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A study of seiches in the Split harbor (Adriatic Sea)

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This paper examines the occurrence of seiches inside the Split harbor (Adriatic Sea). The measurements indicating the seiche periods were carried out with the pressure gauge placed near the harbor entrance. Spectral analysis of the data suggests a resonant behavior appearing in front of the harbor, that covers the periods between 7.7 and 28.5 min. The seiches were documented to occur at the periods of 6.5, 3.0, 1.6 and 1.15 min, and were verified by the barotropic 2D numerical model. In addition, two model runs were executed: the first one with the present topography and the second one with the nautical marina removed (built in 1972). The comparison should quantify the influence of the marina on the seiche characteristics. Namely, the leading seiche modes of 7.1-min and 5.0-min periods, calculated for the present topography, were probably joined in the 6.2-min mode before 1972. On the other hand, the numerical model showed that the 3.0-min seiche mode keeps its period, having the maximum amplitude at the north end of the harbor calculated for both runs. Finally, the seiches may endanger the navigation near the entrance and within the marina during the enhanced seiche episodes.

Key words: harbor, seiches, numerical model, nautical marina, Adriatic Sea

INTRODUCTION

Tides and storm surges are usually of greatest importance in small basins and harbors for ships and small crafts, as they can produce sea level displacements equal to the depth of the basin or even higher. But, other forces can also influence the oscillations of sea level that can endanger the safety of navigation, e.g. free oscillations (seiches) of the harbors (WU *et al.*, 1996). Major force responsible for the occurrence of such oscillations is strong wind pushing the water to the closed end, followed by a sharp change of wind speed and direction (LEE and PARK, 1998).

Thoretical approach to the problem of harbor seiches was handled already by LAMB (1932), who analyzed seiches in closed rectangular and circular basins and took out their natural periods and modes. KRAVTCHNENKO and McNOWN (1955) did similar research also. After that, a number of analytic and numerical studies of the harbor resonance encompassed the effects of bottom friction, wave nonlinearity, viscous dissipation and other influences on this process (e.g. KONSTENSE *et al.*, 1986; MEI and AGNON, 1989; LEE and PARK, 1998).

The investigations of seiches in small bays and harbors have been started rather early in the Adriatic Sea. As such basins form a conside-

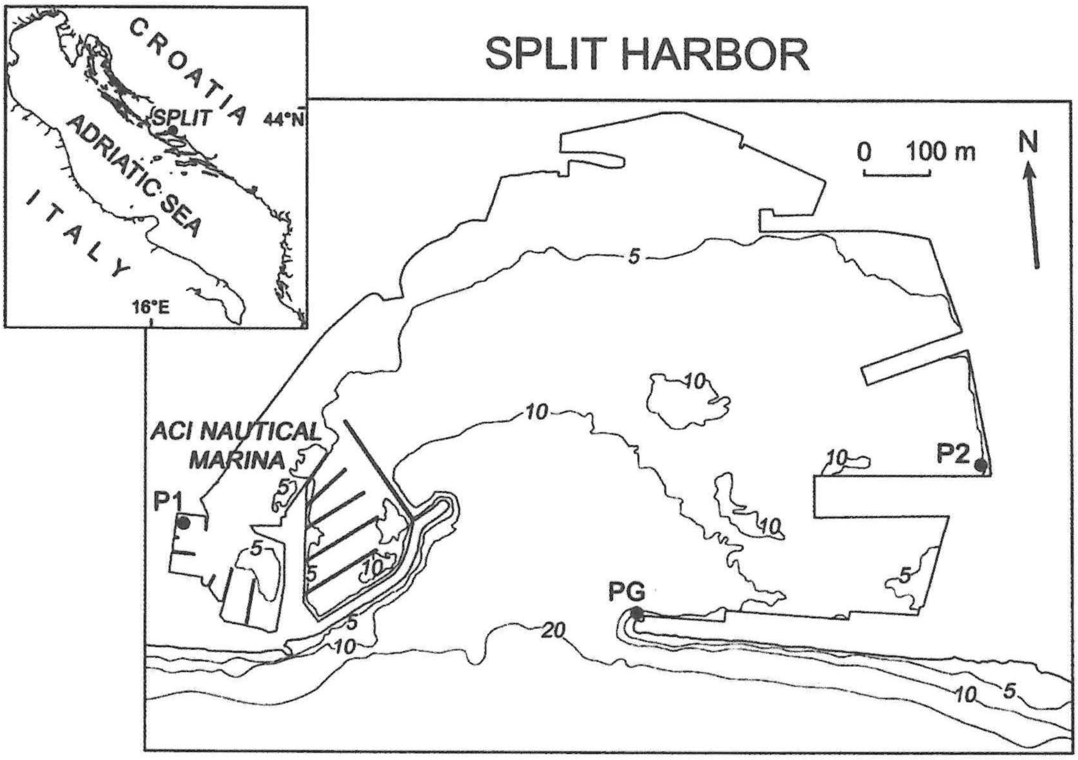

Fig. 1. Bathymetry (in m) of the Split harbor with position of the pressure gauge (PG), and locations P1 and P2 where the modelled sea level spectra are computed

rable part of the eastern coast, STERNECK (1914) applied MERIAN formula and estimated the periods of all the basins covered by tide gauge measurements.

The seiches of the Gulf of Trieste (GODIN and TROTTI, 1975), the Rijeka and Bakar Bays (GOLDBERG and KEMPNI, 1937), Zadar and Pašman Channels (VILIBIĆ and ORLIĆ, 1999) and the Kaštela Bay (ZORE, 1955) were also found and examined. VERCELLI (1941) analyzed the sea-level record collected at Zadar and found seiches of the main harbor having the period of 0.04 h.

This paper will focus on harbor high-frequency oscillations by analyzing the data of the pressure gauge placed in the Split harbor (Fig. 1). The gauge has a time resolution sufficient to capture harbor seiches, but unfortunately, it is positioned near the entrance where the nodal line is expected to be placed. The verification of high-frequency seiches will be done by using a two-dimensional numerical model, computing the seiche properties (phase, amplitude) for the whole harbor. In addition, an influence of the nautical marina (placed within the harbor) on the seiche properties will be investigated, as high seiche amplitudes were modelled inside the marina. Section 2 of this paper introduces the data used and the empirical and numerical tools applied. Section 3 presents findings and modelling studies about the seiches. A discussion of results and conclusions is collected in Section 4.

MATERIAL AND METHODS

Sea pressure at a depth of 3 m (sea level can be easily calculated, as the density is not varying much) was recorded every 30 s with the pressure gauge placed near the entrance of the harbor (Fig. 1). Accuracy of the sea level measurements is 1 mm. The pressure gauge was installed in June 2000 within the MedGLOSS program (Mediterranean Sea Level Observing System). A storm approached the area on 31

August - 1 September 2000, enabling us to analyze high-frequency oscillations including the harbor seiches.

Empirical investigations included spectral analysis, which was applied on time series. The analysis is based on the algorithms developed by JENKINS and WATTS (1968) using 40 degrees of freedom. This analysis revealed energy peaks related to the seiches and other oscillatory movements in the harbor.

The modelling studies encompassed the analyses of the strongest oscillations within the harbor. For that purpose, a two-dimensional barotropic numerical model was applied to the present topography of the basin, and also to the past topography that correspond to the harbor before the construction of the nautical marina in 1972 (Fig. 1). The model is based on the shallow-water frictionless equations (e.g. GILL, 1982; CUSHMAN-ROISIN, 1994):

$$\frac{\partial u}{\partial t} = -g\frac{\partial \zeta}{\partial x} \tag{1}$$

$$\frac{\partial v}{\partial t} = -g\frac{\partial \zeta}{\partial y} \tag{2}$$

$$\frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} + \frac{\partial \zeta}{\partial t} = 0 \tag{3}$$

where u and v are currents directed in x and y axis in time t, ζ is sea-level displacement, H is the depth and g = 9.81 m s^{-2}. Zero sea-level displacement (ζ = 0) is imposed at the harbor's entrance, and the no-cross flow condition is chosen at the boundaries inside the harbor. Integration was done using the ARAKAWA C-grid (ARAKAWA and LAMB, 1977; FLATHER *et al.*, 1991) by applying a "forward-backward" scheme. In order to satisfy the stability constraint, grid resolution was chosen to be 25 m, with a time step of 1 s.

Modelling study outlined the properties of the seiches, namely the amplitudes and phases of harbor modes. Initial condition was imposed to include linear increase of the sea level displacement from the entrance placed most southward (ζ = 0 cm) to the top of the harbor placed most northward (ζ = 20 cm). Integration was done for a 3-day period, and 259200 calculations were performed in time.

RESULTS

Seiches of the Split harbor were investigated by processing the data collected during three periods: 31 August - 1 September, 20-21 September and 1-2 October 2000. The position of the pressure gauge, located near the harbor entrance, should reveal low-energy of the harbor free oscillations. Nevertheless, they can be seen on the power spectrum during severe storms, of which the strongest one occurred on 31 August-1 September 2000 (Fig. 2). Highest energies of sea surface elevation occurred in the wide frequency band from 0.035 to 0.130 min^{-1} (periods from 7.7 to 28.5 min). VILIBIĆ and MIHANOVIĆ (in press) showed that they are related to the PROUDMAN resonance (PROUDMAN, 1953) that appears in front of the harbor and then propagates inside. Seiches can be detected at periods of 0.153 min^{-1} (6.5 min), 0.331 min^{-1} (3.0 min), 0.630 min^{-1} (1.60 min) and 0.870 min^{-1} (1.15 min). Some of them are related to the oscillations of the whole harbor, and some of them are oscillations of smaller parts inside. Nevertheless, the seiches usually have the largest potential energies at the closed end of a basin; so that the highest energies are expected to be inside the marina in the west and in the northernmost part of the harbor.

Modelling studies included the spectral analysis, which is performed on the modelled sea level series for two locations P1 and P2 (Fig. 1). Power spectra, computed according to JENKINS and WATTS (1968) by using 33 degrees of freedom, are shown in Figs. 3a and 3c. In addition, the same procedure is applied to the Split harbor bathymetry that existed before ACI nautical marina was built. Such calculations should reveal the influence of the marina on the behavior of the seiches and the changes

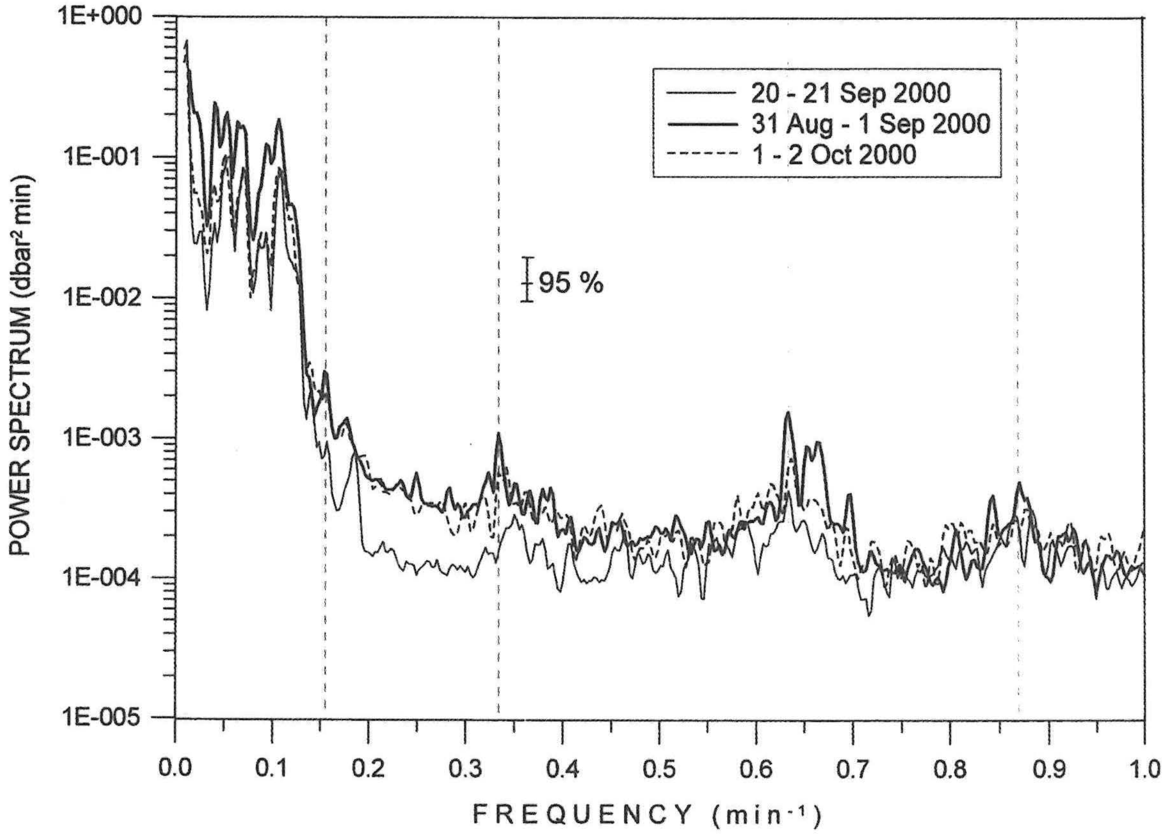

Fig. 2. Bottom pressure (sea level) power spectrum calculated for the periods 31 August-1 September, 20-21 September and 1-2 October 2000 (40 degrees of freedom). Vertical dashed lines indicate seiche periods

that appeared there. Therefore, power spectra calculated for the same positions are presented in Figs. 3b and 3d.

What can be concluded from the comparison of spectra? First, lots of peaks occur as a result of rather complex basin topography, both for the present topography and for the old one. The highest energies take place at periods of 7.1, 5.0, 3.2 and 3.0 min inside the marina (Fig. 3a), while the energies are lower at the opposite side of the harbor (Fig. 3c). Thus, the model slightly overestimates the period of the first mode (7.1 min versus 6.5 min), but reproduces the period of 3.0-minute mode exactly. In addition, a broad energy maximum embracing three separate peaks can be observed at 1.56, 1.57 and 1.58 min at P2 station (Fig. 3c) but not at P1 station (Fig. 3a). It can be attributed to the oscillation of the eastern part of the basin only, since it appears also in the spectrum of observations at that side of the harbor (Fig. 2). Therefore, one may conclude that the model reproduces the empirical findings realistically.

Regarding the model runs that were performed on the harbor topography without the marina, a change in the period of the first mode calculated with the marina (6.2 min versus 7.1 min) can be noticed, but the mode of 3.0-min period (here of 3.1 min) remains unchanged. The 5.0-min mode surprisingly vanishes, revealing this mode as the one defined by the marina, since the highest potential energies are found there. Moreover, by comparing the energies of the first and 5.0-min mode for two runs at P2 station (Figs. 3c and 3d), the energy of 5.0-min seiche together with the energy of the first seiche mode with marina (7.1 min) seems to be translated to the first seiche mode without marina with the period of 6.2 min.

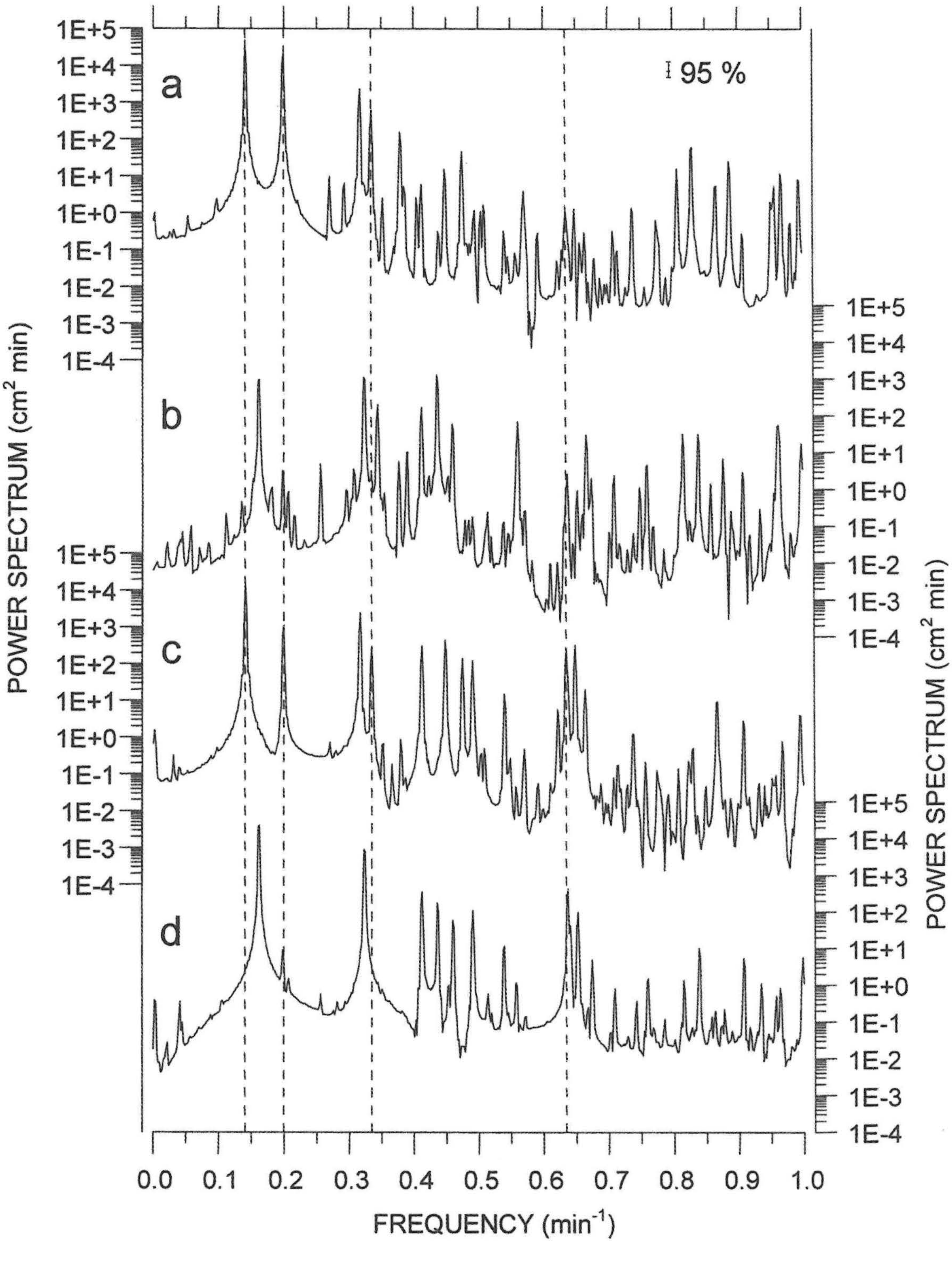

Fig. 3. Power spectra of the sea level displacements modelled at the P1 station (a) with and (b) without nautical marina, and at the P2 station (c) with and (d) without the marina. Dashed lines indicate seiche periods of 7.1, 5.0, 3.0 and 1.6 min

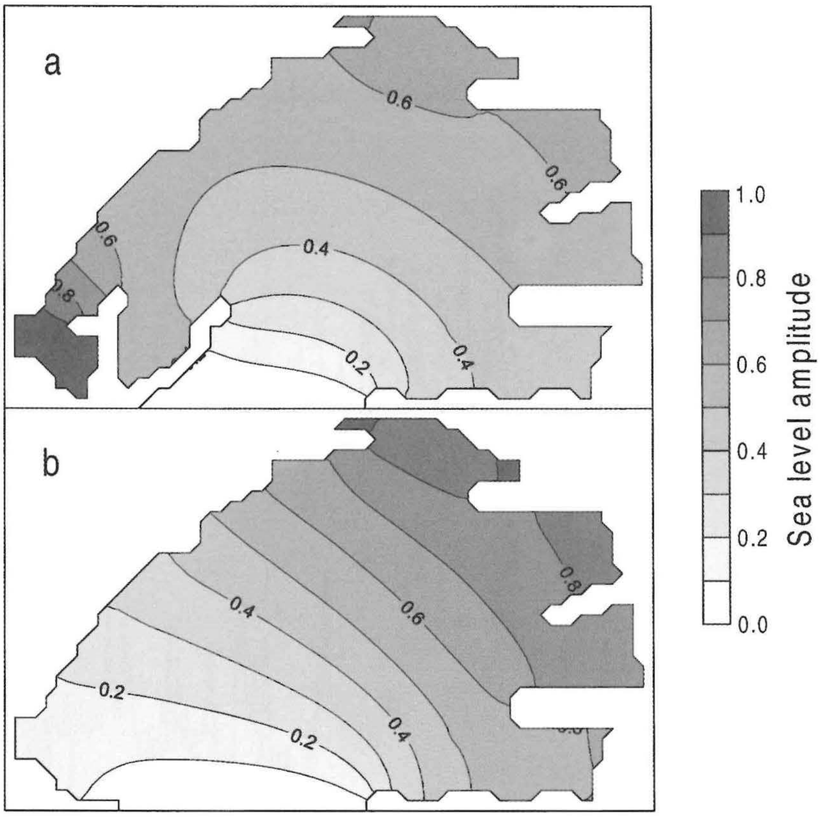

Fig. 4. The distributions of first-mode relative sea level amplitude calculated for the runs (a) with and (b) without the marina. The value of 1.0 equals 16.0 and 16.5 cm for the first and the second run, respectively

Let us consider space distribution of some significant seiche modes. Relative sea level amplitude (normalized by the maximum amplitude) of the first mode, calculated for both runs (with and without the marina), is given in Fig. 4.

It can be noticed that the maximum (relative amplitude of 1.0 that is equal to 16.0 cm in absolute) appears inside the marina, whereas the second maximum (with the relative amplitude of about 0.7) is placed at the north end of the harbor. However, if the marina is removed, the maximum amplitude occurs at the north end of the harbor (16.5 cm in absolute), whereas the relative amplitude equals 0.1-0.2 (absolute amplitude 1.6-3.3 cm) at the position of the marina. Consequently, the seiche amplitude was highly modified in the western part of the harbor when the marina was built. The amplitude of other harbor seiches was affected as well, as it will be shown later. The total potential energy of the first-mode seiche over the whole basin is 5 % larger for the run without marina, probably due to the energy transfer from 5.0-min mode, as it vanishes here. However, the sum of total potential energies of the 5.0-min and 7.1-min modes of model run with the marina is 3 % larger than total potential energy of the 6.2-min mode run without the marina. Therefore, a part of the 5.0-min mode energy is relocated somewhere else.

What can be said about the 5.0-min seiche mode (Fig. 5)? First and foremost, the amplitude considerably increases inside the marina (runs with the present topography), almost three times faster than the amplitude of the 7.1-min basic mode. The rest of the harbor owns amplitude, which is not surpassing 25 % of the maximum modelled in the marina, whereas the nodal line appears just at the entrance of the marina. Consequently, the removal of the marina from the model affected this seiche mode largely,

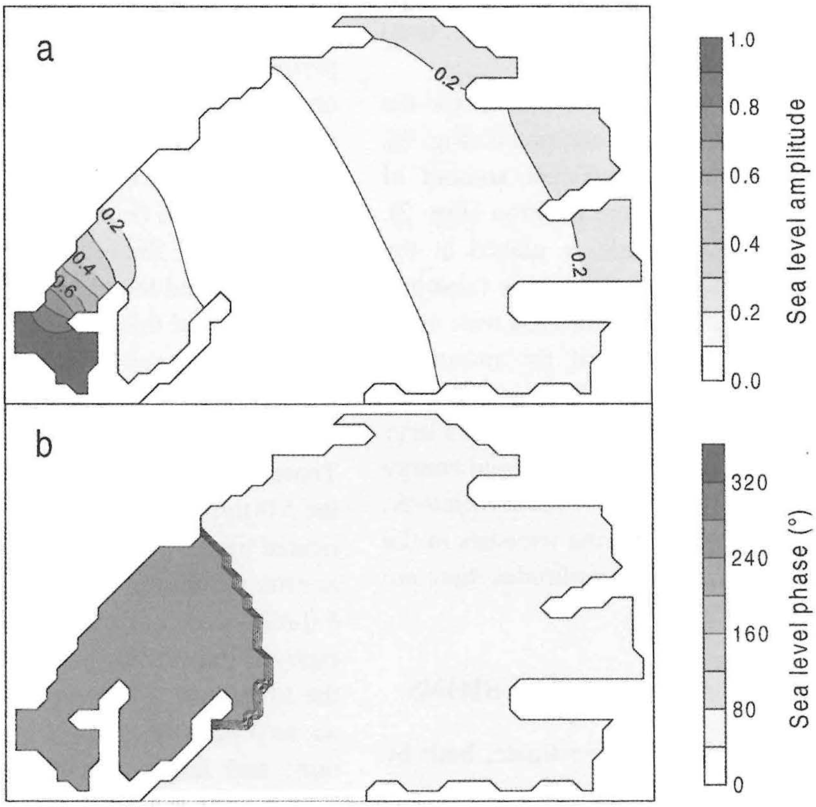

Fig. 5. The distributions calculated for the 5.0-min mode of (a) relative sea level amplitude and (b) phase for the model run with the marina. The value of 1.0 equals 10.0 cm

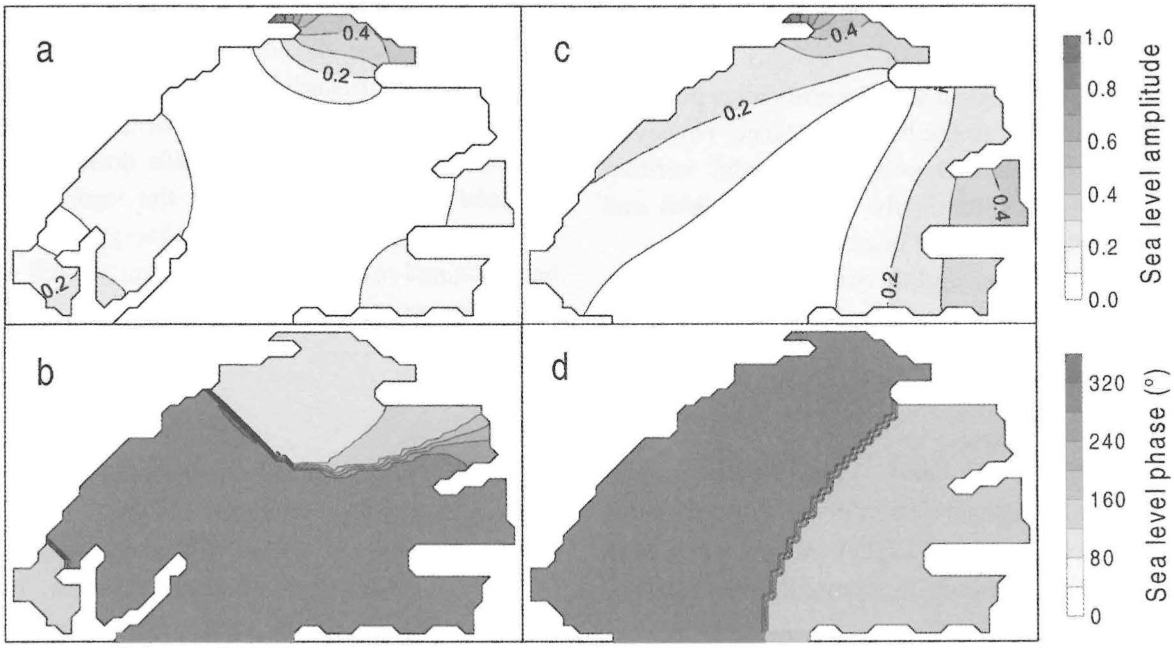

Fig. 6. The distributions calculated for the 3.0-min mode of (a) relative sea level amplitude and (b) phase for the run with the marina, and (c) relative sea level amplitude and (d) phase without the marina. The value of 1.0 equals 4.5 cm for the run with marina and 13.5 cm for the run without marina

relocating its energy toward the first (6.2-min) mode.

Finally, the amplitudes and phases for the seiche mode at 3.0-min are computed (Fig. 6), as this mode contains significant amount of energy at the pressure gauge position (Fig. 2). Maximum seiche amplitude is placed at the small inlet to the north of the harbor (absolute amplitude equals 4.5 cm) for the case with marina included (Fig. 6a). When the marina is removed, the amplitude distribution is similar, but the maximum amplitude is three times larger there (13.5 cm) and the total potential energy of the mode is also larger (2.5 times). Moreover, the nodal line inside the marina vanishes in the second run and the relative amplitudes there are lower than 0.23 (0.9 cm).

DISCUSSION AND CONCLUSIONS

This study attempts to investigate, both by using empirical analyses as well as numerical approaches, free oscillations - seiches in harbors, marinas and small bays, which are a result of strong and sharp changes in the wind and air pressure fields. The periods of the harbor seiches are estimated from the data to be of 6.5 min (uninodal seiche), 3.0, 1.6 and 1.15 min. Seiches are weak at the pressure gauge position, which is close to the harbor entrance. However, the barotropic 2D numerical model verified most of the empirically extracted modes and introduced additional ones.

The model slightly overestimated the period of the first seiche mode (7.1 versus 6.5 min); nevertheless, it reproduced well the 3.0-min period and a group of three separate peaks that are close to each other (at 1.56, 1.57 and 1.58 min). The first mode and especially the 5.0-min mode, have the highest amplitudes within the nautical marina (built in 1972) on the west side of the harbor; therefore, the second model run was performed to compare the seiche properties in that part of the harbor. With the removal of the marine the seiches did not vanish only at the western part of the harbor; the 5.0-min mode surprisingly vanished over the whole harbor. Therefore, the nautical marina obviously drives the 5.0-min mode by its topography, as it is confirmed by the placement of the nodal line at the marina's entrance. In addition, the energy of the 5.0-min mode calculated for the present topography of the harbor is probably transformed to the first mode of the topography without marina, as it comprises lower period (6.2 versus 7.1 min) and larger potential energy (for 5 %). Finally, the 3.0-min seiche mode encompasses the highest amplitude at the north of the harbor rather than in the marina due to the position of nodal lines, disabling the strong rise of sea level amplitude within the marina.

To conclude, the construction of the marina in 1972 significantly influenced seiche characteristics in the western part of the harbor. Moreover, navigation is not safe during pronounced seiche events, while the strong sea level displacements can damage the yachts and boats located inside the inner marina as well as flood the coastal infrastructure.

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Modeliranje seša u luci Split

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SAŽETAK

Ovaj rad dokumentira pojavu seša u luci Split. Mjerenja razine mora (tlaka), na temelju kojih su izdvojeni periodi seša, obavljana su na postaji koja se nalazi blizu ulaza u luku. Spektralna analiza ukazuje na pojavu PROUDMAN-ove rezonance na periodima između 7.7 i 28.5 min, koja je, nakon što se pojavila ispred luke, propagirala prema njenoj unutrašnjosti. Seši se opažaju na periodima od 6.5, 3.0, 1.6 i 1.15 min, što je verificirano i primjenom dvodimenzionalnog barotropnog numeričkog modela. Numerički model je primijenjen na sadašnju batimetriju luke kao i na batimetriju luke bez nautičke marine (izgrađena 1972. godine). Usporedba rezultata modela je dokumentirala utjecaj marine na svojstva seša luke. Tako su današnji osnovni (7.1 min) i prvi sljedeći (5.0 min) mod vjerojatno bili združeni u 6.2-min seš prije 1972. godine. Suprotno tome, 3.0-minutni seš je zadržao isti period, imajući u oba slučaja maksimalnu amplitudu na sjevernom kraju luke. Naposljetku, pojava izrazito jakih seša može ugroziti sigurnost plovidbe u luci, naročito u području nautičke marine.

Ključne riječi: luka, seši, numerički model, nautička marina, Jadransko more