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Original scientific paper

Contribution of Wind and Waves in Exchange of Seawater through Flushing Culverts in Marinas

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Abstract: In this work contribution of wind and waves on the water exchange through flushing culverts between the marina and surrounding water body have been investigated. The hybrid modelling technique was used. Results of culvert discharge, produced by waves on physical model, were implemented in 3D circulation model. Using circulation model, the optimum flushing culverts position in body of breakwater was defined for marinas with hypothetical geometry, characteristic for Croatian Adriatic Sea. The model was forced by wind from 8 directions and velocities 1-5 Bf. Furthermore, numerical simulations were also done for a real - world marina – the Ičići marina. The real breakwater geometry and hydrographic conditions (depths, tides, sea temperatures and salinity) were included. The analysis results show that the flushing culverts may have important contribution to seawater exchange in marina, even in summertime situations with significant wave heights of 0.5 m and duration of 6 hours.

Keywords: flushing culverts; marina; numerical modelling; physical model

1 INTRODUCTION

According to the legal definition, nautical tourism is defined as navigation and staying in nautical ports by tourists for rest and recreation. Croatia has a large number of islands and indented coast what is very suitable for the nautical tourism development. The Croatian coast is protected from direct open sea wave impact, which allows construction of smaller ports. In a wider context, the functionality of marinas/harbours/ports is achieved by building coastal structures, which reduce the open sea wave intensity in sheltered sea areas. Since breakwater construction is the costliest element in the design of a marina, the goal is to reduce its size by choosing a partially or completely naturally sheltered area. Breakwater price increases progressively with sea depth and therefore it is economical to consider locations with depths of less than 10 m. In Croatia, gravity breakwaters protect the largest number of marinas and harbours. Because of this, seawater within a marina is separated from the surrounding seawater and natural circulation is prevented.

Decreased flushing rate and water exchange rate between marina and adjoining sea can be improved by construction of flushing culverts in the body of the breakwater. Their purpose is to improve seawater exchange between a marina and the surrounding water body.

Seawater exchange between a marina and the surrounding sea is generally the result of natural factors such as tidal variability, wind conditions, wave climate and water density gradients [1-4]. One or more of mentioned factors, depending on geographical location, may dominate the flushing process in a marina. If the pollutants concentration is allowed to increase above critical levels, then the result is sub-standard water quality as characterized by reduction in dissolved oxygen and eutrophication. Marina flushing characteristics depend on the structural parameters such as the marina geometry, entrance dimensions, depth and bottom slope [3-5]. As mentioned, flushing culverts (pipes or rectangular openings in the body of the breakwater), the most cost-effective engineering solution, can improve seawater exchange. Flushing culverts application is justified in areas with small tidal variations (such as the Adriatic and the Aegean Sea), where the tide variations difference is not enough for sufficient marina flushing rate [6] or in semi-closed and closed bays where tidal circulation is poor [7]. For this reasons, researches associated with flushing culverts come mostly from the countries with similar oceanographic conditions, from Greece and Turkey in the Aegean Sea [6, 8-17]. These works partially show physical processes in marinas with flushing culverts. Focus is on an analysis of the flushing culverts efficiency in terms of the flow generated by the direct wind or tide action. Wind – induced flow through the flushing culverts is not analysed, except in the area of determining the coefficient of transmission, and the wave agitation of the marina basin. Tidal variations effect is generally recognized as insufficient for the flushing process.

2 PROBLEM STATEMENT

This paper presents the results of numerical simulations and research on the physical model. Aim is to quantify the contribution of flushing culverts in seawater exchange between the marina and the surrounding sea. Firstly, numerical simulations of water circulation through flushing culverts in hypothetical marina, for the isolated wind action, were carried out. Wave action causes high-frequency boundary conditions changing at the entrance and at the exit of the culverts, as well as two-phase flow. In order to define the relationship between wave parameters and discharge through the culverts, the results of physical model were implemented in a numerical model. In this way, the physical modelling results were taken directly as a source function at the flushing culverts positions in the numerical model.

Hypothetical marina has a characteristic geometry for the Croatian Adriatic [18]: marina dimensions - length 300 m, width 150 m. Numerical simulations in hypothetical marina, for the following environmental and construction conditions were carried out (Fig. 1):

- Wind from eight directions (N - North, NE – North East, E - East, SE – South East, S - South, SW – South West, W - West, NW – North West);
- 5 wind speeds (1, 2, 3, 4 and 5 Bf)

- 3 flushing culverts positions along the breakwater (position 1 – P1, position 2 – P2 and position 3 – P3).

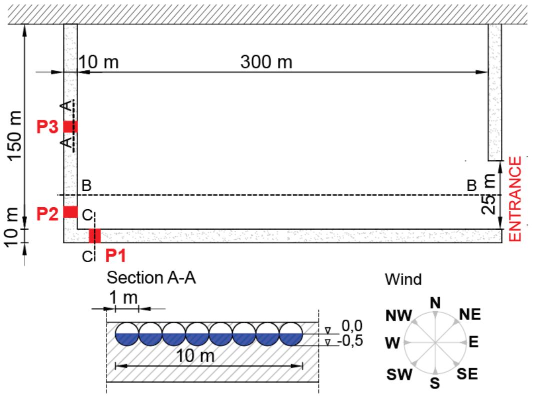

Figure 1 The hypothetical marina scheme with basic geometric features (A-A cross-section through the culverts; B-B vertical cross-section through the centre of the entrance; C-C vertical cross-section through the breakwater; culverts positions: position 1 - P1, position 2 - P2, position 3 - P3)

After determining an "optimal" flushing culverts position in hypothetical marina, the analysis for real – word marina has been carried out (the Ičići marina). The actual geometry of the Ičići marina was used, measured hydrographic characteristics (depth, the variation of tides, sea temperature and salinity) and real time series of wind speed/direction and significant wave heights/period.

Flushing culverts discharge was used as the primary comparative parameter for determining the quality of each analysed solution. In addition, the culverts discharge contribution to marina flushing rate was analysed based on the approach described in [19]. Initially, the tracer mass (non-reactive) is set to 100 for the whole sheltered water area within the marina aquatorium (Fig. 2), and the concentration value 0 elsewhere. In scope of our numerical simulation 0 concentration was set at open boundaries transects (marina entrance and culverts – contact with surrounding water body). Marina flushing causes a decline in mean concentrations of the tracer mass in the marina through the mechanism of convective dispersion. This allows the detection of longer residence time areas (increased tracer concentrations areas). The simulation results are interpreted by the time series of mean tracer concentrations in the marina basin.

3 NUMERICAL CIRCULATION MODEL FOR HYPOTHETICAL MARINA

Numerical model solution for the domain was computed using the Mike 3fm numerical model [20] which was used for conducting simulations too.

An unstructured mesh of the average cell area of 25 m^2 is used in horizontal but sigma structured one (with 7 sigma layers) in the vertical (Fig. 2).

The bottom slope is constant, from 3 to 7 m depth. At defined culvert positions series of 8 circular pipes, 1 m diameter and 10 m total length, was set (Fig. 1). The pipe inlet and outlet are at depth of −0,5 m from the mean sea level (which is set to 0,0 m). Velocity perpendicular to the vertical impermeable boundary is set to 0.

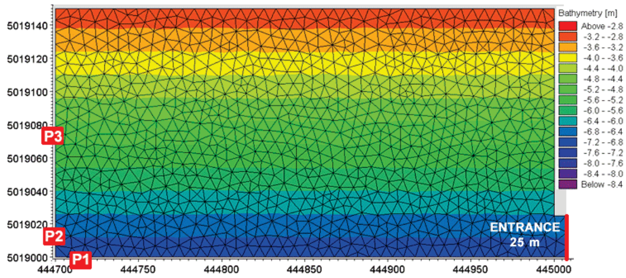

Figure 2 Spatial model domain discretization with triangular cells (hypothetical marina)

Surface elevations at the open boundaries of hypothetical marina numerical model (culvert and marina entrance) are steady during the simulation period. Model was forced with a homogeneous and steady wind field. Wind speed and directions were varied during each simulation. For each wind direction wind speed of 1 Bf (adopted 0,9 m/s), 2 Bf (adopted 2,5 m/s), 3 Bf (adopted 4,5 m/s), 4 Bf (adopted 6,7 m/s) and 5 Bf (adopted 9,4 m/s) was used.

Wind force impact at the sea-atmosphere interface generates three-dimensional circulation, along with sea level denivelation in relation to the open boundaries (marina entrance and flushing culverts on the outer side of marina). The difference between the sea levels at the inner (inside the marina) and outer (on the outer side of marina) sides of culverts causes discharge through pipes. Culvert outflow, due to the gravitational wind waves, was not considered in this part of modelling

The *k*-ε models [21] and Smagorinsky scheme [22] are used for turbulence closure formulation in the horizontal and vertical directions. Dispersion coefficients (Prandtl's number) for the scalar T, S fields were defined with proportionality factor 0,8 in the vertical and 0,2 in the horizontal.

The proportionality factors for the dispersion coefficients of turbulent kinetic energy (*TKE*) and dissipation (ε) were used with the values 1 for the *TKE* and 1.3 for ε in horizontal and vertical directions. Roughness and Smagorinsky coefficients were set as spatially and temporally constant values of 0,01 and 0,2. Since a considerable amount of outer seawater is entering the marina through the entrance transect, heat exchange with the atmosphere does not represent a major contribution to the balance of heat and is not taken into account. The wind friction coefficient is set to value of 0,0013 [23].

Fig. 3 shows the surface current field for the stationary and homogeneous NE and SW wind fields of the 5 Bf speed. Current profile in vertical entrance cross section (cross-section B-B) is shown in Fig. 4. Baroclinic circulation (vertical compensation) is dominant in the entrance profile. The surface layer inward current appears for the wind of NE, E, SE and S directions, and the outward current for the wind of the SW, W, NW and N directions. Since the inward/ outward current surface layer thickness is significantly lower than the thickness of compensating intermediate and bottom layers, current velocities in the surface layer in the entrance profile are significantly higher (Fig. 4).

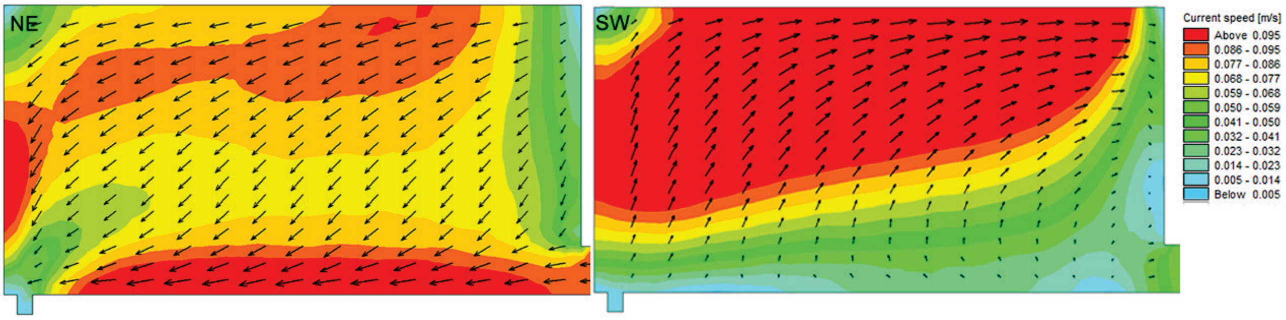

Figure 3 Surface currents for the stationary and homogeneous wind field NE (left) and SW (right) direction and 5 Bf speed (hypothetical marina)

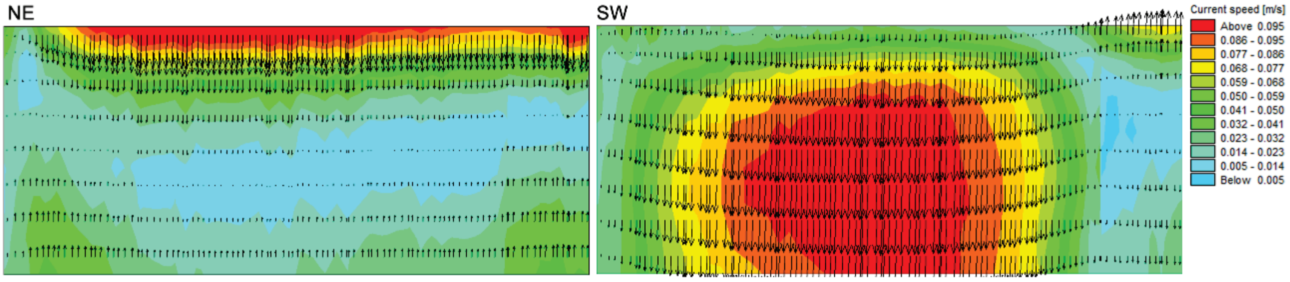

Figure 4 Flow field in vertical section through the centre of the entrance (cross-section B-B) in the case of a stationary and homogeneous wind field for NE (left) and SW (right) wind direction of 5 Bf (hypothetical marina)

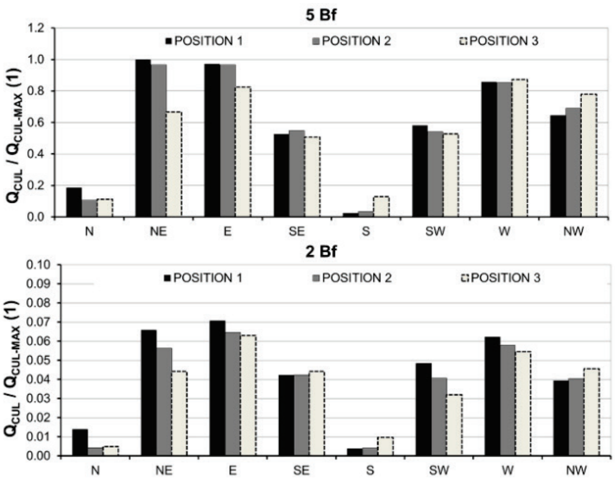

Figure 5 Comparison of culvert discharge (sea exchange) for different wind direction and culvert positions (wind speed 5 Bf and 2 Bf)

As a result of NW wind, deep water rises towards the surface (upwelling), while in case of SE wind water sinks (downwelling) from the surface layer towards the bottom layer. Furthermore, for the other analysed wind directions (N, NE, E, S, SW, W) the upwelling and downwelling process are less intense.

Fig. 5 shows comparison of culvert discharge (normalized to the value of the maximum discharge from all analysed variants), for different culvert positions (1-3), wind direction and speed of 5 and 2 Bf. Maximum discharge $Q_{P\text{-}MAX} = 0{,}2\ m^3/s$ through 8 culvert pipes was obtained at the culvert position 1, for NE wind of 5 Bf speed.

For culverts designed at position 1the most intense marina flushing rate is achieved (maximum seawater exchange volume through culverts) (Fig. 5). Marina flushing characteristics, for the culverts designed at position 1, are on average (for all directions and wind speed) 3% and 10% higher than in the case of culverts designed at positions 2 and 3. It should be noted that marinas are often deep-set into the mainland, making it impossible to design flushing culverts at positions 2 or 3. Fig. 6 shows the ratio of the total discharge trough the marina entrance profile and flushing culverts profile. Culverts contribution on the marina flushing characteristics is on average (for all directions and wind speeds) 1,2% for the culvert at position 1, and 1,1% at positions 2 and 3. Presented small percentage should not be considered as evidence of the ineffectiveness of culverts, since they help seawater renew in the part of the marina aquatorium with longer residence time.

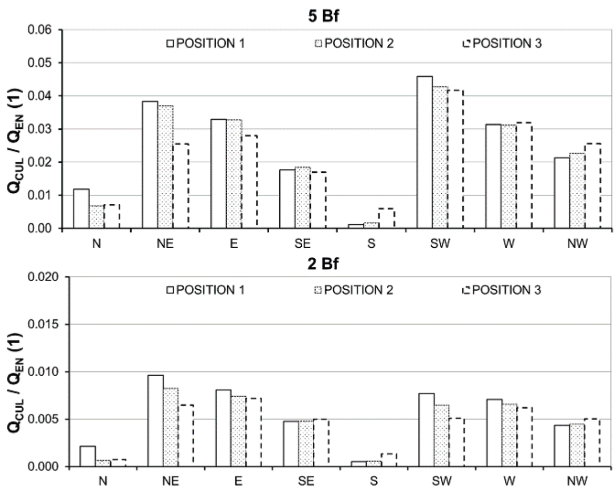

Figure 6 Comparison of the exchanged sea water volume ratio through culverts and the marina entrance with a variation of wind speed / direction and culverts position

4 NUMERICAL MODEL OF WAVE GENERATION

In order to define the wave spectra parameters for deep water area in front of the Ičići marina breakwater (significant wave height H_S and peak periods T_P) numerical model of wave generation Mike 21sw was applied. The results of wave generation simulations were used to define the boundary conditions in the research on the physical model in the wave flume. Fig. 7 shows the numerical model domain for wave generation and spatial discretization with finite volumes. Distance between numerical nodes, located in the centre of each finite volume, is variable and extends from 650 meters in the deep water up to 150 m in the coastline zone. Fig. 7 also shows the significant wave heights (H_S) field for SSE (south - south east) wind of 9,6 m/s (5 bf) speed. Wave parameters data measurements at the position of Rijeka breakwater (in the port of Rijeka) were used for model calibration (Fig. 8). Fig. 8 shows the dependence of the measured significant wave height H_S and peak periods T_P on measured wind speeds W_{wind} for the SSE wind of 12 hours duration [24], as well as the results of numerical calibration.

On the open boundaries zero spectrum was used (no flow of wave energy exists through them). Similarities of numerical results H_S and T_P with measured data on the above-mentioned northward location (Rijeka breakwater in the port of Rijeka) were obtained by variation of the most sensible parameter of the numerical wave generation model - white capping coefficient. The use of this boundary condition formulation excludes the impact of the wave generation in zone of the open sea on waves in the model spatial domain. So, the results of numerical analysis were certainly accurate only for the immediate surroundings of Wave rider station in the port of Rijeka. Since the location of the Ičići marina is southward of the reference Wave rider station, it can be said that the results of numerical simulations provide slightly lower values of H_S and T_P to the real one.

In order to define the characteristics of the wave climate in summertime, when the biggest "ecological" burden (reduced circulation in marina basin and weaker winds) appears, the selected simulation period was: 01.06.2013 - 01.09.2013. The initial conditions of simulation (01.06.2013 12:00) were defined by the absence of waves throughout the modelled area. During the analysed period (01.06.2013 - 01.09.2014), model was forced by wind fields obtained from atmospheric models "Aladin-hr" with a spatial resolution of 2 km and a temporal resolution of 3 hours [25, 26].

Time series of significant wave height H_S, peak period T_P and the prevailing direction of the incident wave were obtained by the extraction of the model results to a point in front of the Ičići marina breakwater, for the analysed summer period. Only one situation is recognized, (25.08.2013 12:00 pm to 3:00 pm), where H_S equalled 0,55 m, with the incident direction perpendicular to the main breakwater of the Ičići marina (Fig. 9). For this situation model value of peak wave periods is T_P = 3 s.

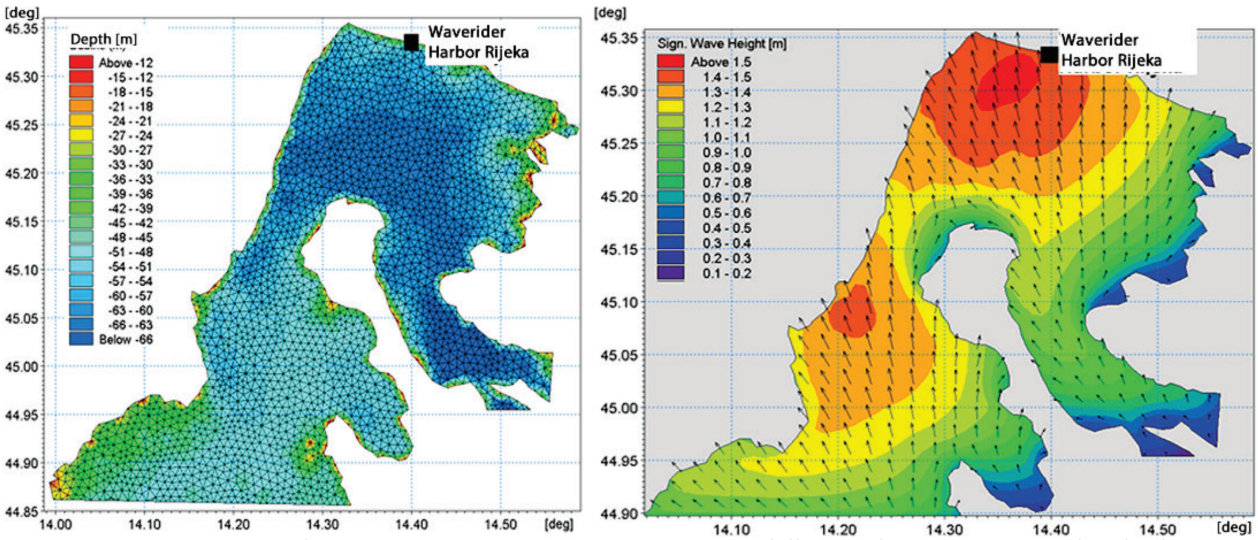

Figure 7 Model domain discretization with finite volume unstructured mesh on bathymetry background (left) and significant wave height model-field of H_S for the wind SSE direction and speed of 9,6 m/s (right)

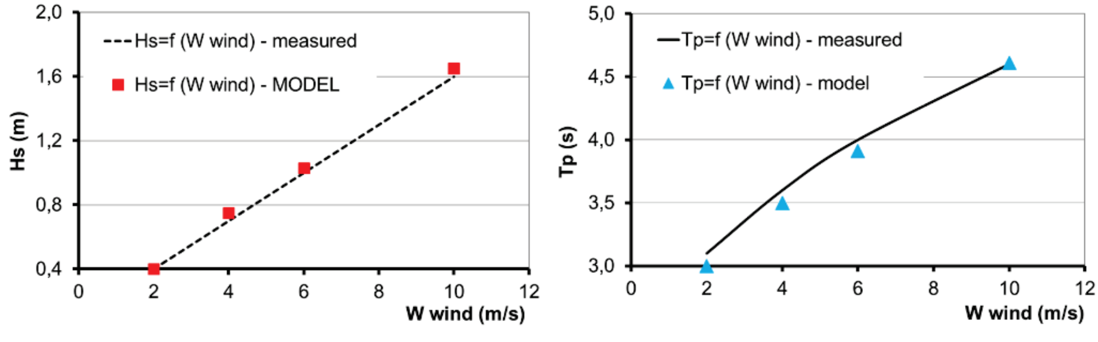

Figure 8 The measured and modelled values of significant wave height H_S and peak period T_P for SSE wind (W_{wind}) and 12 hours duration (Rijeka breakwater in the port of Rijeka

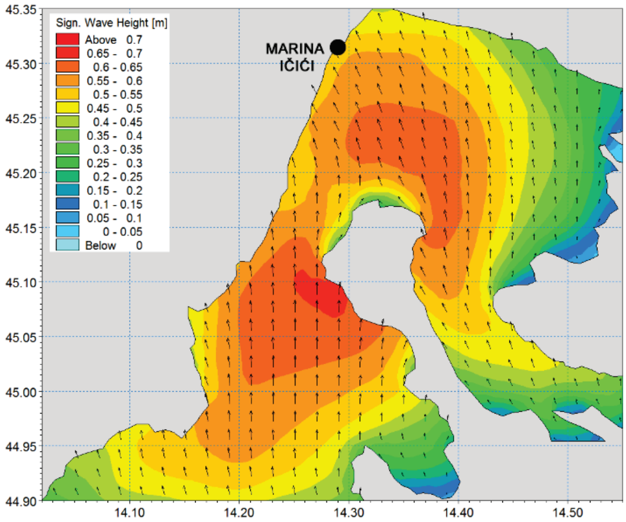

Figure 9 Significant wave heights field on modelled area for 25.08.2013. 12:00

5 PHYSICAL MODEL

The physical model is located in the hydro-technical laboratory of the Faculty of Civil Engineering in Zagreb. Laboratory experiments were performed using piston type generator with built AWACS system (Active Wave Absorption Control System). The wave flume width is 1 m, height 1,1 m, length 20 m. The model is constructed on the basis of Froude similarity criterion, with the length ratio $L_R = 10$ and corresponding culvert discharge ratio $Q_R = L_R^{5/2}$. The current velocity on the outward side of pipe in three points, using ADV device (Acoustic Doppler Velocimeter), was measured, in order to define the average discharge passing through the culvert pipe in course of 5 minutes continuous wave generation with the corresponding spectral characteristics. Results, shown in Tab. 1, are related to the process in prototype scale (nature), and indicate the important wave contribution on seawater exchange through culverts.

Considering the above exposed result in a hypothetical marina and isolated wind action, in which the maximum discharge through the 8 pipes of culvert is $Q_{P\text{-}MAX}$ = 0,2 m^3/s (NE wind direction, 5 Bf speed), action of waves with H_S = 0,6m and T_P = 3,1s provides six times higher seawater exchange through culverts. Mentioned discharge is observed for the incident wave propagation perpendicular to the breakwater axis. Thus, the culvert position 1 has additional benefit as compared to the other two analysed positions, 2 and 3. Discharge value in Tab. 1, for the H_S = 0,6 m and T_P = 3,1 s, was taken as a source function in a numerical model of the Ičići marina. It should be noted that according to the wave generation model in the summer of 2013 (Jul - Sep), only one situation with similar wave conditions (H_S = 0,55 m and T_P = 3,0 s) was recognised.

Table 1 Mean discharge values through the culvert pipe (measured on the physical model)

H_S (m)	T_P (s)	H_S/L_R	L_R (m)	Q_R (m^3/s)
0,6	3,1	0,04	10,0	0,15

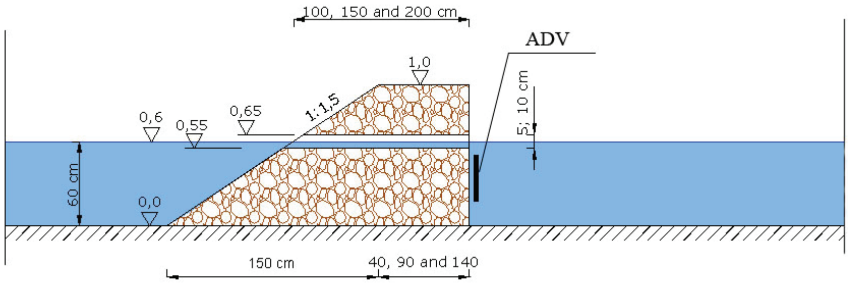

Figure 10 The longitudinal cross section and main dimensions of physical model built in wave flume

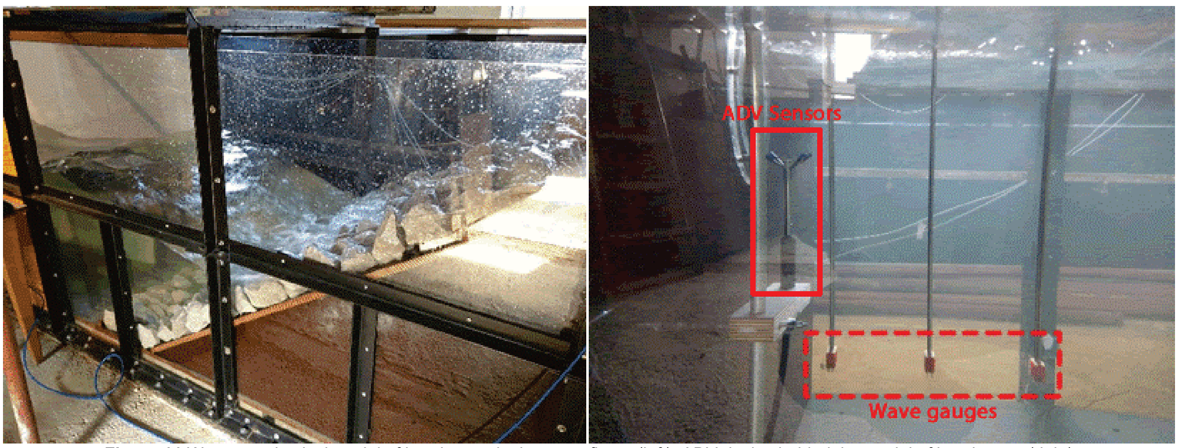

Figure 11 Waves at physical model of breakwater in the wave flume (left); ADV device behind the model of breakwater (right)

6 APPLICATION OF HYBRID MODEL APPROACH (IČIĆI MARINA)

After defining mean culvert pipe flow in the case of wave propagation, based on measurements on the physical model, numerical simulation for the real situation of marina Ičići with realistic forcing was carried out. Ičići Marina model discretization domain is shown in Fig. 12, as well as cross section trough breakwater (section A-A, Fig.

1) and a vertical section through the breakwater (section C-C, Fig. 1).

Surface elevations are variable during the simulations and based on data of the amplitudes and phases of the seven basic tidal signal constituents for the nearest location of tide Gauge station in Bakar [27] (Tab. 2, Fig. 13). At the open boundaries of numerical model (culvert and marina entrance) the sea temperature and salinity fields were used, measured by CTD device at a nearby oceanographic station on 25 August 2008 (Fig. 13). In the summer season 2017, current measurements at position A and B, in marina Ičići, have been carried out (Fig. 14). Results of measured current speeds were used for comparison with the modelled.

The initial conditions are expressed by current velocity values set to 0 m/s for all three directions, to all numeric cells. The initial conditions for the scalar fields of sea temperature and salinity in the vertical direction have been considered on the basis of the measured values shown in Fig. 13, and a homogeneous distribution of sea temperature and salinity in the horizontal direction. Flushing culverts flow due to wind waves is taken into account with the additional boundary condition formulation at the culvert inlet, explicitly defined from the discharge measurements on the physical model (Tab. 2).

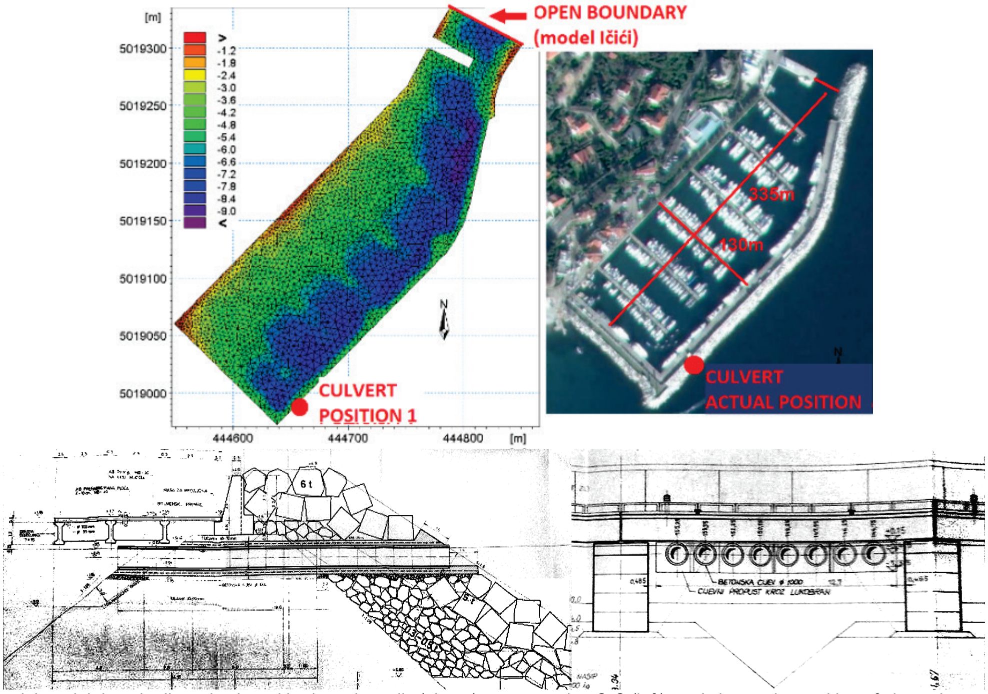

Figure 12 Spatial model domain discretization with triangular cells (above), cross section C-C (left) and view at the position of pipe culverts (marina Ičići)

Table 2 Amplitudes and phases of tidal constituents for Bakar [27]

O1		P1		K1		N2		M2		S2		K2	
amp	phase	amp	phase	amp	phase	amp	phase	amp	phase	amp	phase	amp	phase
(cm)	(°)	(cm)	(°)	(cm)	(°)	(cm)	(°)	(cm)	(°)	(cm)	(°)	(cm)	(°)
4,41	53,1	5,00	65,4	14,06	67,4	1,96	252,0	10,32	250,1	5,75	250,4	1,71	235,4

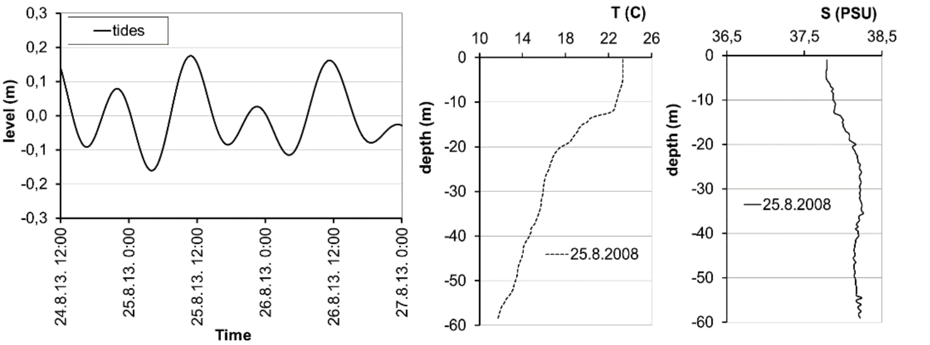

Figure 13 Sea level time series used for open boundary forcing in numerical model of sea circulation for the Ičići marina (simulation start date 24.08.2013. 22:00) and the vertical distribution of sea temperature and salinity at the measuring CTD profile in front of the marina Ičići (φ = 45° 15,5'; λ = 14° 19,0')

Fig. 14 shows the surface current field for the Ičići marina on 25 August 2013 at 12:00 (culvert position 1, on the location Ičići, 6,8 m/s wind speed, direction 147°). Also, comparison of vertically averaged, measured and modelled current speeds, at position A and B is shown for the similar measured situation in summer of 2017 (6,2 m/s wind speed, direction 142°). Vertically averaged measured current speeds at position *A* are 17% lower than modelled and at position *B* 27 % higher than modelled. Fig. 15 shows the field of vertically averaged tracer mass concentration in the marina basin after 48 hours of simulation period (started on 24.08.2013 at 22:00). The situations with culverts at the positions 1, 2 and 3 are displayed, wherein the position 1 is analysed with and without wave contribution (an additional source member at the culvert position with the strength of 0,15∗8 m^3/s). Vertically averaged time series of tracer mass concentration $C_{av}(1)$ in the marina basin area are shown in Fig. 16.

For the culvert at position 3, spatially averaged tracer concentration after 48 h is 1% and 2% lower compared to the situation with the culverts at positions 1 and 2. The position of culvert has a low impact on seawater exchange in the marina. In case of culverts at the position 1, the averaged concentration is 13% lower after 48 hours, if taking into account the discharge through the culverts caused by waves, compared to the situation without waves. If culverts are situated at position 1, including wave contribution, the spatially averaged concentration after 48 hours is 12% and 11% lower compared to the situation with the culverts at positions 3 and 2. The results indicate a significant wave impact for sea exchange through flushing culverts.

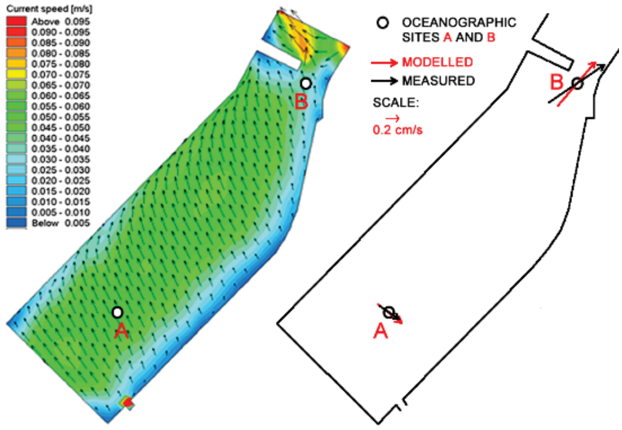

Figure 14 Left: surface current field for the basin of marina Ičići in period of 25.8.2013. 12:00 (wind speed 6,8 m/s, direction 147°); right: oceanographic sites A and B position with comparison of modelled and measured vertically averaged current speeds

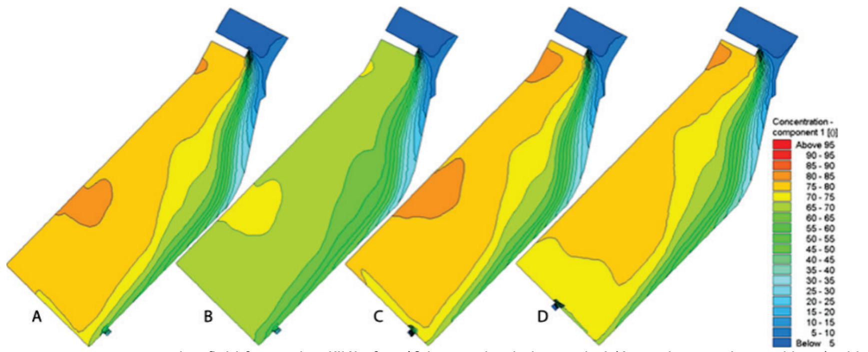

Figure 15 Vertically averaged tracer mass concentration field for marina Ičići after 48 hours simulation period (A – culvert at the position 1 without contribution of waves, B - culvert at the position 1 with contribution of waves, C - culvert at the position 2 without contribution of waves, C - culvert at the position 3 without contribution of waves)

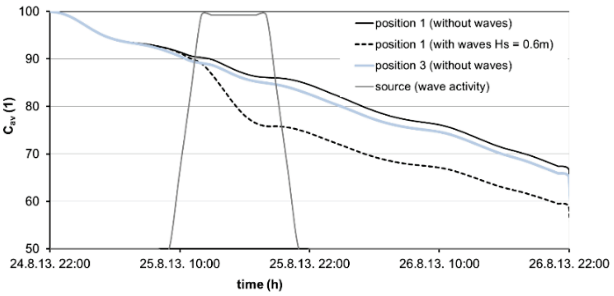

Figure 16 Time series of spatially averaged tracer concentration $C_{av}(1)$ in the marina basin for the analysed situations (position of culverts 1, 2, 3)

7 CONCLUSION

Flushing culverts contribution on seawater exchange in the marina basin using numerical circulation model and the results obtained from physical modelling was carried out. The influence of wind speed and direction, position of culverts and waves on the marina flushing characteristics were analysed.

For the hypothetical marina and isolated wind forcing the highest value of discharge through flushing culverts was obtained for position 1, NE wind direction and 5 Bf speed. Although the discharge through culverts is small in relation to discharge through marina entrance, culverts may improve seawater exchange in the so-called dead zones of a marina. Using the physical model, the ratio of wave parameters and the flow through the pipe for the case of wave propagation perpendicular to the breakwater was obtained. The results of physical modelling were taken directly into the numerical model as a source function at culvert position. Further analysis was carried out for an actual marina - the Ičići marina, which has built-in pipe culverts at position 1. In summertime, when the biggest "ecological" load appears in marinas, the situation for the Ičići marina has been identified, where the wave propagation is perpendicular to the breakwater axis and with similar wave parameters obtained when using the physical model. When comparing situations with and without waves in a case of a culvert located at position 1, seawater exchange is better when waves are included than when they are not. Change in culvert positioning has a small effect on seawater exchange in marinas.

Results obtained show that wind action and wave propagation have notable impact on the flow through flushing culverts in marinas. Due to wave propagation perpendicular to breakwater significant flow through the flushing culverts occurs, even in summertime situations, with the significant wave height of 0,5 m.

In-situ measurements in the Ičići marina are planned in the next part of research. Results of monitored physical oceanography parameters will be used for three - dimensional circulation model calibration. Tidal, wind, wave and density gradient impact on marina flushing trough flushing culverts will be quantified.

Acknowledgements

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