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FIELD AND MODELLING STUDY ON THE HYDRODYNAMICS OF THE HARBOUR OF NEA MOUDANIA (NW AEGEAN SEA)

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Abstract. Modern harbour engineering considers environmental issues of the harbour basin and adjacent coastal areas. The expansion of Nea Moudania harbour, in northern Greece, offers an example of a holistic investigation in harbour hydrodynamics. The objective of this work is the study of the circulation and flushing time of the harbour waters. Field measurements were carried out by means of current and water level recorders. Meteorological data were also collected. The data analysis led to: (a) currents of a few m/s up to 0.20 m/s inside the inner harbour basin, forming mainly 3 eddies depended on the prevailing meteorological conditions, and (b) flushing flow rate estimates of 2–9 m^3/s with corresponding basin renewal times on the order of a day. The water level recordings indicated that the mean tidal amplitude was roughly 15 cm. A 2D hydrodynamic model was applied in parallel to complement the field measurements. The combined field measurements and numerical modelling explained the hydrodynamic conditions in the harbour, leading to important indications with regard to environmental issues of the harbour.

Keywords: field research, numerical modelling, harbour hydrodynamics .

AIMS AND BACKGROUND

Modern methods of port and harbour engineering pay considerable attention to environmental issues. The expansion of a harbour (in the horizontal direction leading to an increase of the harbour area; in the vertical direction leading to an increase and maintenance of effective depths – dredging), a common practice today, may significantly influence the hydrodynamic conditions of the harbour basin and the adjacent coastal zone. These, in turn, are closely related to environmental issues, raising the need for a thorough investigation of harbour hydrodynamics. A detailed study of harbour hydrodynamics is nowadays a very important task which a modern engineer and scientist is called to deal with. This kind of study is usually based on field measurements combined with numerical or physical models.

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The hydrodynamic circulation in a harbour is influenced by wind and tides while the wave-induced circulation is in most cases insignificant. Barometric fluctuations and density variations also constitute complementary external forcing for the coastal water circulation. This paper is focused on the study of the hydrodynamic circulation of a harbour and on the consequent flushing of the harbour waters, e.g. the replacement of harbour waters with open sea water through the harbour entrance. The flushing time can be considered as one of the most critical parameters of an integrated environmental study of a harbour, as it is closely related to the water quality of the harbour basin. This characteristic time has been computed for several harbours worldwide: e.g. in Cabrera harbour, Spain, flushing is achieved within 6 days (Ref. 1) while for the inner basin of Boston harbour, USA, flushing takes between 2 and 10 days (Ref. 2). Referring to the area of northern Greece, the flushing time in a small private marina in the eastern Thermaikos gulf, was estimated to be 2.9 days (Ref. 3). The afore-mentioned flushing times have been estimated either by field measurements or by the application of numerical models.

A research based on combined field measurements and numerical modelling is presented. It aims to the description of the hydrodynamic circulation and the estimation of flushing times of the harbour basin of Nea Moudania. The harbour of Nea Moudania (Fig. 1) is located on the west coast of the Chalkidiki peninsula, on the south-eastern coast of the greater Thermaikos basin (northern Greece). It is an important fishing harbour in the north-west Aegean Sea.

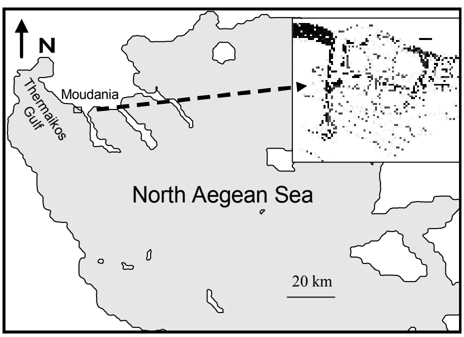

Fig. 1. North Aegean Sea and Nea Moudania harbour topography

The harbour basin occupies an area of 70 000 m^2 and has a mean depth of about 4 m (the total basin volume is 270 000 m^3). The width of the entrance of the harbour is approximately 50 m. The water column in the harbour can be considered homogeneous due to the relatively shallow depths while wind and tide are considered as the basic water circulation forces. Furthermore there are not any river inflows inside or close to the harbour area while the plumes of the rivers along the western Thermaikos gulf do not seem to reach the area of the harbour[4].

EXPERIMENTAL

FIELDWORK

Study of the hydrodynamic circulation inside the inner harbour. For the present study, field research was initially conducted, comprising 24-hour measurement campaigns from July 2007 to December 2007. The time period of approx. 12 h was determined by the well-known semidiurnal type of tide over the Aegean Sea[5,6] which is characterised by period of 12.42 h and small tidal heights of about 0.25 m. For the study of the water circulation within the harbour basin, six 12-hour period recordings were realised; the data were collected by 3 current recorders (mechanical current meters) installed at 3 locations, (#1–3, Fig. 2). Two additional stations (#4–5, Fig. 2) at the entrance of the harbour were included in the research plan (operating not at the same time periods).

Fig. 2. A sketch of the harbour and the locations of current meters

The current recorders of the afore-mentioned type had been successfully used for similar fieldworks in other areas of Thermaikos gulf[6,7]. More analytically, the current meters, submerged in the water column for approx. 12 h, were set to record the sea current speed and direction and store the corresponding values every 5 min. The instruments placed at stations #1–3, close to the sea surface, recorded the intensity and the direction of the currents, during the same time. The depth of the stations #1–3 was approx. 2 to 3 while the distance of the meters from the sea surface was about 1/2 below. Furthermore, meteorological data from an adjacent station of the Forestry Research Institute were collected.

Study of the harbour–basin–water renewal time. For the estimation of flow rates and the water mass exchange between the harbour basin and the external waters, two pairs of current recorders comprising a near surface (o) and a near bed (u) units were moored on each side of the harbour entrance (stations #4–5) at different periods from the ones concerning the study of the inner basin circulation. These current recorders were used for the investigation of the flushing time. A sea level recorder was operated simultaneously. It is to be noticed that no natural (stream) or man made (sewer) fresh water inflow to the basin was observed during the measurements period. Figure 3 combines a photo of the harbour with a sketch with the current meters to the 2 opposite stations 4 and 5 at the entrance of the harbour.

Fig. 3. Photo with a panoramic view of the harbour and a sketch of the deployment and location of the current meters at the entrance of the harbour

The currents speed and direction were recorded and stored every 5 min. Their normal to the entrance components were used for the estimation of the renewal rates. It was assumed that each pair of current recorders characterises the closest half of the basin entrance section A (A=$b \times h$) where b is the basin width and h – the depth. A detailed analysis of the calculations concerning the field data is given in Ref. 8.

NUMERICAL HYDRODYNAMIC MODEL

A 2D (depth-averaged) hydrodynamic model was applied for the study of the water circulation in the coastal area of the Nea Moudania harbour and inside the harbour basin. The area of the harbour was discretised with a grid of a 128×128 cells while the harbour depths were taken from a recent bathymetric map of the harbour. The spatial step for the greater harbour area discretisation and generation of the digital bathymetry file was dx = 5 m while the time step was dt =0.25 s. The harbour bathymetry and the established grid are depicted in Fig 4.

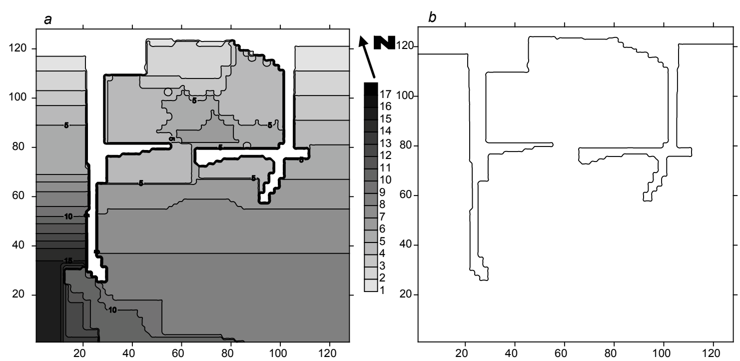

Fig. 4. Bathymetry of the harbour (a) and the grid (b) for the model realisation

The hydrodynamic model is composed by the following, well-known, equations of mass and momentum conservation[9]:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \zeta}{\partial x}+fV+\frac{\tau_{\mathrm{sx}}}{\rho h}-\frac{\tau_{\mathrm{bx}}}{\rho h}+\nu_{\mathrm{h}}\frac{\partial^2 U}{\partial x^2}+\nu_{\mathrm{h}}\frac{\partial^2 U}{\partial y^2}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \zeta}{\partial y}-fU+\frac{\tau_{\mathrm{sy}}}{\rho h}-\frac{\tau_{\mathrm{by}}}{\rho h}+\nu_{\mathrm{h}}\frac{\partial^2 V}{\partial x^2}+\nu_{\mathrm{h}}\frac{\partial^2 V}{\partial y^2}$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Uh)}{\partial x}+\frac{\partial (Vh)}{\partial y}=0,$$

where h is the depth of the water column; U and V – the depth averaged horizontal current velocities; ζ – the surface elevation; f – the Coriollis parameter; τ_{sx} and τ_{sy} – the wind surface shear stresses; τ_{bx} and τ_{by} – bottom shear stresses; ν_h – the dispersion coefficient[10]; ρ – the seawater density, and g – gravity acceleration.

The field equations of the model were numerically solved by an explicit Finite Difference scheme applied on a staggered grid. The boundary conditions consist of: (a) the shear stress components τ_{sx}, τ_{sy} due to the wind velocity (free surface boundary condition),

$$\frac{\tau_{\mathrm{sx}}}{\rho}=C_{\mathrm{s}}W_{\mathrm{x}}\sqrt{W_{\mathrm{x}}^{2}+W_{\mathrm{y}}^{2}}\ ,\quad \frac{\tau_{\mathrm{sy}}}{\rho}=C_{\mathrm{s}}W_{\mathrm{y}}\sqrt{W_{\mathrm{x}}^{2}+W_{\mathrm{y}}^{2}}$$

where W_x and W_y are the wind velocity components along x and y axis, respectively, and C_s – a dimensionless parameter (wind drag coefficient)[6,9,11,12] with values 1.3×10^{-6}; (b) the bed shear stress components τ_{bx}, τ_{by} expressed in terms of the depth averaged current velocities (bottom boundary condition),

$$\frac{\tau_{\mathrm{bx}}}{\rho}=C_{\mathrm{b}}U\sqrt{U^{2}+V^{2}}\ ,\quad \frac{\tau_{\mathrm{by}}}{\rho}=C_{\mathrm{b}}V\sqrt{U^{2}+V^{2}}$$

where C_b a dimensionless constant (bed friction coefficient)[9] with a magnitude 10^{-3}–10^{-2} and U and V – the current velocity components along x and y axis, respectively; (c) the radiation of the surface gravity wave ζ_r from the basin to the open sea across the open sea boundary without back reflection expressed by the Sommerfeld radiation condition (open sea boundary condition), and (d) zero current velocity normal to the coastline (slip velocity is allowed).

RESULTS AND DISCUSSION

FIELD MEASUREMENTS

Study of the hydrodynamic circulation inside the harbour basin. The recorded currents during the study period showed that the current velocity reached 0.19 m/s at station #1, 0.17 m/s at station #2, and 0.11 m/s at station #3. Concerning the currents at the entrance of the harbour basin, the current velocity reached values of the order of 0.4 m/s. Only stations 1, 2 and 3 were involved to the simultaneus recordings of the currents for the field study of the circulation inside the harbour basin. The current recordings at the harbour entrance (stations 4 and 5) concerned mainly the study of the harbour water renewal (next sub-section). The wind speed and wind direction concerning the data from the station is given in the rose diagram of Fig. 5.

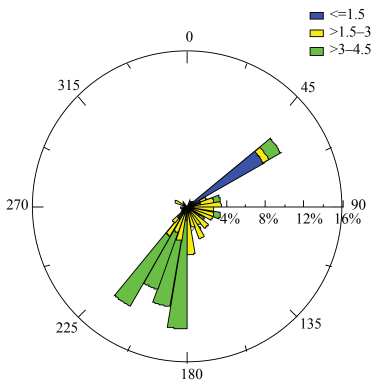

Fig. 5. Wind chart (15th September)

Figure 5 shows that during 12 h of the field works the wind speed varied between ~1 and 4 m/s with southern winds prevailing most of the time. However, the above wind speeds (U_z) corresponded to the wind blowing close to the sea surface level since the meteorological station was located at that level (z). Thus, the wind speed U_{10} at a height of 10 m a.s.l. was then calculated according to the following relationship[13]: $U_{10} = U_z \times (10/z)^{(1/7)}$. Concerning the relation of hydrodynamic circulation patterns in the basin and the wind conditions over the area, it was found that winds with north and south components prevailed during the period of field measurements, which was expected according to historical statistics of the wind conditions in the area[14,15]. However, only the southern winds, more steady and frequent during the deployment periods, caused a quite distinct pattern of circulation. During the period of the fieldworks and under the influence of winds with important southern components, the sea-surface currents in the area of station #1, had a northeastward direction, in the region of station #2 a north-western direction, and in the region of station #3 a north-eastward direction. According to this observation, the hydrodynamic circulation inside the basin, under the influence of southern mainly wind component, was found to have the pattern depicted in Fig. 6.

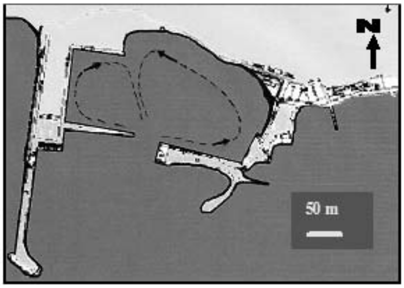

Fig. 6. Circulation pattern from the field works (15th September)

The circulation patterns in the harbour basin could not be clearly described by means of the realised measurements, as the meteorological conditions in the area had a considerable variability. Numerical modelling contributed significantly in this direction.

Study of the flushing time of the harbour waters. A detailed analysis of the computation of the flushing times based on the field data is given in Savvidis et al. (2009). More specifically, measurements of the sea surface level, recorded a tidal range of approx. ±0.15 m, within a 12-hour period which is a characteristic time of the semi-diurnal type of the tidal phenomenon. Consequently, the flushing time due to tide was found to be 6.5 days which led to flushing flow rate Q_{tide} 0.5 m^3/s. The flushing flow rate due to the wind, Q_{wind} (~4 m^3/s) and the flushing time T_{wind} (0.8 days) were also calculated according to the analysis given in Ref. 8. Then, the effective mean flushing time was calculated as $T_{\text{eff}} = 1/(1/T_{\text{tide}}+1/T_{\text{wind}})$. It was found that the estimated flushing times varied between 0.5 and 1.5 days while the corresponding flow rates vary between 2 and 9 m^3/s. These values can be considered as characteristic ones of the mean annual conditions, since they result from the most frequent meteorological conditions in the year. A statistical approach, based on the field data and the wind statistics over a long time period can be found in Ref. 8 where it was calculated that the annual mean flushing time is of the order of 1 day. The study revealed that the tidal current component proved to be much smaller than the wind generated one. So, water flushing is caused mainly by the wind action rather than tide. From the above analysis, it was made clear that wind generated currents was the main flushing mechanism as the tidal currents (calculated from the tidal prism) are checked to be 1 to 2 orders of magnitude lower than the measured currents.

MODEL RUNS

Application of the model – the existing situation. The present study incorporated the complementary application of a numerical model. For the application of the model, the hydrodynamic circulation corresponding to the 12-hour period of the

15th of September was simulated. The time series of the wind, blowing over the greater coastal area of the harbour of Nea Moudania, was used for the simulation. A surface friction coefficient $C_s = 3\times10^{-6}$ was used in the model. Furthermore, the value of 10^{-3} was used for the bottom friction coefficient C_b. The model runs led to the circulation pattern depicted in Fig. 7. The pattern refers to the wind generated circulation while, as explained before, the tidal one is negligible (since the magnitude of tidal velocities is 1 to 2 orders of magnitude lees than the wind currents). It is to be noticed that this circulation pattern corresponds to the time averaged velocity field resulted from the model run for the 12-hour period of the 15th of September.

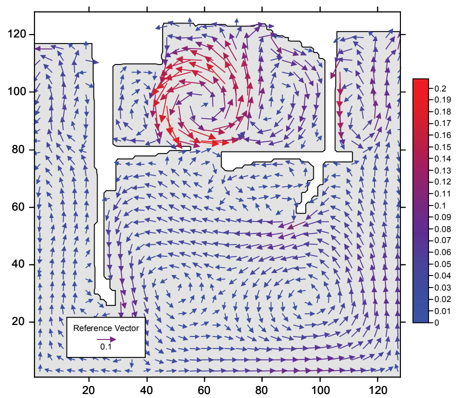

Fig. 7. Circulation pattern resulted from the wind conditions (at 15.09.2007)

According to the model, 3 eddies are formed in the harbour basin: an anticyclonic large one which occupies the larger central area of the inner basin, a smaller cyclonic one in the west part and another anticyclonic one to the east part of the basin. The current speed does not exceed 5 cm/s.

Different scenarios – circulation patterns for north and south winds. For the computation of the characteristic water circulation patterns and the flushing time and flow rate of the harbour waters, numerical simulations were applied for the 2 most frequent wind forcing, i.e. north and south winds. These simulations were applied until steady state would be reached. The persistence of north and south winds over the greater area of Thermaikos is widely reported in international scientific literature as provided in Refs 15 and 16. The wind speed used here was the mean speed of the wind recorded during the day of 15th of September. The results of the model runs are depicted in Figs 8 and 9.

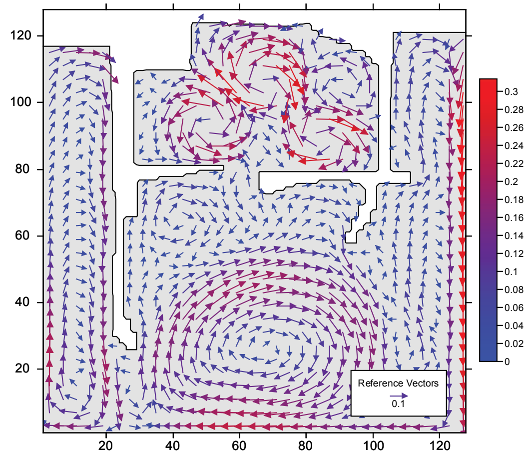

Fig. 8. Currents for north wind

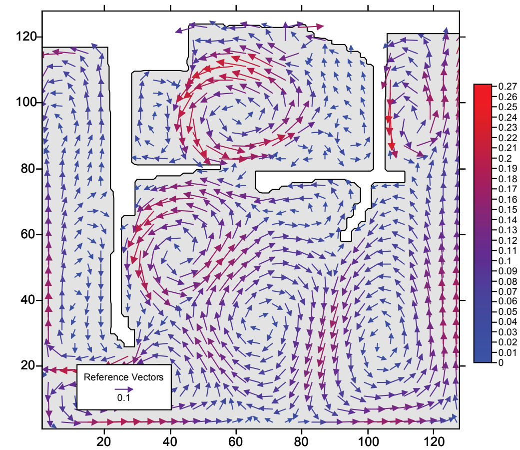

Fig. 9. Currents for south wind

According to the above circulation patterns the following conclusions are reached concerning the harbour hydrodynamics. Under the influence of northern wind 3 main eddies and another smaller one are formed in the inner basin of the harbour: a cyclonic one to the west part of the basin, an anticyclonic one in the north and central parts, a cyclonic one to the north-east and another anticyclone one to the south-east part of the basin. This mode of water movement leads to probable deposition at 4 zones of the inner harbour basin corresponding to the eddies centers. Under the influence of southern wind, a main cyclonic eddy occupies the largest part of the inner basin while 2 other small anticyclonic eddies are restricted to the western and northern parts of the basin. This mode of water movement leads to probable sedimentation at the center of the harbour basin.

Concerning the flushing process, the application of the model for southern and northern winds, under steady state flow conditions, led to flushing times T_s=1.1 days and T_n=2.0 days, respectively.

CONCLUSIONS

The field study revealed the following:

• The currents in the harbour basin varied between 0 and ~0.20 m/s while the circulation pattern depended mainly on the prevailing meteorological conditions.

• The mean tidal sea surface fluctuation range was approx. 0.30 m.

• The tidally induced flushing time was found equal to 6.5 days with corresponding flushing flow rate approx. 0.5 m^3/s. The flushing time estimated by the field measurements varied between 0.5 and 1.5 days (which is mainly determined by the wind).

The modelling study revealed 2 dominant circulation patterns. In more details the following points were highlighted:

• Under the influence of south wind 2 eddies are formed: the main cyclonic eddy occupying nearly all the area of the basin, and a second small anticyclonic eddy, restricted to the west part of the basin. This circulation pattern enhances the probability of sediments accumulation in the central zone of the harbour basin.

• Under the influence of north wind 4 eddies are formed in the inner basin of the harbour: 2 cyclonic ones to the west part and north east of the basin, 2 anticyclonic ones to the north part and the south east part of the basin. This circulation pattern enhances the probability of sediment accumulation in 3 zones of the inner harbour basin corresponding to the center of each eddy.

• Based on the model results, the flushing time was found to be 1 day for south winds (close to the observed values related to the circulation during the field works) and 2 days for north winds.

The methodology outlined in this paper may be used diagnostically or prognostically in other harbour engineering and environmental impact studies.

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