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VELOCITY LAWS APPLIED TO MEASURED SEA CURRENTS

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ABSTRACT

A vessel mounted acoustic Doppler current profiler was used to measure the vertical distributions of current velocities during some monitoring surveys carried out in March 2003, along the Apulian coast (Southern Italy). In the same selected stationing points, at the same time, also a CTD recorder was used to measure water temperature and salinity. The aim of the paper is to investigate these field measurements of sea currents and to model the measured velocity vertical profiles by means of some classical empirical laws, thus testing their ability to reproduce the velocity field. The analyzed data refer to a complex domain, characterized by an irregular bathymetry and a roughness due to non uniform seabed vegetation. Consequently the validity of the theoretical velocity laws along with their classic parameter values has not necessarily to be expected. Therefore, a modified form of the velocity-defect law is here proposed.

1 INTRODUCTION

Previous studies, such as Mossa (2006), De Serio & Mossa (2006), Ben Meftah et al. (2009) pointed out the sensitivity and vulnerability of two sea zones close to the Adriatic and the Ionian coast respectively. Specifically, they referred to the Apulian coast where the eastern wastewater outfall pipe of Bari (the main city of Apulia) is located and to the open north-eastern area of the Ionian Sea where a highly polluting discharge, due to an extensive industrial activity, occurs. These are typical risk factors which may easily endanger the coasts and the entire aquatic habitat. Therefore, in order to assure the respect of the prescribed water quality regulations, a continuous monitoring from the administration in charge is necessary.

Anyhow, it should be observed that sea current magnitude and directions greatly affect the diffusion and mixing of pollutants (Mossa, 2006). Consequently, the mathematical models capable to forecast the hydrodynamics of coastal waters are surely a powerful device in the preliminary planning phase of outfall discharges, whose construction and positioning need to take into account the quality standards set by regulation.

Many mathematical models and laws have been developing, but they are often complex to implement, need for initial and boundary conditions which are not always available and need for validation with field data. The aim of the present study is to propose a simple velocity law to forecast the current velocity distribution along depth in a marine environment, starting from the classical empirical laws originally used to reproduce the velocity field in pipe and open channel flows (Anwar, 1996). The new proposed velocity law has been tested using the current velocities measured during the survey carried out along the Adriatic coast, as shown in Figure 1.

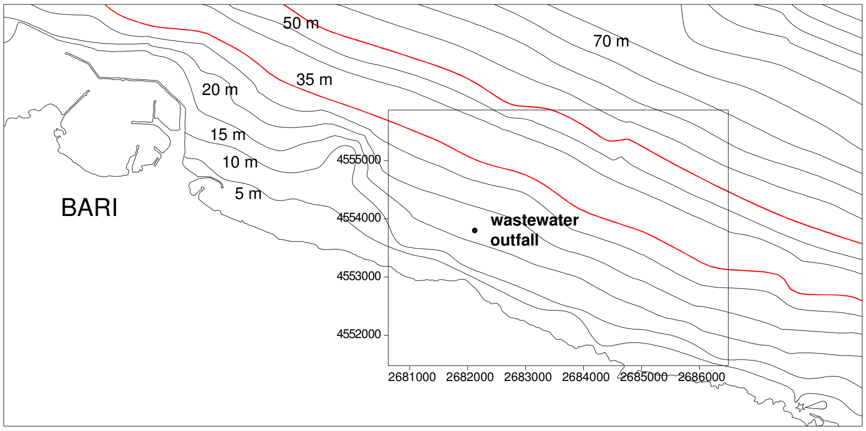

Figure 1. Map of the investigated area. Gauss Boaga reference system is used.

2 MEASUREMENTS FACILITIES AND TARGET AREA

Figure 1 shows the map of the sea area investigated in the present paper, delimited by 5 m and 70 m bathymetric lines. The red dot, located between 15 m and 20 m bathymetric lines, represents the end of the wastewater outfall pipe of the Bari East plant.

As mentioned above, a Nortek AWAC vessel mounted acoustic Doppler velocity profiler was used to measure the sea three-current-velocity components. The AWAC was connected to a gyro and a DGPS in order to take into account the vessel velocity and thus to acquire the current velocity with respect to the seabed. The measurements of the flow were assessed with an acquisition frequency of 0.5 Hz, thus the obtained data were not useful for turbulence analysis, otherwise mean velocities were deduced and examined in the present paper. The measurements were acquired at an interval of 1.5 m along the vertical, starting from 4 m below the water surface, being 4m the blank distance of the AWAC instrument. The velocity range of the instrument is ± 10 m/s and ± 5 m/s in the horizontal and vertical direction respectively, with an accuracy equal to 1% of the measured value ± 5 mm/s. A CTD recorder system by Idronaut Srl was used to measure the water temperature and salinity. The practical salinity is calculated with the formula adopted by UNESCO in 1980. To measure wind intensity and atmospheric temperature, an anemometer by Cometeo and a thermometer by Delta Ohm were used. The detailed characteristics of the used instrumentations are described in Mossa (2006).

3 DESCRIPTION OF THE SURVEY

The survey was carried out on 10 March 2003. Velocity profiles were measured starting at 11:30 and finishing at 16:30. The air temperature was in the range of 11.7 ÷ 13.2 °C, with increasing values during the measurement time. The anemometric regime was characterized by a wind with directions included in the range of 290 ÷ 340 NE and time-growing intensities, ranging from 2.3 to 7.0 m/s. The data were acquired along two transepts of 5000 m of length, following the 35 m and 50 m bathymetric lines respectively (Fig. 1). The offshore transept followed a SE direction while the onshore one followed a NW direction. An average current directed towards the SE was observed. At a depth of 4 m velocity values are in the range of 0.34 ÷ 0.69 m/s. The velocities generally decreases with water depth, while the velocity vectors do not vary much in their directions. The most intense southeastward flow was recorded at greater distances from the coast. The acquired data showed that in the analyzed measurement stations, for periods of some hours, the flow approached a quasi-steady state and the current pattern variations occurred very slowly over time. Moreover a little variation in the flow direction with depth was generally observed, as it can be deduced from Figure 2, which plots, as an example, the distribution of the horizontal current velocities measured at the depth of 4 m and 12 m from the surface.

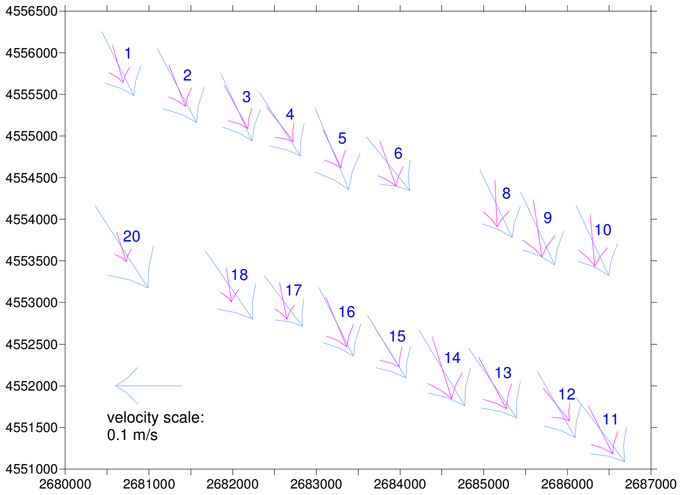

Figure 2. Distribution of the horizontal current velocities at the depth of 4 m (blu arrows) and of 12 m (purple arrows) from the surface.

A vertical gradient of temperature T and salinity *S* is observed in the most superficial layer. The thickness of this layer is quite equal to 10 m in the offshore bathymetric line and to 20 m in the onshore one, with values that increase with depth within this layer, from 10 °C and 36.2 PSU respectively to 13.5 °C and 38.0 PSU. On the contrary, they are quite invariant at deeper water.

As an example, Figure 3 shows the temperature trends for some of the examined stations placed on both the onshore and offshore bathymetric line. Higher values of temperature and salinity are generally observed offshore.

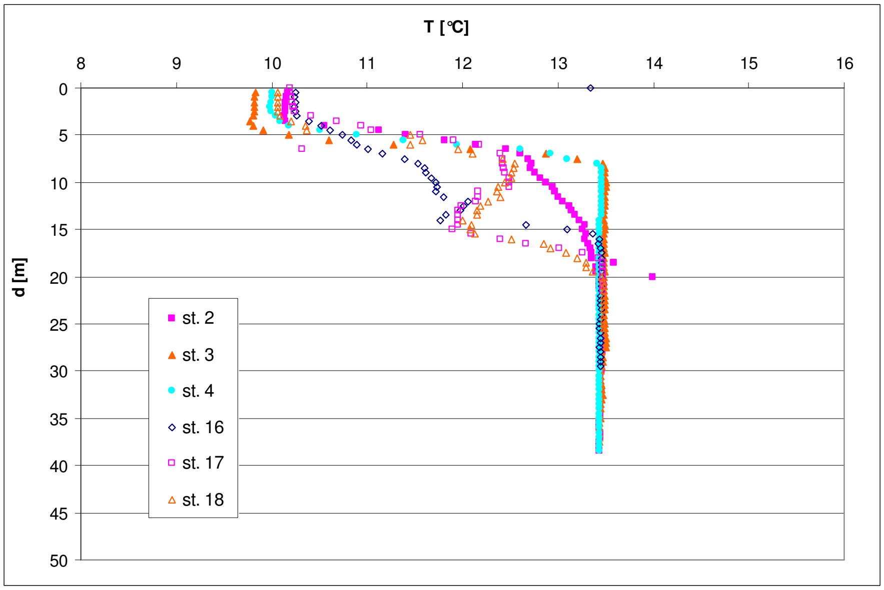

Figure 3. Measured temperatures at some selected stationing points; *d* is the distance from the free surface.

4 THEORETICAL BACKGROUND

Up to the present time, velocity profile analysis in free surface flows has represented a topic widely discussed in literature (Nezu & Nakagawa, 1993; Zagarola et al., 1997; Termini & Greco, 2006; Cheng, 2007), considering that velocity vertical distributions may assume different shapes depending on the hydraulic conditions examined. Moreover, a general law for velocity vertical profiles should usually possess the following attributes (Termini & Greco, 2006): capability to fit quite well the experimental data in a large number of cases; physical meaning of its parameters; capability to allow predictive estimates of velocity field.

Classical theory (Nezu & Nakagawa, 1993) stated that, for free surface flows, in the wall region (i.e. $z/h < 0.2$, with h local total flow depth and z vertical coordinate measured from the bottom) the well known log-law velocity distribution is valid:

$$\frac{u}{u^*} = \frac{1}{k}\ln\left(\frac{z}{h}\right) + B \tag{1}$$

being u the velocity value, u^* the shear velocity, k von-Karman’s constant and B a parameter depending also on the seabed roughness. This distribution may be extended to the entire flow in some cases, referring particularly to shallow waters and open-channel flows where the maximum velocity value is observed at the free surface and small velocity gradient are observed near surface (Termini & Greco, 2006).

In other cases, deviations from log-law systematically occur and they should be accounted for by adding a wake function, thus obtaining the velocity defect law, which is also valid in the outer region ($z/h > 0.2$):

$$\frac{u}{u^*} = \frac{u_{10}}{u^*} + \frac{1}{k}\ln\left(\frac{z}{h}\right) - \frac{2\Pi}{h}\cos^2\left(\frac{\pi z}{2h}\right) \qquad (2)$$

where Π is the so-called Cole’s parameter and u_{max} is the maximum mainstream velocity value (Nezu & Nakagawa, 1993).

5 RESULTS AND COMMENTS

The analysis of the vertical distributions of the velocities assessed during the survey was carried out in the following way. For each examined measurement station the mean flow direction was detected, consequently the vertical profiles were evaluated for the u velocity component along this direction.

In order to apply the log-wake function (Eq. 2) to each vertical profile, supposing that it may fit the observed data starting from the sea bed to the water depth of 4 m, the shear velocity u^* has to be estimated. For each station, the log-law (Eq. 1) was applied to match the field velocity data only in the wall region. It is noticeable to observe that, in the present study, the validity of the log-law can be extended up to $z/h = 0.3$. The fitting procedure provided for both the shear velocity u^* and the coefficient B, assuming $k = 0.41$.

It was observed that the higher values of the correlation coefficients (on average equal to 0.8) were obtained for the points along the offshore transept. Therefore, as a first attempt to derive a general formulation of the vertical velocity distribution, only the stations located along the offshore bathymetric line were afterwards considered in the present study.

As a second step, for each above mentioned station, Equation (2) was applied. In the present case, the velocity u_{max} that was used in Equation (2) was not the maximum value assessed in the whole vertical profile, which generally is located close to the free surface. In fact, both wind and gradient current effects surely affect the surface circulation. The analysis of temperature (Fig. 3) and salinity distributions, for the stations at the bathymetric line of 50 m, shows in the upper layer both the mixing due to wind and the vertical stratification, up to a depth of about 10 m. Consequently, the value of u_{max} in Equation (2) was evaluated taking into account only the u velocities measured in the flow layer below the depth of 10 m. Hereafter, this velocity value will be named u_{10}. A good reproduction of the measured profiles with Equation (2) was achieved in all the tests, up to the relative bottom distance $z/h \approx 0.7$. Indeed, it was argued that the most superficial velocity values were well reproduced only adding a power-law to Equation (2).

Therefore, in the present study, a modified equation is proposed, able to fit with great accuracy the field data along the whole vertical profile:

$$\frac{u}{u^*}=\frac{u_{10}}{u^*}+\frac{1}{k}\ln\left(\frac{z}{h}\right)-\frac{2\Pi}{h}\cos^2\left(\frac{\pi z}{2h}\right)+\gamma\left(\frac{z}{h}\right)^{\delta} \tag{3}$$

where the coefficients γ and δ were estimated with the experimental data. Taking into account the wind effect on the water surface, Dean & Darlymple (1991) proposed that the bottom shear stress is roughly equal to 20% of the wind shear stress. Consequently, for each sampling station, the shear velocity due to wind action at the sea surface, u_w*, was evaluated as

$$u_w^*=\frac{u^*}{0.2^{0.5}} \tag{4}$$

To confirm the validity of this assumption, values of u_w* in the stationing points were also estimated starting from the wind velocity measured during the survey, by means of classical experimental diagrams present in literature (SethuRaman & Raynor, 1975). A good agreement with the results of eq. (4) was observed. Therefore, assuming, guided by the dimensional analysis, that both parameters γ and δ are function of the dimensionless index u_{10} / u_w* and using the experimental data of the present study, we obtained that:

$$\begin{aligned}\gamma &= 4u_{10}/u_w^* \\ \delta &= \gamma/2\end{aligned} \tag{5}$$

From the abovementioned analysis, it is clear that γ and δ have a physical meaning. Figures 4a and 4b show the comparison of the theoretical curves calculated by means of the log-wake Equation (2), the new proposed Equation (3) and the field data. For the sake of brevity, only some selected stationing points are shown.

The validity of the new simple velocity law proposed in this study is evident. The improvement in the theoretical fitting curve calculated with Equation (3), with respect to the one calculated with Equation (2), is clear for those points close to the surface. In order to estimate this satisfactory matching between the field data and the theoretical velocity values derived with the new velocity law, a relative error was calculated as $|\text{measured } u-\text{modelled } u|/\text{measured } u$.

Considering all the investigated stationing points, this relative error is less than 0.2 This result is appreciable, especially taking into account that the measured values were not acquired in a steady channel flow, but rather in the sea, where, as it is well known, the environment is very complex. Anyway, the study is still ongoing and other investigations will be carried out to further validate the proposed Equation (3).

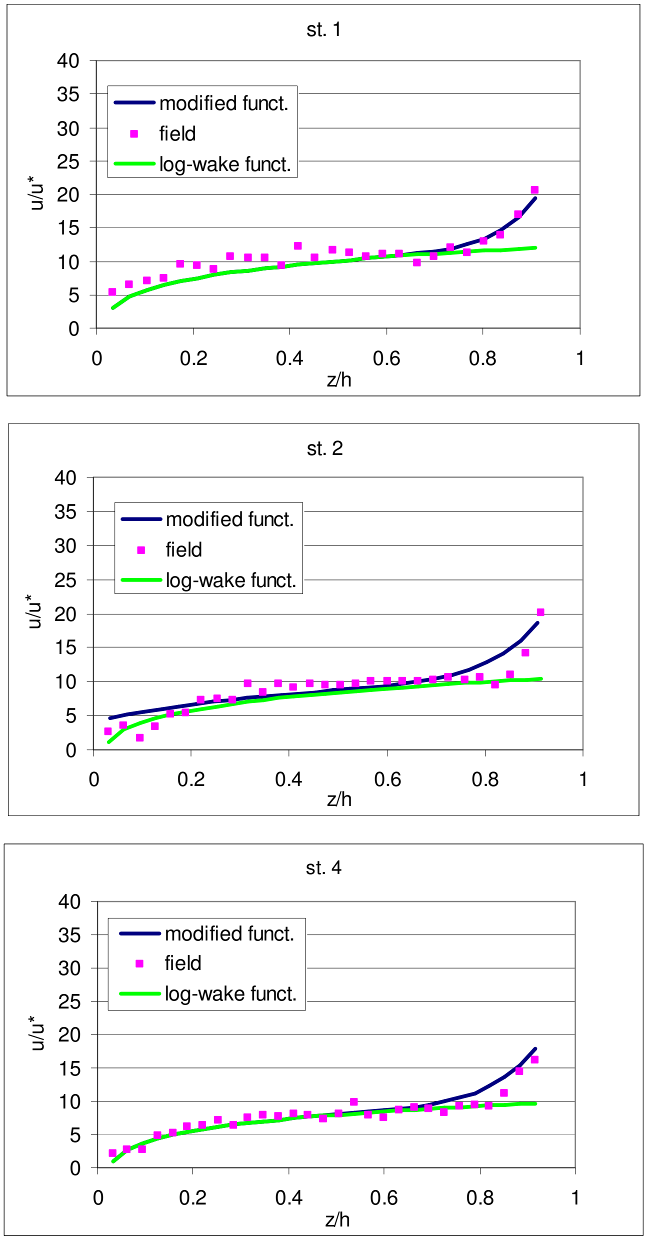

Figure 4a. Comparison in stations 1, 2 and 4 of the vertical profiles of i) measured *u*-velocity components along the mean flow direction; ii) velocity values calculated with log-wake function; iii) velocity values calculated with the new proposed velocity law.

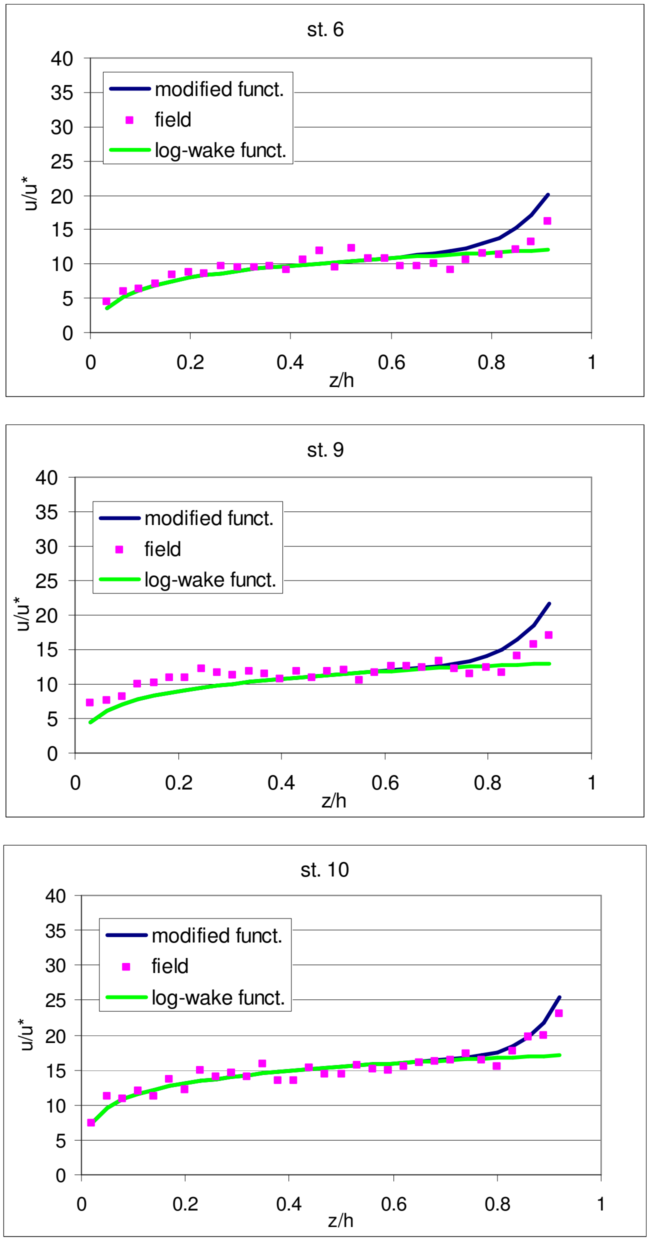

Figure 4b. Comparison in stations 6, 9 and 10 of the vertical profiles of i) measured *u*-velocity components along the mean flow direction; ii) velocity values calculated with log-wake function; iii) velocity values calculated with the new velocity law.

6 CONCLUSION

Field measurements of sea currents were investigated and modeled starting from some classical empirical laws, in order to test their ability to reproduce the velocity field. Once observed that the theoretical velocity laws are valid only in specific region of the water column, a simple model was proposed in the paper which takes into account both the log-wake law and a new power-law. An estimation of its parameters was experimentally deduced and it was found that they depend on both the maximum velocity value, assessed at the depth were wind and stratification effects can be disregarded, and the wind shear velocity. The theoretical velocity values calculated with the new proposed equation well agree with the measured data, also taking into account that the current values were measured in typically difficult field conditions.

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