HYDRAULIC INTERACTION OF THE PERFORATED SEAWALL AND SMOOTH SUBMERGED BREAKWATER

D. Carevic[1], G. Loncar[2], M. Paladin[3]

Abstract

Coastal structures are used for transition of people and goods between sea and land and for protection of coast and internal waters. With an aim to provide safe transition of people and goods, calm sea should be ensured in front of coastline in order to achieve vessels without large movements and no-overtopping coastline.
This work deals with special type of coastal structure which consists of two common types of structures: perforated seawall and submerged breakwater positioned in front of it. A new mathematical model was developed based on the experimental measurements of wave parameters between such tandem. Experimental investigations were conducted in wave channel for monochromatic and spectral waves varying length between constructions (1,2m, 2,4m i 6,2m) and submergence of breakwater (0,06m and 0,1m). The total of 54 hydraulic tests were achieved varying wave and geometrical parameters.
Using a new developed mathematical models for monochromatic and spectral waves the analyse of hydraulic behaviour of such construction is presented and comparison with some other coastal constructions (only solid seawall, solid seawall in tandem with submerged smooth breakwater).

Keywords
hydraulic interaction, submerged breakwater, perforated seawall.

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1 INTRODUCTION

Perforated seawall is sea defence construction which attenuates reflected waves and reduces amount of overtopping. Submerged breakwater causes wave breaking in front of the sea line and reduces wave energy which approach to seawall (in this work perforated seawall). Combination of this two structures provide attenuation of wave heights between them and consequently reduction of the seawall toe erosion, calm sea for berthed vessels and lower seawall crown.
The original descriptions of the perforated seawall hydraulic behaviour, based on heuristic approach, have been published in work [1]. A theoretical model, based on long wave theory, was developed in paper [2], for transmission and reflection coefficient calculation. The model assumed two parallel perforated walls without back wall, and superposition of linear incident and reflected waves. In work [3], a simple analytical model for regular waves was developed predicted for the calculation of the perforated wall reflection coefficients consisted of one perforated and one solid wall. Deriving a several mathematical models in [4], [5] and [6], for reflection characteristics estimation, authors have included complex caisson geometry, influence of foundation embankment and irregular waves. Some other works which deal with perforated structures are [7] and [8].

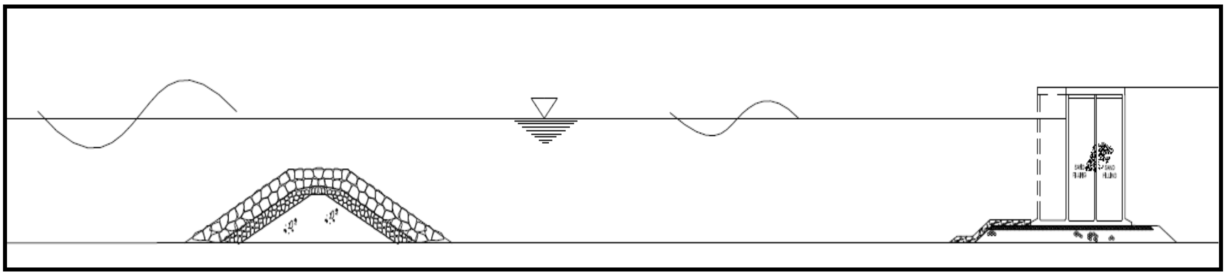

Fig. 1 Perforated seawall and submerged breakwater

LCS (low crested structure) is a type of rubble mound structure with emerged, submerged or zero freeboard causing the wave breaking and the dissipation of wave energy. LCS-s with rubble mound armour are usually used and their functional characteristics (transmission and reflection) are described in the works [9], [10], [11], [12], [13] and [14]. This paper deals with LCS with smooth armour, the type of structure rarely used. The possibility of generalizing the results of this work to be applied for rubble mound structures is obviously limited, so results of this work are mainly intended as basic research of such tandem hydraulic performance.
The defence of rubble mound breakwater with LCS positioned in front of it was investigated in paper [16], where the authors concluded that the run up and run down for the breakwater defenced by submerged LCS are reduced up to 30 and 60%. The damage of the optimally defenced breakwater is reduced by 40–100% compared to a non-defenced (single) breakwater.

The combination of smooth low crested structure and perforated seawall is the main objective of this paper, respectively, the wave attenuation caused by submerged breakwater and perforated seawall.

2 THEORETICAL MODEL

2.1 Theoretical Model for the Calculation of Wave Heights between Perforated Seawall and Smooth Submerged Low Crested Structure

The hydraulic interaction of the submerged LCS and the perforated seawall implies the following: 1. the influence of LCS on the wave heights, and 2. the influence of the perforated seawall on the wave heights.
Part of the wave energy is transmitted over the submerged breakwater in the form of the transmitted wave height H_t, (Fig. 2). Those waves travel toward perforated breakwater and reflect as reflected wave heights H_{tr}. Maximum wave heights which occur between LSC and perforated seawall are equal to summation of transmitted and reflected wave heights for regular waves (as it is indicated on Fig. 2).

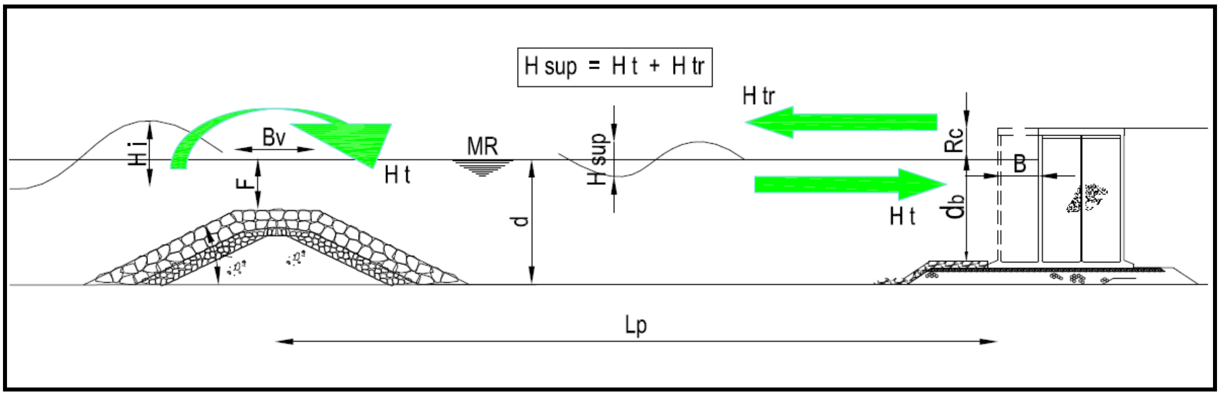

Fig. 2. Definition sketch of smooth submerged LCS and perforated seawall interaction for regular waves

Irregular waves are usually described by spectral and statistical methods. Short-term wave situation is defined by wave energy spectral density function $S_\eta(f)$. In the case of opposite direction traveling waves, the superposed significant wave height ($H_{s\text{-}sup}$) could be calculated according to [18] as it is indicated on Fig. 3.

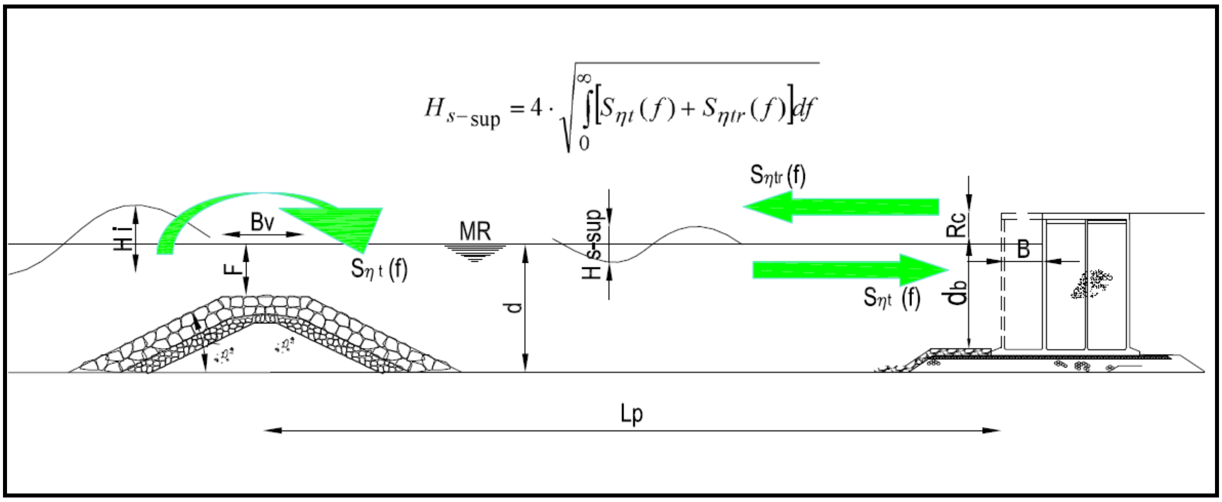

Fig. 3 Definition sketch of smooth submerged LCS and perforated seawall interaction for irregular waves

Transmission over the breakwater and reflection from seawall depend on geometrical characteristics and incident waves parameters. Both phenomena are well described by existing mathematical models. In this work, existing mathematical models for submerged breakwater (chapter 2.3) and perforated seawall (chapter 2.2) will be used for a new mathematical model development, with the aim of the description of the hydraulic performance of such tandem. A new formed mathematical model will allow calculation of wave heights between submerged breakwater and perforated seawall for different incident wave parameters and geometries of structures.

2.2 Theoretical Model for Perforated Seawall Reflection Coefficient Calculation

Regular waves

In the paper [3] authors have derived analytical model for reflection coefficient calculation based on assumption of regular long-crested waves and constant depth of the water in dissipation chamber and in front of the perforated wall.

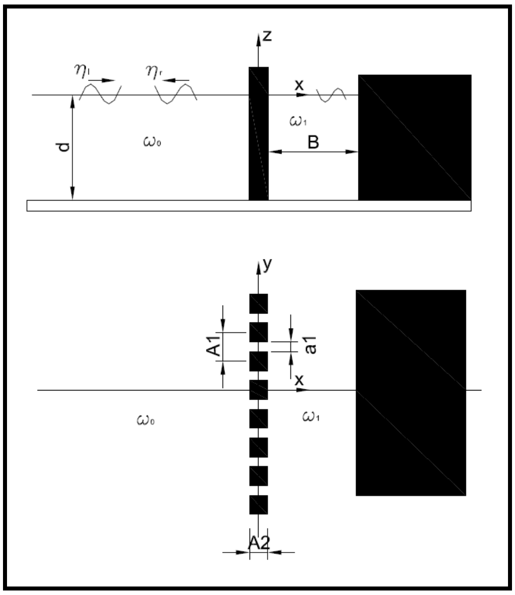

Fig. 4 Sketch of the perforated seawall

They separated domain in two regions, one in dissipation chamber and second one at the outer side. In each region they assumed incident and reflected wave velocity potential. Total potential was assumed as sum of potentials for incident and reflected waves. They solved system of differential equations with assumption that loss of potential energy on the perforated wall is according to [2], [19]:

$$\alpha = \left(\frac{1}{pC_C} - 1 \right)^2 \tag{1}$$

where are:

p porosity of perforated wall,

C_C contraction coefficient of the jet from the perforation hole, C_C=0,4-0,8 according to [19] and equation $C_C = 0{,}6 + 0{,}4p^2$ according to [20].

Solving differential equations they have got system of independent linear equations which give:

$$K_R = \frac{\left[\left(G^2 + W^2\right)^2 + W^2 R^2\left(W^2 R^2 + 2G^2 - 2W^2\right)\right]^{0,5}}{G^2 + W^2(1+R)^2} \tag{2}$$

where are:

$$P = lk \tag{3}$$

$$R = \beta\left(\frac{k}{\omega}\right) \tag{4}$$

$$W = \tan(kB) \tag{5}$$

$$G = 1 - PW \tag{6}$$

$$l = 2C; \quad C = \frac{A2}{2}\left(\frac{A1}{a1} - 1\right) + \frac{2A1}{\pi}\left[1 - \log\left(\frac{4a1}{A1}\right) + \frac{1}{3}\frac{a1}{A1} + \frac{281}{180}\left(\frac{a1}{A1}\right)^4\right] \tag{7}$$

$$\beta = \frac{8\alpha}{9\pi} H\omega \frac{W}{\sqrt{W^2(R+1)^2 + G^2}} \frac{5 + \cosh(2kd)}{2kd + \sinh(2kd)} \tag{8}$$

Reflected wave height can then be defined as:

$$H_r = K_R \, H_i \tag{9}$$

Irregular waves

Mathematical model for reflection coefficient calculation of irregular waves was developed in paper [21]. Model is based on above described model for regular waves. Methodology is based on application of regular wave's model on each spectral component independently. Dissipation coefficient β is calculated for each component with a same wave height H_{rms}-root mean square wave height. Each component of wave spectrum is denoted with subscript „n“:

$$K_{Rn} = \frac{\left[\left(G_n^{\,2} + W_n^{\,2}\right)^2 + W_n^{\,2} R_n^{\,2}\left(W_n^{\,2} R_n^{\,2} + 2G_n^{\,2} - 2W_n^{\,2}\right)\right]^{0,5}}{G_n^{\,2} + W_n^{\,2}(1+R_n)^2} \tag{10}$$

$$P_n = lk_n \tag{11}$$

$$R_n = \beta_n \left(\frac{k_n}{\omega_n} \right) \tag{12}$$

$$W_n = \tan(k_n B) \tag{13}$$

$$G_n = 1 - P_n W_n \tag{14}$$

$$\beta = \frac{8\alpha}{9\pi} H_{rms} \omega_n \frac{W_n}{\sqrt{W_n^{\,2} (R_n + 1)^2 + G_n^{\,2}}} \frac{5 + \cosh(2k_n d)}{2k_n d + \sinh(2k_n d)} \tag{15}$$

$$H_{rms} = \frac{4{,}004\sqrt{m_0}}{1{,}416} \tag{16}$$

where is:

m_0 zero momenth of incident wave spectrum, [m^2]

If discrete distribution K_{Rn} is transformed to continuous curve $K_R(\omega)$, the reflected wave spectrum can be solved as:

$$S_{\eta r}(\omega) = K_R^{\,2}(\omega)\, S_{\eta i}(\omega) \tag{17}$$

2.3 Theoretical Model for Calculation of Transmission Coefficients over Smooth LCSs

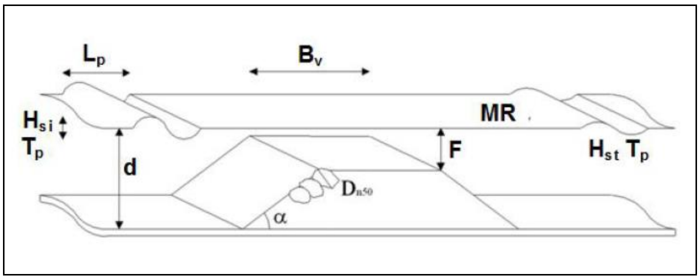

Fig. 5 Definition of symbols for smooth LCS theoretical model

LCS need not be necessarily covered with rock fill. Sometimes smooth and impermeable LCS can be covered with asphalt or concrete armour. The slopes of these LCSs are sometimes more gentle (1:3 or 1:4) than it is the case with the LCS with the stone armour, mostly due to construction reasons.

The asphalt and concrete LCSs are mostly built in dry conditions, and not under the water. The presence of tides enables the building of such structure in dry conditions.

Since the smooth LCSs are different in the process of hydraulic functioning than the breakwaters covered with rock, there are different formulas for the transmission coefficient. The wave transmission can be calculated according to the paper [15]:

$$K_T = [-0.3F/H_{si}+0.75[1-\exp(-0.5\xi)]]\cos^{2/3}\beta \qquad (18)$$

with the minimum K_T=0.075 and the maximum K_T=0.8, and with the following limitations: $1 < \xi < 3$, $0° \leq \beta \leq 70°$, $1 < B_v/H_{si} < 4$. The symbols are :

F	-water depth at the crown, [m],
H_{si}	-significant wave height in front of LCS ($H_{si} = 4\sqrt{m_0}$), [m],
ξ	-Irribaren number, $\xi = tg\alpha/(s_{op})^{0.5}$, $s_{op} = 2\pi H_{si}/(gT_p^2)$,
B_v	-crown width, [m]

Eq.(18) takes the angle wave transmission into consideration by means of the expression $\cos^{2/3}\beta$.

3 PHYSICAL MODEL

3.1 Wave Channel and Measurement Equipment

The experimental research was made in the Laboratory of the Faculty of Civil Engineering in Zagreb. The wave channel width was 1m, the height was 1.1 m, and the depth of water in the channel was d=0.5 m.
The measuring equipment includes the piston wave generator with the installed AWACS system, and the data collection system (sampling frequency 40Hz) produced by DHI (Horsholm, Denmark). Capacitive gauges (DHI) G1-G8 (Fig. 6) were used for measuring the surface elevation. The analysis of the collected data was made by means of the system DHI Wave Synthesizer. The incident wave parameters in front of LCS were determined in the spectral domain by means of the WS Wave Reflection Analysis. The spectral analyses were performed with the following parameters: size of FFT block: 512, overlap: 0.667, Number of subseries: 68, lower cut-off frequency: 0.0 Hz, higher cut-off frequency: 20.0 Hz, Data window: Hanning method, frequency step: 0.078 Hz.

3.1.1 Physical Model of the Perforated Seawall (inter 0)

A wooden model of the perforated seawall was placed into the wave channel at the distance of 15.7m from the wave generator. The model of the perforated seawall was made of wood with the porosity of p=30% (p-ratio of the opening and the total surface of the wall) and with vertical longitudinal openings, and with the width of dissipation chamber of B=0.18m.

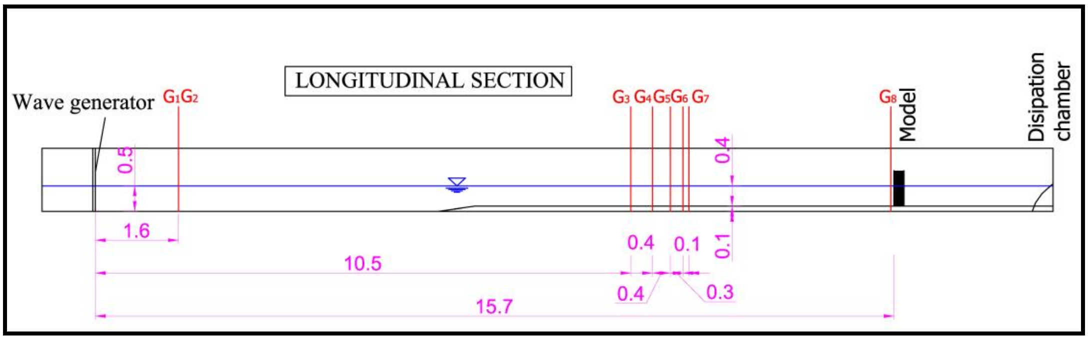

Fig. 6. Longitudinal section of wave channel with capacitive gauges (G1-G8) and perforated seawall (Model) positions (Inter 0)

Tab. 1 Wave parameters used in experiments without LCS (inter 0) and with LCS (inter 1-6)

JONSWAP; γ=3.3, σ_1=0.07; σ_2=0.09;				
Test	T_p [s]	H_s [m]	L_p [m]	L_p/H_s
1	0.68	0.06	0.72	12
2	0.81	0.06	1.02	17
3	1.01	0.06	1.50	25
4	0.89	0.10	1.20	12
5	1.10	0.10	1.70	17
6	1.45	0.10	2.50	25
7	0.99	0.12	1.44	12
8	1.24	0.12	2.04	17
9	1.68	0.12	3.00	25

3.1.2 Physical Model of the Perforated Seawall and Submerged Smooth LCS Interaction (inter 1-6)

The model of the smooth submerged breakwater was made of wood with the crown width of B_v=0,16m, the slopes of 1:2 and the possibility to change the submergence depth so that two depths 0.055m and 0.101m can be achieved (Fig. 7).

Fig. 7. Photographs of submerged low crested structure (LCS) positioned in channel for crown submergence F=0.055m

During the testing the distance of the LCS from the perforated seawall L_{pl} and seawall submergence F varied. There were three distances of the breakwater from the seawall L_{pl}=1.2m, 2.4m and 6.2m used, as well as two submergences F=0.055m and F=0.101m. In this way the total of 6 combinations was obtained. The combinations are called inter1, inter2, inter3, inter4, inter5 and inter6 (Fig. 8).
There were altogether 9 testing procedures for irregular waves conducted according to the Tab. 1. For regular wave the same values as in Tab. 1 have been used: $T=T_p$, $H=H_s$ and $L=L_p$.
The wave parameters from Tab. 1 were used to perform experimental testing for each single interaction, (inter1÷6). Thus, altoghether 54 testing procedures were conducted.

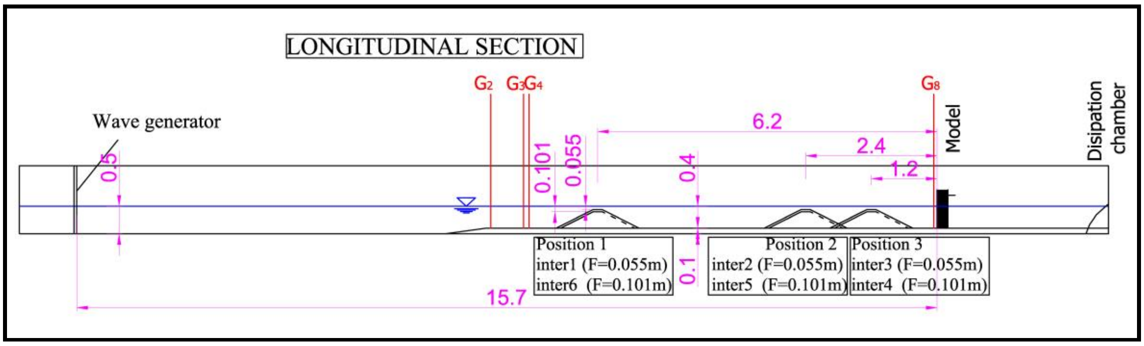

Fig. 8. Longitudinal section of wave channel with the positions of submerged LCS and perforated seawall for three different pool distances, L_{pl}=**1.2m, 2.4m and 6.2m** and two LCS submergence F=**0.055m and F=0.101m**, (inter1÷6)

The gauges G2-G4 were used to measure the oscillations of the water surface in front of the submerged breakwater and gauges G5-G7 between breakwater and seawall. The separation of incident and reflected spectra from the records on the gauges G2-G4 was undertaken by means of the method defined in the [22]. The incident H_{si}, reflected H_{sr} and superposed $H_{s\text{-}sup}$ significant wave heights can be obtained from the incident and reflected spectra.
The time duration for an experiment amounts to ~5 min., which is approx. three hundred waves per an experiment, pursuant to the recommendations from the paper [23]
The calibration of the mathematical model presented in chapter 2.2 was conducted using calibration coefficient Cc and initial measurements on model with only perforated seawall (Fig. 6). The calibration of the mathematical model presented in chapter 2.3 was conducted only for regular waves with aim to get satisfactory agreement of the Eq. 18 with measurements conducted in wave channel only with submerged breakwater. The agreement of the measurements and Eq. 18 for irregular waves was satisfactory.

4 RESULTS

Verification of a new formed mathematical models were conducted by comparison of H_{sup} for regular waves and $H_{s\text{-}sup}$ for irregular waves (Fig. 2 and Fig. 3.) obtained experimentally and theoretically (chapter **Error! Reference source not found.**). Verification is presented on the Fig. 9 and Fig. 10.

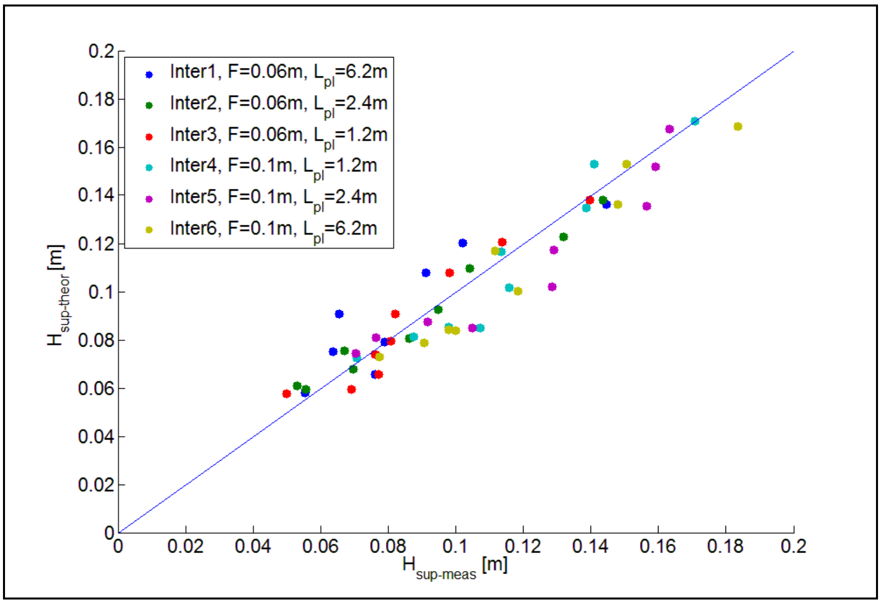

Fig. 9 Verification of the newly formed mathematical model for regular waves by results from wave channel measurements

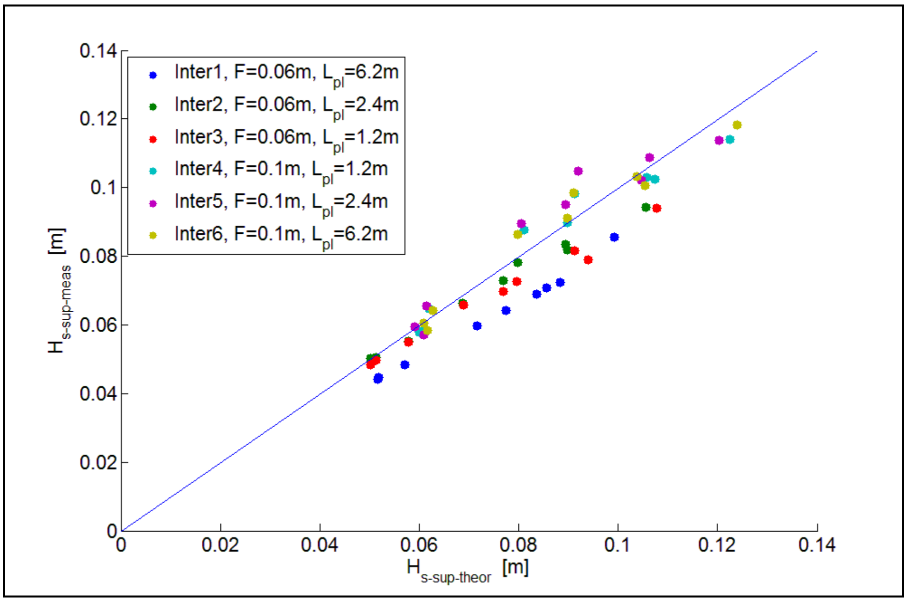

Fig. 10 Verification of the newly formed mathematical model for irregular waves by results from wave channel measurements

It could be concluded that a newly formed mathematical models represent well experimental results and they can be used in geometrical and wave parameters limits of the verification process.

Fig. 11 shows examples of the theoretical and experimental wave spectra reflected from perforated seawall. The agreement is satisfactory because mathematical model represents well energy around peak period as well as occurrence of the energy on higher harmonics.

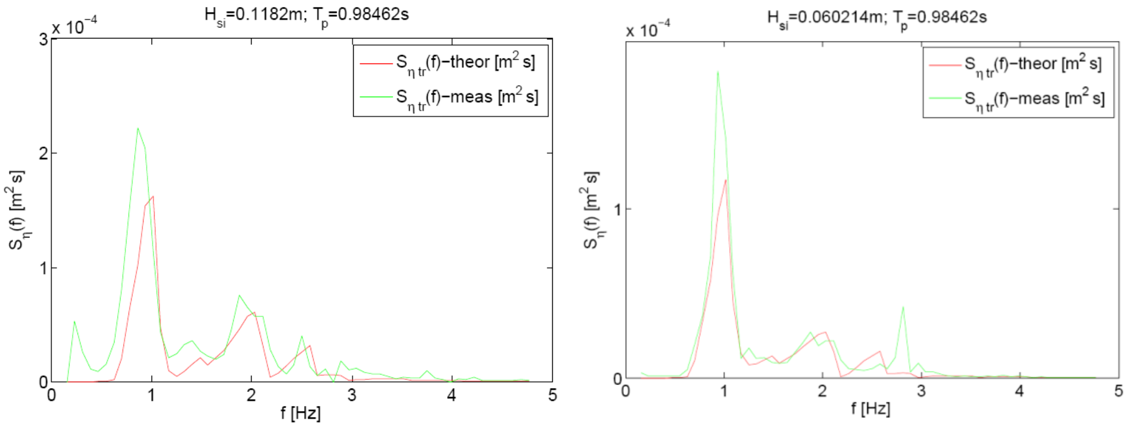

Fig. 11 Examples of theoretical and measured wave spectra reflected from perforated seawall

The variation of the pool length L_{pl} is involved in experimental research with aim to investigate the influence of L_{pl} on the hydraulic performance of such tandem, especially on superposed significant wave height H_{sup} and $H_{s\text{-}sup}$. General conclusion is that there are no obvious confirmations of pool length influence on H_{sup} and $H_{s\text{-}sup}$.

5 DISCUSSION

Further will be presented the comparison of the hydraulic behaviour of:

1. tandem submerged breakwater+perforated seawall (breakw+perf),
2. tandem submerged breakwater+solid seawall (breakw+solid) and
3. only solid seawall.

Superposed wave heights H_{sup} for only solid wall were calculated as superposition of incident and reflected wave heights with reflection coefficient K_R=1. H_{sup} for submerged breakwater and solid seawall were calculated as superposition of wave heights transmitted across submerged breakwater and waves reflected from solid seawall with reflection coefficient K_R=1. H_{sup} for submerged breakwater and perforated seawall were calculated according to new mathematical model presented in chapter **Error! Reference source not found.**.
Fig. 12 shows relationship of parameter H_{sup}/H_i and relative submergence F/H_i. This way is possible to analyse the influence of different types of coastal defence constructions on wave height H_{sup}.
Black dotted line presents theoretical H_{sup} in front of the only solid wall. In that case all wave energy is reflected what gives H_{sup}/H_i=2 (H_{sup}=2 H_i) and it is independent of the parameter F/H_i.
The other lines are separated according to the wave steepness (H/L=1/12, 1/17 and 1/25).
Lines “breakw+solid” presents the amount of energy dissipated by submerged breakwater in comparison to the situation without breakwater (“solid wall”). Curves “breakw+perf” are positioned lower than “breakw+solid” which represents additional energy dissipated by perforated wall.
Lines “breakw+solid” have breakpoints when they reach value H_{sup}/H_i =2. In those points breakwater transmits all incident energy and for greater values of relative submergences F/H_i

the tandem "breakw+solid" behaves like only solid wall. The same breakpoints are visible on curves "breakw+perf". Curvature of the curves "breakw+perf" is resulted because the reflection coefficients of the perforated seawall depend on the incoming wave lengths. The function of the reflection coefficient in relationship to incoming wave height (and length) has parabolic shape.

Colored dotted curves represent limits of the parameter H_{sup}/H_i for the variation of the input wave heights within $H_{i1.1} = 1.1 \cdot H_i$ and $H_{i0.9} = 0.9 \cdot H_i$.

The agreement between measurements and curves "breakw+perf" are satisfactory and it can be concluded that newly formed mathematical model describe well hydraulic behaviour of the submerged smooth breakwater and perforated seawall.

The same presentation as those on Fig. 12 could be produced but for submergence F=0.1m. Because of similarity with Fig. 12 this presentation is omitted.

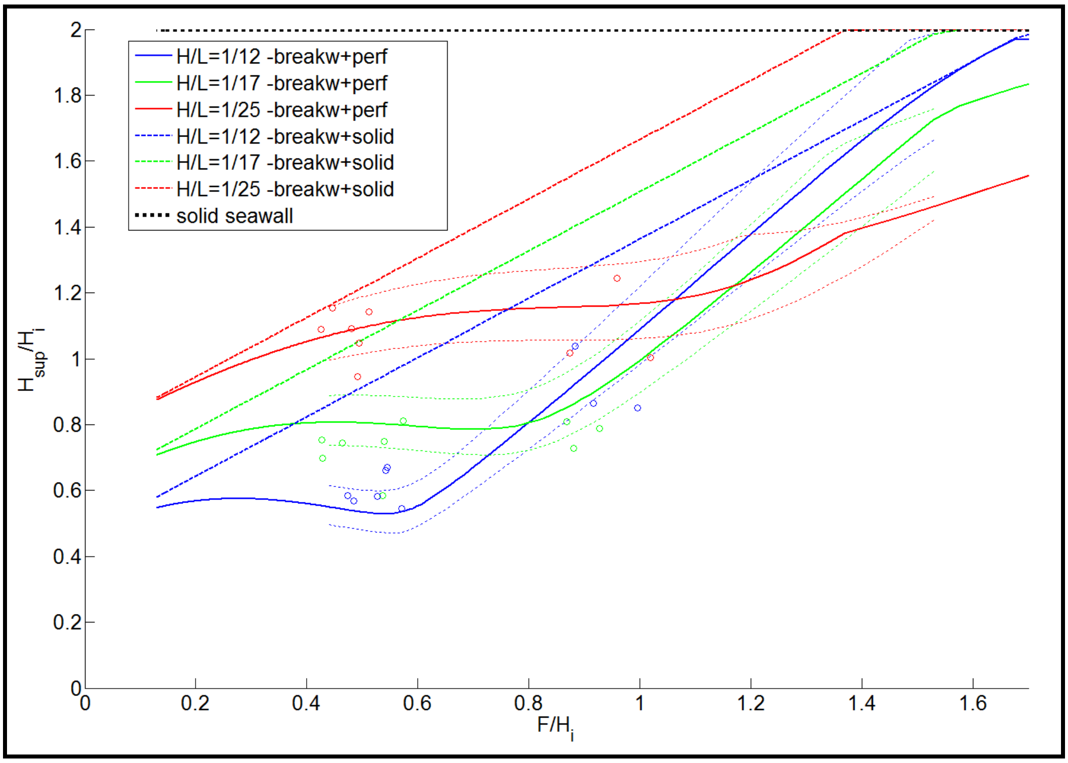

Fig. 12 Comparison of the parameter H_{sup}/H_i for only solid seawall, tandem submerged breakwater and solid seawall (breakw+solid), tandem submerged breakwater and perforated seawall (breakw+perf), F=0.06m, regular waves, "o"-measurements, "····"- upper limit for $1.1 \cdot H_i$ and lower limit for $0.9 \cdot H_i$

Fig. 13 shows the same as previous figure but for irregular waves. It is visible that in case of irregular waves parameter $H_{s\text{-}sup}/H_{si}$ can be maximum 1.41 what is in accordance to measurements presented in [18]. In the case of the irregular waves the assumption of the superposition of wave energies is valid (Fig. 3) unlike in case of the regular waves where the assumption of the summation of the wave heights is valid (Fig. 2.)

In case of the irregular waves the influence of the perforated seawall on the energy dissipation is less than in the case of the regular waves. That is visible from fact that curves for "breakw+perf" are at lower position from "breakw+solid" in case of the regular waves. The main reason is in fact that presentation with spectral parameters as significant wave heights, includes all components from wave spectra which reflects with different reflection coefficient, which finally gives smaller influence of the perforated seawall.

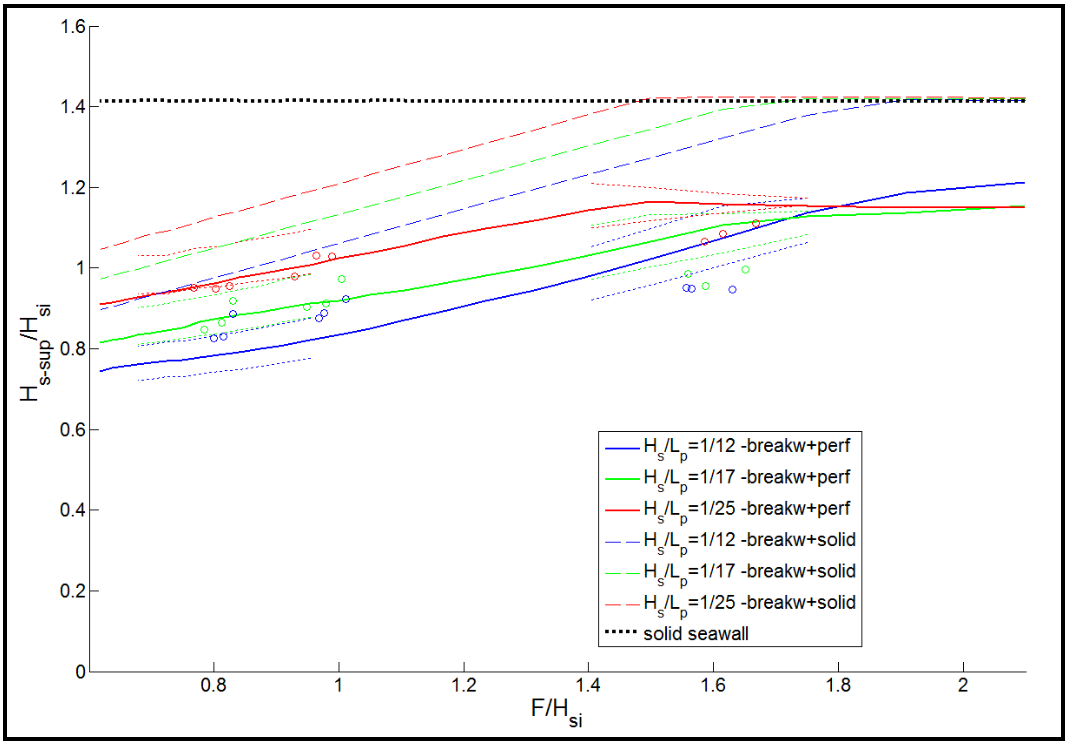

Fig. 13 Comparison of the parameter $H_{s\text{-}sup}/H_{si}$ for only solid seawall, tandem submerged breakwater and solid seawall (breakw+solid), tandem submerged breakwater and perforated seawall (breakw+perf), F=0.06m, irregular waves, “o”-measurements, “····”- upper limit for $1.1 \cdot H_{si}$ and lower limit for $0.9 \cdot H_{si}$

6 CONCLUSION

The experimental investigation, in wave channel, of the smooth submerged breakwater and perforated seawall is conducted with aim to form the mathematical model for calculation of the superposed wave heights between them. The mathematical model is formed from existing models for each type of construction. The verification of a newly formed mathematical model is conducted using results from measurements in wave channel.
Generally, the influence of the submerged breakwater on the energy dissipation is greater than the influence of the perforated seawall, if submergence F is small enough. The submerged breakwaters are cheap rubble mound constructions unlike reinforced concrete perforated seawalls. This leads to conclusion that the application of the submerged breakwater with the crown close to the zero water level in combination with solid seawall is better solution. Only in special cases with great tide oscillations and specific requests on submerged crown, the application of submerged breakwater and perforated seawall is acceptable.

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