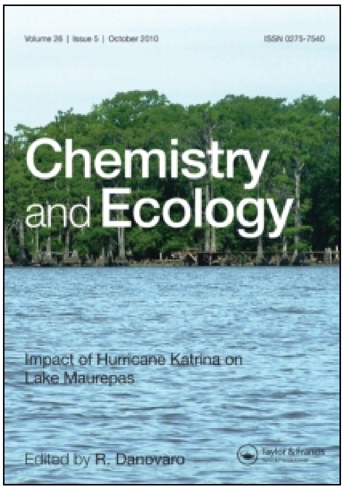

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A multi-layer capping of a coastal area contaminated with materials dangerous to health

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Environmental protection efforts in coastal areas recognise contaminated materials as a critical element of the aquatic ecosystem requiring careful evaluation for their potential remediation. This article considers aspects related to the design of a multi-layer capping for a contaminated coastal area. The area is located just south of the urbanised region of Bari, Puglia Region, along the Adriatic coast of Italy. This area received massive displacement of cement asbestos from residuals of a factory producing concrete pipelines for aqueducts and asbestos boards. The designed reclamation has been proposed in order to allow reuse of the 2.4-km-long coastline for recreational activities. For this purpose, the main objective has been to face aspects related to the problems posed by the design of the adopted capping structure and various constraints related to the natural environment. An extensive numerical study has been carried out to verify the effects of the planned intervention. The local wave climate, wave- and wind-induced circulation, the impact on water quality, and the biological system have been investigated. At present, the intervention is under construction.

Keywords: multi-layer capping; coastal area reclamation; asbestos; rubble-mound breakwaters; numerical models

1. Introduction

During recent decades, the degree of contamination of coastal areas has become an increasing global problem and the subject of extensive research and monitoring programmes. Contaminated hotspots have often been identified at several locations along industrialised and urbanised coastlines. Remediation of contaminated coastal areas is problematic. Different scientific strategies have been developed to assess the impact of pollutants on marine ecosystems. Typically, dredging is adopted as the default remediation method. However, the high costs involved and the difficulty associated with safely removing dangerous materials have led researchers and designers to develop methods for contaminated materials management that do not require removal of the contaminants.

Recently, other methods, including monitored natural recovery (MNR), have received more attention because of the problems posed by dredging and the upland disposal of contaminated

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materials. An attractive remedial approach is *in situ* capping using clean natural materials. Capping isolates the contaminants from the marine ecosystem and potentially retains the contaminated materials, preventing their resuspension and transport to other areas or sites. The first sediment caps were used from the 1800s and earlier to isolate human waste and pollutants downriver or offshore from cities in North America and Europe. Focusing on modern times, environmental capping was first adopted in 1977 by the New England Division of the US Army Corps of Engineers (COE) at the New London Disposal Site. This intervention, which took place in 20 m of water at the eastern end of Long Island Sound, has led to continued application and field observation of the technique. These experiences, together with additional laboratory studies, have encouraged the use of capping in marine environments.

Although capping has proved effective for field use, the technology has achieved only limited acceptance from environmental managers, regulators and the public. The fact is that caps isolate contaminants but do not remove them, and many environmental decision-makers feel uncomfortable with clean-up methods that leave untreated pollutants in place. Their reservations have found certain support in researchers' general lack of knowledge about the behaviour of caps under extreme conditions and the ability of caps to withstand the water surges of a major storm event such as a hurricane. More recently, capping has been shown to be technically feasible from an engineering perspective in field-scale tests. Nistor et al. [1] considered *in situ* capping using clean materials to isolate the contaminants (fine pyrite cinders particles) contained in sediments located in shallow water and subjected to wave and current action at Clark Island, owned by Honeywell International, in Quebec, Canada.

This article presents aspects related to the design and verification of a multi-layer capping in a coastal area contaminated with materials dangerous to health.

2. Materials and methods

2.1. *Study area*

The polluted coastline is located just south of the urbanised area of Bari, along the Adriatic coast of Italy. The considered coastline extends for 2.4 km south of the last of eight detached breakwaters protecting the promenade from extreme wave attacks and finishes in the so-called 'Pane e Pomodoro', south of the old port of Bari (Figure 1). It comprises the recreational area

Figure 1. Aerial view of Bari with the two ports and 'Torre Quetta' (from Google Earth).

called ‘Torre Quetta’. An aerial view (Figure 1) also shows the path and mouth of the drainage channel, called Valenzano, built in the 1930s and entirely surrounding the town of Bari with the aim of avoiding any flooding calamity. The mouth of the artificial Valenzano channel represents a large discontinuity along the 2.4 km coastline.

Work on this unique reclamation started in May 2009 with a view to obtaining a recreational place where a polluted area currently exists. The coastal area has been contaminated by the displacement of cement asbestos from the residuals of a factory that produced concrete pipelines for aqueducts and asbestos boards. The factory, located ~10 km inland of the ‘Torre Quetta’ area (Figure 1), was active for 50 years, opening in 1935 and closing in 1985. The public only became aware of the severe danger from asbestos in 1972. In fact, the area of dry land where waves deposit asbestos cobbles poses a severe danger for humans; in particular, asbestos exposure provokes asbestosis, mesothelioma and lung cancer. More specifically, it has been proved that activities at the factory caused the death of ~50 workers and persons living in the factory surroundings. In Italy, the use of asbestos has not been allowed since 1992.

About 15 years after the factory closed, awareness of the presence of dangerous materials at ‘Torre Quetta’ was lost, in 2001 the area was subjected to a nourishment intervention with cobbles and was officially opened for public recreational use in 2002. However, after initial use by local inhabitants, and after a few intense storms had reshaped the beach, the contaminated material became clear and the area was immediately closed to the public. The local public administration estimated the cost of removing all the dangerous materials, after which the mayor decided to give the go ahead for the design of an *in situ* multi-layer capping intervention, with the final goal of re-opening this stretch of the coastline for recreational and bathing use.

2.2. *Environmental conditions*

The current coastline is the result of several decades of significant seaward accretion of polluted materials. These materials represent a continuous source of contamination, with cement asbestos cobbles subjected to wave and current action, dispersed and transported downdrift. In recent years, the local administration, with scientific support from the Polytechnic University of Bari, have carried out numerous studies into the local bathymetry, the geotechnical characteristics of the rock sediment bed and the aquatic setting, including aquatic vegetation, benthic fauna and fish [2]. These studies allowed a better definition of the scale of the contamination and identified the risk in this setting. The wave climate was determined based on data from the National Sea Wave Measurement Network (RON) (available online: http://www.idromare.com). Since 1989, RON have provided measurements of the wave characteristics in Italian seas under deep water conditions with reliable results in terms of data acquisition rates and temporal coverage. The considered buoy is located offshore of Monopoli (70 m water depth), 40 km south of Bari. The probability distribution function suitable for an extreme wave climate was selected based on Goda’s method [3,4]. The Weibull distribution function was found to be the most suitable.

Analysis of historical tide variation data showed that tide excursion ranges between +40 and −40 cm to the still water level (s.w.l.). Its influence on water circulation can be considered negligible.

Existing cross-shore beach profiles have been observed with an inter profile distance of 25 m and reaching a water depth of 10 m. It appeared that the coastline presents mild and steep slope cross-shore profiles. Profiles P_1–P'_1 and P_2–P'_2 (Figure 2) were selected as representative of the steep and mild slope conditions, respectively.

Field investigations showed that a disease meadow of *Posidonia oceanica* lies parallel to the coastline at a distance of 300 m from the shoreline extending to 600 m.

3. Results and discussion

3.1. *The proposed intervention*

The reclamation intervention consists of beach nourishment covering a multi-layer capping structure to bury the source of the cement asbestos. In order to obtain more effective retention of the nourishing cobbles, a cell-system made up of partially submerged groins and two continuous detached rubble-mound submerged breakwaters were considered; in particular, the two groins at the mouth of channel Valenzano also function to prevent its obstruction (Figure 2).

Figure 3 shows a cross-section of the approved design with the multi-layer capping structure and the detached submerged breakwaters. The multi-layer capping structure will be composed of reinforced geotextile installed directly onto the current bottom and anchored in a shoreline-located trench. The adopted geosynthetics are made of high-modulus woven polyester to absorb high tensile loads and low strains. The geotextile will be covered by a calcareous gravel layer, 20 cm thick; above this, a layer of 100–300 kg of natural stone will be placed.

The surface layer will be composed of well-rounded cobbles from alluvial rivers with a mean diameter, $D_{50} = 5$ cm and sorting, $D_{85}/D_{15} = 1.3$. Each layer has a different purpose: the geotextile layer will prevent any further loss of dangerous materials; the calcareous gravel layer prevents any breakage of the geotextile when displacing the natural stones; the natural stones keep the

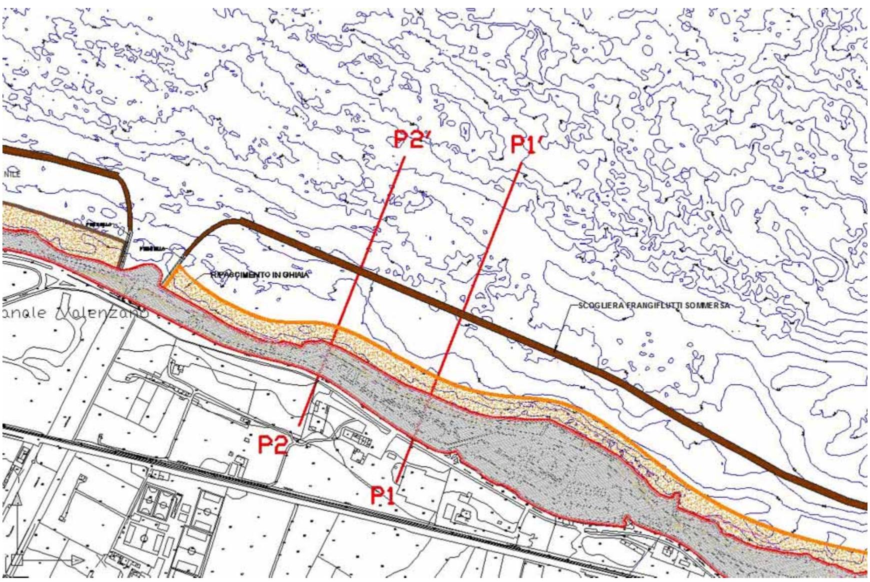

Figure 2. Plan view of the approved design with the position of the P_1–P_1' and P_2–P_2' profiles.

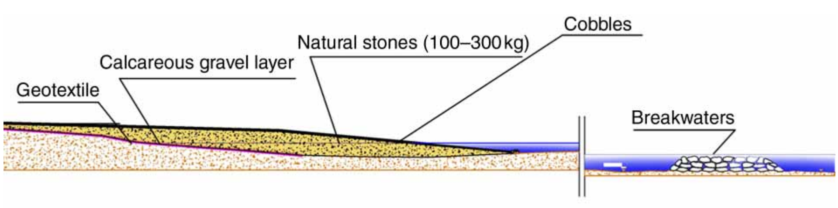

Figure 3. Cross-shore section of the capping structure and detached breakwaters.

geotextile fixed and give permanent definition to the new shoreline position, which is advanced seaward by 30 m; and the rounded cobbles allow people to enjoy the beach.

When built, the cross-shore profile of alluvial rounded cobbles will be dynamically stable under incident waves [5,6]. The expected reshaped profile under a sea storm with a 36-year return period has been calculated; the choice of a 36-year return period is based on risk analysis [7]. Given the final reshaped profile, the geometry of the as-built profile and its thickness have been designed to prevent the under layer of natural stones from being uncovered. The detached submerged breakwaters will break up the waves and dissipate some of their energy. The detached breakwaters have an homogeneous cross-section made of natural stones weighing 1–3 tons. The detached rubble-mound breakwaters present a submergence of 0.40 m with respect to the still water level, with a water depth of 2.70–3.50 m and a 10 m wide crest berm. The use of submerged breakwaters is encouraged by the recent European Framework DELOS (Environmental Design of Low Crested Coastal Defence Structures, EVK3-CT-2000-00041: www.delos.unibo.it). In fact, use of this type of structure for coastal protection has several advantages over conventional structures, not only in terms of its favourable visual impact (which, from the beach-user's point of view is very important), but also because of the allowed wave overtopping, which enhances water renovation rates in sheltered areas [8]. A further desirable feature of submerged breakwaters is that they enhance the development of marine fauna, without endangering bathing and leisure navigation. The breakwaters mostly fill with sand and are naturalised with the seabed. The high permeability of the breakwaters tends to increase barrier colonisation, resembling a natural reef with active marine life (e.g. fish, octopus, vegetation, mussels). These ecological and aesthetic features are important for maintaining the tourist value of the beach and are usually one of the considerations in using such structures for shoreline protection [9].

3.2. *The biological system at the south Adriatic Sea*

Although engineering design and construction of coastal defence structures to protect coastlines have received considerable attention, the ecological consequences of these interventions have been investigated less extensively [10]. Results from the DELOS project indicate that the construction of coastal defence structures will affect coastal ecosystems. The consequences can be seen on a local scale, with changes to the native assemblages of the area [11,12].

The coastal morphology along the southern Adriatic Sea presents a low and rocky seabed, strongly influencing the biocenosis of the investigated area at 'Torre Quetta'. The supratidal zone, outlining the stretch above the high water level, shows a typical stepped bathymetry. A dominant feature of the lower supratidal is the drying low deposit (DLD) community with patches of small crustaceans (detritivore amphipods and isopods), as well as decapods of the *Pachygrapsus* species. The intertidal zone, which lies between the high and low tidal extremes, has similar characteristics. Typical intertidal inhabitants include benthos organisms together with gastropod molluscs (*Littorina* and *Monodonta*). Widespread small algal colonies cover the outer surface of the rocky body, whereas chlorophyceae (*Ulva* species) and phaeophyceae (*Cystoseira* species) are found at greater depths. These species are widely distributed along the south Adriatic Sea and a similar pattern is observed over rocky seabed habitats. There are no species of distinctive environmental worth, although typical individuals were found to be very abundant and predominant in areas characterised by anthropogenic impacts with increasing human pressure in the form of nutrient loading. As common in the shallow coastal environment of the Adriatic Sea, no molluscs, bivalve communities or edible crustaceans, together with a particular fish density are observed. Any biocenosis and protected species particularly sensitive to deterioration are found in shallow water areas to 5 m depth. With increasing water depth, a *Posidonia* disease meadow lies parallel to the coastline.

Preliminary analysis of the simulated distribution of wave and current intensities around the structures indicates that both mean and extreme values of hydrodynamic fluxes will affect barrier colonisation. More details about the wave-induced circulation at breakwaters are given below. Because of high permeability, the rubble-mound breakwaters induce, by improving water oxygenation and quality, a change in assemblages and consequently an increase in biodiversity. A similar case occurred in Ostia, where after protection intervention and nourishment [13], the octopus, another species typical of rocky beds and good water quality, appeared on a naturally sandy beach [9].

3.3. *Mobility conditions for the remaining cement asbestos stones*

The study considered the mobility conditions for the remaining cement asbestos stones lying at the sea bottom after the end of the work. It has been estimated that, because of the specific weight of the material ($\sim 1.2\,\mathrm{t \cdot m^{-3}}$), asbestos stones of 3–5 cm will be moved under wave action even after the work, with a tendency to reach the toe of the capping structure and, eventually, the new swash zone.

The Shields criterion [14] has been adopted to determine the threshold conditions of movement for cement asbestos stones. In its original form, the empirically derived Shields diagram [14] allows calculation of the dimensionless critical Shields parameter, θ_c, which represents an indicator of incipient motion, as a function of the boundary Reynolds number, Re*:

$$\theta_c = \frac{\tau_0}{(\rho_s - \rho) g D} = f(\mathrm{Re}^*), \tag{1}$$

where

$$\mathrm{Re}^* = \frac{u^* D}{\nu}, \tag{2}$$

$$u^* = (\tau_0/\rho)^{1/2} = \text{shear velocity}; \tag{3}$$

τ_0 = bed shear stress;
ρ = mass density of water;
ρ_s = mass density of the particle;
g = acceleration due to gravity;
D = diameter of the particle; and
ν = kinematic viscosity of the fluid.

The dimensionless Shields parameter represents the ratio of the shear forces on the particle, which act to move it, to the submerged weight of the particle, which acts to keep it stable at the bottom.

For values $\mathrm{Re}^* > 400$, θ_c becomes independent of the boundary Reynolds number ($\theta_c = 0.056$); for $\mathrm{Re}^* < 3.5$ the influence of boundary Reynolds number is predominant with a transition region between these two values of Re*.

Threshold mobility conditions for a cement asbestos stone at the bottom have been assessed for $D = 3$ and 5 cm, based on field observations. Asbestos stones were considered to be lying on the sea bottom at water depth, h, taking into account a sea level rise due to a sea storm of 0.5 m above mean sea level. The value of $\theta_c = 0.056$ has been assumed.

The wave-induced bed shear stress, τ_0, has been estimated as:

$$\tau_0 = \frac{f}{4}\left(\rho\frac{V^2}{2}\right) \tag{4}$$

with V = steady-state fluid velocity; and f = Darcy–Weisbach friction factor calculated using the relationship proposed by Schlichting [15]:

$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(h/D\right) + 2.11 \tag{5}$$

The steady-state fluid velocity, V, in Equation (4) was determined using the linear wave theory [16]. Under a progressive wave, the water particle follows an elliptical orbit and presents the horizontal and vertical velocity components u and w. At the bottom, $w = 0$ and u is given as:

$$u = u_b = \frac{H}{2}\frac{gT}{L}\frac{1}{\cosh(2\pi h/L)} \tag{6}$$

with H = wave height, L = wave length and T = wave period. Therefore, the steady-state fluid velocity, V, is assumed equal to u_b.

The critical bed shear stress for incipient motion, τ_c, has been determined considering the maximum value of u_b for a sea storm with $H_{0,12h} = 2.4$ m and $T_p = 8$ s, where $H_{0,12h}$ is the deep water significant wave height exceeded for 12 h per year and T_p is the peak wave period during the storm. (The depth of closure [17] for a given time interval is the most landward depth seaward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore. Hallermeier [18] proposed the first predictive formula to calculate the depth of closure: $d_t = 2H_{0,12h}$, where $H_{0,12h}$ is the significant offshore wave height that is exceeded for 12 h per year).

The threshold conditions for mobility have been obtained with reference to the two different cross-shore profiles: P_1–P_1' and P_2–P_2'. Figures 4 and 5 show water depth along the horizontal axis and diameter D along the vertical axis. Curves obtained based on the Shields criterion separate the no-movement area from the movement area allowing knowledge of whether, for a given value of D and at a certain water depth, the cement asbestos stones would move.

In particular, for the case of profile P_1–P_1' at the toe of the detached breakwaters (Figure 4), stones with $D = 3$ cm do not move at depths >2.60 m, whereas stones with $D = 5$ cm do not move at depths >2.00 m. For the case of P_2–P_2' profile at the toe of the detached breakwaters

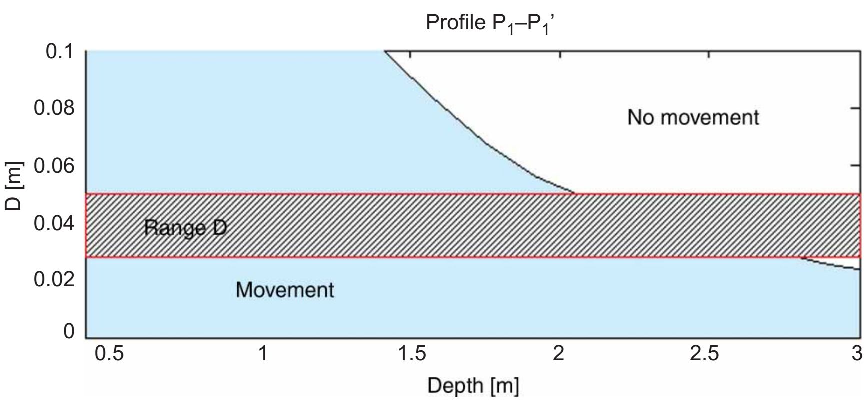

Figure 4. Diameter versus water depth with range of movement. Profile P_1–P_1'.

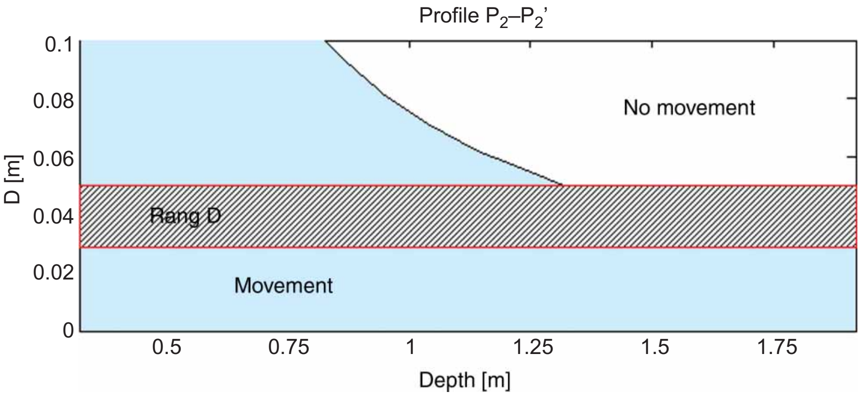

Figure 5. Diameter versus water depth with range of movement. Profile P_2–P'_2.

(Figure 5), stones with $D = 3$ cm move along the entire cross-shore profile, whereas those with $D = 5$ cm are stable when the depth is >1.40 m.

This movement of contaminated materials is not tolerated and, as a consequence, when the construction is completed, it is considered that a seafloor survey between the detached breakwaters and the new shoreline is needed to remove the remaining cement asbestos stones. This will allow the intervention area to be considered definitely safe and to re-open for public use.

3.4. *The numerical study*

An extensive numerical simulation analysis has been carried out at the University of Salento to observe and discuss the characteristics of the hydrodynamic field, prior to and after the intervention, under various conditions of incident waves and wind velocity.

3.4.1. *The wave propagation model*

The wave propagation simulation was conducted using a steady-state directional wave spectral transformation model to predict nearshore waves [19,20,21]. It is a half-plane model so that the wave can propagate only from the seaward boundary toward the shoreline.

The model solves the spectral wave action conservation equation [22] in the two spatial co-ordinates (x and y) and the wave direction, φ, taking into account wave energy dissipation rates because of bottom friction, D_f, and wave breaking, D_b:

$$\frac{\partial}{\partial \mathrm{x}}\left((C_g \cos\varphi + U)\frac{E}{\sigma}\right) + \frac{\partial}{\partial y}\left((C_g \sin\varphi + V)\frac{E}{\sigma}\right) + \frac{\partial}{\partial \varphi}\left(C_\varphi \frac{E}{\sigma}\right) + \frac{D_b}{\sigma} + \frac{D_f}{\sigma} = 0, \quad (7)$$

where $E(x, y, \varphi)/\sigma =$ wave action density with $\sigma =$ angular frequency of the wave; U, $V =$ current velocity components in the x and y direction, respectively; and C_g and $C_\varphi =$ wave celerities.

More details can be found in Phillips [22] and Rivero et al. [20]. The model is capable of simulating wave–structure and wave–current interactions. Moreover, it is able to compute wave diffraction, reflection and wave transmission through and over submerged structures. The model represents wave diffraction by implementing a formulation of the Eikonal equation [20]. Wave reflection is treated as a percentage increase of the local incident wave energy at cells in front of a structure. Wind input, tide variation and wave–wave interactions are neglected in the wave propagation model.

Wave breaking is based on Battjes and Janssen [23]:

$$D_b = \frac{\alpha}{4} Q_b f_p \rho g H_m^2, \tag{8}$$

$$H_m = \frac{0.88}{k_p} \tanh\left(\frac{\gamma_b k_p h}{0.88}\right), \tag{9}$$

$$\frac{1 - Q_b}{\ln Q_b} = -\left(\frac{H_{rms}}{H_m}\right)^2, \tag{10}$$

where:

Q_b = local fraction of breaking waves;
α = empirical coefficient of the order of unity;
f_p = peak frequency given by $f_p = T_p^{-1}$;
H_m = local depth-limited wave height;
H_{rms} = root-mean-square wave height;
k_p = linear wave number calculated using f_p and h; and
γ_b = empirical parameter determining $H_m = \gamma h$ in shallow water.

Battjes and Janssen [23] suggested that $\alpha \approx 1$ and $\gamma_b \approx 0.6$–0.8, depending on the deep-water steepness. In this case, $\gamma_b = 0.7$ was adopted.

The wave energy dissipation rate due to bottom friction is found using the model of Tolman [24]:

$$D_f = \frac{2}{3\pi} \rho f_{wc} u_W^3, \tag{11}$$

where

$$u_W = \frac{\pi H}{T \sinh(2\pi h/L)} \tag{12}$$

is the wave orbital amplitude at the seabed and f_{wc} represents the friction factor calculated using Nielsen equation [25]:

$$f_{wc} = \exp\left[-6.3 + 5.5\left(\frac{\sigma k_N}{u_W}\right)^{0.2}\right] < 0.30, \tag{13}$$

with $k_N = 2.5D$ = Nikuradse's roughness coefficient.

Equation (7) is solved using an implicit finite difference method on a rectilinear grid. It also requires a prespecified wave spectrum as input at the offshore boundary. Jonswap spectrum with peak enhancement factor = 3.3 has been considered.

For the current situation, Figure 6, representative of all cases, shows the wave propagation for $H_{0,12h} = 2.51$ m and $T_p = 8$ s and waves from NNW. Within 300 m south and north of the channel mouth, the bathymetry is milder and waves break $\sim$150 m from the current shoreline. Breaking occurs closer to the shoreline for the rest of coast.

3.4.2. *The wave- and wind-induced circulation study*

A circulation study was carried out, comparing current and future conditions, in order to verify that the wave- and wind-induced current around the designed detached breakwaters is kept active with a positive effect on water quality.

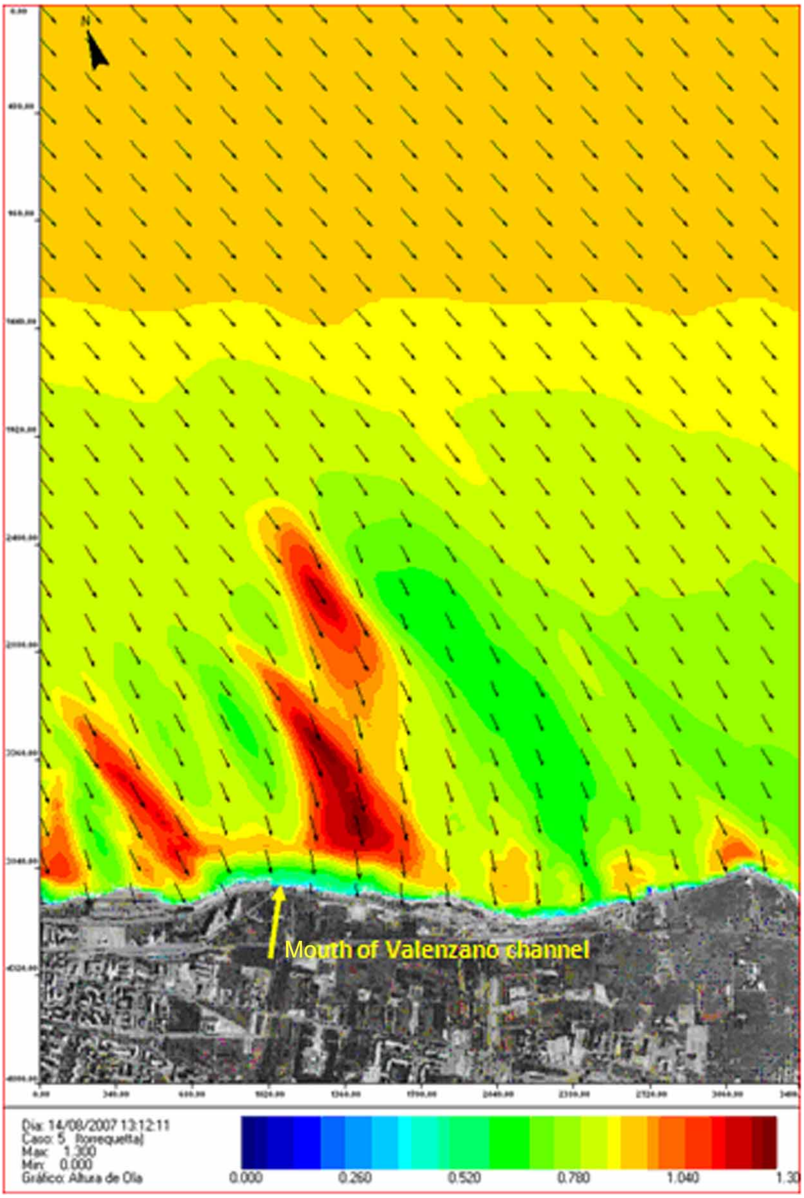

Figure 6. Significant wave height and direction of propagating waves. Sector NNW. $H_{0,12h} = 2.51$ m and $T_p = 8$ s.

The adopted circulation model is based on 3D time-averaged equations [21,26]:

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}[(h+\eta)U] + \frac{\partial}{\partial y}[(h+\eta)V] = 0, \tag{14}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - f_c V + g\frac{\partial \eta}{\partial x} = \frac{1}{\rho(h+\eta)}\left[F_x + W_x - B_x + \left(\frac{\partial R_{xx}}{\partial x} + \frac{\partial R_{xy}}{\partial y}\right)\right], \tag{15}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + f_c U + g\frac{\partial \eta}{\partial y} = \frac{1}{\rho(h+\eta)}\left[F_y + W_y - B_y + \left(\frac{\partial R_{yx}}{\partial x} + \frac{\partial R_{yy}}{\partial y}\right)\right], \tag{16}$$

where:

x = orthogonal coordinate;
y = longitudinal coordinate;
η = free surface elevation;
U, V = average current velocity components (x, y);
h = water depth;
g = gravity acceleration;
ρ = density of fluid;
f_c = Coriolis factor;
F_x, F_y = wave-induced shear stresses (x, y);
W_x, W_y = wind-induced surface shear stresses;
B_x, B_y = shear stresses at seabed; and
R_{ij} = Reynolds stress tensor, assumed isotropic, time-averaged and depth integrated.

Wave-induced shear stresses are calculated using the gradient of radiation stress following the expression of Longuet-Higgins [27]:

$$F_i = -\left[\frac{\partial S_{ij}}{\partial x_j} - \left(\frac{\partial T_j}{\partial x_j}\right)\frac{\partial h}{\partial x_i}\right], \tag{17}$$

where S_{ij} = radiation stress [28]; and T_j = vertical radiation stress [19].

The formulation of shear stresses at seabed used in the model follows a quadratic law of the wave-driven velocity plus orbital velocity:

$$B_i = \left\langle \frac{1}{2}\rho f_{wc}|U + u_W|(U_i + u_{W,i})\right\rangle, \tag{18}$$

where $\langle\ \rangle$ indicates the Darcy's volume average operator.

For a variable r, the Darcy's volume average operator is:

$$\langle \bar{r}\rangle = \frac{1}{V}\int_{V_f} \bar{r}\, dV, \tag{19}$$

where '‾' indicates the time average, V represents the total averaging volume, and V_f is the fluid portion of V.

The Reynolds stress tensor is calculated following the Boussinesq approximation:

$$R_{ij} = \frac{1}{2}\rho\nu_t(h+\eta)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right), \tag{20}$$

where the viscosity coefficient

$$\nu_t = C_\mu\sqrt{k}(h+\eta) \tag{21}$$

is expressed in terms of turbulent kinetic energy, k, with C_μ = coefficient of the order of unity.

A transport equation is used to determine k which accounts for the combined effect of advection, diffusion, production due to wave energy dissipation and shear flow:

$$\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial x} + V\frac{\partial k}{\partial y} = \frac{1}{\rho(h+\eta)}\left[\frac{\partial}{\partial x}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial y}\right)\right] + P - F, \tag{22}$$

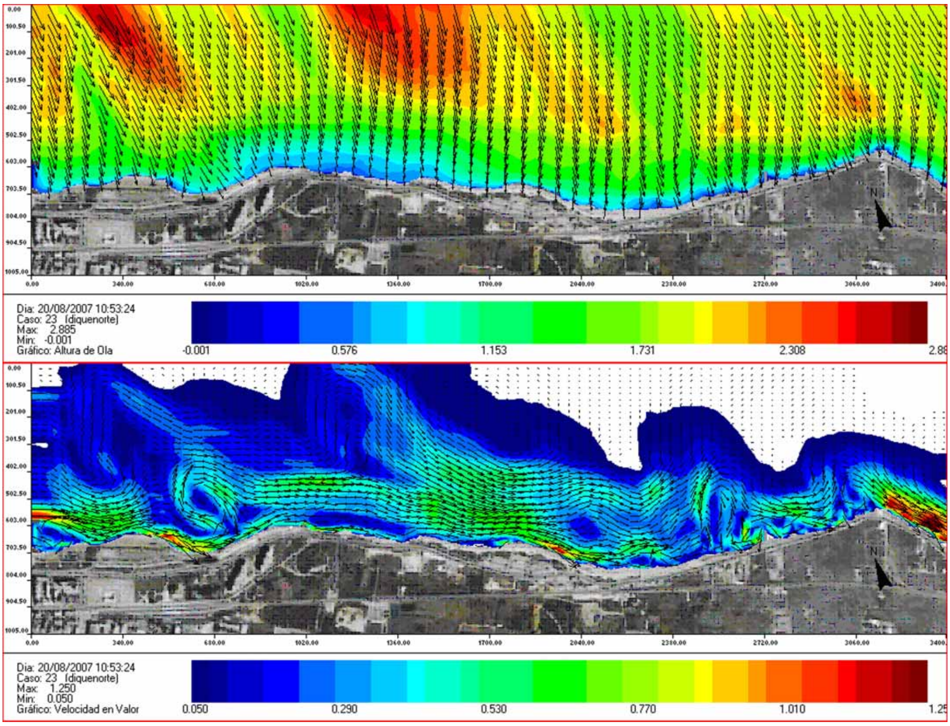

Figure 7. Sector NNW. $H_{0,12h} = 2.51\,\mathrm{m}$ and $T_p = 8\,\mathrm{s}$. Situation without structures. (Upper) Significant wave height and direction of propagating waves. (Lower) Wave-induced circulation pattern. Chromatic velocity scale in $\mathrm{m \cdot s^{-1}}$.

where σ_k = Prandtl–Schmidt number = of the order of unity;

$$P = \frac{D}{\rho(h+\eta)} + \nu_t \left[\left(\frac{\partial U}{\partial x} \right)^2 + \frac{1}{2} \left(\frac{\partial U}{\partial y} \right)^2 + \frac{\partial U}{\partial y} \frac{\partial V}{\partial x} + \frac{1}{2} \left(\frac{\partial V}{\partial x} \right)^2 + \left(\frac{\partial V}{\partial y} \right)^2 \right], \tag{23}$$

$$F = C_D \frac{k^{3/2}}{h+\eta}, \tag{24}$$

with C_D = calibration parameter = of the order of unity.

As an example, Figures 7 and 8 show the wave-induced circulation from the NNW without and with the structures. As expected, a current directed to the south is present.

In order to improve the circulation study, a numerical simulation has been carried out to investigate the solely wind-induced hydrodynamic effects (considering a negligible wave action) with an offshore significant wave height, $H_{s,0} = 0.2\,\mathrm{m}$. This severe scenario allowed us to observe that the presence of the breakwaters does not significantly reduce the wind-induced current circulation and does not influence water quality, even in the absence of waves. Two different wind intensities have been considered, 5 and $10\,\mathrm{m \cdot s^{-1}}$ representing, respectively, milder and stronger conditions.

4. Conclusions

The *in situ* multi-layer capping of dangerous materials at the coastline is a safe, environmentally friendly and viable technology for reclaiming contaminated areas. Although reclamations

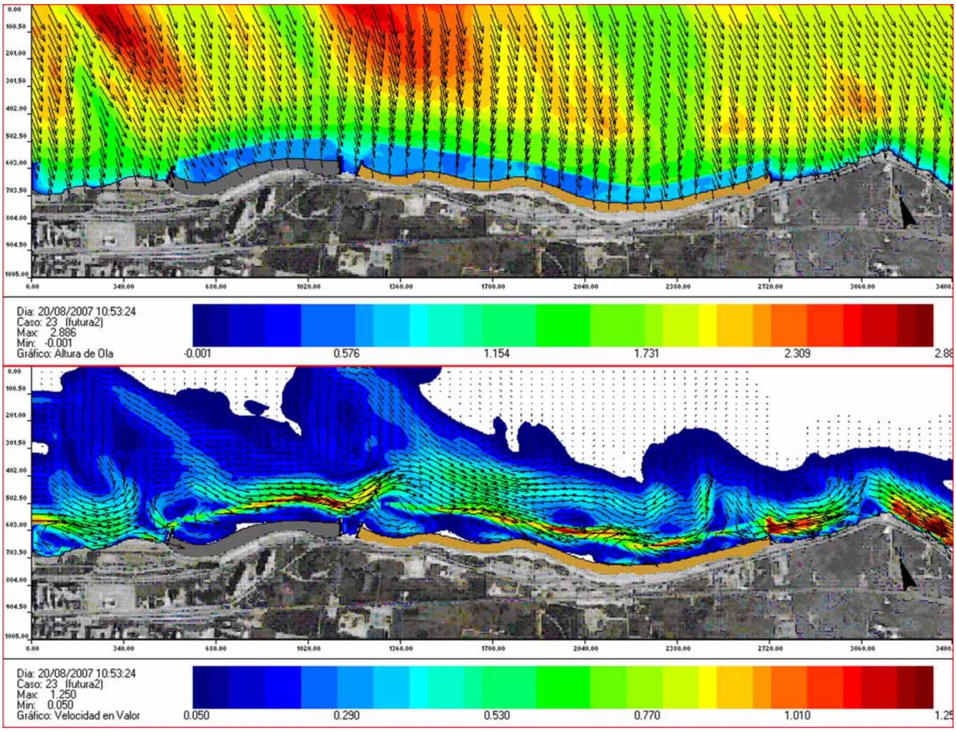

Figure 8. Sector NNW. $H_{0,12h} = 2.51$ m and $T_p = 8$ s. Situation with structures. (Upper) Significant wave height and direction of propagating waves. (Lower) Wave-induced circulation pattern. Chromatic velocity scale in $\mathrm{m \cdot s^{-1}}$.

capping contaminated materials have been shown to be effective on a smaller scale in different countries, an intervention of this size and to obtain a recreational area where previously there was a danger to human health can be considered unique. The case of ‘Torre Quetta’ represents an example of a complex interaction among human health protection, the beach, beach defence structures, the biological system and social activities. The proposed protected nourishment will be positively valued by beach users justifying the investment made (3.8 million euros). The numerical investigation has shown that the current circulation around the structures is kept active with a positive effect on water quality. The designed detached rubble-mound breakwaters reduce the wave energy causing the breaking phenomena, assure the support for active and rich biological communities, enhance water filtration and induce a change of assemblages in the area, increasing biodiversity of the littoral zone. The presence of the breakwaters does not influence the disease meadow of *Posidonia oceanica* which lies parallel to the coastline at a distance of 300 m from the shoreline. Because of the uniqueness of this intervention for the Adriatic sea, a programme monitoring the recovery of ecosystems and recolonisation rates will be carried out.

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