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Use of culverts for improving exchange of seawater in ports

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Subject review

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The quality of seawater in enclosed water basins can be negatively affected by inadequate exchange of seawater. Various culverts (pipe culverts, box culverts, and duct culverts) are presented in the paper as an efficient solution for preventing stagnation of seawater. In addition to positive influence of culvert-induced higher circulation of seawater in the basin, the wave energy penetrating during stormy weather into the protected area via culverts may be a limiting factor. Basic culvert shaping recommendations, relying on the study of previous research and structural solutions for culverts used on Croatian coast, are also presented in the paper.

Key words:

seawater exchange, culvert, waves, harbours, breakwater

Pregledni rad

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Primjena propusta za poboljšanje izmjene mora u lukama

Kakvoća mora unutar ograđenih akvatorija može biti ugrožena nezadovoljavajućom količinom izmjene mora. Ovim radom se prikazuju propusti (cijevni, pločasti i kanalski) kao efikasno rješenje u svrhu izbjegavanja stagnacije mora. Uz pozitivan utjecaj povećane cirkulacije morske vode kroz akvatorij prisutnošću propusta, valna energija koja tijekom olujnog vremena penetrira kroz propust u zaštićeno područje može biti ograničavajući čimbenik. Pregledom prethodnih istraživanja i konstrukcijskih rješenja propusta na hrvatskoj obali, u ovom radu se predlažu osnovne preporuke za oblikovanje propusta.

Ključne riječi:

izmjena mora, propust, valovi, luke, lukobran

Übersichtsarbeit

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Anwendung des Durchflusses zur Verbesserung des Meerwasseraustauschs in Häfen

Die Qualität des Meeres innerhalb der eingeschlossenen Aquatorien kann durch eine unbefriedigende Menge an Meerwasseraustausch gefährdet werden. In dieser Abhandlung werden Durchflüsse (Rohre, Platten und Kanäle) als effiziente Lösungen dargestellt, um eine Stagnation des Meeres zu verhindern. Neben dem positiven Einfluss einer erhöhten Meerwasserzirkulation durch das Aquatorium mithilfe des bestehenden Durchflusses, kann die Wellenenergie, welche während eines Sturms durch den Durchfluss in das gesättigte Gebiet eindringt, ein einschränkender Faktor sein. Anhand der Überprüfung der vorherigen Untersuchungen und Konstruktionslösungen der Durchflüsse an der kroatischen Küste werden in dieser Abhandlung grundlegende Empfehlungen für die Formung des Durchflusses abgegeben.

Schlüsselwörter:

Meerwasseraustausch, Durchfluss, Wellen, Häfen, Hafendamm

1. Introduction

Semi-enclosed basins such as marinas and ports, and naturally enclosed basins such as lagoons and estuaries, often exhibit a problem of low sea water circulation and seawater renewal and, as a result, accumulation of pollutants within the basin [1]. Natural processes that ensure circulation and seawater renewal in semi-enclosed basins include the action of tides, winds, waves, sea currents and coastal and freshwater inflows (rivers, freshwater sources, streams, etc.) [2]. From the mentioned natural flow generators, the most frequently investigated flow generator in ports is the tidal oscillation whose range in most of the world's coastal areas spans from one to several meters. According to the "tidal prism" model [3], each tide introduces new water into a semi-enclosed basin in which, it is assumed, an instantaneous dilution occurs throughout the entire volume of the enclosed basin. The higher the volume of new water that every tide introduces to the basin, i.e. the higher the tidal range, the faster the water renewal in the enclosed basin. In seas where the tidal range is one meter and less (the Mediterranean, the Baltic Sea, the Caribbean Sea), the sensitivity to pollution is relatively high [4]. According to recommendations given by the international organization PIANC [1], the ratio of the volume of new water entering the basin during every tide to

the total volume of the basin at the time of the high tide should be greater than 0.25, preferably 0.35. Therefore, in areas with relatively low tidal oscillations, special attention should be given to passive and active measures for circulation improvement. Passive measures involve design of coastal structures which includes the port layout, the width and position of the port entrance, the sea depth within the port, the slope of sea bottom, and the use of culverts for water circulation, which is the subject-matter of this article. Regarding active circulation improvement measures, pumps and aerators are seldom used because of the cost of their operation and maintenance. According to [5], the ratio of port length X to port width B has a significant impact on the rate of seawater renewal under the influence of tides (other generators such as waves and winds have not been analysed, i.e. only ports with one inlet are analysed). Best geometrical form regarding sea water renewal is exhibited by ports with the ratio $B/X = 1$, while acceptable ratios range between $B/X = 1/2 - 2$. When this ratio is not achieved ($1/2 > B/X > 2$), two or more zones where water rotates are formed preventing seawater renewal in the basin parts farthest from the port entrance. The extrapolation of these results to tidal oscillations of less than 1.2 m has not been established in scientific literature. For curvilinear port geometries, the use of the "planform" factor is recommended: $PF = 4p (P/p^2)$ where:

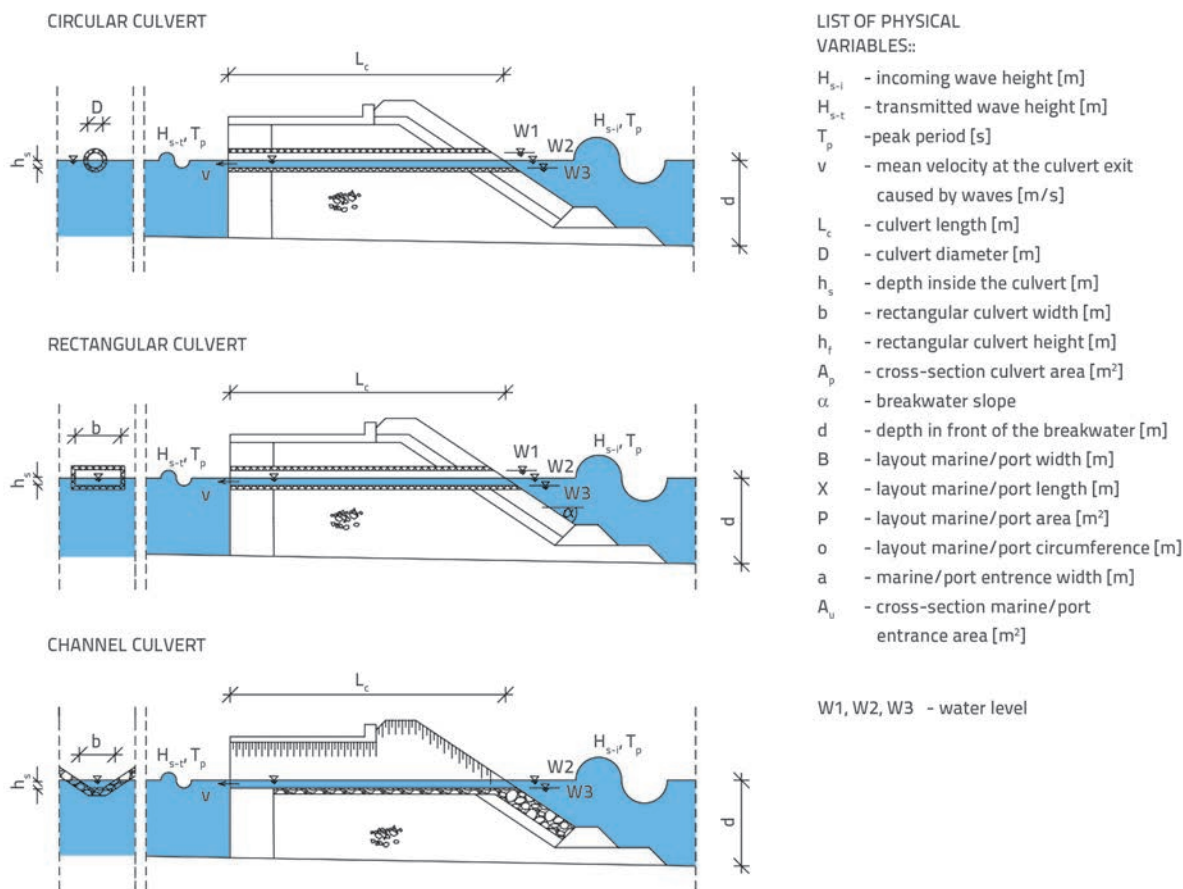


Figure 1. Types of culverts: circular culverts, rectangular culverts and channel culverts; list of physical values

P -basin surface [m^2]; p - basin circumference [m]. According to [1], port basins with a $PF > 0.7$ have good layout predispositions for seawater renewal under the influence of tides, while this is not the case for basins with $PF > 0.4$. According to the same publication, the basin corners (with respect to port layout) are zones where the sea stagnates, and it is recommended to curve the corners in order to avoid the appearance of the so-called "dead zones" with stagnant sea. However, from the commercial point of view, this measure is unacceptable, since some space for accommodation of vessels would thus be lost.

The width of port entrance, e , as related to the surface area of the basin, A , influences sea renewal in ports by tidal oscillations only [1]. Within relatively narrow entrances with the ratio $A/e > 200$, the tides cause flow through the entrance at higher velocities in comparison to situations when entrances are wider. The relatively high velocities ensure creation of larger eddies within the basin and, consequently, better mixing and water renewal. Similar processes occur when the seawater exits the port and mixes with the surrounding "clean" sea. For areas where small tidal ranges are present, the seawater renewal is predominantly influenced by sea currents forced by wind and, consequently, it is appropriate to make the port entrance wider and oriented in the direction of dominant wind. In this sense, sea currents forced by wind stimulate the mixing of seawater in the basin and seawater renewal with the surrounding water [6].

Recommendations given in [1], endorse the use of two entrances regarding port design (for layout forms $1/4 > B/X > 4$) and favour the action of tidal oscillations as the only generator of seawater renewal in ports. It should be emphasized that the cross-sectional area of the second entrance should be approximately the same as the cross-sectional area of the first entrance. It should also be noted that the use of circulation channels with cross-section that is much smaller than that of the port entrance would not be effective (the type of channel/culvert is not indicated). Previous research about the functioning of culverts is presented below. Culverts are structurally divided into three basic types, as shown in Figure 1.

With reference to seawater renewal, researchers emphasize the inadequately low amplitude of tidal oscillations in the sea between Korea and Japan, and shift their attention to the use of culverts embedded in breakwaters, while highlighting wave energy as the dominant generator of circulation through culverts [7-9]. Therefore, they propose a culvert design that uses the incoming wave energy to ensure faster seawater renewal in semi-enclosed basins.

Previous investigation of culvert application can be divided into two parts: wave energy transmission through culverts [10-14], and the influence of natural generators on circulation through culverts [15-19]. A summary of relevant knowledge and recommendations for culvert design is presented in the following sections. Some examples of culvert application is presented in the last section, together with port employee survey results (impact assessment).

2. Water renewal through culverts under influence of wind and tidal oscillations

A numerical model analysis of the influence of wind, tidal oscillations and density distribution in a port model of a rectangular basin was performed in papers [15, 16]. In [15] the focus is set on culverts with a small cross-sectional area where the ratio of the culvert to entrance cross-sectional area of $A_c/A_e = 0.02$ to 0.04 , while the culverts with a larger cross-sectional area and with the ratio of $A_c/A_e = 0.03$ to 0.40 are analysed in [16]. The main conclusion offered in [15] is that the volume flowing through the culvert with a small cross-sectional area is insignificant in relation to the volume flowing through the port entrance. It is concluded that the volume that circulates through the culvert as related to the volume passing through the entrance is 1-2%, which includes both wind action and tidal oscillations. This conclusion is very similar to the one given in paper [1], and it clearly points to the inefficiency of culverts with a small cross-sectional area. Attempts to refute this conclusion will be presented later in Section 5 of this paper.

Detailed analyses of the operation of culverts with larger cross-sectional areas were performed in paper [16] where the influence of culvert layout positioning in breakwater body and the effect of various circulation generators, are investigated. Four culvert positions P1-P4 (Figure 2) were investigated, while the values for the culvert cross-sectional surface area A_c and the entrance cross-sectional surface area A_e were varied. Eight wind directions were modelled, with each wind situation being represented with a linear increase of wind velocity from 0 Bf to 5 Bf and with subsequent decrease in wind velocity, for a total duration of 24 h. The tidal oscillation range was 0.3 m with a 12 h period. The efficiency of a particular culvert position was evaluated utilizing the mean concentration of a conservative tracer $C_{wind\ direction}$ in the entire basin after 24 hours of simulation. The passive tracer at the beginning of the simulation was homogeneously deployed throughout the port volume with a value of 1 mg/l, and the return factor was set to $b = 0$ (in other words, the pollution that came out of the port did not return to the port). Every symbol in Figure 2 is a defined pair $(A_c/A_e$ and $C_{mean-sec}$) where $C_{mean-sec}$ is the mean value calculated for three wind directions $C_{mean-sec1} = 1/3 (C_{NW} + C_W + C_{SW})$ and, similarly, $C_{mean-sec2} = 1/3 (C_{SE} + C_E + C_{NE})$.

It can be concluded that the data for sec 1 result in a smaller value of C_{mean} (lower positioned blue curve), indicating that winds blowing approximately from culvert position to port entrance position result in the smallest values of C_{mean} . Wind directions from sec 2 give worse results (higher positioned red curve), while wind directions that are approximately perpendicular to the culvert - entrance line (S and N winds) generally give the worst results and are not shown here. Exponential curves adjusted to the data from sectors 1 and 2 are shown in Figure 2 in red and blue (Expon).

Regarding the exponential decline of the red and blue curves (Figure 2), it can be concluded that the cross-sectional surface

area of the culvert A_c has a significant role in seawater renewal in ports, i.e. the water quality increases significantly with an increase in cross-sectional area of the culvert. This conclusion applies only in cases when wind is the sole circulation generator. The results obtained in cases with no wind, or when the circulation generator are tidal oscillations only, are shown with black symbols in Figure 2. It can be concluded that C_{mean} values amount to approximately 0.9 mg/l for all culvert positions, which points to a much weaker seawater circulation, compared to the situation involving wind action.

The influence of wind on seawater renewal through culverts is confirmed by field measurements in Opatija Marina, as presented in [19]. In this paper, a clear correlation is established between the specific wind power (J/m²) "delivered" at the marina location and sea volume (m³) that passed through culverts during the same time period.

In the case of culverts with a small cross-sectional area ($A_c/A_e \sim 0.02-0.05$), results from models including wind and models excluding wind ($C_{mean} \sim 0,92$ mg/l and $C_{mean} \sim 0,77$ mg/l) are comparatively similar to the data from the analytical "tidal prism" model [20] ($C_{mean} \sim 0,85$ mg/l), which is defined for the ports without culverts and with only tidal oscillation present. The results suggest that, if all numerical model assumptions are taken into account (the model assumptions shown in paper [16]), culverts with small cross-sectional area do not have a

significant impact on the sea water renewal in ports regardless of the circulation generator (wind action or tidal oscillation). This again confirms the conclusion given in [1] about inefficiency of culverts with a small cross-sectional area.

It should be noted that the influence of vessels and anchored systems on sea water circulation under the influence of wind is not taken into account in the numerical model shown in paper [16]. It can be deduced intuitively that in this case there will be a weaker wind energy transfer to the seawater body and, hence, the circulation will be lower, which will result in a higher positioned blue and red curve in Figure 2.

If the values C_{mean} for the P1 culvert position are observed (red and blue circles in Figure 2), it can further be concluded that the position P1 has higher C_{mean} values as related to other culvert positions (P2, P3, and P4) for both wind direction sectors. This indicates that it is preferable to choose a position further away from the port entrance when selecting an appropriate culvert position, because this activates circulation of a larger volume of water within the basin. In cases without wind (black symbols) there is no indication that the sea water renewal is affected by culvert position.

The above analyses are related to the 24-hour wind impact, which is an isolated short-term case. In reality, the circulation is forced by several generators concurrently, i.e. wind occurs simultaneously with formation of waves and the latter cause some circulation

and sea mixing. This in turn produces a density gradient between the port and the surrounding sea, and additional circulation occurs. In the long term (which implies the entire year), a particular generator can be dominantly responsible for the total circulation through culverts and port entrance, depending on climatological and oceanographic conditions and structural features of the facility.

3. Wave transmission through culverts

Increasing the cross-sectional area of the culvert A_c causes an increase in wave energy that penetrates into the basin through the culvert. The wave energy transmission is defined by the transmission coefficient $K_t = H_{s-t}/H_{s-f}$. Transmission coefficients of a rectangular culvert are studied in [10] for the case of regular waves. The result of the laboratory research is an empirical equation that can only be applied for cases when the sea level is at the culvert axis

$$K_t = -118,5 + 71,1 \left(\frac{L_c}{L}\right)^{0,001} + 47,22 \left(\frac{L_c}{L}\right)^{-0,001} + 0,204 \left(\frac{b}{H_t}\right)^{0,44} \quad (1)$$

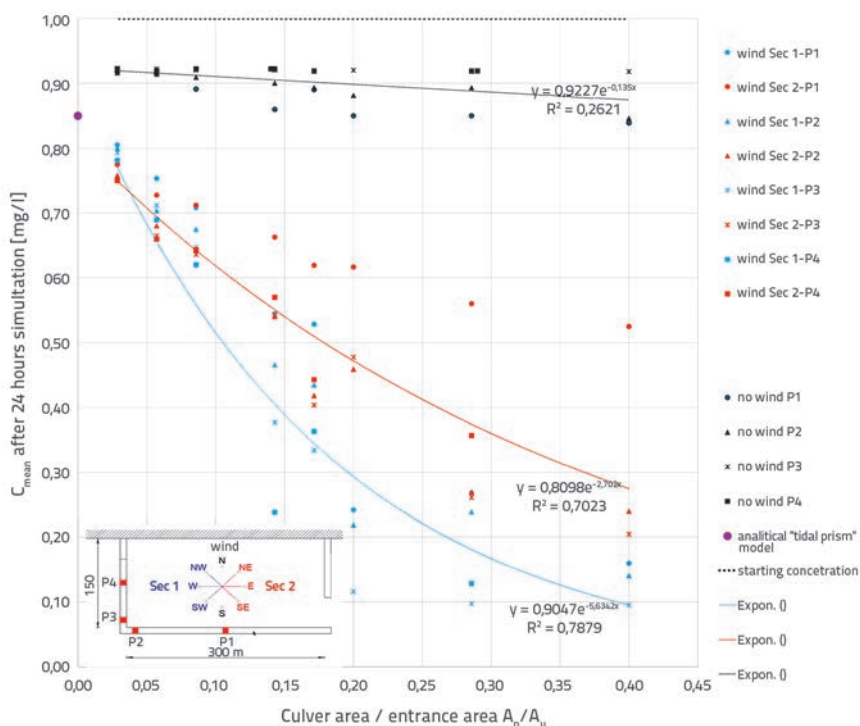


Figure 2. Influence of the ratio of cross-sectional area of a rectangular culvert to cross-sectional area of port entrance (A_c/A_e) on the mean concentration of conservative tracer after 24 hours of simulation. The simulation includes wind action and tidal oscillations for wind direction from sec 1 (NW-W-SW) and sec 2 (SE-E-NE). $C_{mean-sec1} = 1/3 \cdot (C_{NW} + C_W + C_{SW})$; $C_{mean-sec2} = 1/3 \cdot (C_{SE} + C_E + C_{NE})$

where:

- L_c - culvert length
- L - incoming wavelength
- b - rectangular culvert width ($b=D$ for circular culvert)
- H_i - incoming wave height and Iribarren's number $x = \text{tg}(a)/(H_i/L)^{0,5}$
- a - breakwater slope.

Another limitation that concerns the above equation is that it applies only to waves with the ratio of $H_{s-i}/D < 0.8$. The equations given below are applicable for waves with the respective ratio $H_{s-i}/D \geq 0.8$.

The transmission of wave energy through circular culverts was explored in [14] on a laboratory model using irregular waves. The following empirical equations are used to determine the transmission coefficient for three different sea levels relative to the culvert axes (W1, W2 and W3):

$$W1 \quad K_t = 0,711 \cdot [FP]^{0,316} \quad (2)$$

$$W2 \quad K_t = 0,678 \cdot [FP]^{0,235} \quad (3)$$

$$W3 \quad K_t = 1,257 \cdot [FP]^{0,475} \quad (4)$$

In order to define the transmission coefficient, a parameter defined as $FP = E_i D^2 H_{s-i}^{-2}$ is used in paper [12]. In this parameter, E_i is the energy loss parameter and is calculated by multiplying the loss coefficient A (m^{-4}) and the ratio of wavelength to culvert length L_p/L_c ($E_i = A L_p/L_c$). The loss coefficient A is in the range of [0,1] and it describes the energy losses inside the culvert, such as friction in contact with culvert walls and other obstacles within the culvert. As there are no published recommendations for coefficient A , the value of $A = 1$ is adopted in this analysis.

To present the application, the transmission coefficient calculation has been performed for all equations (1) to (4) mentioned in relation to the FP parameter (Figure 3). Transmission coefficient curves are presented and computed directly for (2) to (4) and indirectly via the FP parameter for (1). Figure 3 shows measurements performed on culvert groups (GR4, GR6 and GR8), published for the first time in this article, while the laboratory model and measurement methodology are described in detail in [14].

Generally, there are culverts that have an upper edge (which can be rectangular or circular or can assume some other form) and culverts that do not have the upper edge. Culverts that have an upper edge can be divided into culverts in which water is forced by waves with a wave height significantly higher than the culvert height $H_{s-i}/D \geq 0.8$ or $H_{s-i}/hf \geq 0.8$, and culverts in which water is forced by waves with a wave height lower than the culvert height $H_{s-i}/D < 0.8$ or $H_{s-i}/hf < 0.8$. The former are described with equation (1) and the latter with equation (3). In the case when $H_{s-i}/D \geq 0.8$ the wave energy dissipation at the riprap around the entrance to the culvert is large because the crest of individual waves interacts with the structure above the upper edge of the culvert and is dissipated. For waves with a value of $H_s/D < 0.8$, most waves enter the culvert without dissipation at the entrance and therefore higher transmission coefficients are observed, as shown in curve (1).

On the other hand, differences in transmission coefficient for various water levels (W1-W3) shown in Figure 3 should be observed. It can be seen that the highest transmission coefficients occur at W2 level while the other two levels produce smaller transmission coefficients. It can be deduced from this analysis that fully submerged culverts with a sea mean level close to level W1 should be designed because then the transmission is smaller. The study that includes field

measurements (in Opatija Marina) published in [21] suggests that culvert flows, forced by natural generators, are reduced by almost two times when the culvert is fully submerged in water as compared to partly filled culverts. Consequently, the culvert design should preferably be carried out according to GR6 or GR8 cross-sections shown in Figure 3, where it is recommended to choose level W2 for areas with a small tidal oscillation range.

As already mentioned, transmission coefficients measured for GR4, GR6 and GR8 culvert groups are described in more detail in paper [12]. It can generally be observed that transmission coefficients for culvert groups are higher than those measured for one culvert (for level W2). This is expected because the total cross-sectional area through which

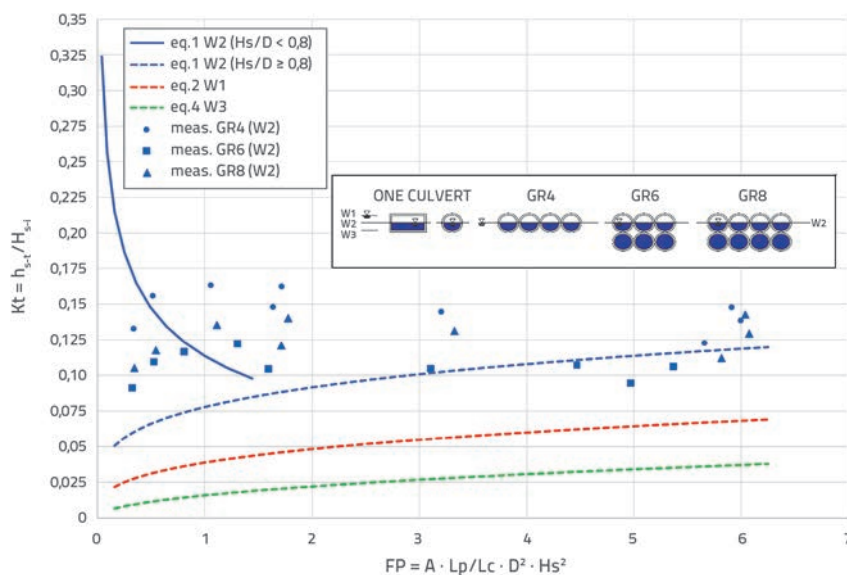


Figure 3. Transmission coefficient K_t for case of rectangular culvert (equation (1)) and circular culvert (equation (2-4)) and data measured for culvert groups

Table 1. Range of parameters in which transmission coefficient equations are applicable (parameters defined in Figure 1); $H = H_i$ for regular waves; $H = H_{s,i}$ for irregular waves; $L = L_p$ for irregular waves; $b = D$ for circular culverts

Equation	Type of applicable type of culvert	Wave type	H/hf	Lc/L	b/L	b/hf	Lc/b	d/L	hs/hf	Kt range
(1)	rectangular	regular (monochromatic)	0.13-1.2	0.23-1.28	0.064-0.24	1-4	3.2-15	0.15-1.0	0.5	0.02-0.4
(2) (3) (4)	circular	irregular (spectral)	0.51-2.48	0.23-1.68	0.015-0.092	1	9.2-32	0.11-0.5	0; 0.5; 1.0	0.05-0.22

wave energy is transmitted is larger. It should be noted that, for simplicity, in the calculation of FP parameter, the influence of more culverts is taken as $4 \cdot D^2$ for GR4 and GR8, and $3 \cdot D^2$ for GR6 (i.e. only culverts at the surface are considered). Furthermore, as observed from measured data, the average transmission coefficient for a group of four surface culverts ($K_{t-GR4} = 0.15$) is higher than the coefficient for eight pipes ($K_{t-GR8} = 0.13$), indicating that the vertically lower row of culverts does not cause an increase in transmission. On the contrary, it slightly reduces the transmission of wave energy. In the case of a group of six culverts, the smallest transmission coefficients ($K_{t-GR6} = 0.11$) were recorded, indicating that transmission is influenced by the width of the culvert group.

The occurrence of water jets that form on the port side of culverts (rectangular and circular) is described in laboratory research on physical models published in papers [11, 14]. This phenomenon is most pronounced at level W3 and decreases as the level increases to level W1. It can be expected that the water jet can attain up to 2 m behind the culvert (for long wave lengths) in the case of level W3. In such situations, vessels positioned near the culvert may be endangered by jet action. Wave heights on the port side are the highest near the culvert exit. Their height decreases as the distance from the culvert exit increases. This process of water height decrease behind the culvert is very similar to the decrease in wave height due to diffraction of monochromatic waves [22], as shown in paper [12]. The coefficients calculated using equations (2) to (4) refer to a point situated at approximately 1.8 m behind the culvert in natural scale, while higher wavelengths are expected near the culvert and lower ones further toward the port. In the case of equation (1) the calculated value K_t refers to the mean value of transmission coefficient, which is obtained by averaging three positions behind the culvert [10]. The range in which parameters are applicable, i.e. in which laboratory measurements were conducted (1-4), is shown in Table 1. The above equations can be applied in the range of parameters defined in the table. In the case of channel cross-section shown in Figure 1, the use of the equation for calculating transmission coefficient for submerged breakwaters is recommended [23].

4. Velocities of wave-forced water flow in culverts

An oscillatory (left-right) motion of water under wave action at the culvert entrance can be observed in the culvert and, hence, an average flow of water mass from the open sea towards the port basin or vice versa can also be seen. Since flow rate in culverts where water is rapidly changing direction is difficult to measure, the water velocity is measured in paper [17] at the exit of the culvert under the influence of waves. The mean horizontal velocity at the culvert exit (Figure 1), which is averaged for a time period of action of a stationary incident wave field, may be an indicator of water flow caused by the waves. Previous research shows that the average velocity in culvert, caused by surface waves, depends on several parameters, while the culvert submergence is dominant, equation (5). With this expression, submergence is taken into account via the submergence coefficient (w), which is defined by the ratio of height difference between the culvert bottom and water surface to culvert diameter:

$$v = \sqrt{gD} \cdot \left[0,097 \cdot \left(\frac{H_{s-i} L_p}{L_c w^4 D} \right)^{0,34} - 0,11 \right] \tag{5}$$

Where symbols denoting physical variables are harmonized according to table shown in Figure 1.

Other parameters affecting velocity in the culvert are wave height ($H_{s,i}$) and length (L_p), and finally culvert diameter (D) and length (L_c).

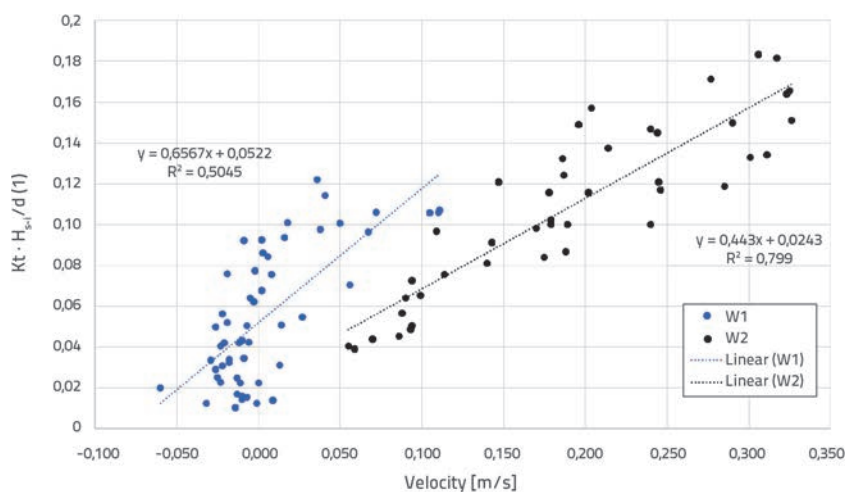


Figure 4. Ratio of transmission coefficient to velocity in circular culvert

In previous research [13], it is assumed that the wave energy transmission (i.e. the transmission coefficient) does not necessarily follow the mean rate of water flow through the culvert. These claims have not been subsequently proven and are published in this paper based on the results obtained on the physical model described in papers [14, 17]. Figure 4 presents comparison between mean velocities measured at the culvert exit and measured transmission coefficients defined by the $K_t \cdot H_{s-t} / D$ parameter, which actually includes the transmitted wave height $H_t = K_t \cdot H_{s-t}$ and culvert diameter D . This diagram shows a very different correlation for levels W1 and W2. An overall linear relation between velocity v and parameter $K_t \cdot H_{s-t} / D$ can be observed on the graph. It can be concluded from this correlation that the mean velocity within the culvert increases (v) with an increase in the transmitted wave height (H_{s-t}). In case the circular culvert is fully submerged in water (W1), the flow is oriented outwards i.e. toward the open sea (depicted as negative velocity in the graph), which is an indication that the flow appears to leave the port through the culvert under certain wave conditions. However, this is only an assumption as the correlation between the flow and velocities measured at one point at the culvert exit has not been confirmed. This unexpected direction of water flow occurs primarily when the wavelengths of incident waves are short. Further numerical analysis will need to be undertaken to describe the mechanisms that are at the origin of the above-mentioned result.

According to research published in paper [18], the influence of waves accounts for 15% of the total volume of water that flows through the culvert from all flow generators combined.

5. Current use of culverts for seawater circulation

There are numerous ports and marinas at the Croatian coast that have built-in culverts in their wave-protection structures. These culverts are used to ensure a more efficient seawater renewal. Some qualitative conclusions were made based on the study of several marinas and according to the survey of staff working in these marinas. In this paper, culvert design solutions are presented for Vitrenjak Port (Zadar), ACI Marina in Split, and Kornati Marina in Biograd, while technical on-site inspections were also made for Zadar Marina (Tankerkomerc), ACI Marina in Vodice, Lav Marina (Podstrana) and for the small craft harbour Zenta in Split. This inspection campaign was conducted during the months of June and July 2018.

5.1. Kornati Marina (Biograd)

The marina in Biograd consists of Kornati Marina and a small craft harbour in the inner part of the basin (Figure 5). A circular culvert with a cross-sectional area of 0.5 m^2 is situated at the root of the western breakwater at position (a). In the vertical direction, this culvert is positioned in such a way that the upper culvert edge is at the mean sea level, which is why the circular culvert is completely submerged most of the time.

A group of two circular culverts (b), located in the channel, allows seawater renewal at the root of the breakwater. On the day of the inspection, the best seawater quality (transparency) was



Figure 5. Kornati Marina and small craft harbour in Biograd; a) circular culvert - $A = 0,5 \text{ m}^2$; b) circular culvert - $A = 1 \text{ m}^2$; c) circular culvert - $A = 3,6 \text{ m}^2$; d) circular culvert - $A = 1,2 \text{ m}^2$; dead zone - red polygon



Figure 6. Small craft harbour Vitrenjak in Zadar; a) channel culvert - $A = 4 \text{ m}^2$

observed in the zone near the culvert while this quality worsened toward the so-called “dead zone” (red polygon in Figure 5). The road crossing (b) constructed in this way (with two circular culverts) ultimately reduces the flow area when compared to the example of a more favourable technical solution in the Port of Vitrenjak (Figure 6) where a larger capacity channel culvert is located.

A group of three circular culverts is located at the root of the central fixed pier (c) to allow circulation within the marine. In the root of the north breakwater (d) there is a circular culvert with the cross-sectional area of 1.2 m^2 .

5.2. Small craft harbour Vitrenjak (Zadar)

A channel type culvert (Figure 6) was built at the location of the Vitrenjak Port in Zadar. The channel culvert is at the root of the primary breakwater. On both sides of the channel culvert there is riprap that enhances dissipation of incoming waves, thus reducing unfavourable wave energy penetration into the basin. The channel width is 6 m and the depth at mean sea level is 0.5 m. The channel is topped by a bridge that allows operation of traffic between mainland and the breakwater.

5.3. ACI Marina Split

Four culverts are situated in ACI Marina Split and the neighbouring small craft harbour (Figure 7). The 0.75 m wide culvert (a) appears to be ineffective as noticeable pollution at the sea surface can be seen at the south side of the culvert.

Two bigger rectangular culverts (b and c) connect the basin with the surrounding sea (3.3 m and 3.8 m in width, respectively). There is a rectangular culvert (d) 4 m in width at the root of the breakwater.

The employee survey revealed that sea circulation occurs via culverts b, c, and d. It was highlighted that clam accumulation in culverts is prevented by regular culvert cleaning operations.

5.4. Small craft harbour Zenta (Split)

A small craft Zenta Harbour, located some 2.5 km away from ACI Marina Split, was also inspected. Some polluted zones were observed in this harbour. The polluted zones are most pronounced in the eastern part of the harbour (marked red in Figure 8). There are no circulation culverts in Zenta Harbour and, furthermore, no other measures have been undertaken to increase sea water renewal. As these two localities (ACI Marina Split and Zenta Harbour) are located close to one another, similar oceanographic, climatic and anthropogenic impacts can be expected in both ports. It can be assumed that worse water quality in Zenta Harbour is caused by the lack of passive or active measures to improve circulation in the harbour. This assumption should be confirmed using appropriate scientific methodology (measurements and numerical modelling).

5.5. Lav Marina at Podstrana

Lav Marina at Podstrana has a 5 m wide rectangular culvert at a depth of 2 m at the root of the main breakwater. The inside

of the rectangular culvert is protected by stone fill material in order to increase dissipation of wave energy. The operation of this culvert type has not yet been investigated, and there are no published papers on this topic.

5.6. ACI Marina Vodice

The ACI Marina Vodice has circular culverts that are located in the main and secondary breakwaters. These culverts have a

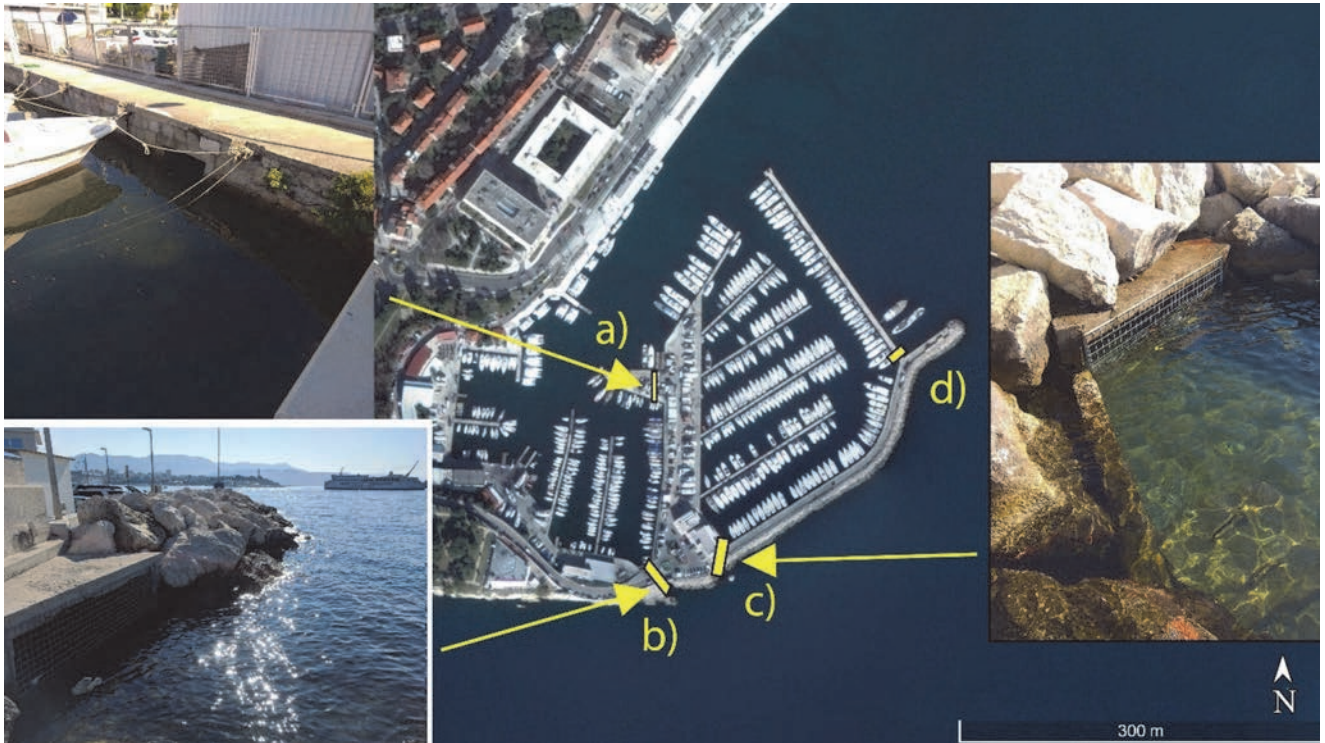


Figure 7. ACI Marina Split; a) rectangular culvert - $A = 0.8 \text{ m}^2$; b) rectangular culvert - $A = 4.2 \text{ m}^2$; c) rectangular culvert - $A = 5.3 \text{ m}^2$; d) rectangular culvert - $A = 12 \text{ m}^2$

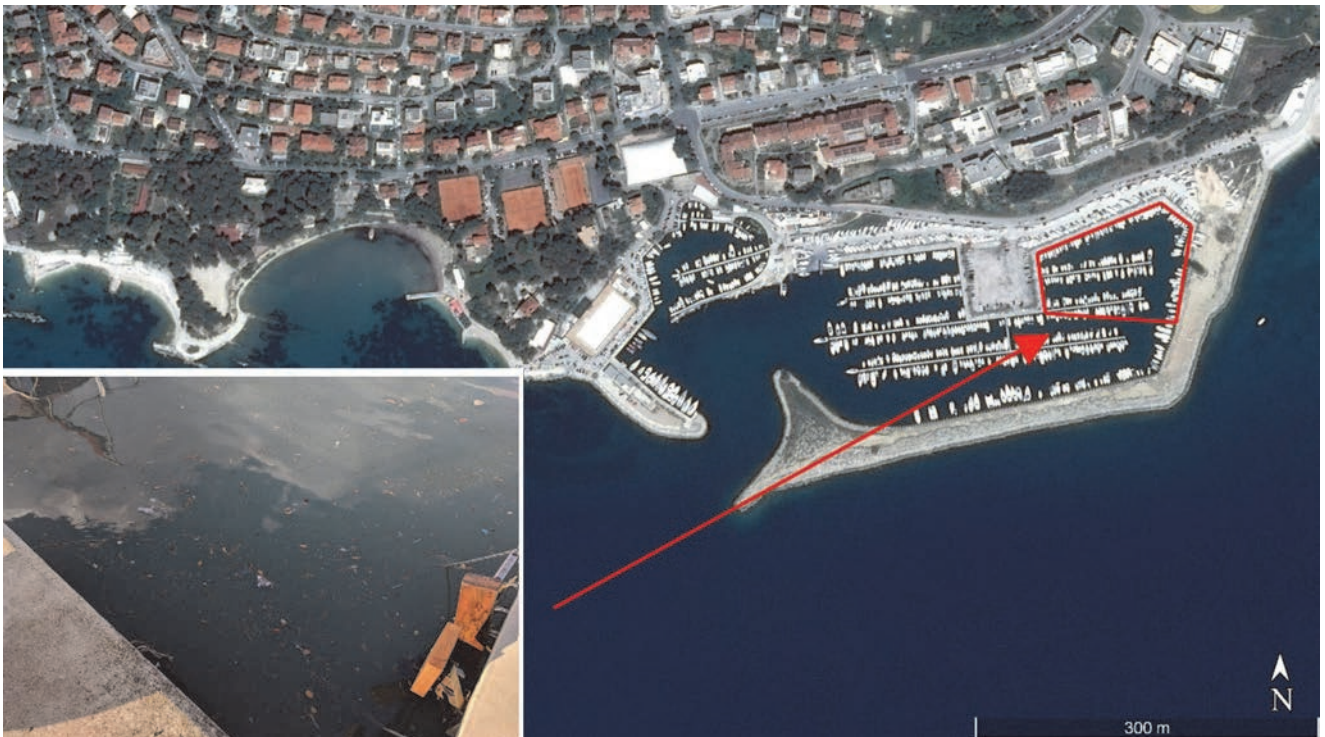


Figure 8. Small craft Zenta Harbour in Split; dead zone - red polygon

cross-sectional area of 6.65 m² and 1.13 m², respectively. There are strong freshwater sources in the marina, which is likely to affect the quality of sea water. The influence of freshwater sources in Opatija Marina is presented in paper [18].

5.7. Zadar Marina (Tankerkomerc)

In Zadar Marina, located within Zadar Bay in Vrulje Cove, the mixing with surrounding sea is ensured by means of a permeable breakwater on pylons. A freshwater stream was also detected, and its flow rate was approximated at 1.5 m³/s (by measuring velocity at water surface).

5.8. Parametric analysis of seawater renewal

Design features of individual ports are calculated below according to literature described in introduction (Figure 9). It should be highlighted that the mentioned design features are defined in literature solely for the purpose of evaluating seawater renewal efficiency with regard to tidal oscillations (culverts were not taken into account). By observing the tidal prism, i.e. the ratio of the amount of seawater flowing through the basin during each tidal oscillation to the total volume of water within the basin, this parameter points to bad water conditions in the majority of ports analysed in this study. For all ports examined, this indicator is significantly below the satisfactory-condition threshold of 0.25. The planform factor points to good conditions in ACI Marina Vodice only, while ACI Split, Zenta and Biograd ports are classified as ports with poor water conditions. Conditions are considered to be moderate in the remaining three ports (Vitrenjak, Belvedere and Zadar). The ratio of the cross-sectional area at the entrance to the basin surface area, indicates moderate conditions, but in Belvedere and Zadar marinas condition is considered bad due to a relatively large entrance compared to the basin surface area. Although the analysed indicators shown in Figure 9 point to mostly poor to moderate seawater quality in the examined ports, the field surveys reveal a better state. Culverts improve

the seawater quality in the vicinity of culverts and thus reduce the so-called "dead zones" within the basin area, which are situated far away from the port entrance. This process was also identified through research based on numerical modelling [13]. The extent of impact on seawater quality depends on geometric parameters of the culvert and oceanographic conditions at the port location, which is a topic for future research. Additionally, the importance of seawater quality as viewed by tourists and people sailing through the area, and the use of active and passive measures for a more efficient seawater renewal, may also be of interest for future research.

Due to unfavourable conditions caused by small tidal oscillations, and considering favourable presence of winds during summer months (maestral), the installation of pipe culverts is highly recommended during construction or retrofitting of port infrastructure (especially that relating to tourism). A particularly positive influence of culverts on seawater quality was identified in the so-called "dead zones" of ports.

6. Conclusion

An overview of current research regarding culvert functioning and influence of culverts on seawater renewal in small basins is presented in the paper. Basic culvert types are identified and defined as follows: circular culverts, rectangular culverts, and channel culverts, and their basic influencing parameters are presented. Recent research suggests a significant impact of wind on seawater renewal through the culverts having a larger cross-sectional area, especially in areas with small tidal oscillations such as the Mediterranean. It has been confirmed that the ratio of the culvert cross-sectional area A_c to the entrance cross-sectional area A_e also exerts a significant influence on seawater quality in the whole basin. The equations for calculating transmission coefficient relating to deep-wave action are defined, and mean velocities occurring in culverts are determined. An overview of culvert use in several marinas and small craft harbours in Croatia is presented. Although culverts (with small cross-sectional areas) do not significantly

impact the total seawater circulation in the entire port basin, their impact on seawater renewal in the so-called "dead zones" is important.

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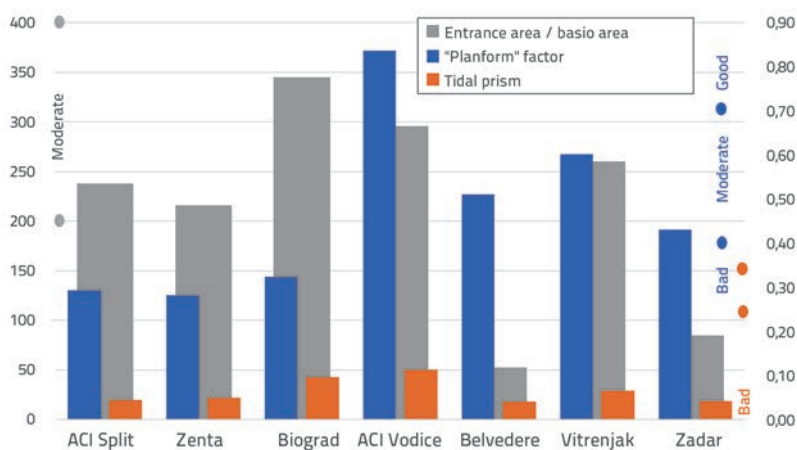


Figure 9. Water quality indicators for inspected marinas and small craft harbours

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