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Experiments on Coupled Wave-Flow-Vegetation Interaction

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***Abstract* – In this study we focus on how understanding, through experimentation using advanced techniques, the dynamic of wave interaction with emergent vegetation. In order to achieve this objective, an experimental study of wave mention through an infinite array of emergent cylinders distributed along a channel bottom was carried out in the Coastal Laboratory at the Polytechnic University of Bari (Italy).**

A series of sophisticated equipment was used to produce and measure the details of this phenomenon, including essentially an electro-valve, equipped with an electromagnetic flow meter and a control device to rapidly open and close it to generate the water waves, a series of ultrasound probes to measure the free surface elevation, and a series of Acoustic Doppler Velocimeter (ADV) probes in addition to a Particle Image Velocimetry (PIV) technique for flow velocity measurements. The measurement methods, instrument calibration, data filtration and some preliminary results are reported in this study.

I. INTRODUCTION

Aquatic plants usually play a fundamental role in maintaining environmental equilibrium system, i.e., water purification by uptaking nutrients, transport and dispersion of nutrients and tracers, protecting and restoring aquatic habitats, transfer of oxygen, carbon sink, increasing light penetration and potential growth by reducing sediment resuspension, acting as a seabed stabilizer, flood control, shoreline stability [1,2]. Natural vegetation in adjacent wetlands is characterized by several aspects (submerged/emerged, rigid/flexible, leafed/leafless, of height/low density), reflecting a number of complex phenomena. Therefore, a good understanding of the interaction processes between a wave-induced flow and an array of vegetation is essential to promote best environmental management practice.

Despite the numerous studies on flow-vegetation interaction [3-13], accurate prediction of the flow features (transport and mixing processes) and the vegetation resistance always remains challenging due to the complexity of phenomenon and its sensitivity to any variation in the surrounding environment.

Flooding resulting from extreme storm events, such as heat waves, tornadoes, seasonal storms, hurricanes and other is a notable risk along coastal areas. These natural phenomena can cause large scale destruction of the ecosystem as well as of human life and property. Vegetation presence can play a major role in minimizing damage from the induced storm surge and waves. to promote best environmental and sustainability practices, we have to consider two fundamental things: i) reducing as minimum as possible the anthropic pressure on the coastal zones, especially, the vegetated coastal areas, ii) trying to understand well the physical reaction of vegetation canopies to waves and induced currents. Most of the previous studies [14-16] confirmed that a water wave propagates through submerged or emerged vegetation field will inevitably lose a considerable quantity of energy, causing the wave attenuation and breaking.

For the sake of simplicity, various models on wave-vegetation interaction approximate the vegetation resistance as a high sea-bottom roughness. In other studies the vegetation resistance is estimated through a drag force, after empirical prediction of a black drag coefficient, as shown in Ben Meftah and Mossa [7]. In reality, the wave-vegetation interaction is more complex than a simple prediction of a drag force or bottom friction factor, but it is a very turbulent flow regime that behaves from large scales, of order the wave-length, to small scales, of order the vegetation stem-diameter [7,13,17]. Unfortunately, up today, a deep and complete understanding of this complex dynamic mechanism is lacked. Therefore, further studies on this issue are needed and strongly recommended.

This paper summarizes how emergent-vertical-rigid aquatic plants, partially obstruct a channel cross flow, can influence the flow structures of a wave motion. To achieve such an objective, an experimental study was carried out. The use of advanced techniques helps to obtain more details on the flow hydrodynamic structure within the vegetation arrays. Moreover, the comparison between the wave behaviours in the channel with and without vegetation presence, clearly highlights the significant effect of the vegetation on the wave features. The analysis of the flow velocity-field shows a substantial role of vegetation on absorbing the wave energy. With area covered by dense vegetation, a partial wave reflection can occur. Vegetation also significantly affects the turbulent mixing and diffusion processes.

II. EXPERIMENTAL SET-UP AND EQUIPMENT

The experimental runs were carried out in a smooth horizontal rectangular channel at the Hydraulic Engineering Laboratory of the Department of Civil, Environmental, Land, Building Engineering, and Chemistry of the Polytechnic University of Bari (Italy). The channel consisted of a base and lateral walls made of Plexiglas. The channel is 25m long, 0.4m wide and 0.5m deep. To create a current inside the channel, a closed hydraulic circuit was constructed. The base water discharge of the channel is gravitationally supplied from a big tank at law pressure, located outside the laboratory. The channel consists of an upstream metallic tank, equipped with a set of stilling grids to dampen inlet turbulence and a side spillway with adjustable height to maintain constant and uniform the entering water head (Fig. 1). An upstream and downstream gates (made of Plexiglas) were used to define the flow depth and mean velocity in the channel. Downstream of the channel, the outlet flow is intercepted by a rectangular metallic tank of 3m long, 1m wide and 1m deep, equipped with a triangular weir (V-notch sharp crested weir) to measure the channel discharge. The water that overflowed the spillway and fed out from the channel is continuously pumped to big tank, located outside the laboratory.

The wave motion was produced by an electronic control device, controlling the opening and the closing of an electro-valve to rapidly attain a maximum discharge, measured by an electromagnetic flow meter.

The model array is constructed of vertical, rigid, circular and threaded steel cylinders. The cylinder height is 0.134 m and has a diameter equal to 0.002 m. The cylinder extremities are inserted into a series of plaques made of Plexiglas of width equal to the channel width and a thickness of 0.02 m. These plaques are fixed along the channel bottoms, forming an obstructed area along 6m. The Plexiglas panel is extended over a certain distance upstream and downstream of the experimental area and is tapered to the channel bottom to minimize flow disturbance. Cylinders were arranged in staggered or aligned formations, varying the distance between stems from 4 cm to 8 cm.

***Fig. 1**. Image of the channel flow with instruments.*

The velocity data were collected using two types of Acoustic Doppler Velocimeter (ADV)-Vectrino system, developed by Nortek, of maximum sampling rate of 200 Hz (Fig. 2). The first type consists of two 3-D ADVs of side and bottom looking probes, with a sampling volume located 5 cm ahead/below the transmitter probe. These Vectrino can be used with a velocity range of ±0.01 m/s to ±4 m/s, have a measured velocity accuracy of ±0.5%, a sampling volume of vertical extent (user selectable) from 3mm to 15mm. For high-resolution measurements, the manufacturer recommends a 15db signal-to-noise ratio (SNR) and a correlation coefficient larger than 70%. Before starting analysis, the acquired data should be filtered and the bad samples, of SNR<15db and correlation coefficient <70%, should be also removed. The second type consists of a Vectrino II, which profiles the water column over a 3 cm range and provides three-component velocity observations with a sampling rate of 100 Hz. It can be used with a velocity range from ±0.1 m/s to ±3 m/s with an accuracy of ±0.5%, a sampling volume location 45-75 mm from the probe, a cell size 1 to 4 mm (user selectable) and an operating temperature from -4°C to 40°C.

For the flow velocity measurements, it was also used a Particle Image Velocimetry. It is an optical method of flow visualization consisting of a dual power laser of high performance and with an extensive range of output energies of up to 425 mJ per pulse and repetition rates up to 100 Hz, a timer box and timer card cable box, camera FlowSense EO 4M-32 with a lens of 60 mm, and software for image analysis (Fig. 3). The PIV is an ideal technique for global and instantaneous measurement of the flow field-velocity, helping to easily construct the flow hydrodynamic structure.

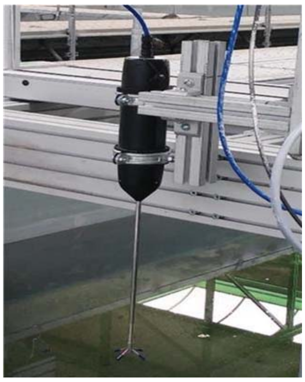

Fig. 2. *Acoustic Doppler Velocimeter -Vectrino system.*

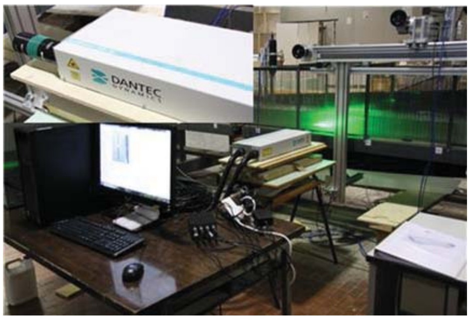

Fig. 3. *Particle Image Velocimetry: power laser.*

For the flow free-surface elevation, six ultrasound probes were distributed along the channel. The ultrasound probe measures from 30 mm up to 3.4 m, has a resolution up to 0,18 mm and a repetition rate up to 75 Hz (Fig. 4).

Before starting any measurement all the instruments are calibrated. The channel base discharge was determined using a calibration curve of equation:

$$Q = 0.3336\sqrt{2g}h^{\frac{5}{2}} \tag{1}$$

where g is the gravitational acceleration and h is the channel base-flow depth.

Fig. 4 shows a definition sketch of the experimental setup. The experimental area, the distribution of the different instruments and other details on the channel equipment are clearly indicated.

Fig. 3. *Ultrasound probe for free-surface elevation.*

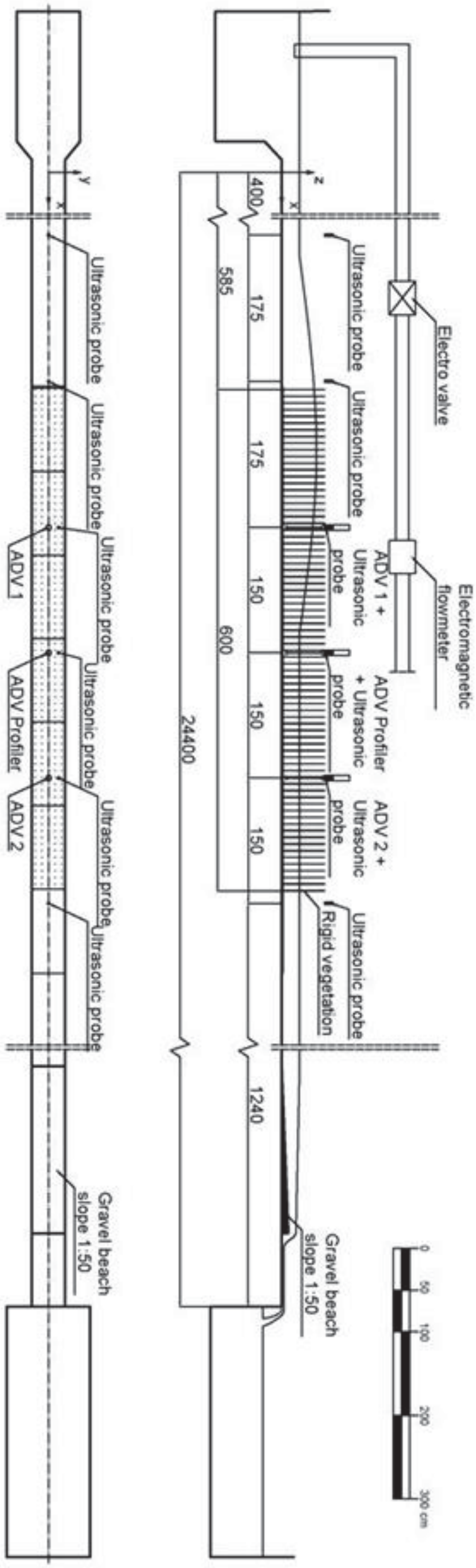

Fig. 4. *Definition sketch of the experimental setup*.

III. PRELIMINARY RESULTS

In order to evaluate the wave characteristics, measurements were firstly carried out in the channel without vegetation canopy. The results clearly show the development of an incident wave with a significant crest, propagating along the channel flow. Thanks to the presence of the several ultrasound probes (Fig. 4), mounted at different positions along the channel axis, the waves characteristics (height, length, period) can be easily determined. In addition to the wave characteristic, the flow velocity-field was also measured, with and without (base-flow) the wave passage. Figure 5 shows an example of the temporal evolution of the free-flow surface at 12 m (s4) downstream of the channel inlet position together with the three flow-velocity components trend at the same position. Herein, U_b, V_b and W_b are the streamwise, the spanwise and the vertical velocity component, respectively, measured at 5 cm from the channel bottom using the ADV of bottom looking probe. Figure 5 indicates a base-flow of depth 10 cm and mean velocity of order 3 cm/s. The streamwise velocity is strongly influenced by the wave passage (first peak), reaching a maximum value of order 9 cm/s. However, the vertical component undergoes very slight variation and the spainwise component always indicates null values, confirming the two-dimensionality of the waved flow field. A wave reflection, due to the downstream gate (second peak) and the upstream tank (third peak) can be also noted.

Figure 6 shows an example of the wave interaction with a vegetation canopy of density 156 stems/m^2. s1, s2, s3 and s4, on Figure 6, indicate the free-flow surface elevation as a function of time in the vegetated area at the positions of 7.5, 9, 10.5 and 12 m downstream of the channel inlet. Figure 6 clearly highlights the strong effect of the vegetation canopy on the wave attenuation. The wave height decrease from a value of 19 cm at 7.5 m to 15 cm at 12 m, with a reduction rate of order 21% over a distance of 4.5 m, obstructed by vegetation.

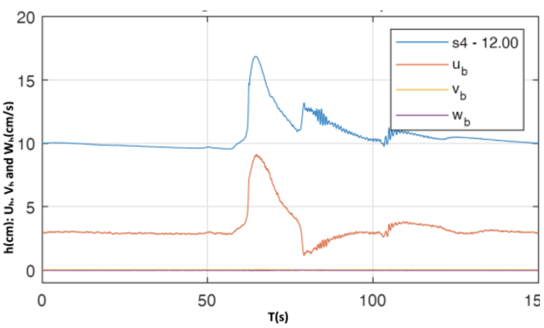

Fig. 5. *Example of velocity and free-surface temporal trend*

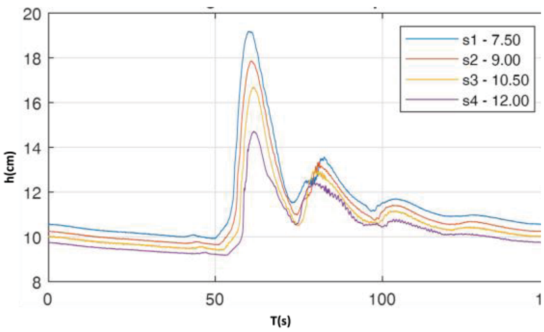

Fig. 6. *Example of the wave interaction with vegetation canopy*

IV. CONCLUSIONS

Many coastal areas around the world are subject to frequent flooding caused by storm surges. These flooding events produce severe damage to coastal and inland regions, causing loss of human life and property.

Since wetland vegetation is most effective in attenuating the wave height by energy dissipation, in this study, we try to experimentally understand how a flood-wave interacts with a vegetation canopy. The simultaneous use of ultrasonic probes, ADVs, an ADV profiler, and a PIV system provides an integrated hydrodynamic-image of the process. The results show a considerable vegetation-effect on the wave attenuation. The wave attenuation increases with the increase of the vegetation density. The wave turbulence structure is strongly affected by the presence of vegetation. Downstream of the vegetation stems, wake areas are formed, leading to the development of intense vortices. The accurate measurements of the flow-velocity fields will enable us to better understand how the turbulence generated by the vegetation affects the wave behavior.

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