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Analysis of Some Solutions to Protect the Tombolo of GIENS

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***Abstract*—**The tombolo of Giens is located in the town of Hyères (France). We recall the history of coastal erosion, and prominent factors affecting the evolution of the western tombolo. We then discuss the possibility of stabilizing the western tombolo. Our argumentation relies on a coupled model integrating swells, currents, water levels and sediment transport. We present the conclusions of the simulations of various scenarios, including pre-existing propositions from coastal engineering offices. We conclude that beach replenishment seems to be necessary but not sufficient for the stabilization of the beach. Breakwaters reveal effective particularly in the most exposed northern area. Some solutions fulfill conditions so as to be elected as satisfactory. We give a comparative analysis of the efficiency of 14 alternatives for the protection of the tombolo.

***Keywords*—**Breakwaters, coupled models**,** replenishment, silting.

I. Introduction

THE geographic coordinates of the tombolo of Giens are 43.039615 °N to 43.081654 °N and 6.125244 °E to 6.156763 °E, between the Gulf of Giens and Hyères harbor. The Almanarre beach consists of the western part of the tombolo, and is subject to coastal erosion. Since more than 50 years research has been conducted to try to understand the dynamics of this erosion [1], [2], and help establishing a protection plan for the coast which presents important economic and environmental impacts. In a preceding paper we collected all available data on the subject, compiled it to numeric format, and calibrated a coupled model using MIKE 21 so as to understand the prominent factors at the origin of this erosion process, and the hydro-sedimentologal dynamics of this complex system [3].

There it was concluded that the tombolo should be divided into four significant cells and that heavy impact occurred mainly during southwestern winter storm events conjugated to atmospheric depression.

In the present study we use our calibrated model and investigate numerically some solution proposals, some arising from engineering consultants, others we propose here. We also give a look to economic aspects of the proposed solutions (costs), to help politics make a decision towards this recurrent and yet costly problem (beach replenishment occurs each year and costs more than $3x10^5$ € a year, without maintaining stable the situation which worsens).

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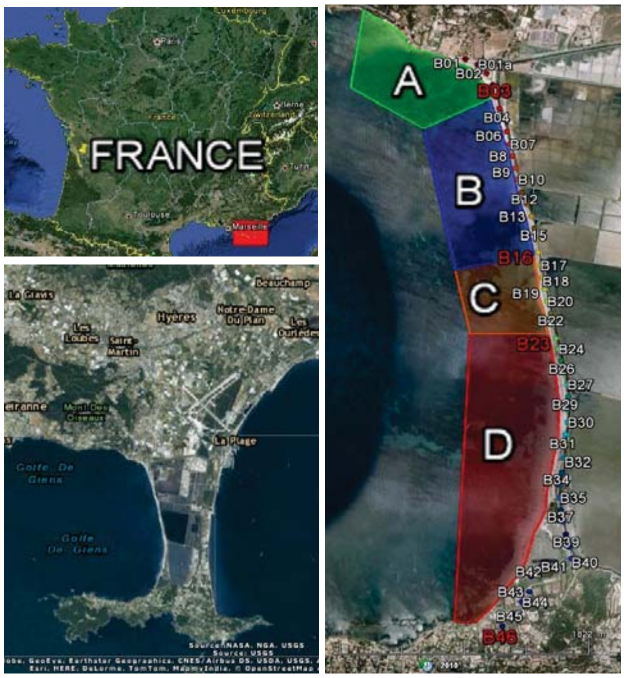

Fig. 1 Western tombolo hydro-sedimentary cells

The cells are determined by their limiting landmarks (Fig. 1). The geometries of the cell are collected in Table I: North (A) is from north boundary to B03, North-central (B) B03 to B16, central (C) B16 to B23, and South (D) B23 to B46 [4]. The North-central zone is the most affected by erosion [2], [5], [6]. The absence of natural sediment supply and ancient anthropic influence weigh also on the erosion process [7], [8]. The coastline has driven back east by 50 m to 80 m in the central zone, 75 m to 90 m in the southern, since 1956 [7]; by 15 m to 20 m in the north zone (average 40 years, 1950 to 1998) [5]. The height of the sand dune has decreased by 0.3 to 1.5 m in the late 80's and the 90's [9].

TABLE I
Hydro-Sedimentary Cells for the Western Tombolo of GIENS

Cell	Mean width (m)	Length (m)	Perimeter (m)	Surface (m^2)
A	533	1257	3074	517070
B	585	1287	3578	703840
C	570	626	2316	325655
D	623	2544	5332	1273597
Total	**2311**	**5714**	**14300**	**1721343**

Hereafter, we will describe previous attempts to protect the tombolo. Then, we investigate soft solutions, solutions with underwater structures, and combined solutions, using our calibrated model. We will estimate there efficiency by the change of global bathymetric volume on the zone of study, and the evolution of the coast profile at different landmarks. We will also investigate the efficiency towards the transport of sediments between cells. And finally we shall estimate the costs for each solution.

We have tested 15 scenarios, among which number 1 corresponds to status quo. The estimation is based on different regimes we identified as characteristic in the previous article, for the data period of year 2008.

The paper ends with a conclusive section.

II. Protection of the Tombolo: The Proposed Alternatives

A. Previous Attempts

The northern beach has been locally protected by a riprap revetment that was recently removed [5]. Indeed, the effect of these blocks on the beach sedimentological balance was negative. After a storm in 1994, which destroyed the dune and submerged the parallel road ("*route du Sel*"), the choice was made to start periodically replenishing the dune [5]. Later, ganivelles were installed (so as to protect from anthropic destruction, the area being highly touristic summer time), and car parkings were organized [5]. Also, the "*route du Sel*" was closed winter time.

The area is protected (Conservatoire du Littoral) and close to a high environmental importance zone (Parc Naturel de Port Cros). This means that any solution to be proposed should take into account visual, environmental, and economic impacts.

Reloading occurs winter time essentially but reveals non-sufficient and costly. Each year the dune is restored (with a mixture of sand and posidonia leaves) but this does not stop the beach drawback in the north central zone.

Alternative 0 will be for us status quo: just go on as it is.

B. Soft Solutions

The submerged area is covered mainly by a posidonia field, which absorbs wave energy, retains offshore sediment transport, and covers during western and south western episodes the beach with posidonia algae that has the property to damp wave impacts to the coast. Recently the decision was taken to preserve this algae coverage, though touristic attractively has little decreased. The preservation of the posidonia field and the maintenance of ganivelles has already limited the erosion process, though the limitation has not been precisely measured.

Replenishment with a sand-algae mixture allows maintaining and restoring the dune in the north-central and north zones.

1) Pure Silting Scenarios

Silting with quarry sand or gravels has been proposed by [10]. It can be envisaged with or without structures. ERAMM proposed reinforcing beach foot by the way, arguing that without additional structure the solution is short term (Fig. 2). Table II shows the description of alternatives 1 and 2, consisting of only silting with quarry sand in restricted areas. The bathymetry comes from our previous paper.

TABLE II
SILTING VOLUMES FOR ALTERNATIVES 1 AND 2

Alternative	Protection	V (m^3)	Length	Width
1	B07 to B11	66680	460 m	136 m
2	North + North-central	218061	2000 m	136 m

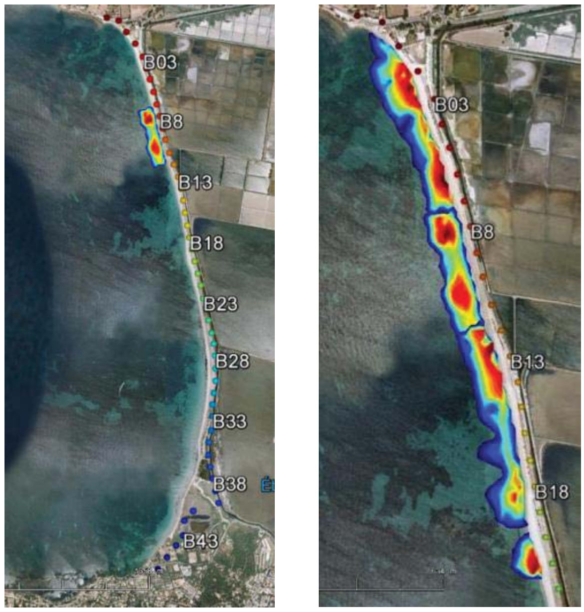

Fig. 2 Variation of bathymetry for alternative 1 - silting in the cell B (left) and alternative 2 - silting in the cells A to C (right).

2) Adding Small Structures to 1 and 2

The next alternatives (3 to 6) will consist in silting and adding a beach foot and immersed breakwaters, or immersed breakwaters with immersed groins (Fig. 3) [10].

The description of these alternatives is collected in Table III.

TABLE III
SILTING AND SMALL STRUCTURES – CHARACTERISTICS FOR ALTERNATIVES 3 TO 6

Alternative		3	4	5	6
Protection		B07 to B11	B07 to B11	North-central	North-central
Silting volume	V	66680	66680	218061	218061
	L	460	460	2000	2000
	W	136	136	136	136
Beach foot	Q	1	1	3	3
	Rc	-1.12	-1.12	-1.12	-1.12
	D	100	100	100	100
	L	150	150	150	150
	B	230	230	230	230
	S	12	12	12	12
Immersed breakwater and groin	Q	None	1	None	3
	Rc	-	-1.12 to 0	-	-1.12 to 0
	L	-	100	-	100
	B	-	380	-	380
	S	-	12	-	12

V = volume (m^3); L = length; W = Width; Q = quantity; Rc = crest freeboard (m); D = shore distance; B = crest width; S = Spacing.

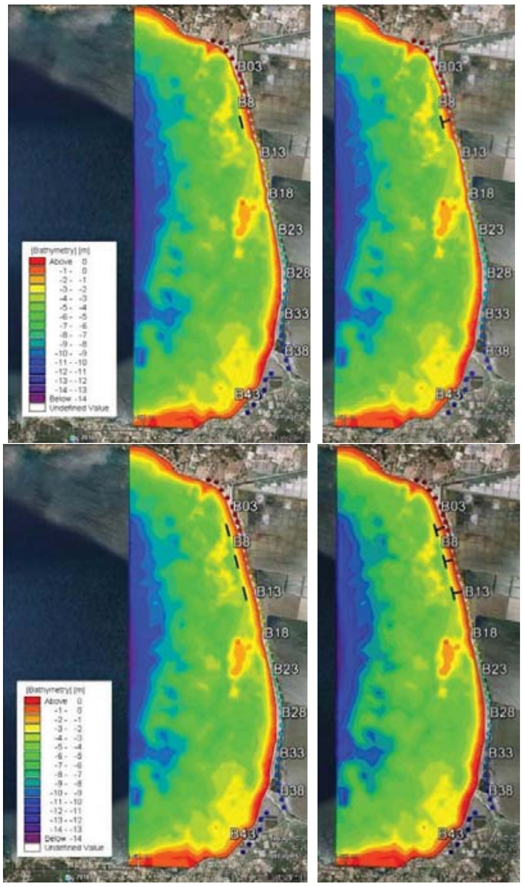

Fig. 3 The alternatives 3 to 6: alternative 3 – silting with one beach foot (left, upper); alternative 4 – silting with one beach foot and one groin (right, upper); alternative 5 – silting with three beach foots (left, lower); alternative 6 – silting with three beach foots and three groins (right, lower)

TABLE IV
CHARACTERISTICS FOR STRUCTURES ALTERNATIVES 7 TO 11

Alternative		7	8	9	10	11
Protection		B07 to B11	North-central	North-central	Whole beach	Whole beach
Offshore immersed breakwaters	Q	None	2	2	4	4
	Rc	-	-3	-3	-3	-3
	D	-	400	400	400	400
	L	-	340	340	340	340
	B	-	280	280	280	280
	S	-	12	12	12	12
Close shore immersed breakwaters	Q	1	3	3	6	6
	Rc	-2	-2	-2	-2	-2
	D	200	300	300	300	300
	L	440	340	340	340	340
	B	-	280	280	280	280
	S	12	12	3	3	3
Immersed breakwater with groin	Q	2	None	3	None	3
	Rc	-2 to 0	-	-2 to 0	-	-2 to 0
	L	200	-	300	-	300
	B	440	-	620	-	620
	S	12	-	12	-	12

L = length; Q = quantity; Rc = crest freeboard (m); D = shore distance; B = crest width; S = Spacing.

C. Hard Coastal Protection Solutions

We propose protection solutions with two barriers of breakwaters, one close and one further away offshore [1], [11]. Breakwaters will be either made of concrete, either from riprap [11]. In the model the two alternatives are treated as solid. Table IV and Fig. 4 give a description of scenarios 7 to 11.

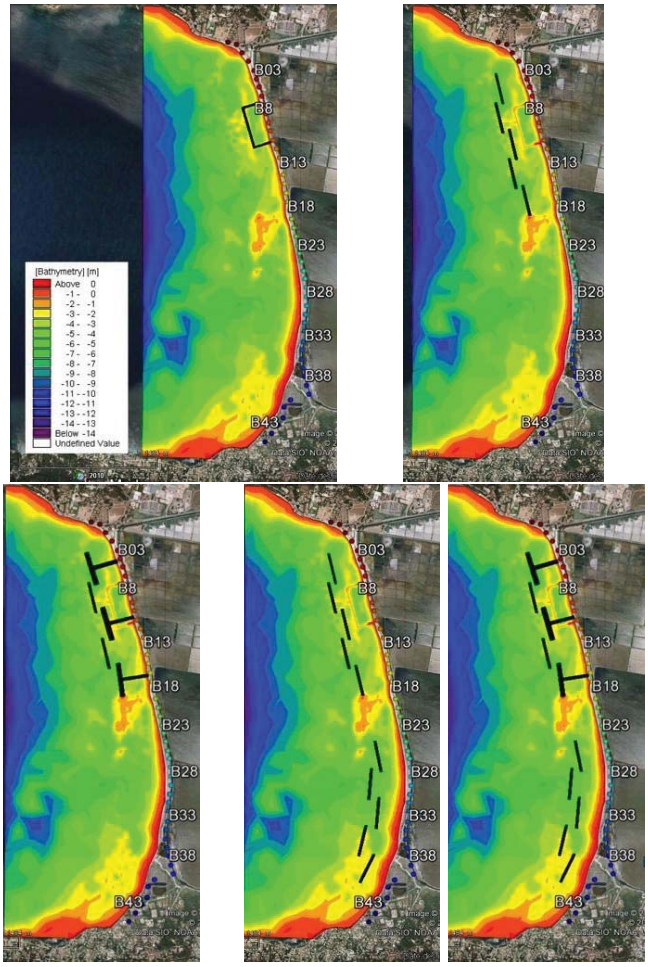

Fig. 4 The alternatives 7 to 11: alternative 7 - one close shore immersed breakwaters and two immersed groins (left, upper); alternative 8 - two rows of 5 breakwaters (right, upper); alternative 9 - two rows of 5 breakwaters with the addition of 3 groins (right, lower); alternative 10 - two rows of 10 breakwaters (middle, lower); alternative 11 - two rows of 10 breakwaters with the addition of 3 groins (right, lower)

D. Combined Alternatives (Soft and Hard)

The combined alternatives are numbered from 12 to 14: alternative 12 is as alternative 7 but with beach replenishment from landmark B07 to B11. And alternatives 13 and 14 are respectively as alternatives 8 and 9, with the same replenishing as alternative 12.

III. SCENARIOS EVALUATION VIA NUMERICAL SIMULATION

Our model couples wave, current, and sediment transport [12]. It was calibrated as described in our previous paper.

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Immersed structures are simply represented by a change in bathymetry, with mean grain size equal to D_{50} = 20 cm which makes it « solid » (unaffected by sediment transport, Manning and rugosity are those of rock).

Table V gives a description for all the scenarios:

TABLE V
CHARACTERISTICS OF ALTERNATIVES 0 TO 14: SUMMARY

Alt.	Silting (m^3)	Structure length (m) Beach foot	Immersed breakwater +groin	Immersed breakwater Close	Far
0	Dune preservation				
1	66680				
2	218061				
3	66680	150			
4	66680	150	100		
5	218061	450			
6	218061	450	300		
7			400	440	
8				1020	680
9			900	1020	680
10				2040	1360
11			900	2040	1360
12	66680		400	440	
13	66680			1020	680
14	66680		900	1020	680

A. Domain

The structured mesh includes 2276 nodes and 4365 elements. A local refinement with higher spatial resolution has been made at the proximity of immersed structures. The overall computational mesh is shown in Fig. 5. The mesh size is smaller than 219 m (offshore), and greater than 2 m (proximity of immersed structures).

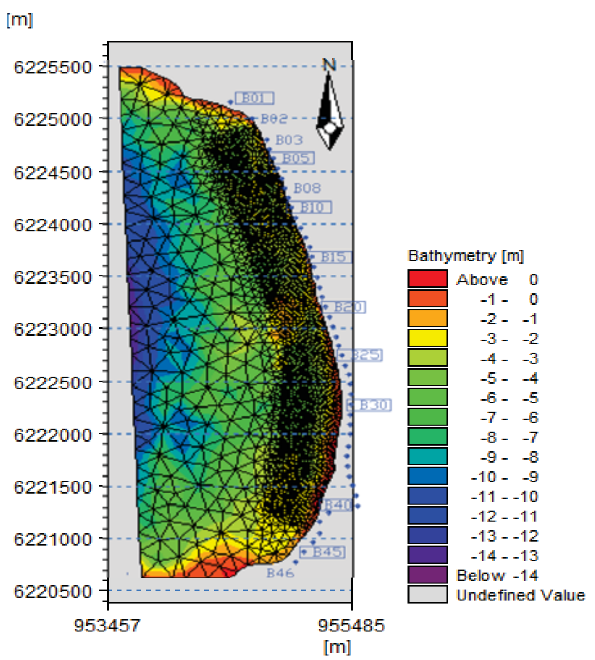

Fig. 5 Domain and grid structure

B. The Evaluation of the Efficiency of a Scenario

The model is run over two significant types of conditions as defined in our previous paper. One is average yearly based on 2008 observations, which are relevant for the 1995 to 2010 period. The other is of type tempest with south-western conditions which are the worse for erosion phenomena, but also western conditions and mistral episodes. These conditions are used as border conditions for the grid.

1) Global Volume Change of the Area

The graph of the variation of the volume change per day is shown in Fig. 6.

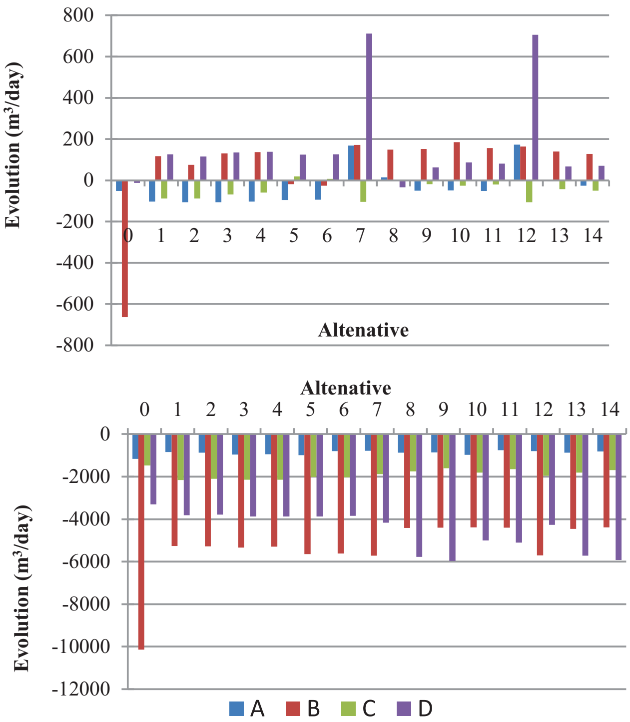

Fig. 6 Volume variation per cell annual (upper) and storm (lower) conditions

The volume change was estimated from -650 m^3/day (annual condition) to -10^4 m^3/day (storm condition) if we do nothing (alternative 0). In general, all the solutions reduce the phenomenon of marine erosion of the tombolo of Giens (Fig. 6). The greatest increase in total volume (711 m^3/day) was observed in the alternative 7. Fig. 6 shows all areas are eroded by storm, with major erosions in zone B and D. The solutions fall by about 50 percent erosion in area B, but they are accompanied by an increase in erosion area C and D. Zone B has the most fluctuations. Other areas show less fluctuation (Fig. 6).

2) Beach Profile Evolution

We have extracted from the simulation the beach profile evolution at landmark B08 with reference point alternative 0. First we look at the alternative's effect under annual conditions, and we group alternatives by type: the first group is alternatives 1 to 6 (Fig. 7) with reference point alternative 0;

the second group is alternatives 7 to 14 (Figs. 8 and 9) with reference point alternative 0.

The alternatives 2, 10, 11, 12 and 14 even generate accretion from 100 m (normal condition) to 200 m (storm condition) first meters of the profile. However, between 300 m and 400 m (in the gap between two rows of breakwater), a significant erosion has taken place.

In the other alternatives, the profile was attacked at the layer near the coast (100 m from the landmark B08).

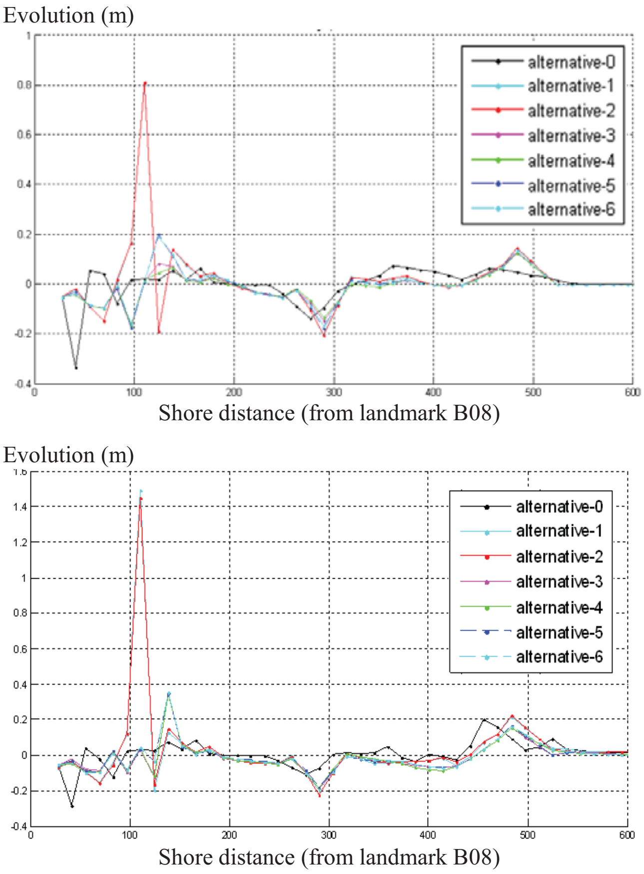

Fig. 7 Change in bathymetry landmark B08 annual (upper) and storm (lower) conditions for the alternatives from 1 to 6

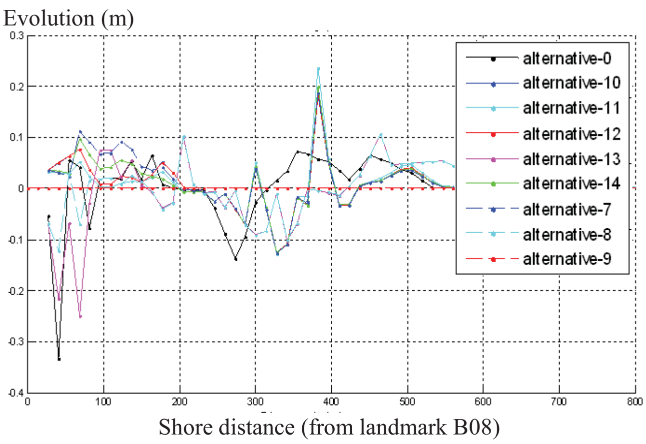

Fig. 8 Change in bathymetry landmark B08 annual conditions for the alternatives from 7 to 14

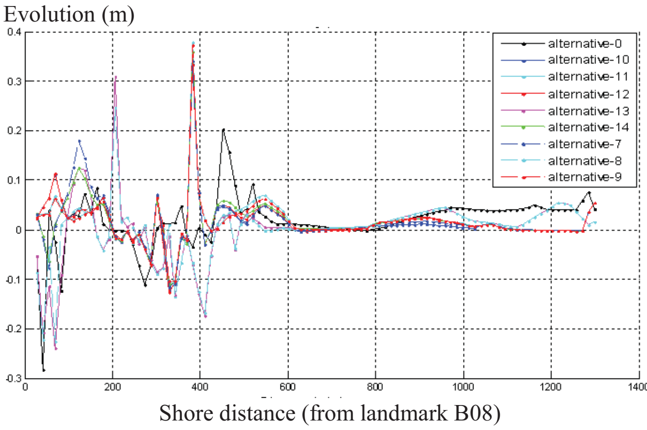

Fig. 9 Change in bathymetry landmark B08 storm conditions for the alternatives from 7 to 14

3) Sediment Transport per Cell

Fig. 10 shows the sediment transport per cell for 14 alternatives.

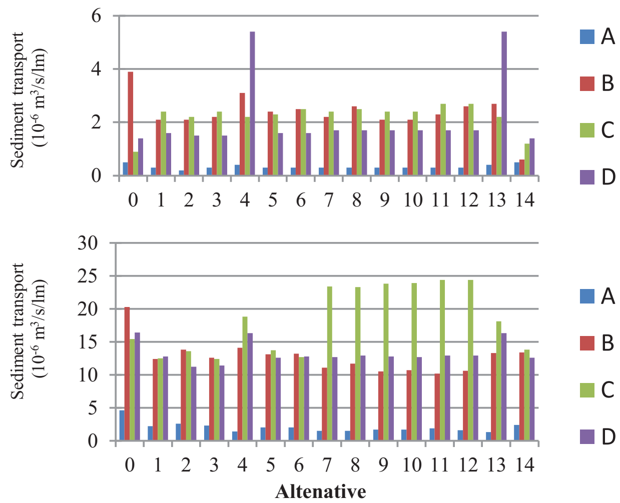

Fig. 10 Sediment transports per cell, annual (upper) and storm (lower) conditions

Sediment transport has also been extracted on profile B08 for the different alternatives. We observe (Figs. 11-13) that sediment transport decreases between 100 m and 200 m. The alternatives 10, 11, 13 and 14 generate accretion at this profile.

In the alternative 0, the total sediment transport varies between 80 to 600 m^3/year/lm (annual condition) and 350 to 5600 m^3/year/lm (storm condition) (Fig. 11).

In alternatives 1 to 6 (Fig. 11), the sediment transport of the first 100 meters increase. Between 100 m and 200 m, there was a decrease in sediment transport. The highest transport is observed in alternative 1, which is equal to about 480 m^3/year/m (annual condition) and 7200 m^3/year/m (storm condition).

In the alternative 7 to 14 (Figs. 12 and 13), the first sediment transport 200 m meters decrease except alternatives 12 and 14. The alternative 7 showed a slightly smaller sediment transport in the first 200 meters. The highest transport is observed in the alternative 13, which is equal to about 350 m^3/year/m (annual condition) and 6000 m^3/year/m (storm condition)..

The result shows that the sediment transport decreasing trend between 100 m and 200 m from the B08 profile. The presence of the breakwater in alternative 10, 11, 13 and 14 may limit this phenomenon.

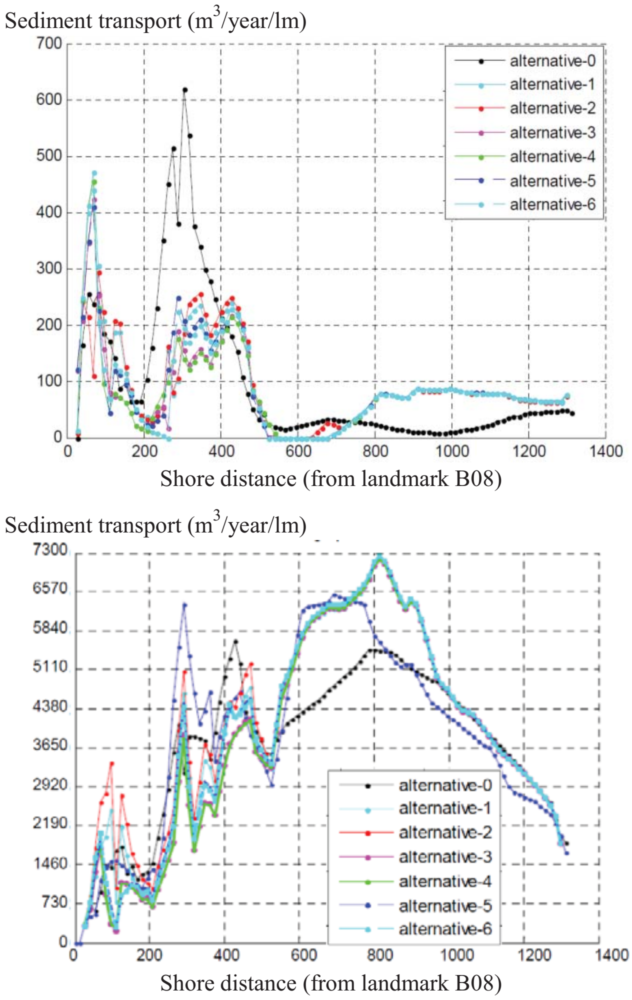

Fig. 11 Sediment transport profile B08 annual (upper) and storm (lower) conditions for the alternative 0 to 6

1) Wave Attenuation

a) Wave Height and Period Attenuation

We consider $K_{t1} = H_t / H_i$ for wave heights attenuation coefficient [13], [14], and $K_{t2} = T_t / T_i$ for period attenuation, where subscripts «i» refer to initial (offshore conditions), and «t» refers to terminal (at the coast). An extraction point close to the coast (-1 m) and one offshore (-3 m) have been defined, at which the model gave the results in the Table VI.

The wave attenuation coefficients for wave height vary from 0.56 to 0.88. The wave attenuation coefficients for wave period vary from 0.84 to 0.92. We observe here that alternatives 3, 4, 5, 6 and 12, 13 and 14 are the most efficient for wave attenuation.

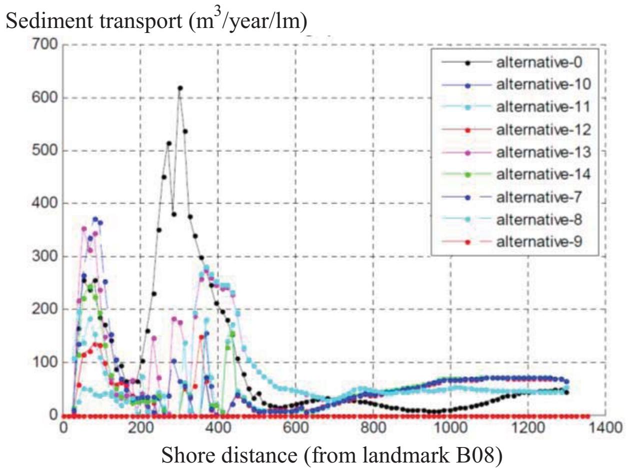

Fig. 12 Sediment transport profile B08 annual conditions for the alternative 0 and 7 to 14

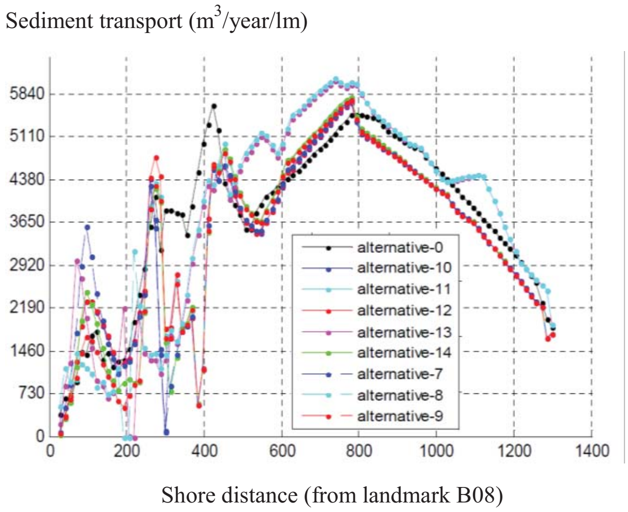

Fig. 13 Sediment transport profile B08 storm conditions for the alternative 0 and 7 to 14

TABLE VI
WAVE ATTENUATION COEFFICIENTS

	Annual						Storm					
	Height (m)			Period (s)			Height (m)			Period (s)		
Alt.	H_i	H_t	K_{t1}	T_i	T_t	K_{t2}	H_i	H_t	K_{t1}	T_i	T_t	K_{t2}
0	0.8	0.7	0.88	4.5	4	0.89	1.6	1.1	0.69	7.7	7.1	0.92
1	0.8	0.7	0.88	4.5	3.9	0.87	1.6	1	0.63	7.7	7	0.91
2	0.8	0.7	0.88	4.5	3.9	0.87	1.6	1	0.63	7.7	7	0.91
3	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	6.9	0.90
4	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	6.9	0.90
5	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	6.9	0.90
6	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	6.9	0.90
7	0.8	0.7	0.88	4.4	3.9	0.89	1.6	1	0.63	7.7	7.1	0.92
8	0.8	0.6	0.75	4.5	3.9	0.87	1.6	1	0.63	7.7	7.1	0.92
9	0.8	0.6	0.75	4.5	3.9	0.87	1.6	1	0.63	7.7	7.1	0.92
10	0.8	0.6	0.75	4.5	3.9	0.87	1.6	1	0.63	7.7	7.1	0.92
11	0.8	0.6	0.75	4.5	3.9	0.87	1.6	1	0.63	7.7	7.1	0.92
12	0.8	0.6	0.75	4.4	3.8	0.86	1.6	0.9	0.56	7.7	7	0.91
13	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	7	0.91
14	0.8	0.6	0.75	4.5	3.8	0.84	1.6	0.9	0.56	7.7	7	0.91

Alt. = Alternative

b) Energy Density Attenuation

We have extracted from the simulation the density of energy distribution for the four cells with reference point alternative 0.

Fig. 14 Extraction point close to the coast

An extraction point close to the coast (-1 m) from E01 to E12 has been defined (Fig. 14), at which the model gave the results in Figs. 15 and 16.

Fig. 15 shows the density energy distribution for all cells A to D in normal and storm conditions. The alternatives 2, 3, 5, 6, 12, 13 and 14 are the most efficient for energy density attenuation.

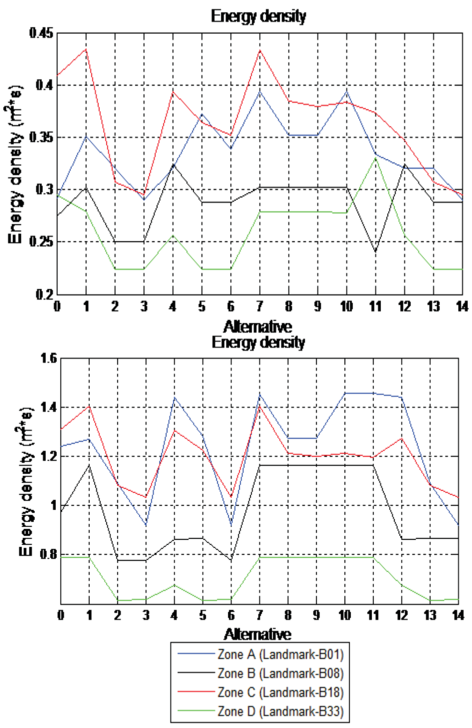

Fig. 15 Density energy distribution for four cells in the annual conditions (upper) and storm conditions (lower)

Fig. 16, for north-central zone, also shows that the alternatives 3, 4, 6, 12, and 14 are the most efficient for energy density attenuation.

In summary, we observe that the alternatives 2, 3, 5, 6, 12, 13 and 14 are the most efficient for energy density attenuation.

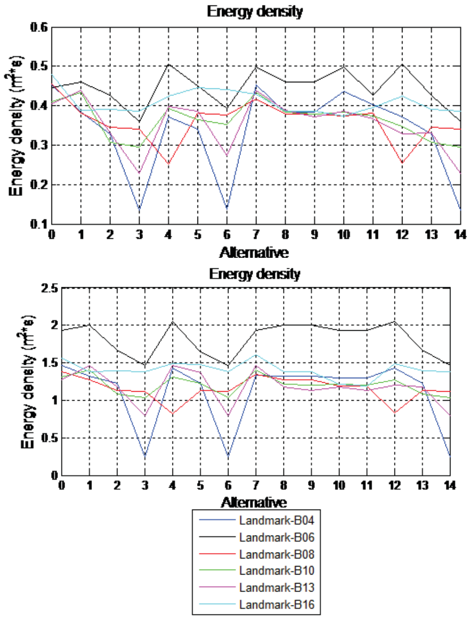

Fig. 16 Distribution energy density for north-central zone (B) in the annual conditions (upper) and storm conditions (lower)

2) Cost Effectiveness

The estimation of cost is based on estimation of costs of materials, and structures by linear meter of length. Other costs should be taken into account as follow up costs for bathymetry, communication. However these extra costs will not be integrated in our calculus, displayed in Table VII.

The protection of Western tombolo in Giens requires the construction of structures. Otherwise the « *route du Sel* » will disappear and this may cause practical problems for circulation and security regarding the access to the peninsula of Giens. As predicted, without intervention, the coast line should drawback from 15 m to 40 m.

The city of Hyères was thinking about implementing a new road, tracing in the middle, north to south, of the tombolo. An analysis of 35 projects of road constructions in France between 1997 and 2002 reveals a mean cost for a standard road of 5 M€ BT/km [15]. Thus the cost of a new road would be of at least 20 M€ BT, without taking into account environmental impacts (natural protected zone) and visual impacts.

Compared to, our solutions imply costs ranging from 0.9 M€ BT to 11 M€ BT.

TABLE VII
COSTS FOR THE ALTERNATIVES 1 TO 14

Alt.	Silting (m³)	Length (m)				Cost (€ before tax)		
				Immersed BW				
		Beach foot	Immersed BW + GR	Close shore	Second row	Construction	Maintenance	Total
1	66680					733 480	88 000	821 480
3	66680	150				1 114 630	88 000	1 202 630
4	66680	150	100			1 368 730	88 000	1 456 730
7			400	440		2 134 440		2 134 440
2	218061					2 398 671	88 000	2 486 671
12	66680		400	440		2 867 920	88 000	2 955 920
5	218061	450				3 542 121	88 000	3 630 121
8				1020	680	4 319 700		4 319 700
6	218061	450	300			4 304 421	88 000	4 392 421
13	66680			1020	680	5 053 180	-	5 053 180
9			900	1020	680	6 606 600		6 606 600
14	66680		900	1020	680	7 340 080	-	7 340 080
10				2040	1360	8 639 400		8 639 400
11			900	2040	1360	10 926 300		10 926 300

Alt. = alternative; BW = breakwater; GR = groin.

IV. RECOMMENDATIONS FOR THE PROTECTION

We first observe that the results of simulation, whatever the alternative, conform to the general knowledge of the study area. The choice of an optimal solution among the alternatives should be driven by taking into account several criteria. We then give a mark towards criteria for each alternative, from very good ("++") to very very bad ("---") [11]. The preceding section helps us completing the Table VIII.

We observe that silting and replenishment seem unavoidable for the preservation of the beach.

We use a Matlab statistic toolbox to create clusters from Table VIII matrix, using hamming distance in the pdist function and then applying linkage.

We could of course ponderate the criteria and drive different clusters, but at this point we are making no decision so this is reserved for future work.

TABLE VIII
ALTERNATIVE'S MARKS FOR CRITERIA

Alternative	Criteria*							
	1	2	3	4	5	6	7	8
1	+	-	-	-	+	+	+	+
2	-	-	-	-	+	+	+	+
3	+	-	++	-	+	-	-	+
4	+	-	++	-	+	-	-	+
5	-	-	++	-	+	-	-	+
6	-	-	++	-	+	-	-	---
7	+	-	-	-	-	-	-	--
8	+	-	+	+	-	--	--	-
9	+	-	+	+	-	--	--	--
10	+	+	+	+	-	--	--	-
11	+	+	+	+	-	--	---	--
12	+	-	++	-	-	-	-	-
13	+	+	++	+	-	--	--	--
14	+	+	++	+	-	--	--	--

* 1 = volume change; 2 = profile change and sediment transport; 3 = wave reduction; 4 = dune preservation; 5 = soft solution; 6 = cost; 7 = environmental impact; 8 = impact on recreational activities.

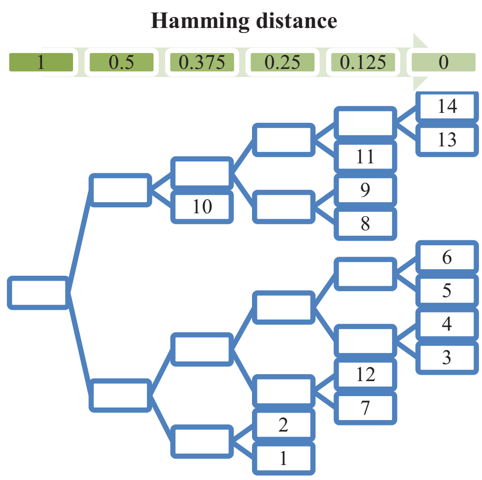

Fig. 17 Non oriented cluster analysis of alternatives versus criteria using Hamming distance

Fig. 17 pictures the clusters from Table VIII, there are 3 clusters at 0 Hamming distance (13-14, 3-4, 5-6), 5 clusters at distance 0.125, one of which groups solutions 11, 13, 14. Going further, at distance 0.25 we have 6 clusters, and at distance 0.375 (meaning any two cluster members differ at 3/8 coordinates in the Table VIII) we obtain 4 clusters (8-9-11-13-14, 10, 3-4-5-6-7-12, 1-2). Finally, we end with two clusters on the 50% disagreement level, 8-9-10-11-13-14, and 1-2-3-4-5-6-7-12.

If we wish to push on the erosion criteria alternatives 10, 11, 13, 14 reveal comparable and best performance in this aspect.

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