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THE ROLE OF THE TIDAL AND WIND FORCES ON THE HYDRODYNAMIC FLOW PATTERN IN THE AUGUSTA HARBOUR (ITALY)

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The hydrodynamic circulation in the coastal area of the Augusta Bay (Italy) is analysed in the present paper. The Augusta Harbour is an important economic infrastructure located in the eastern part of the Sicily. Due to the heavy contamination generated by many chemical and petrochemical industries active in the zone, the harbour was declared as Contaminated Site of National Interest. In order to mitigate the risks connected with the industrial activities located near the harbour it is fundamental to analyse the hydrodynamic circulation. Since no significant change exists in the water density, the current inside the Augusta Bay is mainly due to the relative contribution of the wind force acting over the free surface and the tidal motion through the mouths. Tidal oscillations measured at the eastern mouth and the wind measured in the meteorological station closest to the coastal area were imposed in the numerical simulation. Due to the geometrical complexity of the domain and the presence of several piers along the coast, a curvilinear boundary-fitted computational grid was used, where the cells corresponding to land areas or to the wharfs were excluded from the computation. In order to validate the numerical model, comparisons between numerical results and field measurements were performed. On the basis of the numerical results, the estimation of the current in the basin was achieved, showing the specific role of wind and tidal oscillation in the hydrodynamic circulation inside the harbour.

INDRODUCTION

The preservation of coastal areas became a primary issue because of the increasing anthropogenic pressure and the extension of urban areas. Rivers, lakes and the sea were the natural receiver of raw urban and industrial wastewater for a long time. This scarcely sustainable practice leads to an increased researcher interest in the analysis of the hydrodynamics of environmental water bodies. In such fields, the hydrodynamic circulation is mainly driven and influenced by several elements: among others the bathymetry, the tidal oscillations, the wind field or the aquatic vegetation distribution. In order to selectively investigate on the relative contribution between these elements, several experimental observations (see Alpar and Yuce [1] and literature therein cited) and numerical simulations (see among others De Marchis *et al.* [2]) have been performed in coastal lagoons. In the last decades several researches were carried out, through numerical simulations, in order to investigate on the different effect of the external forces on the hydrodynamic circulation.

Due to the fact that coastal waters are often characterized by shallowness, two-dimensional shallow water numerical models have been extensively developed (see, among others, Krámer and Józsa [3], Vethamony *et al.* [4], Babu *et al.* [5] and Ferrarin and Umgiesser [6]). The greater part of the studies focused on the relative contribution, on the flow field, between the wind and the tidal forces, sometimes reaching different conclusions. Vethamony *et al.* [4], in fact, using a calibrated 2D shallow water numerical model, predict the tides and tidal currents in the Gulf of Kachchh, India, without taking into account for the wind field; Babu *et al.* [5] demonstrated that, in the same case study, the wind play a fundamental role.

In order to correctly simulate the hydrodynamic circulation in the marine environment, characterized by 3D features, the use of fully 3D numerical models is required. Balas and Ozhan [7] carried out 3D numerical simulation in the Göksu Lagoon (Turkey). They found that, even if the water depth is quite shallow, the wind drives the current causing recirculation phenomena in the vertical plane, thus motivating the use of 3D numerical models. Grifoll *et al.* [8] studied the hydrodynamic within the Bilbao Harbour (Spain), by means of the 3D numerical simulation carried out using the Regional Ocean Modelling System. The authors found that the circulation pattern is affected from the tide, the wind and the presence of freshwater as well. The need of accounting for both wind and tide forces in coastal waters was also demonstrated by MacCready *et al.* [9] in their study of the Columbia river estuary. Recently, De Marchis *et al.* [2] pointed out the relevance of the investigation on the relative contribution of the different forces that affect the hydrodynamics, reproducing the circulation in the lagoon Stagnone di Marsala (Italy). The authors, using a 3D numerical model, found that the wind strongly modifies the circulation modulated by the tide. Moreover, they found that, despite the shallowness of the water body, below the free-surface the wind generates wide recirculation regions, increasing the water mixing.

The resolution of engineering problems in coastal areas, like harbours, it is essential the understanding of the hydrodynamic circulation and of the forces that dominate the circulation patterns. Harbour infrastructures and protection artificial barriers can modify the water circulation patterns and can limit the flushing between the harbour and the open sea. The main objective of this paper is to analyse the hydrodynamic behaviour of a complex domain, Augusta Harbour, in order to understand the effects induced by the wind and the tide and analyse the importance of its driving mechanisms.

MATERIALS AND METHODS

Study area e monitoring data

The Augusta Harbour is one of the more densely industrialized Italian sites. In the last decades, many chemical and petrochemical industries have been working in this coastal area, causing heavy consequences especially in the water body environment. The harbour is protected by artificial barriers that enclosed the natural gulf of the Augusta Bay. The harbour, shown in Figure 1, is located in the eastern coast of Sicily (Italy) and is connected to the open sea through the southern and the eastern mouths. The two entrances, about 400 m wide, are characterized by the maximum water depth (about 40 m) and ensure the transport of mass and the water mixing between the harbour and the open sea. The harbour area is about 24 km^2. It extends about 8.0 km in the North-South direction and 4 km in the East-West direction, while its average depth is about 15.0 m (see Figure 1). Due to the intense petrochemical activities a series of piers are located along the western coast. The bottom is covered by sand and fine sediments. Some rivers (among others Cantera and Marcellino) drain into the water body. Despite of this, due to their ephemeral nature and discontinuous freshwater discharges, their contribution can be neglected. Furthermore, due to the three breakwaters, the circulation is not influenced by waves (Lisi *et al.* [10]), suggesting that the circulation is influenced by tide and wind and the harbour can be analysed as a costal lagoon.

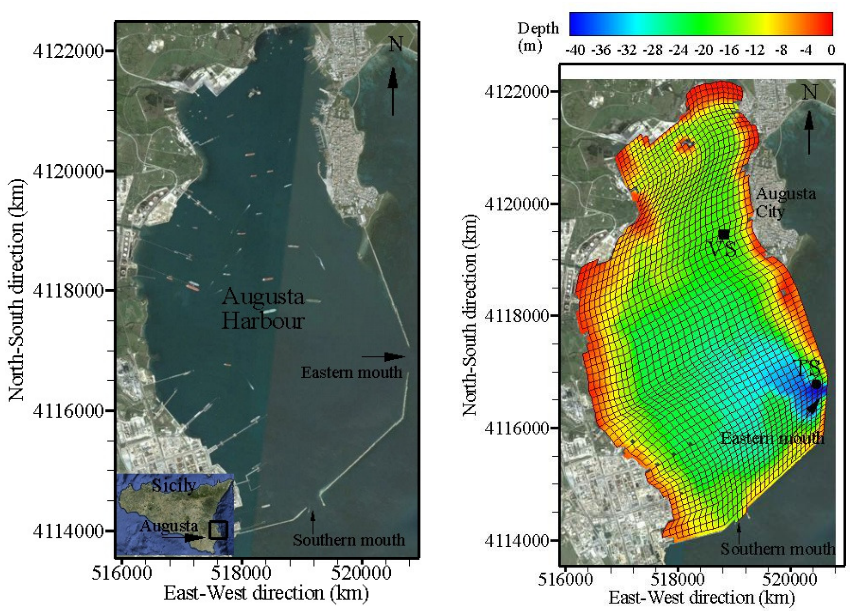

Figure 1. Augusta Harbour. Left: satellite map. Right: Bathymetry of the harbour and computational grid, reduced by a factor of four. VS: measurement station for the velocities. TS: measurement station for the water levels.

The particular topography, the presence of the piers and the averaged depth suggest that to simulate the hydrodynamic of the lagoon a fully 3D numerical code is required.

In order to reproduce the hydrodynamic circulation inside the harbour and validate the obtained numerical results, a field campaign measurement is required. Specifically, the water level, wind velocity and its direction were measured and used as input data to force the model. Velocities were instead measured inside the water body to compare the numerical results. The wind speed and direction, imposed in the numerical model, was measured through the Belvedere (SR) station located at a distance of about 1.5 km South from the harbour. On the other hand, the time variation of the free surface elevation (TS, Tidal-Station) was measured near the inlet mouth located in the East part of the breakwaters, see Figure 1.

Both water levels and wind velocities were acquired every minute and the mean value is recorded every hour. As shown in Figure 1, a single point Acoustic Doppler Current Profiler (ADCP) placed inside the harbour collected the current velocities (VS, point). The registered data were thus used to corroborate the numerical results obtained by the present simulations. The field campaign used in the present research was carried out from the 10th to the 16th of October 2006. In Figure 2, the imposed water elevation at the mouths and the wind components forced at the free surface are plotted.

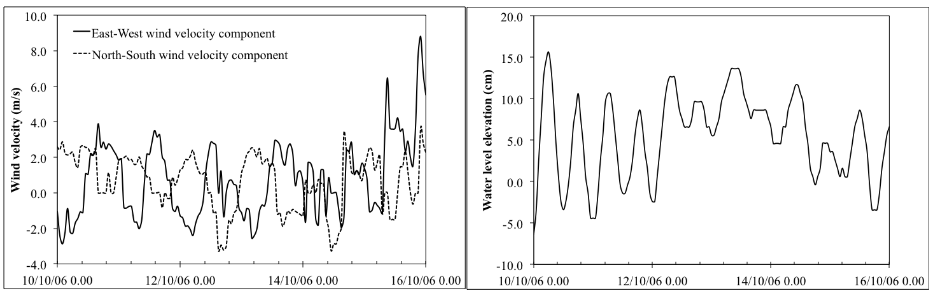

Figure 2. Left: wind velocity components measured at the station Belvedere (SR) located at the point N 37,2566 - E 15,2272. Right: Free surface elevation registered at the eastern mouth (TS station).

The fully 3D hydrodynamic model and the numerical simulations

To simulate harbour circulation the Reynolds averaged continuity and momentum equations were solved. In the standard conventional summation approach read:

Errore. $+ u_j$ **Errore.** $- \nu$ **Errore.** $+$ **Errore.Errore.** $+$ **Errore.Errore.** $- g\delta_{ij} = 0$

i, j = 1,...3 (1)

Errore. $= 0$ i = 1,..3 (2)

where t is the time, x_i the *i-th* axis (with the East-West, North-South and vertical directions aligned with the axes x_1, x_2 and x_3, respectively), u_i the *i-th* component of the Reynolds averaged velocity, ρ the water density, p the Reynolds averaged pressure, g the gravity acceleration, ν the kinematic viscosity, δ_{ij} the Kronecker delta and τ_{ij} the Reynolds stresses. The pressure p can be decomposed into an hydrostaticand a non-hydrostatic pressure part, which is independent of the vertical coordinate:

$$p = \gamma[(z_B + h) - x_3] + \rho q \quad (3)$$

where z_B is the bed elevation from an horizontal plane of reference, h is the depth of the water column and q is the non-hydrostatic pressure.

Introducing equation (3) into equation (1), the Reynolds Averaged Navier-Stokes equations can be rewritten as:

Errore. + u_j **Errore.** – ν **Errore.** + **Errore. Errore.** + **Errore. Errore.** – g **Errore.** = 0 i, j = 1,..3 (4)

where the last term is null for i = 3, since the independence of z_B and h from x_3. The turbulent stresses τ_{ij} are calculated using the k – ε turbulence model in the 'standard' formulation (Launder and Spalding [11]), while the free surface movements are calculated according to the *kinematic boundary condition*:

Errore. + u_1 **Errore.** + u_2 **Errore.** – u_3 = 0 (5)

Due to the specific case of study, an high grid anisotropy occurs. Specifically, the horizontal domain is much larger than the vertical one. In order to overcome this difference, the turbulence closure is achieved by using a non-isotropic eddy viscosity coefficient (details on the mathematical formulation can found in De Marchis *et al.* [2]).

The above presented system of equations was resolved using a 3D numerical model solver PANORMUS (Parallel Numerical Open-source Model for Unsteady Flow Simulation), available at Napoli [12]. The code is a second-order accurate both in time and space. The algorithm used is based on the *Fractional-Step* method, where the solution is splitted into two steps, a *predictor-step*, where the equations are solved assuming an hydrostatic pressure distribution without imposing mass conservation, and a *corrector-step,* where a Poisson-like equation is solved to obtain a conservative velocity field. In environmental engineering applications it is fundamental to correctly reproduce the movement of the free surface elevation, which is calculated at each time step according to equation (5). Details on the numerical discretization can be found in Lipari and Napoli [13].

In order to analyse the effect of wind and tide on the hydrodynamic circulation inside the Augusta harbour two numerical simulations were performed. In the first one (hereafter referred to as WT, Wind-Tide), in order to reproduce the hydrodynamic flow field and to compare the numerical results with the observed data, both tidal oscillation and time variable wind speed were imposed as input data. On the other hands, in the second simulation (hereafter referred to as WNT, Wind-No-Tide), the current was enforced imposing the wind speed only, thus neglecting the tidal effects. In this way, it is possible to separate the relative contribution between the effect induced by the wind and the effect induced by the tide in the enclosed coastal area. In both cases, the computational domain was discretized using 64 x 128 x 16 cells in the East-West direction, North-South direction and vertical direction, respectively. In Figure 1 the horizontal projection of the computational grid is reported. In the vertical direction a non-uniform grid was used with a refinement near the bottom and near the free-surface. A numerical simulation was carried out discretizing the physical domain into 128 x 256 x 32 cells. Since no discernable difference as been found when the grid was refined, the coarse grid was used, thus reducing the computational time cost. To simulate the flow in the lagoon the logarithmic wall-law was imposed at the land boundaries while, the null normal derivatives are imposed at the eastern and southern contour of the mouths. Due to the geometrical complexity of the domain, the presence of the barriers and the piers, a curvilinear boundary-fitted computational grid was used. The cells corresponding to land areas were excluded.

The numerical model has been extensively validated against laboratory and field experiments in several different conditions can be found in De Marchis *et al.* [2] and literature there reported.

RESULTS AND DISCUSSION

In order to validate the applied simulation code, the numerical results obtained imposing both the wind and the tidal forces were compared with the data collected in the field campaign. In the following Figure 3 the comparison is shown, where it can be observed that measured and modelled velocities exhibit a very good agreement especially in the North-South direction. In the East-West direction, a slightly worse agreement has been found. The water level variations, not shown here, were well captured too.

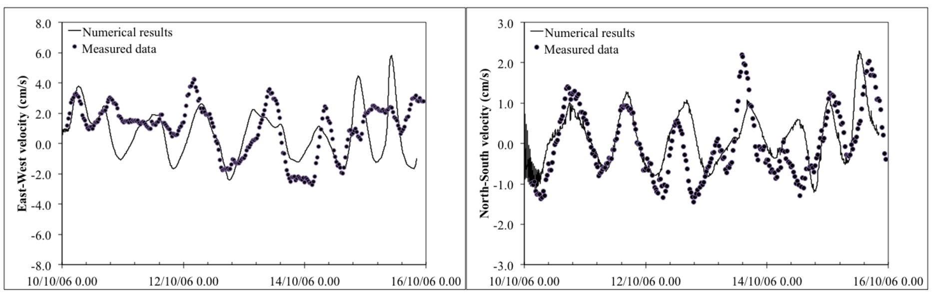

Figure 3. Comparison between measured and modelled velocity components in the VS station, located at about 10 m depth. Left: East-West velocity component; Right: North-South velocity component.

The differences between modelled and measured E-W velocity can be mainly attributed to the fact the imposed wind was measured in a location far from the harbour of about 1.5 km and that the wind was considered variable in time but constant in space. Despite the differences, it can be concluded that the numerical model is able to predict the current inside the Augusta harbour, thus the numerical model was applied to investigate on the relative contribution of the tide and of the wind on the circulation pattern.

In the following the comparison between the numerical results obtained with the two test cases WT and WNT is presented. In Figure 4, the velocities components for the two test cases at 10 cm depth are compared. The igure clearly shows that the general trend of the velocity is quite similar, thus suggesting that the circulation inside the harbour is mainly driven by the wind force. In the figure, to improve the clarity, the wind velocity components are reported too. The picture shows that, when the wind and the tide act in the same direction (see for example the period around 11/10/06 12:00), the current velocity obtained in the WT case is greater than the velocity modelled with the WNT. On the other hand, when the wind and the tide act in the opposite direction, the current is higher in the WNT case (see for example the time period 13/10/06 11:00). This occurs when the wind blows in the East direction while the tidal waves enter inside the harbour from the mouths and propagate toward the coast. Similar consideration can be made comparing the wind, confirming that the wind play a fundamental role, driving the hydrodynamic circulation inside the Augusta Harbour, while the tide causes a variation of the maximum events.

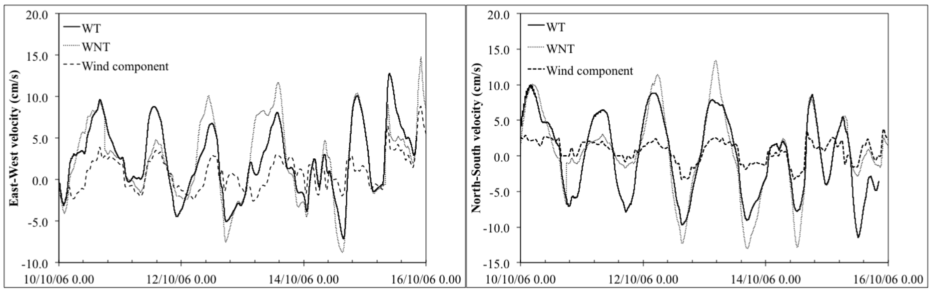

Figure 4. Comparison between the velocities components obtained with the two numerical simulations WT and WNT in correspondence of the VS point. The velocities are registered at 10 cm depth. The wind velocity component is expressed in m/s.

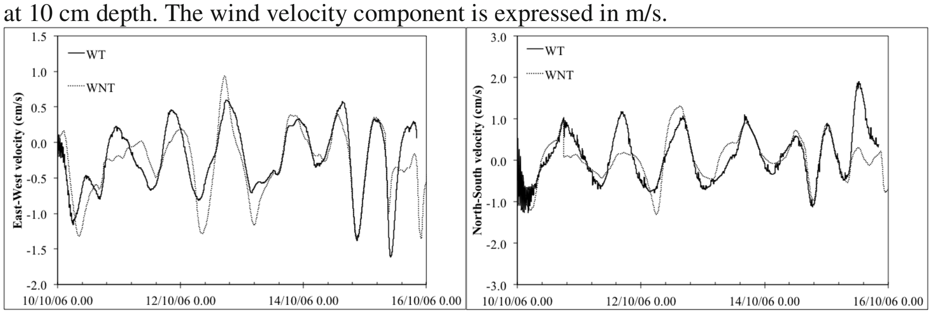

Figure 5. Comparison between the velocities components obtained with the two numerical simulations WT and WNT in correspondence of the VS point. The velocities are registered at 13 m depth.

CONCLUSIONS

A fully 3D numerical model has been applied in order to simulate the dynamics of the Augusta Harbour, located in the East coast of Sicily (Italy). In order to further validate the numerical model, the results have been compared with measured data. The comparison showed the ability of the code to reproduce the hydrodynamic inside the harbour. Both the trend and the range of the water level variations have been captured as well as the current velocity. The numerical model was thus used to separate the effects of the wind and tide on the flow field. In order to this, the comparison between numerical results obtained forcing the flow field with wind and tides (case WT) and wind only (case WNT) shows that the main force acting in the harbour area is the wind, while the tide produces a low impact on the circulation, modifying the maximum and minimum peaks of velocity only. This can be attributed to the three artificial barriers that strongly reduce the interaction between the open sea and the coastal area. Despite the numerical results showed the ability to reproduce the observed data, a certain level of unsatisfactory agreement between measured and simulated velocities was found in some periods especially in the East-West direction. This result, along with the fact that the wind plays a fundamental role, suggests that a more accurate spatial discretization of wind data must be obtained by empowering the monitoring network and that the IBL development, due to the different roughness of land and water surface, must be taken into account.

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