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Resonance in Ploče Harbor (Adriatic Sea)

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In this paper, we extract and validate high-frequency oscillations in the port of Ploče, based on sea level data from one year (March 2002-March 2003) measured at a tide gauge in the harbor. Frequency was analyzed by applying stationary (spectral) and non-stationary (wavelet and filtering) analyses of the data to extract temporal characteristics of the fundamental seiches with a period of 30 min. Seiches are pertinent throughout the year, but their maximum amplitude doubles (up to 25 cm) during the summer. Modeling studies showed that seiches are primarily a result of incoming waves from the open sea, generated by resonant coupling with air pressure traveling waves. In contrast, direct wind forcing has a minor influence on seiche generation. Seiches endanger ferries and small moored boats as well as large cargo ships in harbors where strong currents (greater than 50 cm s^{-1}) appear during extreme events.

Key words: harbor resonance, tide gauge, empirical analysis, numerical models

INTRODUCTION

Sea level oscillations and currents are of great importance for the safety of navigation during ship maneuvers in and out of harbor. Tides are the major cause of sea level changes in the open ocean (PUGH, 1987) but seiches and storm surges usually play a major role in enclosed seas and lakes. The Mediterranean Sea is an example of a low-tidal region with tides up to 50 cm, except in its small shallow basins such as the Gulf of Gabes and north Adriatic Sea (TSIMPLIS *et al*., 1995). Tides can have an amplitude up to 1 m in the northern Adriatic and rapidly decrease towards the south where they reach a maximum of 30 cm (CUSHMAN-ROISIN & NAIMIE, 2002). For example, the average tidal range in the area of Ploče Harbor (Fig. 1) is 23 cm (HYDROGRAPHIC INSTITUTE, 2000). Therefore, surges may have an important role in the Adriatic Sea where they can be as high as 1 m, whereas seiches can change the sea level in harbors and bays up to 50 cm in a short time. The amplitude of seiches in Bakar Bay in the northern Adriatic can be as high as 25 cm within 20 min (CEROVEČKI & ORLIĆ, 1989) while in Split Harbor in the mid Adriatic they can be up to 15 cm within 7 min (VILIBIĆ & MIHANOVIĆ, 2002).

Besides sea level oscillations, seiches in bays and channels can produce rather strong currents, resulting in severe ship damage due to surging (WIEGEL, 1964; RAICHLEN, 1966). The entire Adriatic can be agitated in a way that it freely oscillates within a period of 21.2 h and generate an amplitude up to 1 m in the north Adriatic (CEROVEČKI *et al*., 1997; RAICICH *et al*. 1999; VILIBIĆ, 2000). Such an oscillation results from a strong alongshore southeasterly wind (Sirocco) which raises the sea level towards the closed end, followed by rather sharp changes in wind speed and direction during the passage of atmospheric fronts (RAICICH *et al*., 1999). However, large harbor and bay seiches are mostly excited by an incoming wave generated by a tsunami or by resonant coupling with the atmosphere (MILES, 1974; MORISON & IMBERGER, 1992; OKIHIRO *et al*., 1993; HENRY & MURTY, 1995; ARAI & TSUJI, 1998).

The latter effect is known as a force that produces strong sea level oscillations in some bays and harbors in the Adriatic and Mediterranean Seas. Namely, traveling waves and disturbances in the atmosphere can excite barotropic waves in the sea at certain depths by a resonant mechanism called PROUDMAN resonance (PROUDMAN, 1929, 1953) and trigger local seiches when hitting coastal areas (AIDA *et al*., 1972; HIBIYA & KAJIURA, 1982; RABINOVICH & MONSERRAT, 1996, 1998; VILIBIĆ & MIHANOVIĆ, 2003; VILIBIĆ *et al*., 2005). The combined effect was called double resonance by RABINOVICH (1993), and was responsible for damaging the city of Vela Luka in June 1978 (50 km WSW from Ploče Harbor) with 3 m high waves lasting 15 min (ORLIĆ, 1980). Part of Stari Grad city (60 km WNW of the harbor) was flooded and shell farms were flushed away in Mali Ston Bay (30 km SE of the harbor) in June 2003 by the same mechanism (VILIBIĆ *et al*., 2004), enhanced by topographical constraints in some parts. Although the phenomenon is rare in the Adriatic, it occurs almost regularly in some regions of the Mediterranean such as the Balearic Islands (GOMIS *et al*., 1993; CANDELA-PEREZ *et al*., 1999; RABINOVICH *et al*., 1999).

In this paper, we validate the intensity and nature of high frequency oscillations in Ploče Harbor. The area is specific by its location next to the Neretva River delta where the high sediment rate (up to a meter per decade; HYDROGRAPHIC INSTITUTE, int. com.), changes its bathymetry. Fundamental harbor seiches were examined in detail, as they are dominant in the harbor, by analyzing tide gauge data collected during one year (March 2002 - March 2003) and by modeling with a two-dimensional numerical model.

MATERIALS AND METHODS

Ploče Harbor is located in a semi-enclosed bay consisting of an outer and two inner basins (Fig. 1). Both inner basins are influenced by freshwater inflows from river outlets. The major branch of the Neretva River empties into the bay southeast of the harbor entrance, strongly contributing to sediment fluxes in the wider region. The tide gauge station is located at the narrow passage between the inner and outer basins, near the cargo docks and the waterway of cargo ships (up to 100.000 BRT) that leads to the inner docks of the harbor. In addition, there is a harbor for ferries and small boats in the city of Ploče in the northeast part of the bay

The gauge is a float-type in stilling well with a diameter of 1 m, connected with the outer sea through an 8-m long and 20-cm wide pipeline. By applying the linear friction theory to the system, an approximate transfer function may be calculated (Fig. 2), allowing for a portion of high-frequency oscillations to pass into the sea level series. Data are sampled every minute and the vertical resolution is set to 1 mm, which is also the accuracy of the measurements. Therefore, about 50% of the energy at Nyquist frequency (0.5 min^{-1}) is aliased in the series, and our analyses were restricted to frequencies low enough not to be significantly aliased by high-frequency oscillations. This range covered only the fundamental and most significant harbor seiches.

One year of sea level data, from March 2002 to March 2003, was analyzed. Both stationary and non-stationary techniques of time-series analysis were applied to the data. Classical spectral analysis with 40 degrees of freedom (JENKINS & WATTS, 1968) resulted in significant

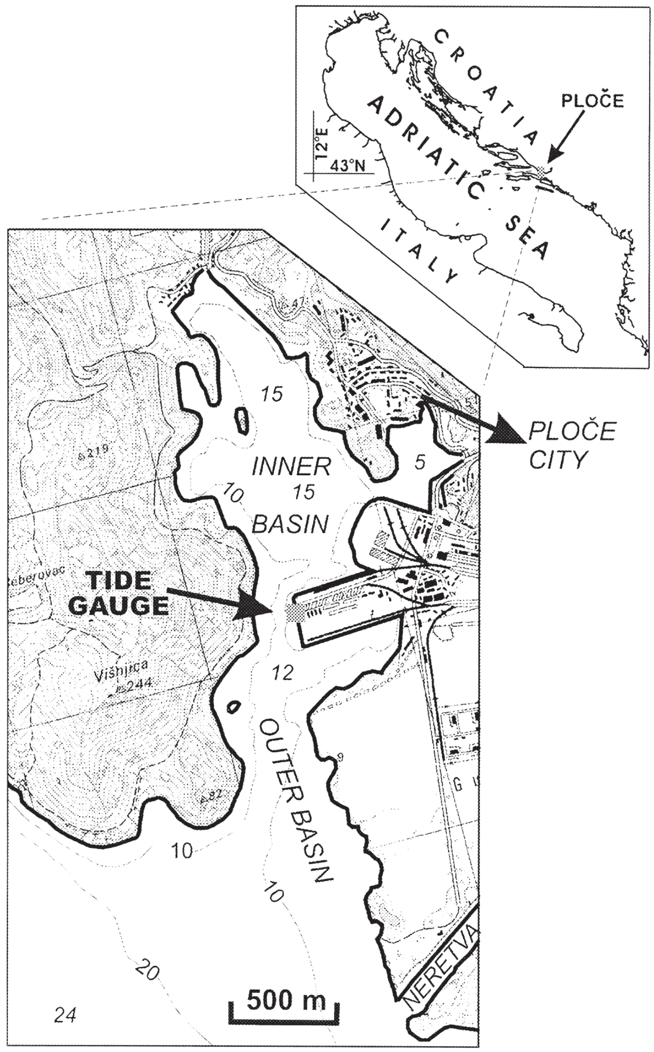

Fig. 1. Bathymetry of Ploče Harbor, showing the location of the tide gauge. Depths are given in meters

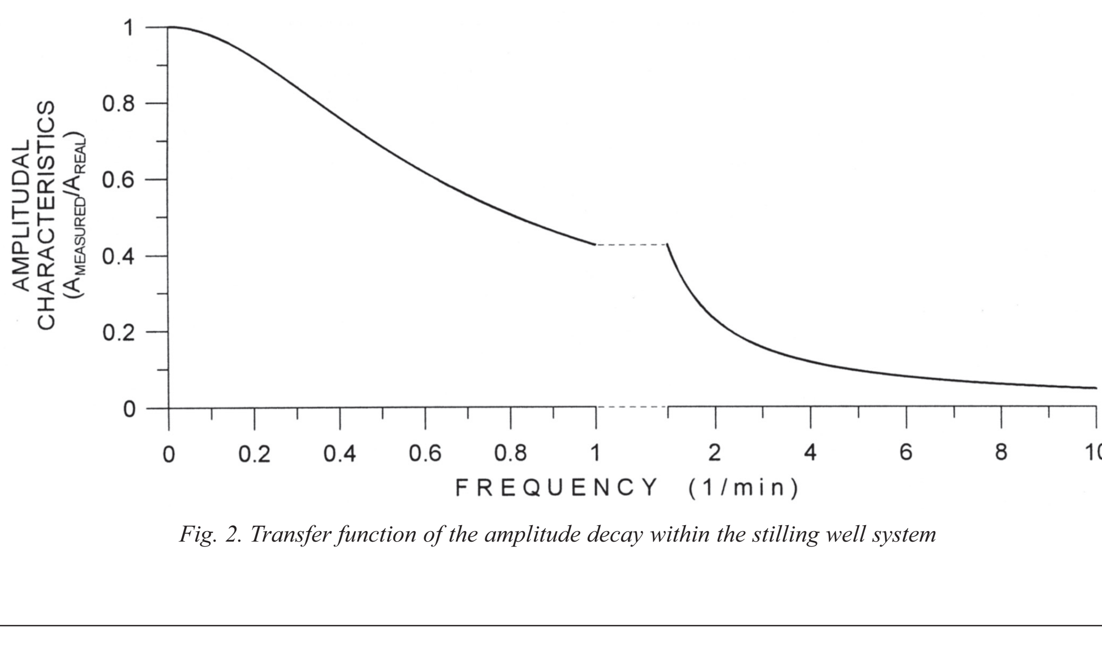

Fig. 2. Transfer function of the amplitude decay within the stilling well system

peaks of energy in the high-frequency band. The strength of seiche peaks was tracked using non-stationary wavelet analysis (TORRENCE & COMPO, 1998). The band-pass filtering procedure (Z. PASARIĆ, unpublished, based on ORMSBY, 1961) was applied to the series with cutoff periods of 25 and 40 min to extract the fundamental harbor seiche that was detected by spectral analysis to extend 30 min.

Hydrodynamic modeling was undertaken with the two-dimensional, non-linear finite-difference model 2DD developed by BLACK (1995) and also for the modeling of double resonance in June 2003 (VILIBIĆ *et al*., 2004). An explicit leapfrog solution was applied to solve the two-dimensional momentum and conservation equations. To satisfy the stability constraint, a grid resolution of 50 m was chosen along with time steps of 1 s. Realistic simulations were not performed as no qualitative data were available in the wider region that could satisfactorily reproduce the incoming atmospheric waves and wind distributions. Therefore, the modeling was used to compute sea levels and currents within the harbor through artificial events, and to quantify them in relation to the safe navigation of cargo and passenger ships. First, the model was forced by a white spectrum signal imposed at the entrance of the harbor to simulate seiche excitation by open sea waves. This model run (run 1) resulted in a significant energy peak at 31.5 min, denoting it as the fundamental seiche in Ploče Harbor. Another peak at 8.8 min (second harbor mode) had a significantly lower energy and was not relevant for determining total sea level oscillations and navigation safety. Therefore, the model was forced by the single sinusoidal wave of 31.5 min and 5 cm amplitude at the harbor entrance to give the distribution of the seiche current and sea level amplitude inside the harbor. The model was also directly forced by the harbor wind of 20 m s^{-1} lasting for 1 h (run 2) with a drag coefficient γ of 0.001, being characteristic of the Libeccio wind (a strong but short-lasting SW wind) that occurs during frontal passages (FURLAN, 1977).

RESULTS

First, let us examine the energy distribution over periods shorter than 10 h (Fig. 3). The annual spectrum shows significant oscillations at 4.1, 2.6, and 1.5 h, the first of which was documented by VILIBIĆ *et al*. (2005) to be fundamental to the semi-enclosed bay surrounded by mid Adriatic islands.

The energy of the 4.1 h seiche is significant since Ploče Harbor is located deep inside a semi-enclosed shallow area. The energy peak of the 30 min seiche was even more significant

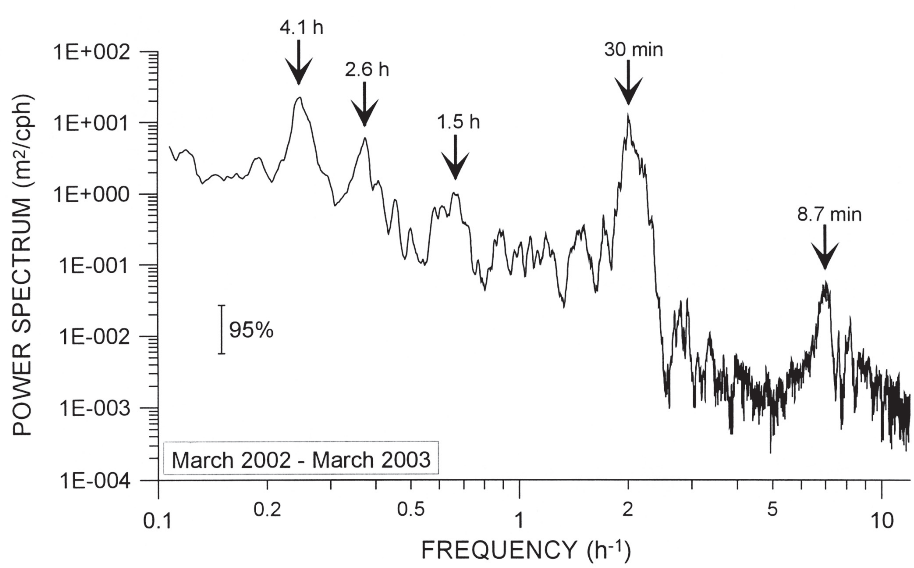

Fig. 3. Power spectrum of one-year sea level data (March 2002-March 2003). Periods of significant energy peaks are indicated

compared to the surrounding frequencies. Such a strong oscillation belongs to the fundamental mode of Ploče Harbor and was verified by the numerical model (below), whereas the low-energy peak during the 8.7 min seiche is related to the first mode of the harbor seiche.

Main harbor seiches persist throughout the year with mean amplitudes varying between 1.6 cm in February and 2.8 cm in August (Fig. 4). It is suspected that incoming open-sea waves excited the maximum amplitudes that occurred in June (25 cm) and August (22 cm), as these values are double the rest of the values (10-15 cm). These waves are generated by resonant coupling of traveling air-pressure waves with shallow waters above the off-shore plateau (VILIBIĆ *et al.*, 2004) that are directed towards the coast. In June 2003, these waves interacted with the coastal topography by transferring energy to the local seiches, flooding the city of Stari Grad, and exciting seiches in Ploče Harbor with a maximum amplitude of 25 cm (VILIBIĆ *et al.*,

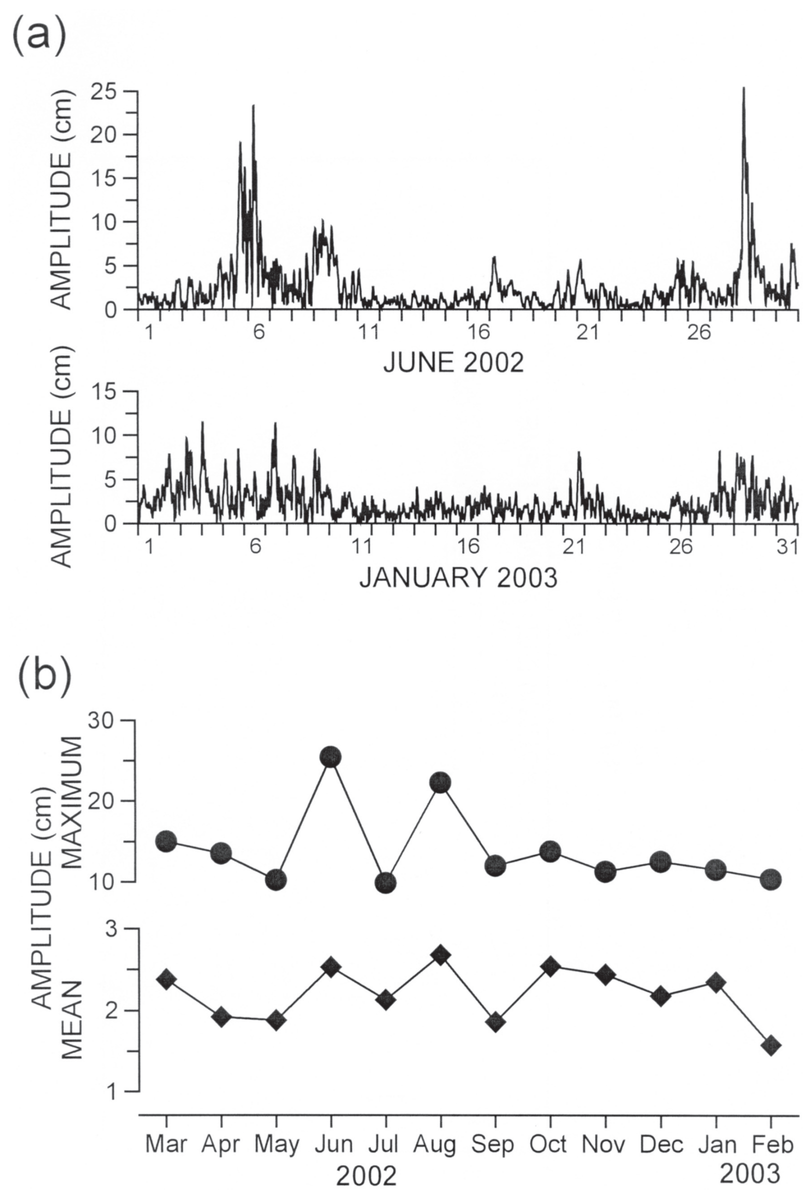

Fig. 4. Seiche amplitude: (a) band pass time series (cutoff periods of 25 and 40 min) in June 2002 and January 2003; (b) maximums and means from March 2002 to March 2003

2004). Extreme sea level amplitudes were also recorded a year later, during the passage of a traveling air-pressure disturbance on 21 August 2004 (VILIBIĆ *et al*., 2005).

Applying non-stationary wavelet analysis can easily validate the significance of a seiche. Maximum high-frequency energy appears almost constantly in the band surrounding the 30-min seiche throughout the whole year (June, for example, Fig. 5). Although pronounced for a day or two and decreasing rapidly, it remains at significantly high levels.

Two case studies of harbor seiches are presented in Fig. 6. Unfortunately, no high-frequency air pressure or wind data were available for the Ploče region, so we used 2-min air pressure series measured at Split (100 km NW of Ploče) to demonstrate the existence of high-frequency pressure waves. Hourly winds were recorded at Ploče in February 2003. Strong seiches appeared on 5-6 June with amplitudes as high as 25 cm, comparable to the tidal signal in the area. It seems that they were forced by air pressure waves outside the harbor, as waves of 2-3 h and 1-2 hPa (amplitude) reached the area at the same time and lasted for about 24 h. However, pressure waves also contained large amounts of energy on other frequencies (Fig. 7), presumably as a result of the variety of gravity waves that approached the region together with the main disturbance. In addition, a number of energy peaks may have been the result of a single cosine disturbance (called *sinc* function), which was documented during the June 2003 episode by VILIBIĆ *et al*. (2004). After that, the seiche amplitude dropped to less than 5 cm and remained low on the following days.

Another case occurred in early February 2003. A strong drop in air pressure on 3-4 February (about 30 hPa in 36 h) denotes a deep cyclone approaching the area. Such synoptic disturbances produce strong Sirocco winds (FURLAN, 1977; RAICICH *et al*., 1999) with mean velocities up to 25 m s^{-1}. However, this cyclone resulted in a Sirocco wind that blew most of 4 February, but with speeds lower than 10 m s^{-1}. Although not as pronounced as in June 2002, high-frequency waves were seen in the air pressure series. Conclusively, some seiche energy is obtained from wind, but open-sea Proudman resonance is presumed to be the major excitant.

To prove the latter hypothesis, a two-dimensional numerical model (BLACK, 1995) was applied to the harbor, both by simulating the waves generated by open-sea Proudman resonance (run 1) and by simulating a strong inland Libeccio wind (run 2), the best choice of

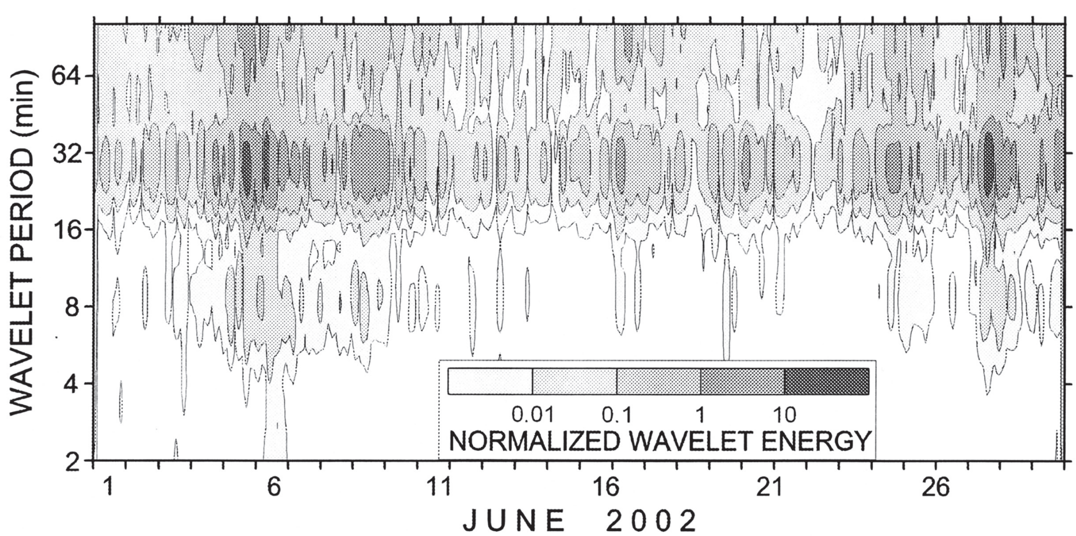

Fig. 5. Sea level energy calculated by wavelet analysis (Torrence and Compo, 1998) for June 2002. The spectrum is normalized by the respective variance (176 cm^2)

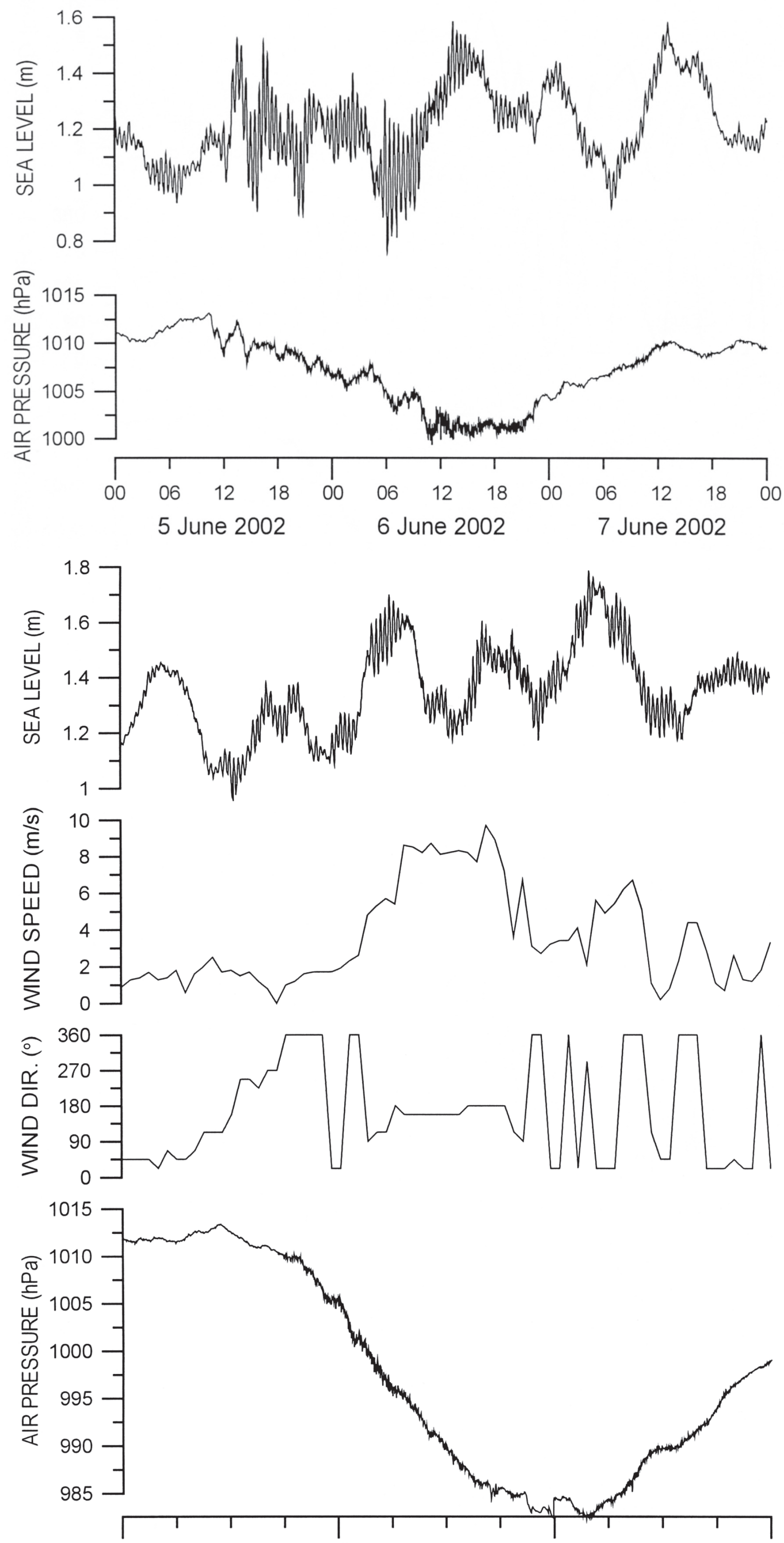

Fig. 6. Sea level at Ploče and air pressure at Split recorded during seiche episodes on (a) 5-7 June 2002 and (b) 3-5 February 2003. Hourly wind speed and direction were also recorded at Ploče in February 2003

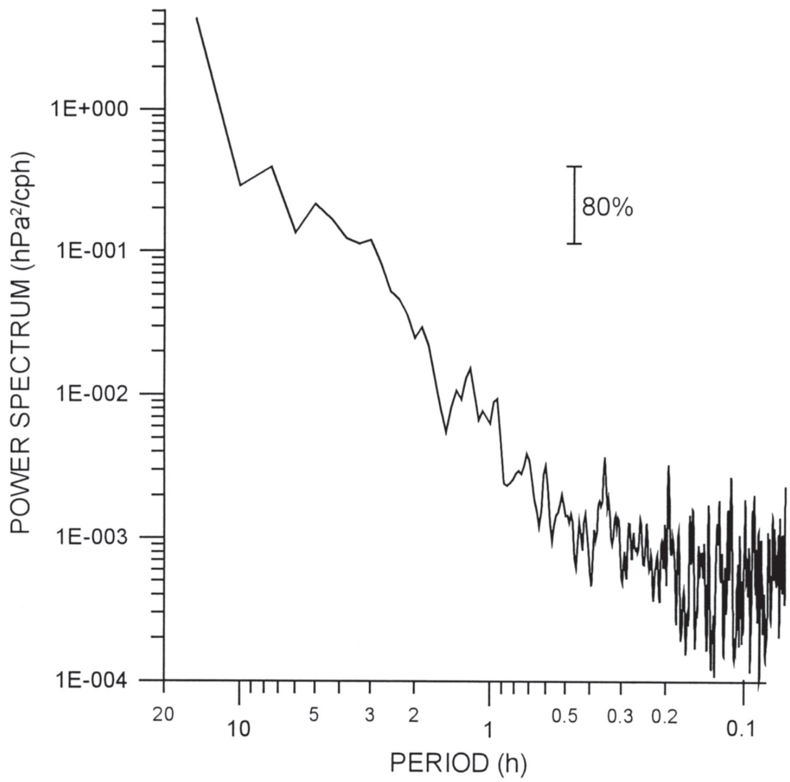

Fig. 7. Air pressure power spectra computed from data collected 4-8 June 2002

wind for the piling up of water and excitation of seiches in the harbor. Realistic modeling was not performed due to the unsatisfactory air pressure and wind data collected in the area during the events of interest. At first, modeled fundamental seiches had a period of 31.5 min in both runs, clearly visible in the power spectra at any grid point (not shown). However, run 2 ended in a maximum seiche amplitude of about 2 cm at the top of the basin, significantly lower than observed amplitudes, showing that wind does not excite large seiches in Ploče Harbor.

Run 1 ended with a 3-fold increase of the incoming wave at the closed end of the harbor (Fig. 8). Seiche amplitude changed rapidly in the passage between the outer and inner basins, resulting in rather strong currents there. The amplitude modeled at the tide gauge location was approximately 70% of the maximum that occurred in both inner basins. The maximum amplitude can be as high as 35 cm in the inner basins, since the maximum amplitude at the tide gauge location was measured at 25 cm. Conclusively, seiches can play a major role when extreme sea levels and flooding occur in the harbor, particularly in the city of Ploče on the shoreline of the small inner basin. On the other hand, currents were strongest in front of the tide gauge, located at the major constriction of the bay. Maximum velocity was modeled at about 50 cm s^{-1} at this point, derived when seiches were 10 cm high at the tide gauge. Currents can reach 100 cm s^{-1} there during extreme events and surges should be anticipated by ship personnel when maneuvering large cargo ships in the narrow (~200 m) area of the constriction during strong seiche activity. A secondary maximum current occurred to the southeast (about 800 m from tide gauge). Here, the currents were around half the maximum, yet still can affect maneuvering of ships entering the harbor.

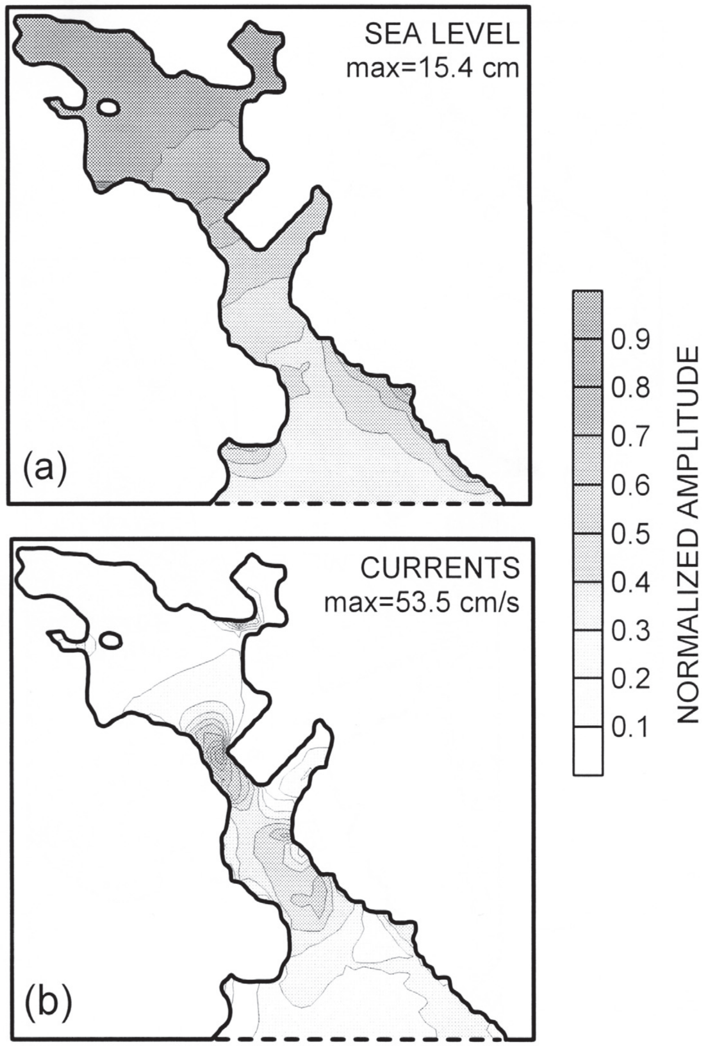

Fig. 8. Modeled distributions of (a) relative sea level and (b) relative current velocity amplitudes of the fundamental seiche with a sinusoidal wave imposed at the harbor entrance

DISCUSSION

The paper comprises analyses and modeling of seiches in Ploče Harbor during a one-year period (March 2002 - March 2003). As the harbor is shallow and close to the Neretva River mouth where the sediment deposit is high, high-frequency oscillations can affect navigation within the harbor due to sea level displacement and strong currents within the narrow constriction between the inner and outer basins. In addition, the area has low tides. Therefore, major components affecting sea level in the harbor are processes that occur in the Adriatic Sea – storm surges and seiches – as well as free oscillations in the harbor.

Despite seiches in the broader region (4.1, 2.6, and 1.5 h), a major phenomenon is the fundamental harbor seiche, with a period of 30 min and an amplitude up to 25 cm. The seiche is forced by two processes: (i) incoming waves from the open sea, which result from resonant coupling with air pressure waves, and (ii) direct wind stress on the sea surface. The first process is dominant, whereas wind does not produce any significant seiches in the harbor.

The modeled amplitude was greatest in the inner basins, about 40% higher than at the tide gauge. The largest amplitude was in the vicinity of Ploče city, where it can endanger the ferries and small boats that are usually moored there. For comparison, the total sea level range was 153 cm during 1955-1999 at the Split tide gauge (VILIBIĆ *et al*., 2000), some 100 km to the northwest (the tidal signal is almost the same there as in Ploče), while the range of seiches in Ploče Harbor was modeled to be approximately 70 cm, occurring presumably once a year. Conclusively, seiches cause almost half the sea level range in Ploče Harbor.

Seiche-induced currents can have an even more critical impact on safe navigation, particularly in complex harbors with narrow constrictions such as Ploče Harbor. Simulated fundamental seiche currents have a velocity up to 50 cm s^{-1} but can probably reach 100 cm s^{-1} during extreme events, and are greatest in the constricted area along which cargo and passenger ships travel to the docks. Consequently, seiche analyses should be encompassed in any analysis regarding sea level changes and current fields in the harbor, including the building of coastal infrastructure as well as in navigation safety assessment studies, especially since cargo traffic is certainly to increase in the future.

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Rezonanca luke Ploče

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SAŽETAK

U radu su opisane visokofrekventne oscilacije u luci Ploče, izdvojene iz godišnjeg niza podataka visine razine mora (ožujak 2002-ožujak 2003) mjerenih na mareografu u luci. Analize su provedene koristeći stacionarne (spektralna) i nestacionarne (wavelet i filtriranje) analize, izdvajajući vremensku promjenjivost osnovnog seša perioda 30 minuta. Seš je izražen tijekom cijele godine, no amplituda mu je dvostruko veća (do 25 cm) za vrijeme ljetnih mjeseci. Primjenom numeričkih modela pokazano je da je seš rezultat dolazećih valova s otvorenog mora, generiranih rezonantnim procesima od strane putujućih atmosferskih težinskih valova. Nasuprot tome, vjetar ima zanemariv utjecaj na stvaranje seša. Seš može ugroziti male brodice na vezu u gradu Ploče kao i velike teretne brodove na putu prema vezu, stoga što se u suženjima unutar luke mogu pojaviti vrlo jake struje (preko 50 cm s^{-1}) koje mogu ugroziti sigurnost plovidbe.

Ključne riječi: obalna rezonanca, mareografi, empirijska analiza, numerički modeli, Jadransko more