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THE (IM)POSSIBILITY OF REDUCING THE METEOTSUNAMI AMPLITUDE BY CONSTRUCTING PROTECTIVE BREAKWATERS

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Preliminary notes

Shallow water gravity wave caused by motion of atmospheric disturbances increases its amplitude through energy transfer enabled by the Proudman resonance. The waveform signals get further amplified reaching the funnel shaped port basin. If the incoming wave group contains frequencies close to the port's eigen frequencies the resonance with a further increase of wave amplitude is likely to occur. The whole phenomenon is called meteotsunami, and an example of this phenomenon occurred on 21 June 1978 in Vela Luka, where the wave height was registered to be 6 m. The paper deals with carrying out the numerical analysis of the sea level dynamics in the final point brought about due to wave excitation with a maximum height of 0,19 m in front of the entrance to the Vela Luka Bay. In response to the wave excitation in the port's final point, the obtained wave height was 5,5 m. Furthermore, the analysis involving the influence of hypothetical vertical impermeable breakwaters, set on two variant positions outside the entrance to Vela Luka was carried out. The model results indicate that there is a relatively small decrease in wave height.

Keywords: *numerical model, meteotsunami, Vela Luka*

(Ne)mogućnost smanjenja amplituda meteocunamija izvedbom zaštitnih lukobrana

Prethodno priopćenje

Plitkovodni gravitacijski val uzrokovan gibanjem atmosferskog poremećaja povećava svoju amplitudu kroz energetski transfer omogućen Proudmanovom rezonancijom. Nailaskom na lučki bazen oblika lijevka dešava se dodatna amplificija valnog signala. Ukoliko valna grupa koja nailazi sadrži i frekvencije bliske lučkim vlastitim frekvencijama moguća je i pojava rezonancije s daljnjim povećenjem valnih amplituda. Cjelokupna pojava naziva se meteocunami, a primjer te pojave desio se i 21.6.1978. u Veloj Luci, pri čemu su registrirane valne visine od 6 m. U radu je provedena numerička analiza dinamike morskih razi u krajnjoj točki Vele Luke uslijed valne pobude s maksimalnim visinama od 0,19 m ispred ulaza u zaljev Vela Luka. Kao odgovor na valnu pobudu u krajnjoj točki luke dobivene su valne visine od 5,5 m. Analiziran je utjecaj hipotetskih vertikalnih nepropusnih lukobrana, na valne visine u samoj Veloj luci. Korištene su dvije varijante pozicije ispred ulaza u Velu Luku. Modelski rezultati ukazuju na relativno malo smanjenje valnih visina.

Ključne riječi: *numerički model, meteocunami, Vela Luka*

1
Introduction
Uvod

Each water body fully or partially enclosed and exposed to a physical activity undergoes free oscillations in the form of normal modes [1]. The frequency of basic normal modes and higher harmonic oscillations are determined by three-dimensional geometry of surface rigid boundaries around water masses [2]. One of the characteristic manifestations of normal mode oscillations in sea water mass is the phenomenon called seiche [3]. A significant contribution to scientific research in this field was made by Lamb (1945 [4]), Proudman (1953 [5]), Defant (1961 [6]), Platzman (1972 [7]), Wilson (1972 [8]) and Miles (1974 [9]).

Seiche can be seen as a phenomenon related to a combination of free and forced oscillations. The appearance of disturbing force results from the expulsion of the natural system of mass balance, and simultaneously activates the reaction force system that attempts to restore the equilibrium position. In water mass systems the gravitational force represents the reaction force. After the cessation of activity disturbance the system achieves free oscillations dependent only on the characteristics of a system. The impact of disturbing force is limited to the setting of the initial oscillation amplitude. The usual occurrence of seiche in natural mass systems is associated with a period of the action of disturbing forces during which the forced oscillations appear. After the termination of the disturbance the oscillations vanish through the dissipative process caused by friction with the solid boundary.

Semi-closed sea system such as a bay can be triggered to oscillate by meteotsunami, initiated in the open sea by the resonance of shallow water gravitational waves and atmospheric disturbances [10]. The wave height of the forced gravitational shallow water wave during the propagation in the bay can achieve further significant amplification depending on the bay's geometry. This is exactly the phenomenology that generated a wave phenomenon, which in June 1978 flooded Vela Luka with the registered altitude of +3 m regarding the sea level of the port [11,12,13].

This work presents the results of numerical analysis of meteotsunami propagation through the Bay of Vela Luka. The used sea level dynamics on the open model boundary (Fig. 1) in front of the Vela Luka Bay was obtained on the basis of numerical analysis of meteotsunami propagation in the broader area of the southern Adriatic (Fig. 1). Establishment and results of the model propagation of meteotsunami in the broader area of the southern Adriatic are presented in detail in [14]. The model of the broader area implies, among other things, the simulation of the generation of gravitational shallow water wave at atmospheric disturbances moving at a speed of 24 m/s from the SE directions (214° and 222°). In such conditions of incoming directions and propagation speeds, the most intense oscillations of sea levels take place in front of the entrance to the Vela Luka Bay ([14] - Fig. 5). The resulting model oscillations of the sea level in front of the entrance to the Bay were subjected to FFT spectral analysis. The spectral analysis detected the energy maxima on frequencies close to Vela Luka Bay's eigen frequencies.

The model research of meteotsunami propagation through the Vela Luka Bay was conducted with the performance of hypothetical vertical impermeable breakwaters, located in front of the harbour entrance (Fig. 1). For the purposes of comparison with the above analysed case the same boundary conditions were used. The aim of this research is to verify the possibility of protecting the port of Vela Luka from meteotsunami by constructing standard breakwater protection.

2
Spatial Domain of Applied Numerical Models
Prostorna domena numeričkih modela

The area covered with the numerical models spatial domain, based on the finite volume (HD-KV) and finite differences (HD-KD), is shown in Fig. 1. Models HD-KD and HD-KV are hydrodynamic numerical models made in Danish Hydraulic Institute, with commercial name MIKE21 HD, [15,16,17]. The model HD-KD is using mesh with equidistant spatial grid step $\Delta x = \Delta y = 25$ m (Fig. 2). Model HD-KV uses finite volumes method with continuous and unfolded triangular elements-cells. In this way the unstructured mesh was obtained in the spatial domain. Triangular mesh has variable space step $\Delta l = 10$ m - 100 m (Fig. 3). The applied spatial step is in accordance with the recommendations for the implementation of the analysis of resonance in the coastal areas [18].

The nautical maps (1:25 000) were used for digitization of bathymetry in the model area of the Vela Luka Bay. Bilinear interpolation was used on positions of numerical nodes for which there are no measured values of depth. Fig. 4 shows two analyzed positions of the hypothetical vertical breakwaters in the models spatial domains. The analysis of their impact on the wave heights reduction in the area of Vela Luka was conducted.

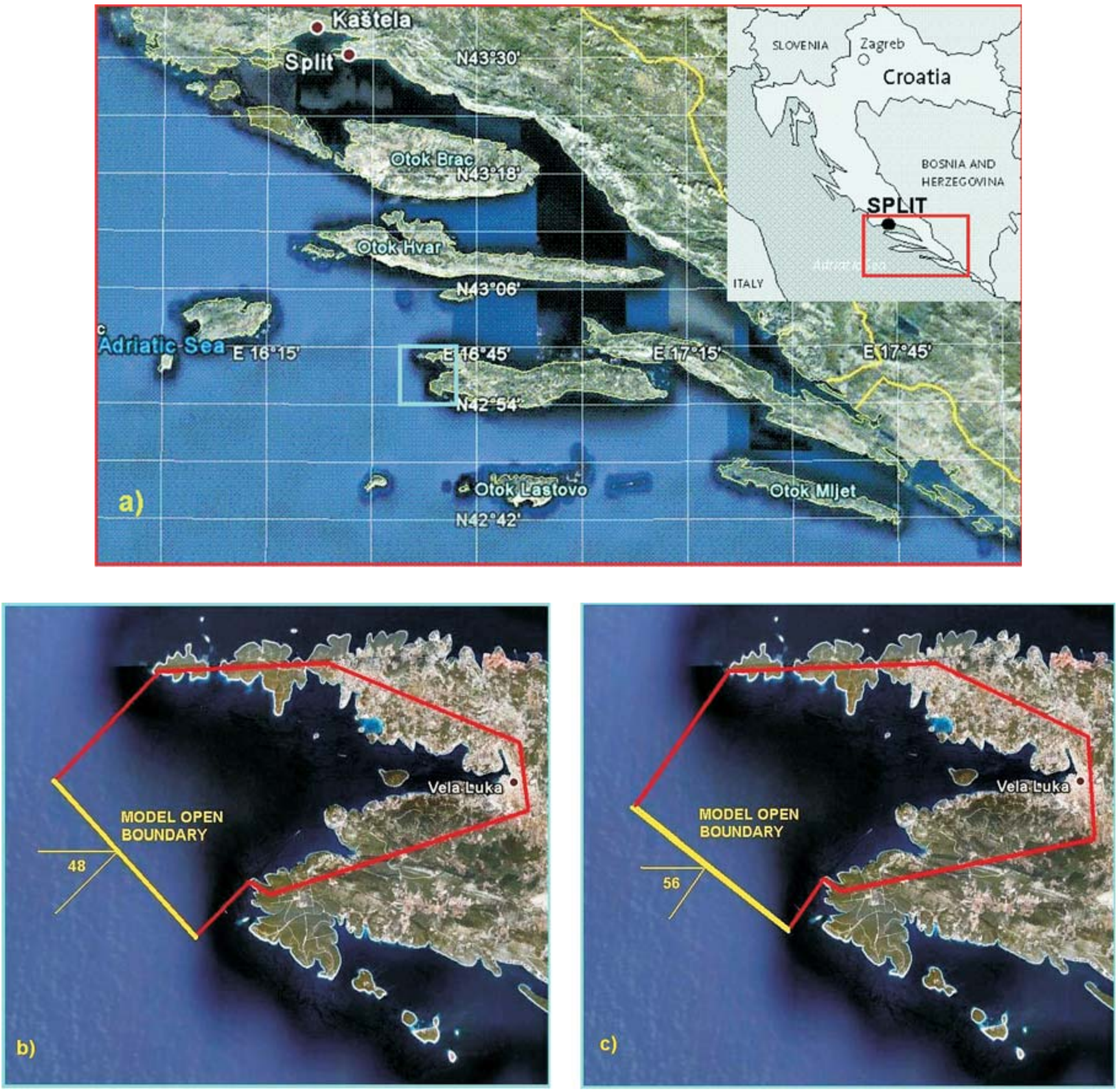

***Figure 1** Broader area of south-eastern Adriatic and the area covered with the numerical models spatial domain, based on the final volume HD-KV and finite differences HD-KD (a – broader area of south-eastern Adriatic; b -models spatial domain for disturbance propagation with direction 222°; c - models spatial domain for disturbance propagation with direction 214°)*

***Slika 1.** Šire područje jugoistočnog Jadrana i područje pokriveno s prostornim domenama numeričkih modela HD-KD i HD-KV (a – šire područje jugoistočnog Jadrana; b – modelska prostorna domena pri propagaciji poremećaja iz smjera 222°; c - modelska prostorna domena pri propagaciji poremećaja iz smjera 214°)*

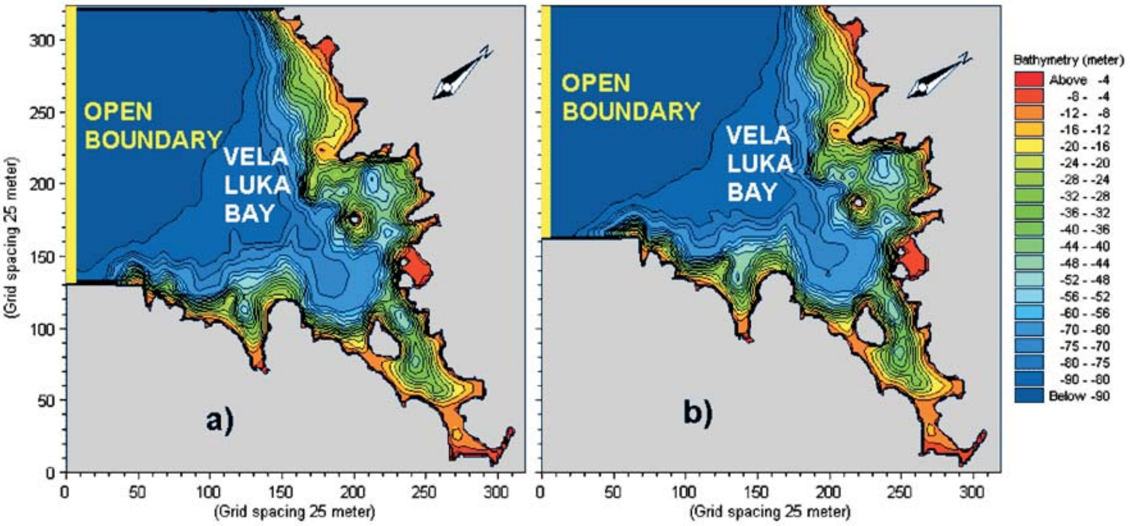

Figure 2 *Finite difference grid with bathymetry in the HD-KD numerical model spatial domain (a - disturbance propagation with direction 222°; b - disturbance propagation with direction 214°)*
Slika 2. *Mreža konačnih diferencija s batimetrijskom podlogom korištenom u prostornoj domeni modela HD-KD (a - propagacija poremećaja iz smjera 222°; b - propagacija poremećaja iz smjera 214°)*

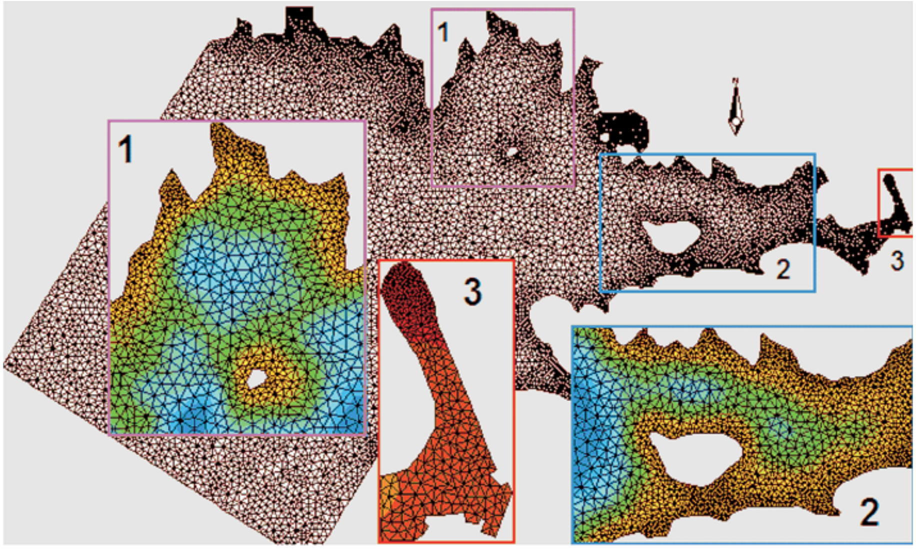

Figure 3 *Finite volumes flexible mesh used for spatial domain discretization in the HD-KV numerical model (spatial domain for disturbance propagation with direction 214°)*
Slika 3. *Fleksibilna mreža konačnih volumena korištena u diskretizaciji prostorne domene modela HD-KV pri propagaciji poremećaja iz smjera 214°*

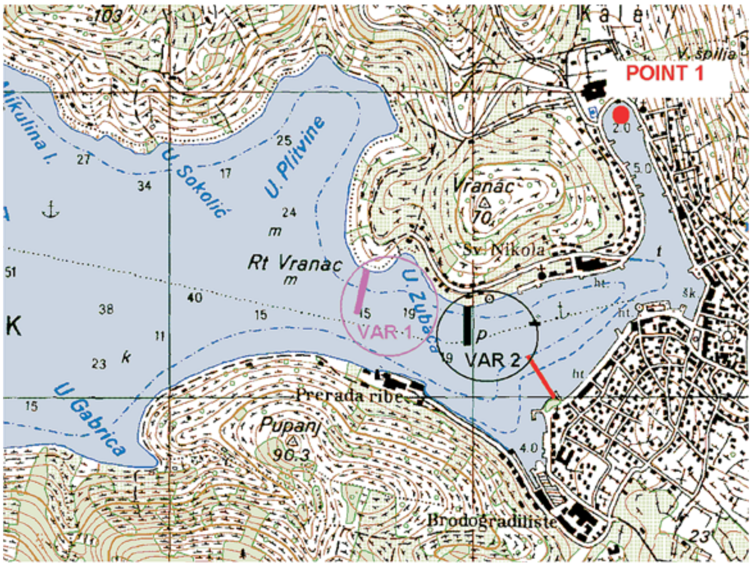

Figure 4 *Two analyzed position variants of the hypothetical vertical breakwaters in the models spatial domains and position of control point 1.*
Slika 4. *Dvije analizirane varijantne pozicije hipotetskih vertikalnih nepropusnih lukobrana u prostornoj domeni numeričkih modela i pozicija kontrolne točke 1.*

3
Boundary conditions
Rubni uvjeti

Using the numerical analysis of the sea level dynamics in the broader area of the southern Adriatic, with propagation of shallow water wave caused by atmospheric disturbances from directions 222° and 214° at a speed of 24 m/s [14], the fluctuation level in front of the entrance to the Vela Luka bay (Fig. 5) was obtained. These data were used for the boundary condition at the open boundary numerical model KD-HD and HD-KV (Fig. 1). Tab. 1 shows the nomenclature of the executed numerical analysis.

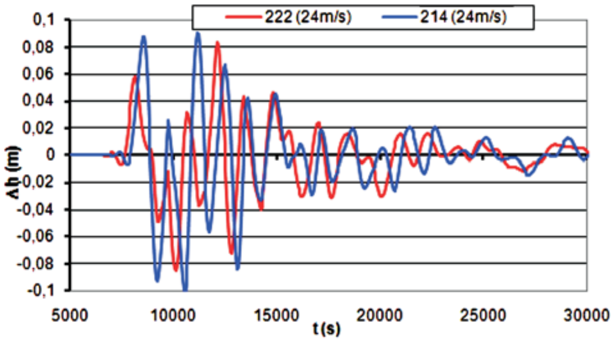

Figure 5 *Surface elevations in front of the Vela Luka bay used for open boundary condition in HD-KD and HD-KV models (according to the results obtained within* [14]*)*
Slika 5. *Vremenski niz morskih razi ispred uvale Vela Luka koja se koristi za rubni uvjet na otvorenoj granici modela HD-KD I HD-KV (prema rezultatima dobivenim u sklopu* [14]*)*

Table 1 *The nomenclature of the executed numerical analysis*
Tablica 1. *Nomenklatura provedenih numeričkih analiza*

No	Numerical experiments	Model used	Relevant figures
1	0-222-HD-KD	HD-KD	Figs. 1b, 2b
2	0-214-HD-KD	HD-KD	Figs. 1c, 2b
3	0-222-HD-KV	HD-KV	Fig. 1b
4	0-214-HD-KV	HD-KV	Figs. 1c, 3
5	1-214-HD-KD	HD-KD	Fig. 4 – VAR 1
6	2-214-HD-KD	HD-KD	Fig. 4 – VAR 2

The result of the FFT spectral analysis of the time series of sea level dynamics (Fig. 5) is shown in Fig. 6.

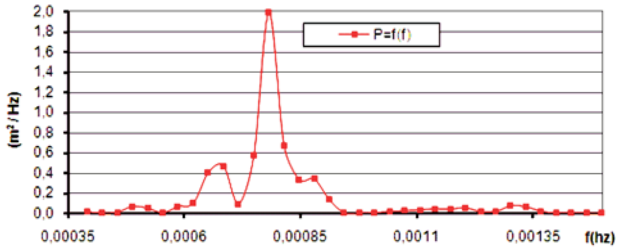

Figure 6 *Power distributions of linear wave components per frequencies as result of FFT spectral analysis execution on the surface elevation time series shown in Fig. 5*
Slika 6. *Raspodjela snage po linearnim valnim komponentama dobivena provedbom spektralne FFT analize na vremenskoj seriji morskih razi prikazanih na slici 5*

The Fig. 6 indicates that local extremes occur in relatively isolated relevant frequencies that correspond to periods of 34,1; 24,4; 21,3 and 12,8 minutes. According to the results of recent experimental research [19] the basic modes of eigen periods of Vela Luka Bay's are 35; 25,3; 11,6 and 8 minutes. It is obvious that the closeness of the bay's eigen periods and periods of excitation with the highest energy content causes the resonance in the analyzed region of the bay. Resonant mechanism occurred, so that further wave height increase is realised.

4
Numerical models
Numerički modeli

Numerical models of HD-KD and HD-KV solve the two-dimensional, (in horizontal plane), unsteady incompressible fluid flow in a vertical homogeneous layer under the assumption of hydrostatic pressure distribution. System of equations of the shallow fluid contains a vertically integrated continuity equation (1) and momentum conservation (2, 3) of Cartezian coordinate system [15, 16, 17]:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=0, \tag{1}$$

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\bar{u}\bar{v}}{\partial y}=-gh\frac{\partial \xi}{\partial x}-\frac{\tau_{bx}}{\rho}+\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(hT_{xx}\right)+\frac{\partial}{\partial y}\left(hT_{xy}\right)\right], \tag{2}$$

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{u}\bar{v}}{\partial x}+\frac{\partial h\bar{v}^2}{\partial y}=-gh\frac{\partial \xi}{\partial y}-\frac{\tau_{by}}{\rho}+\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(hT_{xy}\right)+\frac{\partial}{\partial y}\left(hT_{yy}\right)\right], \tag{3}$$

where: h water depth ($h = \xi + d$); d depth in undisturbed level; ξ water level elevation; $\bar{u}$, $\bar{v}$, velocity components in x and y direction averaged at depth; g gravitational acceleration; ρ density; x, y spatial coordinates; t time; τ_{bx}, τ_{by} stress at the seabed; T_{xx}, T_{xy}, T_{yy} lateral stress.

Friction with the bottom is defined by equation 4:

$$\tau_{bx}=\frac{\rho\cdot g\cdot\bar{u}\cdot\left|\bar{u}\right|}{C^2}\;;\;\tau_{by}=\frac{\rho\cdot g\cdot\bar{v}\cdot\left|\bar{v}\right|}{C^2}, \tag{4a,b}$$

where: C is Chezy coefficient ($C = (1/M)\cdot h \approx 1/6$ with M being Manning roughness coefficient).

Lateral stresses, T_{xx}, T_{xy}, $T_{yy,}$ in the momentum equations contain the influence of turbulent momentum. Averaging vertically and sub-incremental spatial fluctuations on the scale model are realized using the formulation of the cinematic effective coefficient of turbulent viscosity E. It allows short-wave damping oscillations and related effects on reproduction of sub incremental parameters.

$$T_{xx}=E\frac{\partial\bar{u}}{\partial x}\;;\;T_{xy}=\frac{1}{2}E\left(\frac{\partial\bar{u}}{\partial y}+\frac{\partial\bar{v}}{\partial x}\right)\;;\;T_{yy}=E\frac{\partial\bar{v}}{\partial x} \tag{5a,b,c}$$

$$E=C_{sm}^2 l^2\left[\left(\frac{\partial\bar{u}}{\partial x}\right)^2+\frac{1}{2}\left(\frac{\partial\bar{u}}{\partial y}+\frac{\partial\bar{v}}{\partial x}\right)^2+\left(\frac{\partial\bar{v}}{\partial y}\right)^2\right]^{1/2}, \tag{6}$$

where l is the distance between two numerical nodes and C_{sm} constant of used Smagorinski formulations adopted with the value 0,4.

The models HD-KD solve the system of partial differential equations by finite difference method in rectangular calculation network in which the elevation variable is defined in the nodal points. The flux variables are centrally placed between nodal points [20]. The time-centred implicit scheme is used with equations solved by the one-dimensional non iterative steps, alternating between x and y directions (Alternative Direction Implicit "scheme with the" Double Sweep "algorithm solving).

The HD-KV numerical model uses spatial and continuous unfolded triangular elements, (finite volume), covering thus the spatial domain with the unstructured grid [21, 22, 23]. Members are calculated using Riemann's solver with Roe's approximation [24, 25].

An important element of the application of numerical models is the routine that allows "flooding" and "drying" of numerical cells. It enables their activation or deactivation in the equation of continuity and momentum conservation equations. Initiation of converting a numeric cell from a "dry" to a "wet" one takes place when reaching water depths of 0,2 m and conversion from "wet" to "dry" happens at the depth falling under 0,1 m.

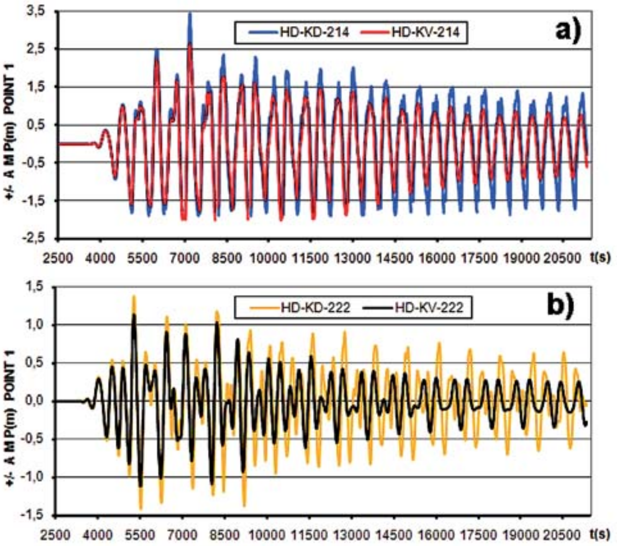

***Figure** 7 Surface elevations in control point 1 obtained with HD-KD and HD-KV models (a - disturbance propagating with direction 214°; b - disturbance propagating with direction 222°)*

***Slika** 7. Morske razi u kontrolnoj točki 1 dobivene modelima HD-KD i HD-KV (a - propagacija poremećaja iz smjera 214°; b - propagacija poremećaja iz smjera 222°)*

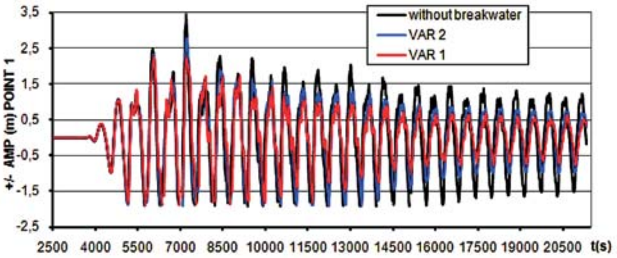

***Figure 8** Surface elevations in control point 1 obtained with HD-KD model for the variant solutions (VAR 1, 2 – Fig. 4) of the breakwater position (disturbance propagating with direction 214°)*

***Slika 8.** Morske razi u kontrolnoj točki 1 dobivene modelom HD-KD pri postavljanju lukobrana na varijantnim pozicijama 1 i 2 (propagacija poremećaja iz smjera 214°)*

5
Model Analysis Results
Rezultati modelskih analiza

Fig. 7 shows sea levels dynamics in the control point 1, located at the end of Vela Luka (Fig. 4). The results are for HD-KD and HD-KV-models, (border in Figs. 2 and 3), with the dynamics of sea level in Fig. 5, obtained from the model of the broader area of the southern Adriatic [14]. Fig. 7 indicates that the model HD-KV, regardless of the use of equal roughness coefficient and viscosity in models HD-KD and HD-KV, has pronounced dissipative properties. Furthermore, in the case of disturbance occurring at direction 222°, after the first few wave disturbances have passed, the model HD-KV restricts the development of the wave's negative amplitude. This is probably the result of superposition of the reflected waves from the port's enclosed area with the incoming wave disturbances.

The maximum value of the positive wave amplitude obtained by the model HD-KD is 3,45 m and by the model HD-KV it is 2,64 m. Taking into account that at the occurrence of meteotsunami on 21 June1978 in Vela Luka was registered height ≈ 3 m, it can be concluded that the atmospheric disturbance propagated from SW direction with direction 214°.

Fig. 8 shows the dynamics of sea level in the control point 1, located at the end of Vela Luka (Fig. 4). The results are for HD-KD model with the sea level dynamics in Fig. 5, obtained from the model of the broader area of the southern Adriatic [14]. The vertical breakwater was set up on variant positions 1 and 2 (Fig. 4) and with the already existing jetty marked in red in Fig. 4.

In the position of control point 1, for variant 1, the positive maximum amplitude is 2,27 m (Fig. 8). In the case of variant 2 the corresponding value is 2,8 m (Fig. 8). According to the model results, it is clear that the construction of the breakwater in the form of vertical impermeable barrier does not provide effective form of protection against possible occurrence of meteotsunami. It is also important to note that vertical barriers can cause reduction of wave energy evacuation from the port, i.e. slowed down amplitude oscillations vanishing, (harbour paradox, [26, 27]). However, the model results show the opposite situation, which is the consequence of increased dissipation in the narrow area around the hypothetically constructed breakwaters.

6
Conclusion
Zaključak

The numerical analysis of meteotsunami propagation in the Vela Luka Bay was conducted. The dynamics of sea levels in the Vela Luka's final point was monitored, and the maximum wave amplitude of +3 m above sea level was obtained as a model result. This value is in accordance with the values registered on June 21, 1978.

For the implementation of numerical analysis, two numerical models were used. One is based on the finite volume and the other on the finite difference method. Both models are established at the same spatial domain and used to solve the same system of shallow water equations.

Both models use the same boundary condition in terms of the sea level dynamics on the open boundary in front of the Vela Luka bay. The adopted non-stationary boundary condition was obtained on the basis of generation and propagation of meteotsunami in the broader area of the southern Adriatic during the activity of the atmospheric disturbances at a speed of 24 m/s from the SE directions (214° and 222°). Following the FFT spectral analysis on the applied boundary conditions the energy maxima were noticed at the frequencies very close to the Vela Luka Bay eigen frequencies.

The port's protection from flooding through construction of the classical breakwater, performed in order to reduce the wave height, proved insufficient by conducted impact analysis. Also, such solution could reduce exchange of water.

7
Literature
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