Assessing the impact of sand extraction on the shore stability : project for a methodological framework

Florence Cayocca[1] and Béryl du Gardin

Ifremer, B.P. 70,29280 Plouzané, France
[1] Corresponding author fcayocca@ifremer.fr

Abstract

Extractions along the French coasts (English Channel and Atlantic coasts) take place in 1 to 8 meters water depth, 1 to 6 km from the coast line. French regulations require that dredging companies provide an environmental impact assessment (EIA) in order to obtain an authorisation to extract sand, gravel or carbonate sands. Currently however, the content of such EIAs has not been precisely defined. As a governmental research agency, Ifremer is charged with the assessment of the scientific content within these studies. A research program has been initiated in order to deliver a methodological guideline to end-users, so as to better limit impacts on the stability of the coastline as well as to set up appropriate monitoring. This paper presents existing empirical formulas allowing to easily assess the impact of a sandpit on the coastline, as well as the work in progress attempting to define more refined criteria depending on different situations.

1 INTRODUCTION

Sand mining in coastal regions is subject to different regulations throughout the world. While a minimum water depth is commonly used as a restrictive criterion for providing mining licenses in numerous countries, no such limit is used in France. As a result, extractions may very well be carried out in shallow areas where wave propagation might be altered by the sand pit or by the cutting off of a sandbank. In a general erosional context of sandy coasts, such practices are often (rightly or wrongly) held responsible for beach recession.

One of Ifremer's roles is to assess the validity of environmental impact studies carried out by dredging companies when submitting their license applications. In order to improve its expertise (and possibly refine the requirements of the environmental impact assessments), Ifremer has initiated a research program aiming at better understanding the impact of sand pits in shallow water on the bottom morphology. While monitoring of extraction sites is now required and can help us understand how the morphology of sand pits evolves depending on the local physical processes (waves, currents, geometric characteristics of the pit, bottom slope, sediment size *etc.*), we need to be able to predict long term evolutions in order to reduce negative impacts due to poor coastal management.

Several international programs aim at establishing sensible regulations in order to use the existing resources with minimum impact to the physical environment (such as the European Project SANDPIT or documents edited by the International Council for the Exploration of the Sea : ICES). In line with these projects, Ifremer's goal is to provide end users (coastal managers, dredging companies, consultants) with guidelines defining the content of Environmental Impact Assessments (EIA), as well as monitoring strategies. After briefly describing the current regulations in France, we will present the existing empirical formulations to be used as a first approximation in order to assess physical impacts on the coastline in simple cases. These formulations have to be used with care since they cannot necessarily be applied to complex situations. We have been exploring the possibility of using a morphodynamic model in order to predict as rigorously as possible long term effects of a sand pit. The fourth section of this paper describes the work in progress in order to reproduce evolutions of a sand pit as modelled in a flume experiment from Migniot and Viguier (1983).

2 REGULATIONS

No absolute criterion such as a minimum water depth or distance from the coast is used in France : each application for a dredging permit requires an Environmental Impact Assessment from a consultant chosen by the dredging company. The whole licensing procedure related to marine aggregates is actually similar to the procedure applied for mining on land. The administration responsible for reviewing the requests is the Department of Industry. Local authorities, regional administration for industry, research and environment as well as scientific and technical state agencies are also consulted. Once the decision to issue the license has been made, an additional procedure has to be undertaken in order to obtain official permission from the State to use public land (the sea floor belongs to the French State) before being allowed to actually start dredging. All together, these procedures may take up to 3 years.

Since no guideline accurately defines the content of Environmental Impact Assessments, the quality of the studies carried out by consultants for the dredging companies may vary greatly. Even though the current procedure is quite cumbersome, regulating authorities have invested little time thus far into improvements due to the small amount of materials extracted along French coasts : about 3 Mm^3 per year in the past 5 years (the largest exploitation extracts less than 1 Mm^3 per year). Within European efforts to encourage sustainable development, Ifremer's project aims at

- better understanding possible effects of sand mining on the stability of the coastline,
- providing sensible guidelines in order to better ensure preservation of the environment,
- ultimately contributing to simplify the procedure.

3 IMPACT ASSESSMENT

3.1 Types of impact

Impacts of a sand extraction site (whether it takes the shape of a sand pit or a sand bar exploitation) depend on :

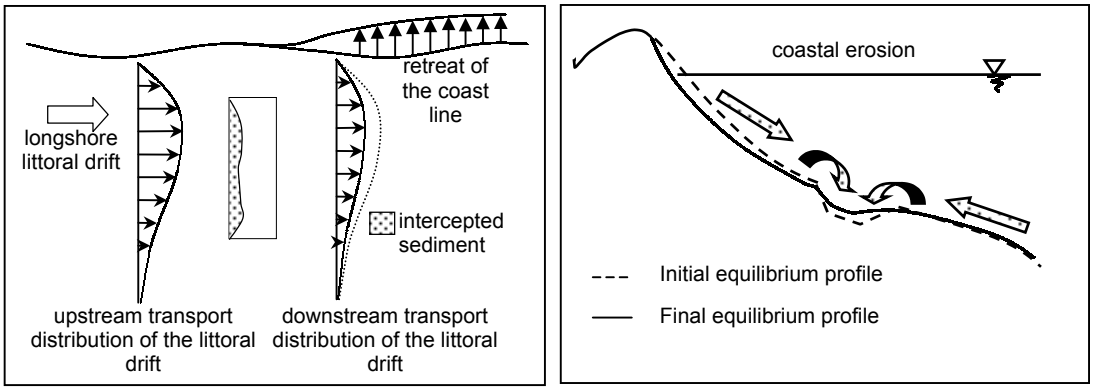

Figure 1 : longshore and cross-shore interception of sediment

- geometrical parameters such as the shape of the site (length and width relative to the direction of incident waves), depth, the distance from the coastline and the bathymetry between the site and the coast line,
- hydrodynamic parameters such as waves, currents and
- sedimentological parameters (grain size, rheology).

The new bottom configuration after the extraction has taken place induces modified patterns of wave propagation and sediment transport. Under these new conditions, the geometry of the site itself and of the area influenced either directly by the new bathymetry or indirectly by the new wave propagation will reach a new equilibrium. Locally, and depending on the nature of the outcropping sediments after dredging, the bottom of the extraction site may be smoothed, while the whole site may migrate under the influence of dominant currents. Effects on the coastline may result from interception of the longshore sediment transport or of the seasonal cross-shore transport (Figure 1). They also result from the new pattern of wave propagation, mainly refraction by the extraction pit (increased wave heights on either side of the pit, Figure 2), and modification of the breaking location.

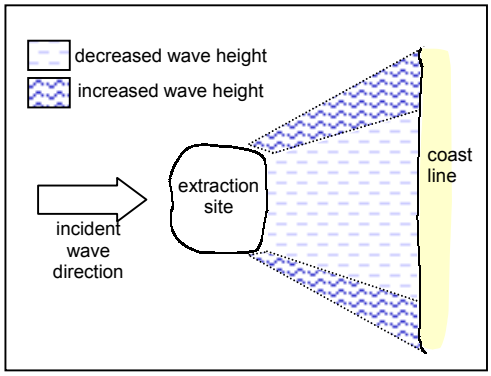

Figure 2 : effects of the extraction site on wave refraction

Limited alterations of the coastline will therefore be ensured as long as :

- the extraction site is located outside the “active transport zone” where interception of long-shore or cross-shore transport may occur,
- the position and shape of the extraction site do not induce negative effects on the wave propagation such as increased wave heights in sensitive areas.

These two factors are investigated hereafter.

3.2 Determination of the active transport zone

3.2.1 Cross-shore transport

Winter wave conditions tend to erode the higher portion of the beach profile by increasing offshore bottom currents and transporting sediments offshore, while summer conditions tend to replenish the upper profile. This seasonal cross-shore transport is limited to a water depth called depth of closure beyond which the bottom profile is not affected by seasonal variations in wave conditions (Pilkey et al., 1993), (Work and Dean, 1995), (Nicholls et al., 1998). A widely used and well validated formulation for this depth of closure concept was derived by Hallermeier (1978) and modified by Nicholls *et al.* (1998), and reads

$$d_{ct} = 2{,}28 * H_{s(12h,t)} - 68{,}5 * \frac{H^2_{s(12h,t)}}{g * T^2_{s(t)}} \qquad (1)$$

where d_{ct} is the depth of closure derived from the time length of observation t, $H_{s(12h,t)}$ is the highest significant wave height of non breaking waves that occur for more than 12 hours during t, and T_s the associated period. As time of observation increases, d_{ct} also increases (since the highest significant wave height is likely to increase), and this formulation is not valid in situations of accretion.

Hallermeier (1981) also derived a generally more restrictive water depth independent of the time of observation :

$$d_i = H_{sm} T_s \sqrt{\frac{g}{5000 * D_{50}}} \qquad (2)$$

where H_{sm} is the mean of the annual distribution of significant wave height, T_s the corresponding period and D_{50} the median grain diameter. This formulation also takes into account sediment mobility through the grain diameter, which makes it more “portable”.

3.2.2 Long-shore transport

While some work has been completed regarding interception of long-shore transport by dredged channels (usually perpendicular to the direction of the littoral drift), little has been published on the influence of extraction s (Katsui and Bijker 1986; Ting 1986, van Rijn, Sutton et al., 1994). A method to determine how far from the coast line a sand pit can be placed consists in finding the water depth beyond which the littoral drift is considered non-significant (Hanson and Kraus, 1989). Assuming that :

- the littoral drift due to a given significant wave height H_s is limited to a water depth d_{lt} such as

  d_{lt}=1.6 x H_{sb}

  where H_{sb} is the breaking wave height,

- the contribution of each wave height to the annual littoral drift Q is proportional to the occurrence f of this wave height and to $H_{sb}^{2.5}$,

$$Q \propto \sum_{H_s} f H_{sb}^{2.5} ,$$

they define the critical depth $d_{l,i}$ beyond which less than i% of the annual littoral drift will occur :

d_{li}=1.6 x $H_{sb(i\%)}$

where $H_{sb(i\%)}$ is the significant wave height (at the breaking point) of the waves responsible for less than i% of the annual littoral drift.

Comparison of the magnitude of the limited water depths prescribed by these formulas in order to avoid interception of long-shore and cross-shore sediment transport is shown Figure 3, assuming a realistic relationship between wave heights required for the computation (see figure caption). This comparison shows that Hallermeier's formulation (equation 2) is in this case the most restrictive. However this result depends on the wave climate, and the most restrictive formulation should be used according to every particular situation.

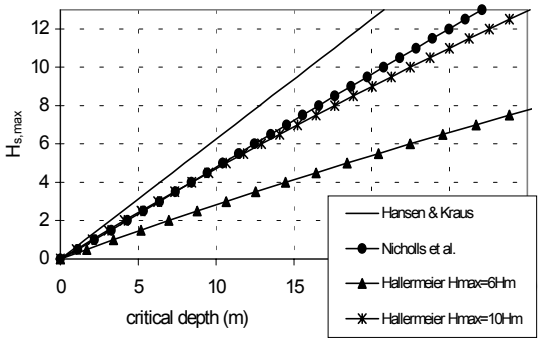

Figure 3 : comparison between the depth of closure d_{ct} calculated from Nicholls *et al.* and the depth $d_{l2\%}$ beyond which 2% of the annual littoral drift occur, as a function of the maximum significant wave height, assuming that $H_{s(12h,t)}$=$H_{sb(2\%)}$, $H_{s,max}$=6 x H_{sm} (or $H_{s,max}$=10 x H_{sm}) and T_{sm}=aH_{sm}+T_0 with a=1 m.s^{-1} and T_0=8.5s.

3.3 Modification of wave propagation

As they reach the extraction site, waves are refracted in such a way that waves travelling above the deeper regions accelerate and reach the coastline earlier than they would have without the sand pit (Figure 4). This relative advance Δt was quantified by Migniot and Viguier (1983) for the case of a straight coast and wave incidence normal to the shore :

$$\frac{\Delta t}{T} = l_s\left(\frac{1}{\lambda_0} - \frac{1}{\lambda}\right)$$

where λ is the wave length above the sand pit and λ_0 the wave length at the same water depth without the sand pit. The author found from their experimental results that refraction effects on the shore evolution were negligible as long as :

$$\frac{\Delta t}{T}\frac{\lambda_{sc}}{L_{sc}} \le 0.02$$

where L_{sc} is the distance from the pit to the shore and λ_{sc} is the average wave length over the distance L_{sc} (du Gardin et al., 2002).

This simple formulation could be improved to take into account oblique incidence, and to explicitly include sedimentological parameters.

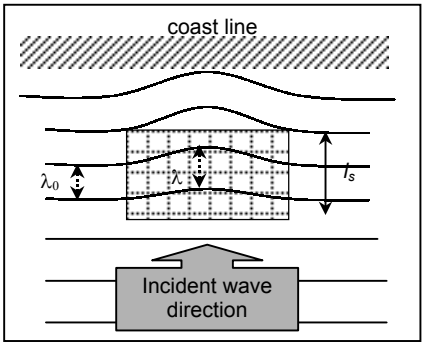

Figure 4 : relative advance of the waves due to refraction above a sand pit.

When extractions consist in exploiting sand bars on which wave were breaking before the exploitation (water depth above the bars : d) and still break afterwards (new water depth over the bar : d+p), the relative increase in wave height between the sand bar and the shore can be computed (Figure 5). Assuming that the maximum wave height after breaking H_{max} does not exceed the wave height at breaking (which implies that there is no wave growth after the first breaking) and using Battjes and Jansen's breaking criterion, we get :

H_{max}=γd with γ=0.75.

Hence the relative increase of wave height due to the sand bar lowering reads

$$\frac{\Delta H_{\max}}{H_{\max}} = \frac{p}{d} .$$

This simple formulation may be used to set a maximum thickness of material to be removed in order to not increase waves by more than a given value.

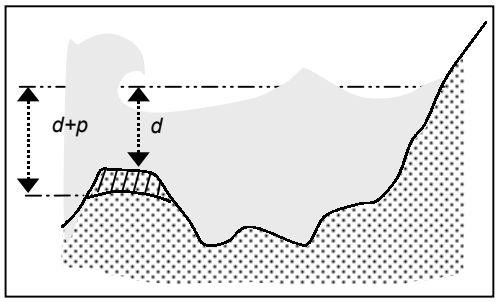

Figure 5 : schematic geometrical setting for exploitation of a sand bar.

Numerical simulations were used to investigate the relative influence of several parameters on the variation of wave height at the breaking point due to the presence of a rectangular pit. (Armède, 1999; du Gardin et al., 2002). The main process taken into account during these simulations was the wave refraction. The results showed that :

- regarding the 3 dimensions of a rectangular pit, for a given volume, the worsening factors are (in decreasing order) : the dimension perpendicular to the wave crests, the depth of the pit, the dimension parallel to the dominant wave crests. In the schematic case of a straight coast and a dominant wave direction, the least harmful configuration is therefore a shallow rectangular pit with the longest side parallel to the wave crests.

- a small directional spreading of the waves is a worsening factor : nearly mono-directional waves such as swell enhance refraction effects.

- the distance from the shore is of course of influence.

However, in complex situations, more advanced computations need to be carried out in order to better predict what the effect of an extraction site will be on the wave propagation.

4 PHYSICAL EXPERIMENTS AND NUMERICAL SIMULATIONS

Physical experiments were carried out in 1979 and 1983 (Migniot and Viguier, 1983) in order to quantify the effects of a sand pit on the surrounding morphology in a configuration representative of conditions along the French Atlantic coast. One set of experiments was run in a clear glass flume in order to find a critical wave height above which the pit fills in, depending on the water depth. The relationship they found therefore defines the depth of closure, *i.e*. for a given wave climate, the distance beyond which no local transport is observed. Experimental results are in perfect agreement with observations carried out in the field (experimental data points fit Hallermeier's curve, eq. 2). This result confirms the validity of the scaling suggested by Migniot and Viguier to transpose evolutions observed in the flume to evolutions in nature.

Another set of experiments was run in a wave tank. They reproduced 3-dimensional, long-term morphological evolutions of the pit itself and of the coastline. The results were used to derive design criteria (such as water depth and orientation of the pit) only valid in the circumstances of the experiments (*i.e.* given wave and tide conditions, sediment size and bottom slope).

Restrictions stemming from the application of empirical formulas derived from flume or tank experiments are a result of 1) the scaling always required between model and nature, 2) the limited number of situations that can usually be reproduced in an experiment (different grain sizes, geometrical configurations, wave and current conditions *etc*.). Numerical models are very flexible in that respect. On the other hand, the accuracy of long-term morphodynamic predictions still needs to be improved. In order to assess the capacities and limitations of existing numerical models to predict general trends of evolution in different circumstances, we decided to apply a numerical model to the Migniot and Viguier experiments. Our goal here is not to simulate the field configuration represented by the scale model, but to simulate the actual evolutions observed at the scale of the experiment. Once the numerical model has been shown capable of predicting reasonable evolutions (under progress), it can be applied to a variety of situations, from which general design criteria should be derived.

5 CONCLUSIONS

Sensible environmental impact studies need to be carried out in order to ensure sound use of marine resources in agreement with other users, while preserving the quality of the environment. While the exploitation of aggregates on land is also surrounded by controversy, the limited impact of marine aggregate extractions must be assured in order to preserve the activity as well as the environment.

The different configurations of the coastline along European coasts partly explain why regulations are different from one country to the next : minimum water depth or distance from the shore are not necessarily relevant in all cases. However, long–term effects of aggregate dredging on coastline stability are not well known, and more research needs to be done in order for numerical models to accurately predict such impacts. Meanwhile, practical guidelines need to be developed in order to ensure proper use of marine resources. Existing empirical relationships are available as first approximations in order to limit the size and location of extraction pits, and Ifremer (along with other European institutes) is working at developing new criteria from numerical simulations representing different configurations as observed along European coasts.

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