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Multi-chamber OWC Devices to Reduce and Convert Wave Energy in Harbour Entrance and Inner Channels

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ABSTRACT

Physical model tests on a new Italian concept of wave energy converter named SeaBreath were carried out in the 36 m x 1.0 m x 1.4 m wave flume of Padova University. Beside energy harvesting, the device has a secondary purpose, i.e. it plays the role of a small floating breakwater. An example application is proposed for the deep "Petroli Channel" in the Venice Lagoon, that is plagued by continuous bank and marsh erosion induced by excessive waves generated by boats and ships.

KEY WORDS: Wave Energy Converter; Floating Breakwater; Oscillating water column; Ship generated waves; Wave flume tests; Wave transmission; Venice Lagoon.

INTRODUCTION

The Sea Breath is a patented Italian device of the Multi-chamber Oscillating Water Column (M-OWC) attenuator type, www.seabreath.it.
Demonstration phase (i.e. the phase following research and development) for Wave Energy Converters (WECs) requires that devices are tested for several hours at sea, in locations easily and frequently accessible (Kofoed and Frigaard, 2009).
At the earlier stage, economic opportunity suggests that the scale of the device used for demonstration is included in the range 1:4 to 1:10, since several parts of the structure are likely to be substituted. Due to scaling reasons (the weight scale is equal to the geometrical scale to the power 3 and the energy scale to the power 3.5) such systems produce far too little energy (i.e. from $4^{3.5}$=128 to $10^{3.5}$=3160 times lower) to justify their construction costs.
In order to support the testing of these devices, it is worthwhile to find a useful combined application and thus increase the chances of its initial installation. Under these circumstances, even a failure of the WEC (resulting in learned experience) may not result in a complete fiasco (if the secondary function is satisfactorily fulfilled).
One possible application is to couple the WEC to a floating breakwater (FB), and enhance the performance (reduce wave transmission) by means of the conceptual device used to harvest energy.

It is intuitive that if the WEC is capable of converting a large amount of the incident wave energy into electricity, the wave transmission past the device must be significantly reduced, possibly more compared to a mere FB.
The classical FBs is referred to as a "passive" device, whereas a floating body equipped with an energy harvesting device is referred to as "active".
This research topic is developed by the Authors within the support of the EU FP7 Theseus "Innovative technologies for safer European coasts in a changing climate" (THESEUS). The main applications are directed towards the protection of marinas subject to long waves, or towards the protection of coasts from flooding.
A similar application, at a smaller scale, is here proposed: the FB aims at reducing the wave agitation in the ecologically sensible Venice lagoon, where waves are generated by boats, frequently sailing along the lagoon channels, and, to a minor degree, by ships entering the Venetian Port.
It is generally believed that ship generated waves, being less frequent compared to wind waves, have a marginal contribution to erosion. In the Venice Lagoon, due to its the peculiar dynamic, this is not entirely true. It is well known that the bed level tend to deepen and the effect of both wind and ship waves is critical for the environment (Rinaldo, 2001, Zonta et al., 2007).
For example, in order to protect the lagoon from boat generated waves, different kind of structures were tested along the Canale Somenzera S. Giacomo, close to Burano island.
Large vessels, or ships, that may occupy a significant fraction of the cross-sectional area of the channel, are more dangerous as they generate both a long wake that propagates into very shallow water and, on top of this, a train of direct and transverse short waves of considerable height. Over the shoals, the long wakes produce high, near-bottom current velocities (Bauer et al., 2002), leading to substantial sediment resuspension and consequent increase dredging demand. Short waves are responsible for the sediment pick up, thus significantly enhancing the negative effects. The combined effect of wind waves and tidal currents is known to have a maximum at the Petroli Channel (Umgiesser et al., 2004), that is therefore a suffering environment.
Evaluation of the propagation of low and high frequency waves generated by vessels in the lagoon can be carried out with fairly simple methods (e.g. mild slope equations, see Ohyama and Tsuchida, 1997).
Aims of this contribution are:

i) to present the newly patented WEC named Sea Breath.
ii) to show a possible innovative application of a WEC as attenuator of ship generated short waves, with clear benefits both for the navigation issues and for the bank stability along dredged channels.
iii) to show a possible application.

The first section presents the operating principle of the SeaBreath device. Its performance was studied in the second half of 2010. Additional tests, carried out in early 2011, show that an accurate design of the structure, quite effective at high frequencies, may reduce wave transmission also for long waves.

The proposed application involves the deep channel named “Canale dei Petroli” in Venice Lagoon, that is plagued by continuous bank and marshes erosion induced also by ship generated waves, so dangerous for the ecosystem when the maximum allowed vessel speed is exceeded.

THE SEA BREATH

The device is invented and patented by Dott. L. Rubino and developed under the financial support of Merighi Group (www.seabreath.it). It is an elongated structure, formed by a series of aligned rectangular chambers with open bottom (Fig. 1). The device is aligned perpendicularly to the incident wave crests, i.e. it is of the attenuator type of WECs.

In its final configuration, the device is intended to float. The floating body dynamics and the mooring system still need to be analysed, though. It would be much more convenient for the moment to consider a similar but virtually fixed device, or possibly anchored with piles.

If we stick to the classification proposed by Thorpe in 1992 (see for instance Thorpe, 2000) the SeaBreath is of the Oscillating Water Column (OWC) type, since each chamber behaves as a OWC.

When air in each chamber is compressed, it is directed by non-return valves toward a longitudinal high pressure duct; when air is decompressed, low pressure air is directed toward a low pressure duct. The peculiar recirculation system of the device includes further details that increase performance under irregular wave conditions and allow the device to “breathe”, hence the name.

A unidirectional impulse turbine connected between the high and low pressure ducts is ideally used to generate energy. Since the wave travels from one chamber to the other, the induced flow is rather steady, with consequent benefits for the turbine efficiency.

The principle of redirecting the flow derived by a certain number of chambers is common to other devices, see for instance the Leancon, www.leancon.com (Kofoed and Frigaard, 2008). We propose for this sub-type of OWC devices the name “Multi-chamber OWC”, in short M-OWC.

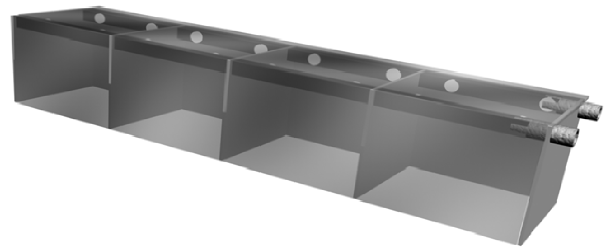

Fig. 1 Longitudinal section of the Sea Breath.

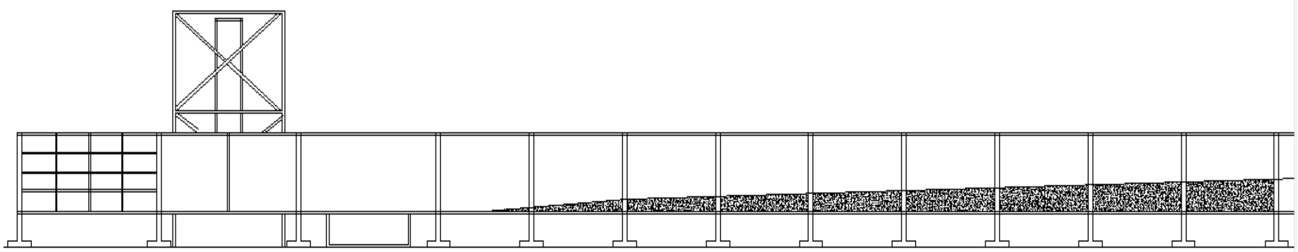

Fig. 2. Wave flume cross section.

PHYSICAL MODEL TESTS

The facility

Physical model tests on the SeaBreath were carried out in the 36 m x 1.m x 1.4 m wave flume of Padova University (Fig. 2). The wavemaker is a oleodynamic roto-translational paddle equipped with a hardware wave absorption system.

To perform the tests, a fixed bottom was used. Water depth at the structure was 0.78 m.

Past tests and available model

An extensive set of tests carried out in the second half of 2010 on three different phases allowed the evaluation of the SeaBreath behaviour.

First, the chamber size was investigated, and the ratio between the height of the wave in each chamber and the incident regular wave height was characterized.

Then, a model with a dummy Power Take Off (PTO) was examined. The PTO is essentially an artificially induced pressure drop along a rubber pipe that connects the high and low pressure ducts. The performance is studied as a function of the load on the PTO (i.e. different degrees of pressure drop).

Finally, the efficiency was investigated under irregular wave conditions for optimal values of the PTO load.

The model dimensions are 1.5 m x 0.3 m x 0.25 m (Fig. 3). The tested model is fixed to a supporting frame, with constant draft equal to 0.10 m. Such model is equipped with the dummy PTO system.

Fig. 3. Available model dimensions.

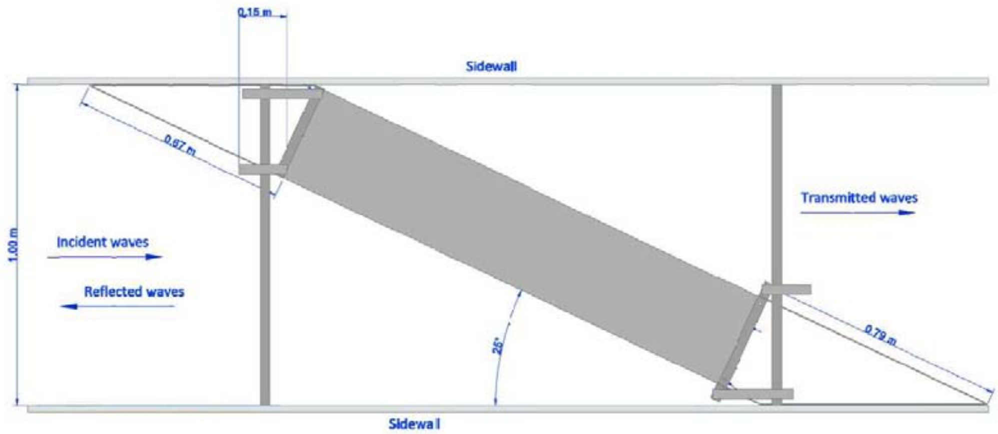

Fig. 4. Set up of the experiments.

Test provided the desired proof of concept, since some energy was produced and a unidirectional flow was measured, although it was constant only for a limited range of wave periods. Performance curves were given as a function of incident wave height and period, for perpendicular wave attack.

Aims and methods

New tests were carried out at beginning of 2011 in the same Laboratory.
Aim of the new tests was to assess the wave transmission due to ship generated short waves and the contribution of the PTO to reduce wave transmission.
In order to achieve the aim, it was essential to observe the structure response under oblique waves, such as the transverse waves that are caused by boats and ships.
In view of a possible application, such as the Petroli channel of the Venice lagoon, a reference scale was considered. Incident waves were assessed to have height in the range 0.3-0.5 m and period in the range 2-4 s. In the last section, some guidelines are given with regard to the choice of these values.

Table 1. Tested conditions

Wave type	H [m]	T [s]
Reg_01	0.03	0.518
Reg_02	0.03	0.621
Reg_03	0.03	0.826
Reg_04	0.03	0.935
Reg_05	0.03	1.042
Reg_06	0.03	1.149
Reg_07	0.03	1.266
Reg_08	0.03	1.515
Reg_09	0.03	1.818
Reg_11	0.04	0.621
Reg_12	0.05	0.826
Reg_13	0.05	0.518
Reg_14	0.06	0.935
Reg_15	0.06	1.042
Reg_16	0.06	1.149
Reg_17	0.06	1.266
Reg_18	0.06	1.515
Reg_19	0.06	1.818
Reg_20	0.06	0.621
Reg_21	0.09	0.826
Reg_22	0.11	0.935
Reg_23	0.11	0.826
Reg_24	0.12	1.042
Reg_25	0.12	1.149
Reg_26	0.12	1.266
Reg_27	0.12	1.515
Reg_28	0.12	1.818

Based on past tests carried out by the Authors on concrete FBs (Ruol et al, 2010), it can be assumed that a WEC device 3 m wide is suited to the desired application. Such a breakwater is not overdesigned, and the additional contribution of the system harvesting energy should be appreciable.
Aiming at reproducing a device 3 m wide with a 0.3 m wide model, the resulting geometrical scale (used to design the incident waves) becomes 1:10.
The effect of boat generated waves (as well as the high frequency component of ship waves) is simplified by trains of 30 regular waves. The limited train duration is necessary to avoid reflection and transversal waves, that slightly grow after approximately 100 waves. The low frequency component associated with ship waves are not investigated, as full wave transmission (k_t=1) is easily predictable.
Table 1 lists the complete test sequence.

The test set up

The WEC is designed to have its axis parallel to the channel axis. In our application, the WEC is imagined to be placed at the side of the navigation channel, and therefore subject to oblique transverse waves.
In order to simulate the approach of the transverse ship generated waves, the model is placed with 25° obliquity with respect to the flume axis, and therefore subject to oblique waves (see Fig. 4). Side plates are added to reduce side effects. Fig. 5 shows the 3 D rendering and Fig. 6 is a picture of the obtained set-up.

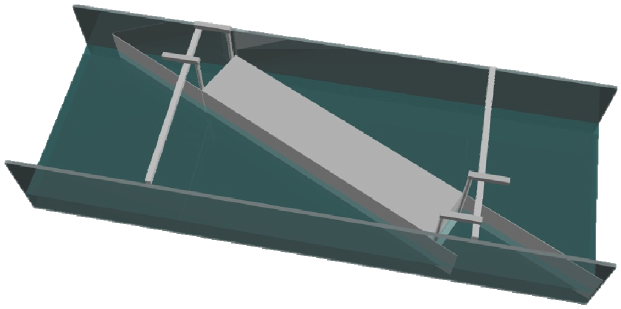

Fig. 5. Designed set up.

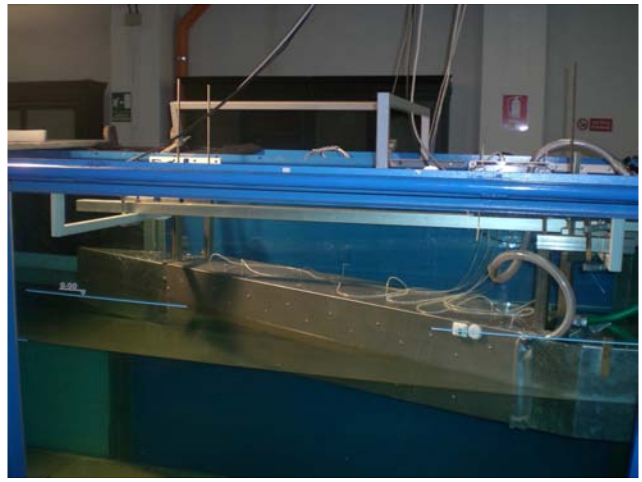

Fig. 6. Obtained set-up.

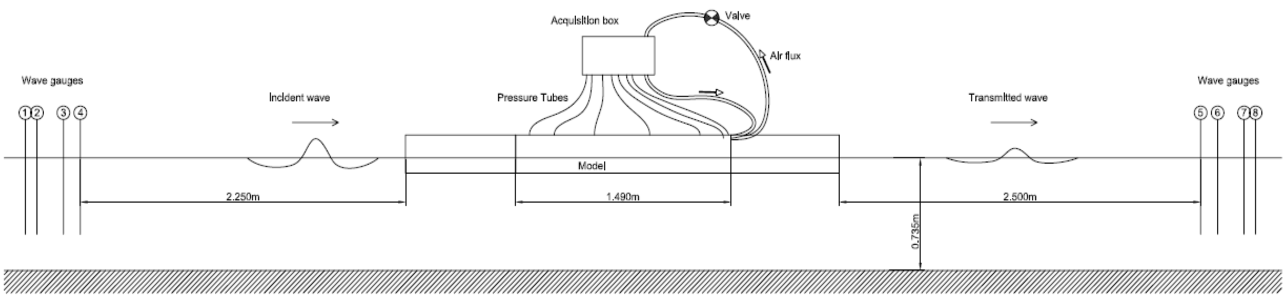

Fig. 7. Instrumental apparatus.

The measurement system

Waves were measured by means of two arrays of 4 capacity-type wave gauges, placed in front and behind the device, at a sufficient distance from it, as in Fig. 7.
Incident and reflected waves were identified according to the method described by Zelt & Skjelbreia (1992), that allows to back-evaluate the analysis error.
Average pressure in each of the 4 chambers (with a redundant measure in the first chamber) was evaluated by means of 5 pressure gauges. Pressure in the chamber propagates within thin plastic pipes to the gauges (Fig. 8). Design pressure head is a small fraction (=1/100) of the atmospheric pressure (it is generally much smaller) and therefore air behaves as an incompressible fluid. Consequently, celerity of pressure signal is infinite (no time shift is expected) and the pipe deformation is negligible (pipe elasticity is not an issue).
The pressure difference between air in the low-pressure and high pressure duct is measured by an additional differential pressure gauge.
The flow is measured by means of a magnetic flowmeter.
All pressure gauges and the flowmeter were assembled by University of Padova and placed into a single water resistant box.

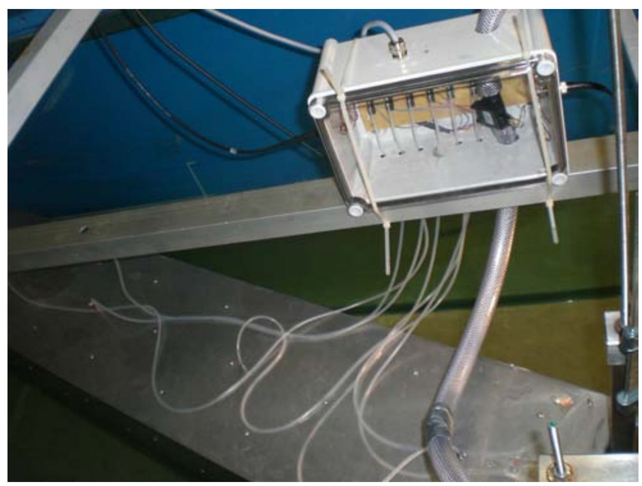

Fig. 8. Box containing the pressure gauges and the flow-meter.

TEST RESULTS

Tests results are given in terms of wave attenuation or, more precisely, of the ratio between transmitted and incident wave height (transmission coefficient k_t). Fig. 9 plots the wave transmission as a function of the non dimensional parameter k^2WP (k is wave number, W and P are structure width and draft) proposed by Ruol et al., (2010). This non-dimensional parameter accounting for the geometry of the cross section compared to wavelength, is seen to be quite suited to describe the transmission past a floating breakwater.

In order to observe also the effect of wave height, waves are represented with different colours based on the target incident wave (H_i). As expected, for long waves transmission is almost complete (k_t is close to 1.0) whereas for short waves transmission is quite low (k_t is close to 0).

It may be observed in Fig 9 that in presence of long waves (on the left of the graph), the transmission (k_t) is lower for high waves (target H_i=0.10 m) than for small waves (target H_i=0.03 m). Even if this difference is not so high, this behavior is unexpected and possibly justified by two reasons: on the one hand, there is some significant difference between target and measured waves for long wave conditions, so that height classes are not uniform (the measured values of H_i is similar in presence of long waves); on the other hand, small and long waves are generated with some asymmetry by the wavemaker and the identification error in the reflection analysis was higher, leading to a small error also in the transmission coefficient (ratio of transmitted and incident measured values).

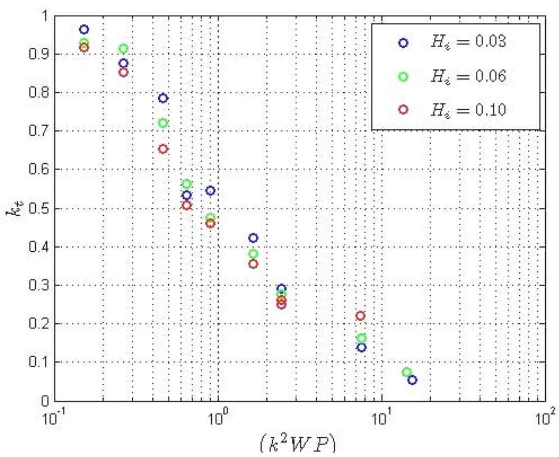

Fig. 9. Measured wave transmission.

Interpretation of effect of wave obliquity

Transmission coefficient plotted in Figure 9 can be easily predicted if the width of the structure is measured along the main wave direction.

Such apparent width is $W/\sin(\theta)$, θ being the structure obliquity (note that for different angle definitions, $\cos(\theta)$ may be more appropriate then $\sin(\theta)$).

Fig. 10 compares results relative to 8 different types of FBs (Ruol et al., 2010) and the results described above (considering the apparent width rather than the structure width). The good fitting of the new results with the previous dataset confirms the appropriate choice of the parameter in the x-axis.

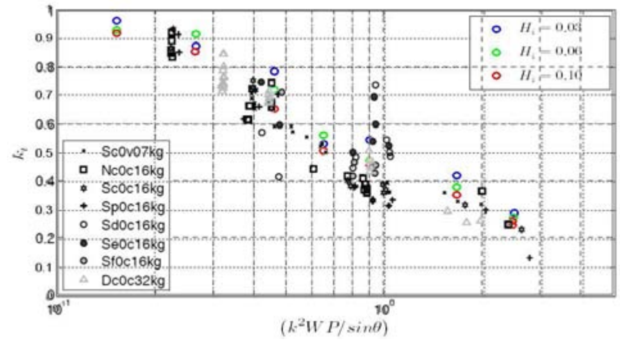

Fig. 10. Superposition of results obtained in these tests (colored empty circles) and in Ruol et al (2010) experiments, relative to floating breakwaters. In the legend, the labels give the weight of the Π-shaped floating structure.

Effect of PTO

The PTO certainly contributes to extract part of the incident wave energy. The obtained power is calculated multiplying the measured flux by the measured pressure difference at the turbine inlet and outlet.

Unfortunately the measured efficiency of the device was too low in presence of the higher tested waves. Most probably, the PTO load selected for these tests, the lowest possible (no concentrated pressure drop), was still excessive (due to the pipe diameter), reducing the efficiency especially for H > 0.03 m.

It appeared evident that the high flow observed during these oblique tests would have required ducts of increased size (both inside and outside the device), and that a new design is necessary.

In fact, in the original design orientation, the device was directly exposed to a 0.3 m wave front, whereas in this new configuration the device is exposed to a front equal to the flume width, i.e. 1.0 m. This causes an increase of the air discharges.

Fig. 11 documents the measured efficiency η (generated power/incident energy flux), decreasing with wave height.

A decrement proportional to at the power 0.5 is justified when the pressure drop is too high. In fact, if the air flow velocity (V) in some contracted area along the path is dominating (given by the Bernoulli value), velocity in the system is always proportional to the square root of the pressure drop, i.e. the square root of the incident wave height. The pumped volume becomes limited by the duct diameters.

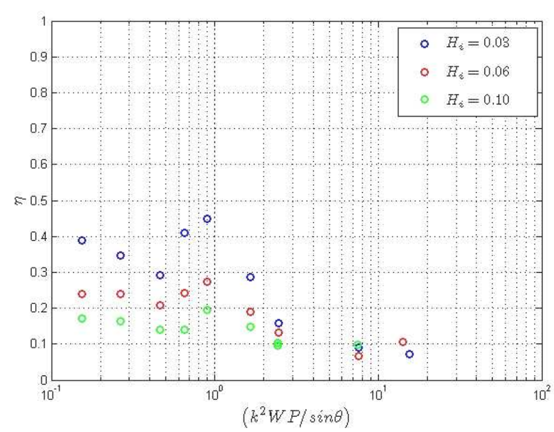

Fig. 11. Efficiency of the PTO (obtained from air discharge and pressure drop).

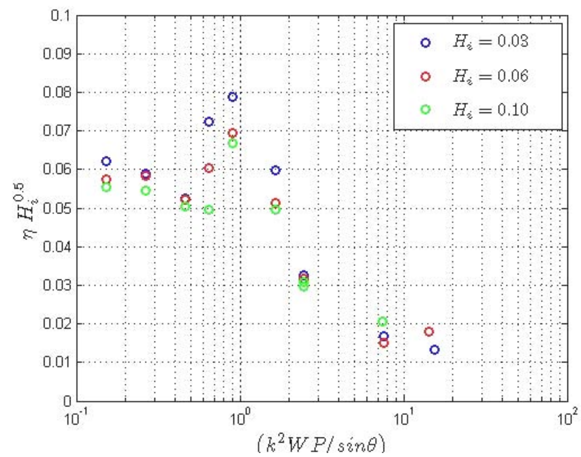

Fig. 12. Proof that $\eta H^{0.5}$ is independent from *H*.

In short, due to the presence of such extreme head loss, the discharge Q is given by:

$$Q=A*V \propto \sqrt{\Delta p} \propto \sqrt{H} \qquad (1)$$

Where *A* is the duct area, *V* the velocity, Δp is he head, *H* the wave height, and the resulting generated power ($\Delta p\ Q \propto H^{1.5}$) being proportional to the $H^{1.5}$ for all wave height exceeding a low threshold, at given wave period. Since the incident wave energy is proportional to height to the power 2, we obtain that efficiency decreases with $H^{0.5}$ if the PTO load is excessive.
As a proof of the above considerations, the value of $\eta\ H^{0.5}$ is plotted in Fig. 12, and -as stated above- the value is independent from the wave height (points with different height are grouped together).

In short, it is argued that a device with larger ducts would have had a much higher efficiency in presence of long waves. The expected efficiency is probably the one measured for the smallest waves.

EXAMPLE APPLICATION

The Petroli Channel

Works for the 1st industrial Port of Marghera, in the Venice Lagoon, started in the twenties, and access was provided by the Vittorio Emanuele channel, 10 m deep, through the Lido mouth (Cavazzoni, 1995).
In the fifties, the 2nd industrial area was built and, some time later (1960-1970), it was served by the Malamocco-Marghera channel (locally called "Canale dei Petroli"). Its main purpose is to keep the traffic directed toward the oil terminal in San Leonardo and to the industrial area away from the city.
After entering the lagoon through Malamocco inlet, the channel (Fig. 13) heads directly west towards the mainland cutting through natural tidal channels. It then makes a sharp right-hand turn North, where it stretches alongside the mainland for 14 km in an almost straight path.

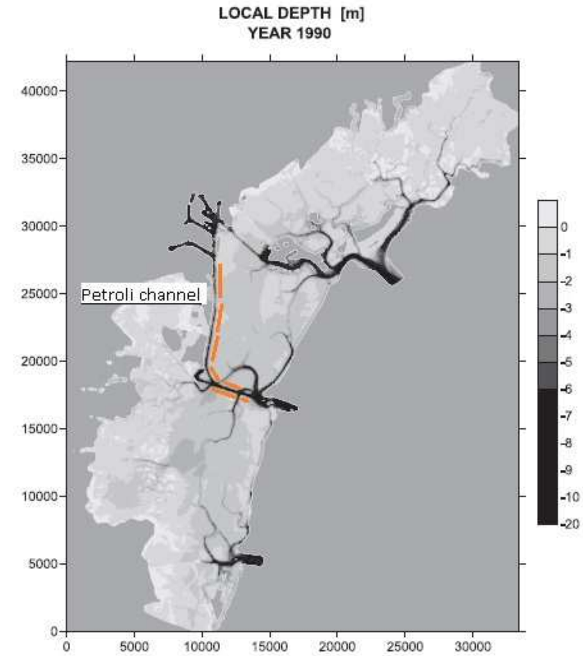

Fig. 13 Bathymetry of the Venice Lagoon, with position of the channel between Marghera and Malamocco. From Umgiesser et al. (2004), modified.

The channel (much deeper that originally design) has changed the lagoon dynamics and, by increasing the flow speed in internal areas, has destroyed many small lagoon channels and saltmarshes. Observation of salinity show, for instance, that the environmental conditions were significantly altered.
Its presence is sometime considered responsible also for enhancing the well-known flooding problems of Venice, bed erosion, overall saltmarshes degradation and it is a source for contaminants in the Lagoon.
A discussion of the effects of the Petroli Channel is provided by Rinaldo (2001).

Ship generated waves

A substantial amount of literature exists concerning the development and propagation of waves from passing vessels, including experimental information (e.g. Velegrakis et al., 2007; Torsvik et al., 2009).
Basically, V-shaped steady-state ship waves are created behind the ships as they move. A schematic pattern is described by the Kelvin waves, obtained assuming that a point impulse moves at a constant velocity: two kinds of waves are generated, transverse waves, moving in the same direction as the ship, and divergent waves, moving at angle θ relative to the ship. A cusp is formed where these waves meet, and the wedge angle between them is 38°56' (Newmann, 1978).
In addition, when a ship of considerable cross section moves along a narrow channel, a large amount of water is displaced. A ship 200 m long sailing at 3 m/s generates a perturbation lasting about 60 s.

The effect of the ship wakes and the consequent sediment resuspension induced by the passage of commercial vessels through the Petroli channel, was investigated in Rapaglia et al (2010). One example of the records for two large ships is given in Fig. 14. Pressure gauges were used to measure the ship generated waves in few locations (PS1 to PS10). Ship velocity is frequently close to the maximum allowed, of order 5 m/s. The different type of ship waves had height varying from 0.04 to 0.57 m. The “significant” value i.e. the average of the upper third, is 0.39 m.

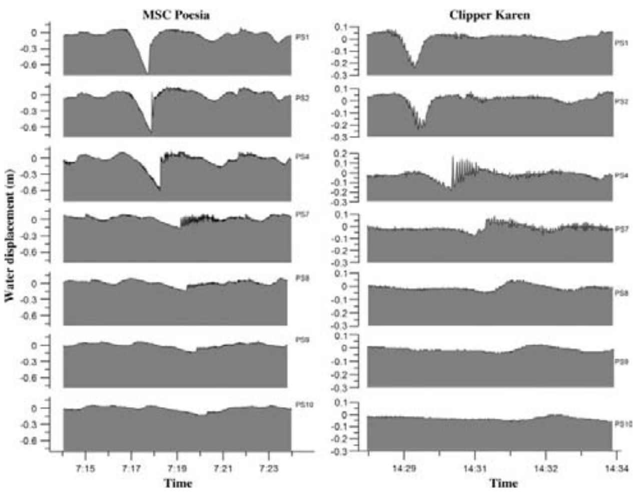

Figure 14. Example of waves induced in the Petroli channel by two ships moving away from the channel from top to bottom: left: MSC Poesia. Right: Clipper Karen. From Rapaglia et al., (2010).

Their measurements depict a clear image: the wake profile is initially a small crest followed by a deep, asymmetric trough and a trailing crest. The trough depth decreases over the shoal. The leading crest moves forward away from the trough while the trailing crest steepens the rear edge of the trough. Such waves are very long, with period of the order of the minute.
The wave celerity travelled at 3 m/s from PS1 to PS4 (250 m distant), so that the average depth between such control points is about 1 m.
On top of the trailing crest, short period waves develop at a certain distance and become quite intense (location PS4, on the right and PS7, both records). Due to the 1 Hz sampling frequency used in Rapaglia et al. (2010), short waves are not completely defined in duration.
These are the waves addressed in the present study.

Waves generated by small boats

Short waves are generated by the many small boats crossing the lagoon and, as discussed above, represent part of the disturbance produced by large ships.
Measurements were carried out for 25 ships travelling along a 6 m deep channel at the S. Clemente Island (Liberatore, 1988; D’Alpaos and Liberatore, 1993), i.e. on the west of the Petroli channel.
Observed wave height was included in the range 0.02 - 0.52 m, and typically 0.17-0.24 m. In those observations, wave periods ranged from 1.8 to 2.0 s (peak frequency from 0.49 to 0.54 Hz).
By reanalyzing the data in D’Alpaos and Liberatore (1993), wave height can be approximated by Eq. (2):

$$H=\alpha V^2/g \qquad (2)$$

where V is the ship velocity and H the wave height, α being in the range 0.1-0.2 for boats with velocity lower than 5.5 m/s.
The ships considered by Eq. 2 are much smaller than those described in Fig. 12. In fact, small boats only generate the short period waves.

The practical problem of reducing short waves generated by vessels induced the local Authority to set up an experimental campaign in 2010 in the Canale Somenzera S. Giacomo (see Faedo, 2010).
Approximately 100 measurements of wave trains generated by small ships were collected. Wave transmission past 9 different kinds of structures was evaluated: a floating breakwater, two sheet piling structures, a sand bags barrier, 4 rubble mound Low Crested Structures (LCS) and a LCS made with gabions.
Wave heights were consistent with Eq. (2) and with experiments carried out by Liberatore and D’Aplaos (1993).
Observed wave transmission was rather high. Especially in presence of high tide, all structures provided a transmission coefficient of order 0.9. The considered floating breakwater cross section in the occasion was in fact rather small.

An analysis of shipping statistics from the Port Authority of Venice (Report 2009 available online) showed that approximately 10 large ships pass through the Petroli Channel every day in average (5000 ships, one third directed to the oil terminal), whereas the number of passages of small boats is more than one order of magnitude larger.
A simple application is carried out aiming at evaluating the amount of energy that could be intercepted by the proposed design.

Table 2. Waves generated by ships and boats and energy fluxes. Cg is group celerity.

	V	T	H	Occur-rence	Cg	Incident Energy Flux	k^2WP	kt	Ht	Transmit-ted energy flux
	m/s	s	m	%	m/s	W/m	-	-	M	W/m
ship (low freq)		180	0.4	6.3%	3.8	383	0.0	1	0.40	383
ship (high freq)	5	3.5	0.375	6.3%	3.0	262	0.8	0.65	0.24	111
boat	3	1.8	0.135	31.3%	1.6	18	5.0	0.2	0.03	1
boat	4	2	0.24	31.3%	1.8	65	3.5	0.21	0.05	3
boat	5	2.3	0.375	31.3%	2.1	189	2.3	0.33	0.12	21
				Average		**125**		**Average**		**38**

Effect of the active FB

An active FB made of steel, 3 m wide, anchored on piles, could be reasonably placed along the Petroli channel in order to reduce the short waves generated by boat and ships. Fig. 13 shows possible placements of the structure. A 1 kW turbine could be installed in one of the modules. Of course the reason to produce energy (few kWh/year) is merely to proceed in the WEC development. Other modules of the breakwater should be equipped with a dummy PTO (a concentrated head loss along the air ducts), in order to ensure the purpose of enhancing the FB performance.

For this application, tentative ship generated wave conditions are selected based on the available data of the channel traffic (Tab. 2). Large ships provide two contribution that are considered separately, a long wave and a short wave. The active FB is only effective for the latter component. In case of waves generated by small boats, on the contrary, the FB can significantly shelter the lagoon.
Based on the test results (Fig. 9), the transmitted energy flux is assessed to be 38 W/m. Compared to incident energy flux, 125 W/m, only 30% of the energy is transmitted past the active FBs.

CONCLUSIONS

Specific tests were conducted in order to observe whether the SeaBreath can effectively attenuate the waves generated by small boats, that compromise the ecosystem of the Venice lagoon.

The SeaBreath, an Italian WEC concept is described and proposed as an active FB, i.e. a FB equipped with a mechanism that can convert or simply dissipate some of the incident wave energy.

It was found that the active FB behaves as a conventional (passive) device in case of short waves, and attenuation is indeed significant. Transverse ship waves are transmitted even less than perpendicular ones, and a simple method is proposed to quantitatively predict the effect of obliquity in the transmission coefficient, i.e. to consider in the design formulae the apparent width rather than the structure width.

It was found that the PTO is capable of harvesting (or dissipating), for long (and small) waves, up to 40% of the incident wave energy, i.e. the active device has some effects also when the passive FB is well-known to have no influence (Isaacson and Bhat, 1998). This is advantageous, since long waves are more problematic than short ones.

Experiments did not confirm the same efficiency in presence of long and high waves, but several arguments are given to support the fact that the device duct diameter needs to be increased.

An application to the Petroli channel (Venice Lagoon) showed that a great benefit could be provided in presence of the active FB. This could be a great opportunity to deploy the SeaBreath in a real environment, in order to test different technical solutions, the durability of some components (like valves) and its ecological impact (e.g. biofouling).

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