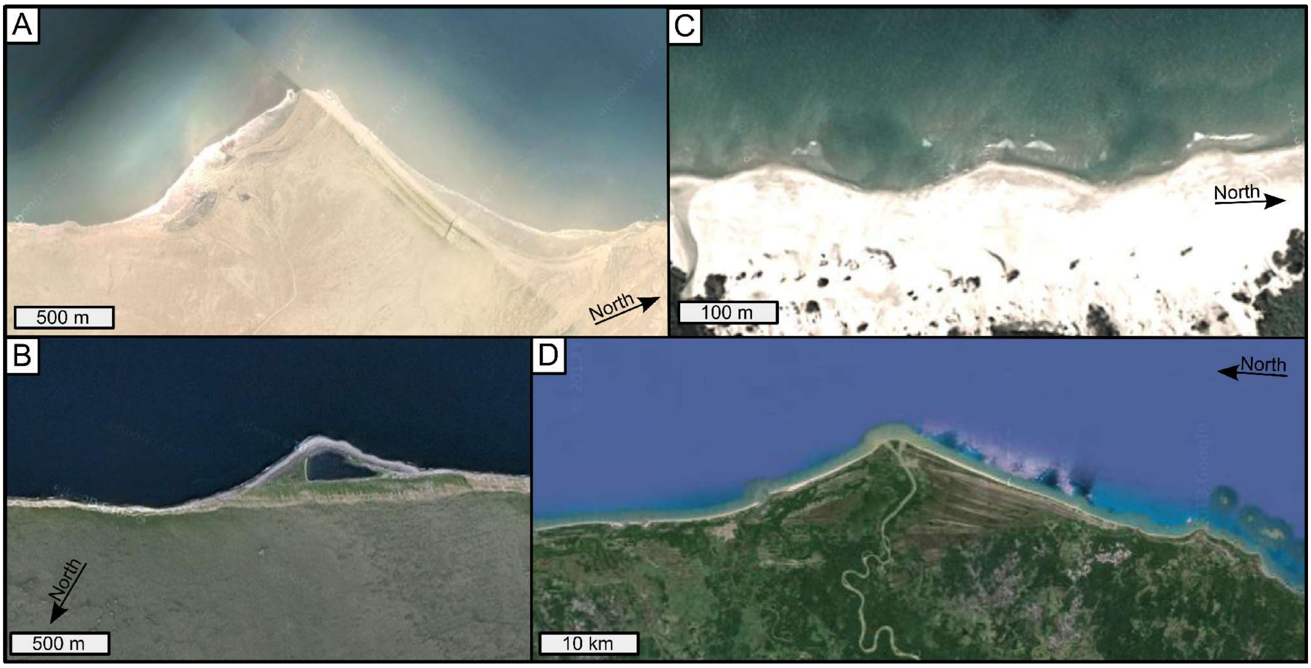

Figure 1. Examples of cuspate spits along shorelines. (A) Cuspate along the eastern basin of the Caspian Sea, the Garabogazköl Aylag y (Lat: 41.7813301; Lon: 54.3315601), (B) Cuspate in the north-eastern part of the Langandensbyggö peninsula in Island (Lat: 66.3351803 ; Lon: -14.7930432), (C) String of cuspates along the Lebanon shoreline (Lat: 32.8597276 , Lon: 35.0629139), (D) Cuspate morphology combining with the Belmonte river mouth, Brazil (Lat: -15.8595914 , Lon: -38.8902677).

THE NON-LINEAR PELNARD-CONSIDÈRE EQUATION

In this work, we make the asumption that seabottom and shoreline changes driven by strict cross-shore dynamics smooth and counterbalance over time. We consider that the consequence for the net change in the shoreline position over years is weak (Ruessink and Terwindt, 2000; Marino-Tapia et al., 2007). Indeed, at a long time scale, mean cross-shore profile is assumed to be at equilibrium (Hanson and Kraus, 1989; Dean, 1991), i.e. net cross-shore transport equals zero. The significant contribution to the long term shoreline change is thus from longshore dynamics (Allen, 1981; Aagaard and Greenwood, 1995). This asumption is at the origin of the formalism proposed here for the edification of cuspate spits.

Having this in mind, a basic mass balance equation states that the volume of sand required to move a profile cross shore is the shift of shoreline times the height of the active profile. Let be y = S(x, t) the equation of the shoreline position in a fixed (x, y) coordinate system with the x-axis oriented alongshore, the y-axis oriented offshore and t the time (Fig. 2A). S(x, t) satisfies:

$$\frac{dS}{dt}+\frac{1}{h_0+B}\frac{dQ_L}{dx}=0 \qquad (1)$$

where h_0 is the closure water depth (seaward which no significant transport occurs), B is the active berm height, h_0 + B is the height of the active profile (Fig. 2B). The total amount of sediment transported alongshore Q_L is related to the alongshore flux of energy available for the nearshore per unit length along the shoreline (Inman and Bagnold, 1963):

$$Q_L(x)=\frac{KF_L(x)}{(\rho_s-\rho)g(1-p)} \qquad (2)$$

where ρ_s and ρ are densities of sediment and water respectively, p is the porosity, g is the acceleration of gravity. The dimensionless parametre K is an empiric constant. The energy flux to the beach F_L is defined by :

$$F_L=C_g.\varepsilon_0\cos(\delta_0-\theta)\sin(\delta_0-\theta) \qquad (3)$$

where $\cos(\delta_0-\theta)$ is the ratio of incoming energy that goes from the closure water depth through the nearshore to the shoreline. In other words, it is the ratio of energy between two infinitely (dL) close wave rays that acts on an infinitely small dx shoreline segment (Fig. 2A). Forth, $\sin(\delta_0-\theta)$ is the longshore contribution of the total incoming energy. At the closure water depth h_0 , the incoming energy is classically defined with the expression derived from linear wave theory :

$$\varepsilon_0=\frac{1}{8}\rho g H_0$$

with H_0 the wave height. This energy propagates at the group velocity C_g . This velocity must be calculated at the point where the energy flows into the active domain, that is at the closure water depth h_0. In this case, the linear wave theory provides the simple formulation:

$$C_g=C_{g0}=\frac{g}{4\pi}T_0 \quad .$$

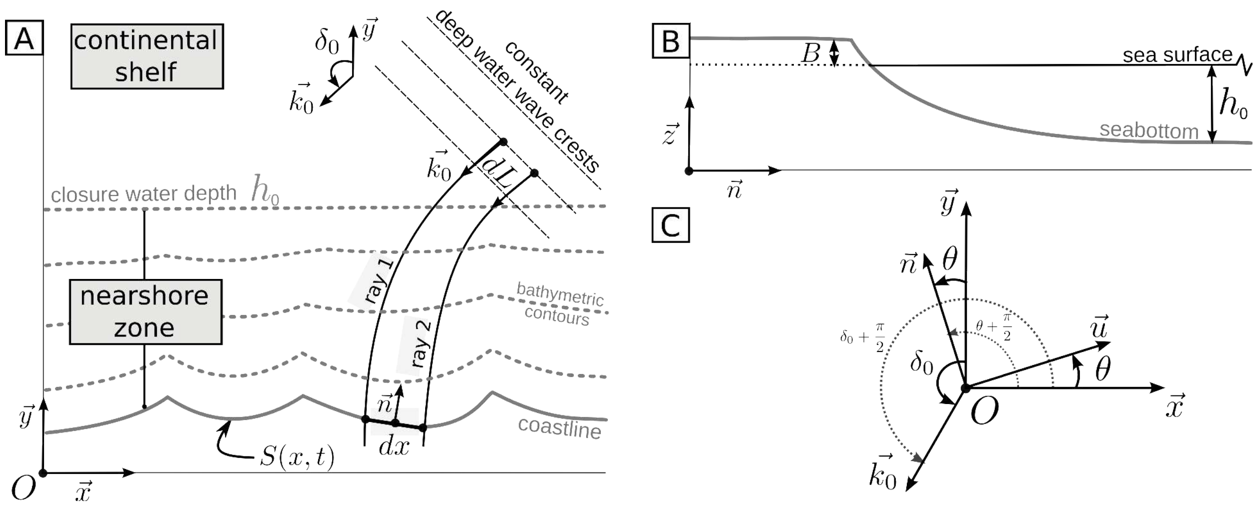

Figure 2. Sketchs for the design of the mathematical model. (A) a plan view of the nearshore and shoreline. x-axis is oriented longshore. y-axis is oriented seaward. From deep water, waves (example of Ray 1 and Ray 2) propagate from the top to the bottom of the figure and refract depending upon bathymetric contours. (B) Definition of the normal n to the shoreline, the berm height B, and of the closure water depth h_0. (C) Relative orientation of vectors and angles used in the paper.

The longshore transport rate Q_L is thus:

$$Q_L = 2C_L \cos(\delta_0 - \theta)\sin(\delta_0 - \theta) \quad (4)$$

with:

$$C_L = \frac{K \rho g H_0^2 T_0}{64\pi(\rho_s - \rho)(1-p)} \quad (5)$$

Several formulations for the alongshore transport rate were successively derived from Eq. (3) (e.g. Komar and Inman, 1970; Komar, 1971; Bailard, 1984). Reviews and compared analyses of alongshore transport formulae were also performed (Bayram et al., 2001). Here, the sediment transport is stricly controled by F_L, the longshore portion of flux of energy ε_0 per shoreline unit length. No matter what type of wave transformation occurs in the nearshore. The only significant information is the fact that $\delta_0 - \theta$ varies along the shoreline and that the energy that flows in the nearshore upward the shoreline depends upon this. This point of view is quite different from that chosen by other authors (for more explanations, see Ashton et al., 2001).

The combination of Eqs (4) and (1) is a model of long-term shoreline changes S(x, t) under mean wave forcings and mean sediment features. Until now, several strategies have been tested to find solutions for this kind of problem. First, Pelnard-Consideré (1956) (and a significant subsequent literature) had the idea to linearize the problem so that a single linear diffusion equation describes the planform evolution of S(x, y). More recently, Asthon et al. (2001) and Asthon and Murray (2006) solved the problem numerically, with an expression of Q similar (but not equal) to that of Dean and Dalrymple (2002), and introduced a diffusion coefficient that depends on θ (and may be thus negative). Asthon et al. (2001) focussed on rythmic foreland spits. Another striking idea was to introduce some non-linearity with an "expansion of the flow and the bottom perturbations in a truncated series of eigenfunctions of the linear problem" (Calvete et al., 2002; Falquès et al., 2008) which is not discussed here. The latter works concerned more specifically rythmics shoreline patterns like beach cusps. These works argued that shoreline connected features including foreland spits originate in instabilities. We provide a new solution of the problem.

The angle θ between the local normal to the shoreline and the y-axis (Fig. 2C) satisfies:

$$\sin\theta = \frac{dS/dx}{\sqrt{1+(dS/dx)^2}}$$

$$\cos\theta = \frac{1}{\sqrt{1+(dS/dx)^2}} \quad (6) \text{ and } (7)$$

Eq. (4) can be rewritten in the following Eq (8):

$$Q_L = C_L[\sin 2\delta_0(\cos^2\theta - \sin^2\theta) - 2\cos 2\delta_0 \sin\theta\cos\theta]$$

Developing Eqs (6), (7) in Taylor series until order two in $\partial S/\partial x$, and combining Eqs (1) and (8) results in

$$\frac{dS}{dt} = G_0 \cos 2\delta_0 \frac{d^2S}{dx^2} + 2G_0 \sin 2\delta_0 \frac{dS}{dx}\frac{d^2S}{dx^2} \quad (9)$$

This is a nonlinear diffusion equation. When waves are directed along the x-axis (alongshore wind/wave forcings) $\sin 2\delta_0$ is zero and Eq. (9) reduces to a classical diffusion equation (Pelnard-Considère, 1956) with G_0 the longshore diffusivity. Another way to obtain Pelnard-Considère is to linearize Eq. (9). For this reason, we could name Eq. (9) the

non-linear Pelnard-Considère equation.

In such a formulation, G_0 is given by:

$$G_0 = \frac{C_L}{h_0 + B} \quad (10)$$

And one will notice that

$$G_0 = G(H_0, T_0, \delta_0, \rho, \rho_s, p, h_0 + B) \quad (11)$$

which means that G_0 is a function of wave properties, sediment properties and basic geometrical informations.

DERIVATION OF THE CUSPATE EQUATION

From Eq. (11), we know that G_0 depends upon most of the "environmental" variables of the problem, *i.e.* those relative to the geometrical context and the forcings. As long term dynamics is mostly driven by mean values averaged to the historical/ geological time scale, we can consider that H_0, T_0, ρ, ρ_s, p are constant through time or vary very slowly. In the same manner, h_0 + B may not change as seabottom is always to the equilibrium (Short, 1999, p. 45, Fig 3).

Let us consider the following particular scenario in the frame (0, x, y) (Fig. 2A). At t = 0, we have a non perturbed shoreline for x $\in [-\infty, +\infty]$. At time t_0, a x-symmetric and positive defined perturbation appears that develop on both sides the origin O and extend in $[-x_f, +x_f]$, being zero beyond. The building of such a cuspate spit supposes that the alongshore sediment transport results from two main dominant forcings varying close enough to $\delta_0 = \pm\pi/4$. Under these conditions Eq. (11) splits in two equations with solutions S_R (for $\delta_0 = +\pi/4$) and S_L (for $\delta_0 = -\pi/4$) satisfying :

$$\frac{dS_{R/L}}{dt} = 2G_0 \sin(\pm\pi/2) \frac{dS_{R/L}}{dx} \frac{d^2 S_{R/L}}{dx^2} \qquad (12)$$

As one can consider that the two forcings compete through time, we can substitute the real system represented by the two Eqs. (12) by a model based on a distributed solution satisfying :

$$\frac{dS}{dt} = \begin{cases} 0 & \text{for } x \le -x_f \\ 2G_0 \dfrac{dS_R}{dx} \dfrac{d^2 S_R}{dx^2} & \text{for } -x_f < x \le 0 \\ -2G_0 \dfrac{dS_L}{dx} \dfrac{d^2 S_L}{dx^2} & \text{for } 0 \le x \le x_f \\ 0 & \text{for } x \ge x_f \end{cases} \qquad (13)$$

We already recalled that cuspate spits are self-similar patterns. Thus it is obvious to take into account the (x,t) dependence of S through a self-similar variable ξ so that:

$$S(x,t) \Leftrightarrow S(\xi,\tau) \quad \text{with} \quad \xi = \frac{x}{t^{1/3}} \qquad (14)$$

Applying this variable substitution to the operators d/dx and d/dt, we derive a new writing of Eq. (13):

$$\begin{aligned} &2G_0 S_{R,\xi\xi} + \frac{1}{3}\xi = 0, \xi \in [-\xi_0, 0] \\ &2G_0 S_{L,\xi\xi} - \frac{1}{3}\xi = 0, \xi \in [0, \xi_0] \end{aligned} \qquad (15)$$

Integrating twice, we obtain another expression with 4 distinct constants to be determined by the geometrical behavior of the cuspate spit. We impose to S to be continuous and positive defined at ξ=0. In addition, we impose discontinuity of the derivative of S at ξ=0. And we impose to S to be zero at the points ξ_0 where S_ξ=0. We obtain a set of equations with a single unknown parameter *a*. Going back to the original coordinates (x,y), we get a new equation.

This equation is an exact solution of the problem developed in Eq. (9) adapted to the growth of any cuspate spit. Figure 3 displays some examples of plots of the expression S(x,y) derived here at various arbitrary times and for various values of the control parameters. Each curve could be cuspate spits like those in Fig. 1. The expression of the solution in the original coordinates is given by the following Eq. (16):

$$\frac{dS}{dt} = \begin{cases} 0 & x \le -\sqrt{6a}\, t^{1/3} \\ \dfrac{1}{2G_0}\left\{\dfrac{2}{3} a\sqrt{6a} + \dfrac{ax}{t^{1/3}} - \dfrac{x^3}{18t}\right\} & -\sqrt{6at}\, t^{1/3} \le x \le 0 \\ \dfrac{1}{2G_0}\left\{\dfrac{2}{3} a\sqrt{6a} - \dfrac{ax}{t^{1/3}} + \dfrac{x^3}{18t}\right\} & 0 \le x \le \sqrt{6at}\, t^{1/3} \\ 0 & x \ge \sqrt{6at}\, t^{1/3} \end{cases}$$

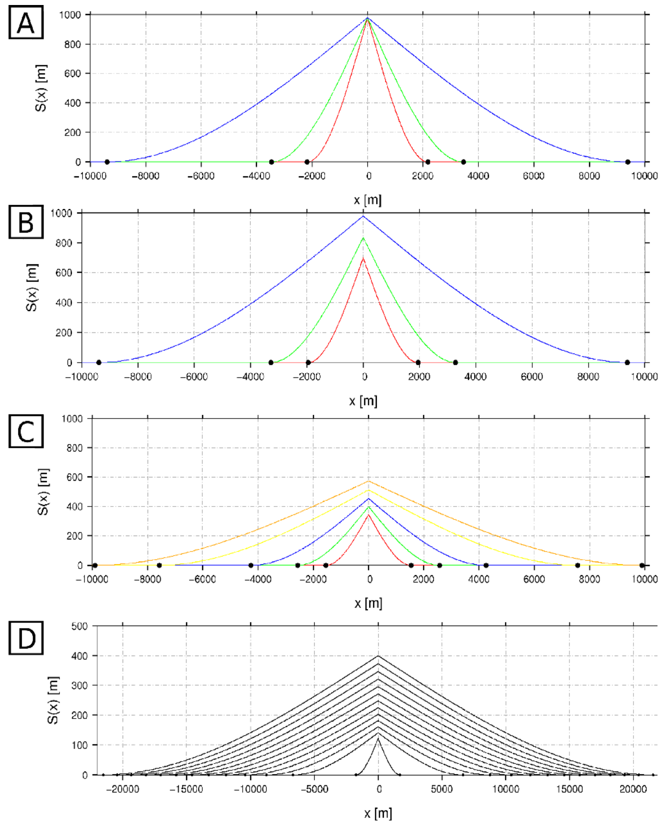

Figure 3. Various cuspate spits calculated from the mathematical model proposed in Equation (16). The different plots correspond to the configurations given below. Parameters to be set are G_0 and a. G_0 is given by K = 0.77, ρ = 1025 kg.m^{-1}, ρ_s = 2400 kg.m^{-1}, H_0=1.5 m, T_0 = 10 s, κ = 0.55,h_0 = 10m. The definition of the parameter a (arising from the integration) changes in the various plots: (A) parameter a is constant set to 20; (B) parameter a ranges from 16 to 20; (C) parameter a ranges from 10 to 14; (D) parameter a ranges from 5 to 11; the various curves represent cuspate geometry from 1 year to 450 years.

At this stage, the model must be developed further more. Indeed, unlike the longshore diffusivity G_0 which traduces the ability of the system to transport sediment alongshore, the parameter a has no clear physical meaning, as it simply results from an integration process. The plots in the Figure 3 are consistent with highly symmetric geomorphic features; but, at this stage, we have no way to use the model for applications.

USING THE CUSPATE MODEL

From Eq. (27), the length $\lambda(t)$ of the foreland spit is :

$$\lambda(t)=2\sqrt{(6at^{1/3})} \tag{17}$$

For x=0, Eq. (16) results in:

$$S(0)=\sqrt{(6)}a^{3/2}/(3G_0) \tag{18}$$

Making power three Eq. (28), and deleting a to the power of 3/2 from equations, we get the expression:

$$S(0)=\frac{\lambda^3}{2G_0.72t} \tag{19}$$

If t_p is the present time, let call

$$\Delta t=t_p-t_0 \tag{20}$$

the time required to nucleate and to develop the cuspate spit from an initial moment t_0. For convenience, let rename S(0) with A_p. With this formalism, Eq. (19) can be rewritten:

$$\Delta T=\frac{1}{2G_0}\cdot\frac{\lambda_p^3}{72A_p} \tag{21}$$

where A_p and λ_p are respectively the amplitude and the alongshore length of the cuspate spit in the present day. These parameters can be easily measured on an aerial photograph or by satellite imagery (Fig. 4), following the simple protocol described below.

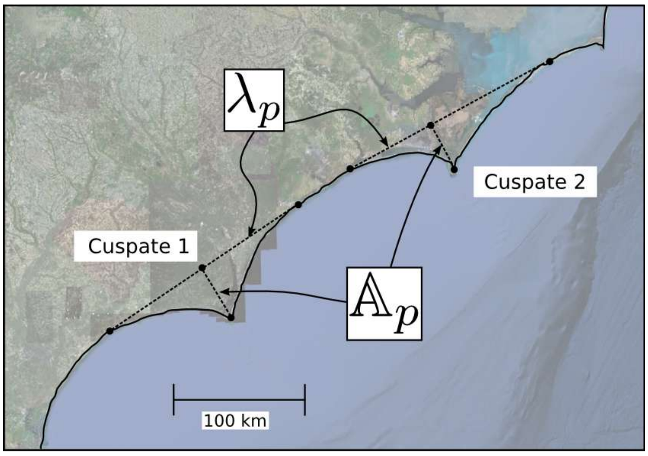

Figure 4. Sketch of two cuspate spits along the Carolina Coast, from Asthon et al. (2001). The two cuspates (1 and 2) display well defined wave length λ_p and wave amplitude A_p. Those parameters can be estimated with the methodology described in the text.

To quantify A_p and λ_p for a given cuspate, the following method is applied: a) draw a line at the tangent to the shoreline; it intersects the shoreline in two points. This defines a segment which length is the cuspate length λ_p ; (b) from the head of the cuspate spit, draw the perpendicular line to the segment defined in (a); the point at their intersection and the point at the head of the cuspate form a new segment which length is the amplitude A_p of the cuspate spit.

Eq. (21) can be considered as a method for the datation of a cuspate spit knowing the mean alongshore diffusivity and the geometrical features of the cuspate in the present day. Alternatively, the cuspate model can be thought as a tool to quantify the mean alongshore diffusivity G_0 having informations on the geometry of the cuspate spit and its age. Indeed, let consider that the present day geometry of a cuspate is known, as well as its age Δt (e.g.: dated by its occurence in an artificial continental water body damned at a given period; or directlty dated by any well-adapted datation method). These informations can be robustly retrieved from field works by geologists. From Eq. (21), it reads directly:

$$2G_0=\lambda_p^3/(72.A_p.\Delta T) \tag{22}$$

The calculation of such a mean alongshore diffusivity from parameters expressed at the geological/historical time scale is interesting for the classification of the paleo-system concerned with respect to well-known existing littoral systems (such as described in Dean & Dalrymple, 2002).

Another obvious application is to calculate the mean active profile (or the mean wave height or period) of the system at a given time knowing the present day geometry and all the other long-term mean forcings. Combining Eqs (5), (10) and (21), we have:

$$h_0+B=\frac{9K\rho gH_0^2T_0A_p\Delta T}{2\pi(\rho_s-\rho)(1-p)\lambda_p^3} \tag{23}$$

The benefit of this last application could be debated for recent cuspates. Indeed, one will claim that there exists other ways to calculate an active profile directly from data in the field (e.g. considering the analysis of wave data at a buoy, and the subsequent extraction of a closure depth). Nevertheless, for ancient cuspate spits, it seems obvious that the calculation of $H_0^2T_0$ directly from Eq. (23) would provide significant semi-quantitative restrains for the reconstruction of paleo-wave regimes. Indeed, the parameters ρ_s, ρ, p could be determined by analysis of sand properties within the cuspate deposits. λ_p and A_p could be determined by direct surface observation (or seismic investigation if the cuspate is buried). h_0 could be determined by the identification of the location where wave ripples vanish, and B by the identification of the position of the shoreline and the highest location concerned by wave impact.

A BRIEF AND MORE FORMAL DISCUSSION

The cuspate model offers the opportunity to calculate usefull parameters for coastal engineering and geosciences. But applications under real conditions are far beyond the objective of this paper, although they could be presented in future works.

Nevertheless, the cuspate model highlights a more fundamental result. Indeed, in their numerical analysis of the growth of cuspate spit, Ashton & Murray (2006) suggested that there exists an approximated relationship between the age and the length of a cuspate. They wrote (Eq. (10) in their paper):

$$\Delta t\approx\left(\frac{K_1}{D_{sf}}H_0^{12/5}T^{1/5}\right)\Delta x^2 \tag{24}$$

where Δt is our ΔT (the age of the cuspate), Δx^2 is λ_p^2 the cuspate length squared, and D_{sf}, K_1 and others can be considered as constant and are ignored in the following. The authors derived this approximated relationship from the equation at the origin of their numerical model and from an analysis of numerical simulations.

In this paper, we demonstrate with Eq. (21) that a formal relationship between the age and the length of the cuspate is mathematically correct, and that this relationship is definitively controled by a power law as Ashton & Murray (2006) suggested. Although the term to the power is different (3 in our case, 2 in the case of Ashton & Murray), these two totally independent proofs give more confidence in the reality of such a relationship. The occurrence of a power law suggests also that more underlying physics remain to be analyzed.

Last, Ashton & Murray (2006) sustained the idea that, contrary to a traditional point of view, the wave angle in deep water strongly controls shoreline perturbations, through their so-called anti-diffusional high wave angle instability. In this paper, we demonstrate that deep water wave features H_0 and T_0 drive non-linear shoreline instabilities in a simple way, with absolutely no need of what occurs to waves in the nearshore. This is also a formal confirmation of what was suggested by Ashton & Murray (2006). Forth, we demonstrate that there is no need to transform – by quite complex and obscure operations – shallow water variables into deep waters ones (Equations (1), (4) and (5) of Ashton & Murray, 2006) to get this result.

CONCLUSION

From what can be called the non-linear Pelnard-Considère equation, we develop an explicit formulation of the growth of a symmetrical cuspate spit through time. This formulation can be applied (a) to the calculation of the age of a cuspate spit, (b) to the determination of a mean alongshore diffusivity in the vicinity of a cuspate spit, or (c) to the calculation of a paleo-active profile or informations on paleo-wave regimes after some simple geological field data. More substantially, the paper confirms the works of Ashton & Murray (2006) in the sense that it provides an alternative formal proof of what was suggested. In a near future, the cuspate model will be more deeply explored, tentatively extended to other geomorphic features, and engineering/ geological applications will be engaged to confirm its relevancy.

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