CONCERT-Japan
Research and Innovation Joint Call

Efficient Energy Storage and Distribution
Resilience against Disasters

RAPSODI Project

Risk Assessment and design of Prevention Structures
fOr enhanced tsunami DIsaster resilience

Deliverable D6 – Numerical Modelling of Tsunamis in Harbours and Bays
2nd year of funding

20120768-D6-R
3 March 2015
Revision: 1/ May 2015

NGI
PARI
Middle East Technical University
Civil Engineering Department
Technische Universität Braunschweig

CONCERT JAPAN
Connecting and Coordinating
European Research and Technology Development with Japan
www.concertjapan.eu

This work was supported by funding received from the
CONCERT–Japan Joint Call on Efficient Energy Storage
and Distribution/Resilience against Disasters

Project information

Name of the project:	RAPSODI
Start of the project:	01 July 2013
Duration (no. of months):	24
End of the project	30 June 2015
Name and country/region of each partner	NGI, Norway; PARI, Japan; TU-BS, Germany; METU, Turkey
Overall budget	383 k€

Client

Client:	CONCERT-Japan Joint Call Secretariat
Client's contact persons:	CONCERT-Japan Coordinator The Scientific and Technological Research Council of Turkey (TUBITAK) Ms. Filiz Hayirli (filiz.hayirli@tubitak.gov.tr) concertjapan@tubitak.gov.tr Phone: + 90 312 468 5300 (ext.1910) CONCERT-Japan Joint Call Secretariat Centre national de la recherche scientifique (CNRS) Ms. Lucie Durocher (lucie.durocher@cnrs-dir.fr) Phone: + 33 (0)1 44 96 47 14 Fax: + 33 (0)1 44 96 48 56 http://www.concertjapan.eu
Contract reference:	NGI 229578/H20; METU 113M556; TUBS 01DR13016;
Settlement numbers	PARI 2013 H25 国際第 1-33 号 2014 H26 国際第 1-17 号

For NGI

Project manager:	C.B. Harbitz
Prepared by:	Dr. Gulizar Ozyurt, Dr. Ahmet Cevdet Yalciner, Rozita Kian, Betul Aytore
Reviewed by:	C.B. Harbitz

Publishable summary

One of the objectives of the consortium of Risk Assessment and design of Prevention Structures fOr enhanced tsunami DIsaster resilience (RAPSODI) project is to assess the applicability of numerical modeling of tsunami in harbors and ports. Ports are one of the essential transportation hubs to provide continuous service not only under normal conditions but also and mainly under post disaster conditions. Therefore resilience of ports becomes an important requirement after the disasters. Within the project period it is planned to bring together the different data and background studies for Haydarpasa port in Marmara Sea in Turkey to explore resonance potential synergies in the region and develop further ideas and perform further research to understand the possible amplifications during tsunami and/or long wave attack to the port and to develop and propose the mitigation measures in order to have better resilience of port after marine hazards. In this regard, Deliverable 6 – "Numerical modeling of tsunami in harbors and ports" is prepared within the first work package of the RAPSODI project. Amplification of waves lead to harbor damage by direct and/or indirect effects at first, and then resonance in harbors exacerbate the damage. The report describes the harbor damage and harbor resonance and seiches due to tsunami and shows the resonance periods in Haydarpasa port in Marmara Sea as a case study. It calculates the resonance periods and current velocity and momentum fluxes in the harbor using the numerical model NAMI DANCE. The key objective of this report is to obtain the spatial and temporal changes of main tsunami parameters and their adverse effects on harbor performance by analysing the critical tsunami parameters (water elevation, current speed, and momentum fluxes) in the port.

Numerical modeling of tsunamis in harbors are discussed in two categories i) the harbor damage and ii) the harbor resonance. First, an overview of those possibilities are introduced and described. In order to determine the level of tsunami hazard and develop measures to increase resilience, the effects of main tsunami hydrodynamic parameters in shallow zone and at land area investigated. Distribution of resilience against disasters in harbors, water level and current amplifications, and some examples of tsunami induced hazards in harbors from different prefectures during the 2011 Japan event are compiled and presented based on an extensive literature survey.

The main tsunami hydrodynamic parameters are; (i) maximum positive amplitude, (ii) maximum current velocity, (iii) maximum flow depth, (iv) maximums of hydrodynamic forces, (v) maximum of momentum flux, (vi) maximum negative amplitude, (vii) the arrival time of the first wave, (viii) the arrival time of maximum wave, and (ix) the duration of the inundation and withdrawal of tsunami. Since basins' depths are shallow at all long wave conditions, the tsunami surge modeling in a harbor becomes applicable by using the governing equations under long wave conditions. Those are used to compute and evaluate the effects of main tsunami hydrodynamic parameters in shallow zone and at land in order to determine the level of tsunami hazard and develop the measures to increase the level of the resilience of the study area.

Ocean waves cannot generate enough energy to affect open coasts by resonance amplification. But they can cause hazardous oscillations when they enters the enclosed or semi-enclosed basins and harbors. Wave radiation via the semi-enclosed basins is an important factor in decaying energy. On the other hand, making the harbor entrance narrower, the amplification of arriving wave occurs. Therefore, dams, dikes, and other harbor protecting structures could tighten the entrance width, and then intensive resonance oscillations take place inside the harbor, this phenomenon is harbor paradox. Hence, both harbor resonance period and harbour damage parameters could be related by harbor structures design which determines the harbour geometry.

To conclude, resonance inside harbors due to tsunami waves can exacerbate the damages by amplifying the water level changes, currents, and momentum fluxes. An example of assessing possible amplifications due to resonance is presented in this deliverable for consideration of future work. The presented study has been focused on the distribution of water level and current velocity amplifications due to the long wave motion inside Haydarpasa harbor. The fully reflective boundaries inside the ports (such as Haydarpasa port) should be considered as the critical locations under the extreme wave conditions.

Contents

Review and reference page

1 Introduction

Since ports and harbors are vital hubs of transportation, their performance is very important in usual functioning and also in the case of disaster for post disaster operations. Resilience of harbors and coastal utilities due to marine hazards is a major issue for post disaster operations and also its recovery. Large wind waves and tsunamis are known as a damaging hazard to port and harbor facilities. Wind waves, especially those with long period spectral components can cause resonance inside harbors leading to large vertical motions and strong currents. Tsunamis can also lead to huge damages. Large vertical motions can be created inside a harbor due to the geometric amplification of long waves. Even resonance can be excited when the tsunami is composed of a train of long waves (Lynett, 2010). In the node locations, the resonant motions cause very strong currents and when these currents interact with harbor structures, they can create large eddies which have very large transport potential to damage mooring lines and lead ships trap into rotation (Okal et al., 2006).

One of the most important factors in creating dangerous and destructive seiche oscillations in bays and harbors is the tsunamis (Honda et al., 1908; Munk, 1962; Wilson, 1972; Murty, 1977; Mei, 1992; Rabinovich, 2008). Great catastrophic trans-oceanic tsunamis were generated by the 1946 Aleutian (magnitude Mw = 7.8), 1952 Kamchatka (Mw = 9.0), 1960 Chile (Mw = 9.5), and 1964 Alaska (Mw = 9.2) earthquakes. The events induced strong seiche oscillations in bays, inlets and harbors throughout the Pacific Ocean (Van Dorn, 1984). It is important to compute and evaluate the effects of main tsunami hydrodynamic parameters in shallow zone and at land in order to determine the level of tsunami hazard and measure the level of the resilience of the study area. The main tsunami hydrodynamic parameters are; (i) maximum positive amplitude, (ii) maximum current velocity, (iii) maximum flow depth, (iv) maximums of hydrodynamic forces, (v) maximum of momentum flux, (vi) maximum negative amplitude, (vii) the arrival time of the first wave, (viii) the arrival time of maximum wave, and (ix) the duration of the inundation and withdrawal of tsunami (Yalciner et al., 2015).

It is necessary to know about return period of the threatening waves and probability of the extreme inundation in ports and harbors in assessment of tsunami hazard and in emergency management, planning evacuation routes and resource allocation. The shallow water equations are sufficient to solve tsunami problems inside the harboırs. As application three different (15 November, 2006, 13 January, 2007, 4 October, 1994) tsunamis from Kuril Islands have been studied and their effects on US coasts and amplifications in Crescent city harbor are investigated by Uslu (2008). The sensitivity of California harbors against tsunamis generated from Kuril islands are concluded.

Generally tsunamis in shallow water zone lead to sea water level rise and fall, strong currents, forces (drag, impact, uplift, etc.), drawdown, scour, and morphological changes (erosion, deposition), debris and debris flow, dynamic water pressure, resonant oscillations and seiches (Yalciner et al., 2014). The aim of this chapter is to present the effects of tsunamis on harbor operations and consequently the harbor resilience by using a numerical modeling tool (NAMI DANCE). The spatial and temporal changes of main tsunami parameters are investigated and their adverse effects on harbor performance are identified by analysing the critical tsunami parameters (water elevation, current speed, and momentum fluxes) in the port. Finally, the functional loss of port and the necessary strategies for reduction of tsunami impact and increase of resilience are also discussed. On this purpose, Haydarpasa port is selected as a case study area to evaluate the tsunami motion inside the port and understand the resilience of the port after the tsunami by focusing on the tsunami parameters effect on special point of the harbor (Yalciner et al., 2015; Kian et al., 2015).

Amplification of waves lead to harbor damage by direct and/or indirect effects at first, and then resonance in harbors exacerbate the damage.

2 Harbor Damage

Local topography and the height of the incident tsunami affect the damages in respective coastal areas. Since port areas are vulnerable to tsunamis, damages are inevitable even if there is small level of inundation. The propagation of tsunamis near shore are due to wave transportation, which are wave shoaling, refraction, diffraction, also depending on the topography of submarine can become a bore and/or breaking tsunami. It is noticeable that generally because of deep entrance of the ports, tsunamis act neither like bore nor breaking tsunami. Since tsunami is not like a bore in protected ports, a tsunami wave usually does not overtop the breakwater and the tsunami induced water elevation is lower than the height of breakwater crest. This leads tsunami to enter the port via openings in the breakwaters. Therefore, people have time to run away from the area because the water elevation in the port is relatively slow. Of course in the case of large tsunamis, a huge mass of water will overtop the breakwaters and enter into the port. As a result, there will be an inundation and lack of time to evacuate the region. During a tsunami, seawater will intrude into the land if the height of water level is higher than the ground level of the port. In order to facilitate cargo-handling, the land area of ports are usually flat, therefore, there is venture of flooding while after the inundation occurs. In shallower water depths, tsunami affects more severely. But for the facilities in Japanese ports, no significant damages recorded. However, it is important to consider the damages because of rapid currents due to tsunamis. Generally, main port damages can be summarized as damages from: parting of vessel moorings, manoeuvring movements which are not controlled or transporting unmoored vessels due to tsunami currents, vessels when they are lifted out of water, sediment scouring or deposition due to a tsunami (PIANC, 2009).

Tsunami induced currents inside the ports and harbors are very complicated. Eddies and gyres can be generated where the currents are concentrated. Therefore, scouring occurs around breakwaters and then sediments deposit at the basins in ports and harbors (PIANC, 2014).

According to the PIANC (2014), the Great East Japan Tsunami induced destructive damages in the Iwate, Miyagi and Fukushima ports. Since several tsunamis took place in that area, many simulations and measurements have been used to mitigate the disasters by using past data. Actually, the Great East Japan Tsunami was greater than these previous events and demolished the breakwaters and seawalls and then led to wide region of inundation.

From geotechnical point of view, the possible damage induced by earthquakes and resultant tsunamis, the damages can take place in the ports are summarised as:
High-response acceleration, vast deformation, liquefaction.
Tsunami wave force, flow hydraulic force (drag force), buoyancy, and impact of floating objects.
The reasons of damage mechanism have not yet been illuminated. However, numerical simulations of the propagation and inundation of the Great East Japan tsunami showed a decrease in the impact of the tsunami by the offshore breakwater in the Port of Kamaishi (PIANC, 2014).

The mechanism of the failures of the tsunami defences was studied using experiments and it was concluded that the overtopping current was the main cause of the failure. Furthermore, the results show that the tsunami defence structures decrease the tsunami severity during overtopping if they are not broken or overturned.

3 Harbor Resonance

Problems of harbor resonance can be caused by swell waves and tsunamis as regular waves and also by storm wind waves as irregular waves. Indeed for most of the ports regular waves cause less frequency of occurrence, therefore, most of practical studies should be performed considering incoming irregular short waves. However, resonance problem in harbors are usually studied with regular waves in practice (Girolamo, 1995).

The harbor oscillations are generated in two steps: first, generation of long waves in open seas, second, forcing of the harbor oscillations when the long waves intrude in the basin (Rabinovich, 2008). If the frequency of coming tsunami waves match with the resonance frequencies of the harbor then serious devastation occurs. Large tsunami amplification of Port Alberni in Alaska tsunami 1964 because of resonance is a good example (Murty, 1977; Henry and Murty, 1995). One of the other problems due to tsunami in harbors is oscillations.

Professor Omori in 1902 noticed that distinguished periods of observed tsunami waves are similar to the ones caused by usual long waves in the same basin. He explained that part of the sea oscillates such as fluid pendulum with its own frequency and the coming tsunami waves make similar seiches as the ones made by other types of external forces (Honda et al., 1908). Many articles for several regions of the world ocean affirmed this consequence (Miller, 1972; Van Dorn, 1984; Djumagaliev et al., 1993; Rabinovich, 1997; Rabinovich et al., 2006; Rabinovich and Thomson, 2007).

One of the indispensable natures of harbor oscillations is that even small vertical motions can go along with large horizontal water motions (harbor currents); more resonance take place whenever the period of these motions coincides with the natural period of swing or yaw of a moored ship (Wiegel, 1964; Sawaragi and Kubo, 1982). Strong currents due to the seiches have taken more concern than sea level variations due to seiche in port and harbor functions. It is noticeable that the maximum current velocities take place at the nodal lines. Hence, the nodal lines should be considered unsafe regions comparing to other locations (Rabinovich, 2008).

Strong currents in the harbor induced by 2006 and 2011 tsunamis in Crescent City caused whole damages which were not because of land flooding because there was not any in 2006 tsunami and very small flooding in 2011 tsunami. These events prove the importance of strong tsunami currents and their impacts in ports and harbors (Amanda et al., 2014). Tsunami currents are usually predicted by numerical models, and only few of studies have been validated by real measurements. In tsunami of Hokkaido in 1993, the peak current velocity was estimated 10-18 m/s (Shimamoto et al., 1995; Tsutsumi et al., 2000). The peak tsunami current speeds of the 2010 Chile and 2011 Japan tsunamis in the coast and entrance to Humboldt Bay shows that currents are focused at the harbor entrance. Thus, any floating or submerged thing near the harbor or port corner has considerable potential to experience strong and rotational currents (Amanda et al., 2014). It is possible to compute the current speed by tsunami deposit analysis. However, this method leads to obtain peak currents not the time history of the flow.

Wave radiation via the semienclosed basins such as harbors, bays and inlets is one of the important factors in decaying energy. Making the harbor entrance narrower, the amplification of arriving wave occurs. Therefore, dams, dikes and other harbor protecting structures could tighten the entrance width, then intensive resonance oscillations take place inside the harbor named, this phenomenon is named harbor paradox (Miles and Munk, 1961). Considerable long waves are generated by enhancing the atmospheric disturbances above the ocean during the resonance action. The resonant effects may noticeably amplify ocean waves entering the coast. Ocean waves cannot generate enough energy to affect open coasts by resonance amplification; they can cause hazardous oscillations when they intrude the harbors as semi-closed basins. Besides, large oscillations inside a harbor can be formed if the external forcing has sufficient energy. Tsunami waves which are generated in open oceans can be serious enough even in absence of additional effects. Therefore, upon measurements tsunami waves generated in 2004 Sumatra earthquake had wave height around 1-2 m, but atmospherically generated tsunami can lead hazardous rates just in the case of some external resonance. This is the main difference of tsunami waves and meteotsunamis (Titov et al., 2005).

Another noticeable fact is that the difference in spectral peaks among several tide gauges records is declarative of effect of local topography. For instance, in the Pacific coast of Vancouver Island, the most significant peaks in the tsunami spectra were for Winter Harbor and Tofino Harbor. Actually, the period of observed tsunami waves are principally relevant with the resonant properties of the local topography rather than characteristics of the source. Hence, different earthquakes generate similar tsunami spectra in the same region (Honda et al., 1908; Miller, 1972; Rabinovich, 1997). The resonant properties of each area are the same forever; although large seismic sources produce low frequency modes and vice versa (Rabinovich, 2008).

Theoretical solution for the problems of basin oscillations in closed basins is based on solution of Helmholz equation and different numerical algorithms can be used to solve it. According to Yalciner et al. (2007) there are two procedures to calculate the frequencies of free oscillations: First; using continuous force function to agitate the basin with only one frequency and then repeat the task with other frequencies. Second; using a single force function with a certain frequency and then analysis the spectrum of water surface fluctuations along time. In this study the second method is applied by inputting a single wave with a certain short period. Then time history of water surface fluctuations are stored in gauge locations. Using Fast Fourier Transformation (FFT) technique, frequency spectrum of saved time histories should be determined. The peaks in spectrum curves show the frequency of free oscillations. We investigate the propagation and amplification of long waves using numerical model (NAMI DANCE which solves nonlinear form of shallow water equations and it is applied to several tsunami events worldwide (Zaytsev et al., 2008; Ozer et al., 2008; 2011a; 2011b; Yalciner et al., 2010; 2014). The code computes the sea state according to the user defined time steps, time histories water surface fluctuations and velocities at selected locations (Kian et al., 2014). It is noticeable that the shape or amplitude of the inputted initial impulse does not affect the frequency of free oscillation. The method can compute the periods larger than the period of initial impulse. In order to catch the water surface fluctuations properly for spectrum analysis, the time step must be small and simulation duration must be reasonably long.

The model is tested and verified using enclosed and semi enclosed square basins (Kian et al, 2015). When basin is rectangular and enclosed with constant water depth, then the periods of free surface oscillations ($\mathrm{T_n}$) can be calculated according to Eq. 1.

$$T = \frac{2}{\sqrt{gd}}\left[\left(\frac{n}{L}\right)^2 + \left(\frac{m}{B}\right)^2\right]^{(-1/2)} \quad n = 0,1,2,3,\ldots \quad m = 0,1,2,3,\ldots \qquad (1)$$

Where L is the length and B is the width of the basin, d is the water depth, and $\mathrm{n, m}$ are integer numbers represent each mode (Raichlen, 1966). If one of the boundaries is open (in semi-enclosed basins) the period is calculated according to Eq. 2.

$$T = \frac{1}{n}\frac{4L}{\sqrt{gd}} \qquad n = 0, 1, 2, 3, \dots \qquad (2)$$

Eq. 1 shows that the longer the basin length (L) or the shallower the basin depth (d), the longer the oscillation period. According to Korrgen (1995) the wavelength of (n = 1) mode is twice the length of the basin and the wavelength of other modes equal to one half, one third, one forth and so on, of the wavelength of the fundamental mode (Figure 3.1). Maximum currents take place at the nodal lines, but the minimum currents take place at the antinodes. Water motions at the oscillation nodes are horizontal, and at the antinodes they are vertical. (Rabinovich, (2008)

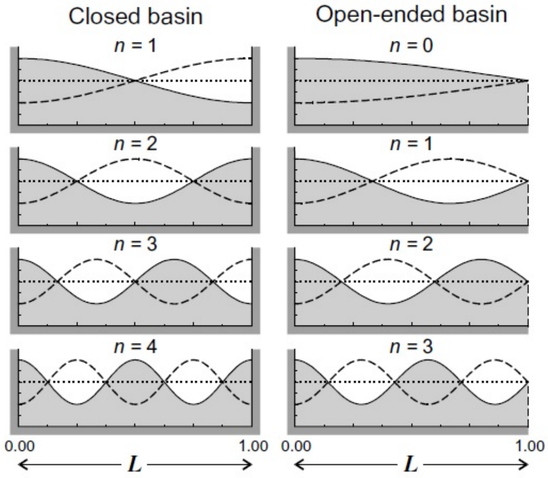

Fig. 3.1 Surface profiles for the first four seiche modes in closed and open-ended rectangular basins of uniform depth. (Source: Rabinovich, A. B., Seiches and harbor oscillations, 2008)

4 Case Study, Haydarpaşa Port, the Sea of Marmara

Anatolia which surrounded by Aegean, Mediterranean, Black and Marmara Seas has been exposed to several natural disasters. The Sea of Marmara is an inland sea and its coasts have been attacked and impacted by more than 30 tsunamis in history for two millenniums. Among those tsunamis, the 17 August, 1999 Izmit tsunami is the one which well surveyed and provided useful data of coastal effects of tsunamis in the region (Altinok et al., 2000; 2001 and Yalciner et al., 2002; Yalciner et al., 2015). The highest populated mega city Istanbul, located at north coast of the Sea of Marmara is one of the main centers of all economic activities in Turkey. There are numerous ports in Istanbul and those are in different sizes serving different activities from commercial to leisure purposes. One of the main ports in the Sea of Marmara is Haydarpasa port which serves not only cargo but also passenger transportation. In this study, Haydarpasa port is selected as a case study area to understand the motion of tsunamis inside the port and identify their effects on harbor performance. In the study, the spatial and temporal changes of main tsunami parameters are investigated and their adverse effects on harbor performance are identified by analyzing the critical tsunami parameters (water elevation, current speed and momentum fluxes) in the port. Resonance oscillations and resultant wave amplifications inside the basins are other important adverse effects which cause damage on structures and interruption of harbor functions (Kian et al., 2015; Yalciner et al., 2015).

In order to compute the period of the basin an initial impulse is inputted, and a simulation is performed. The time histories of water surface fluctuations are computed at several numerical gauge points inside the harbor. The spectral analysis by using Fast Fourier Transform technique is applied to the records of all numerical gauge points and respective spectrum curves are obtained. The peaks of spectrum curves of each numerical gauge location are also determined. The peaks of spectrum curves coincide with the resonance frequencies. The computed frequencies are discussed by comparing with the frequency of the waves which occur in the Marmara Sea in regard to their possible amplification and effects to Haydarpasa port. Finally the functional loss of port and the necessary strategies for reduction of tsunami impact and increase of resilience are also discussed (Yalciner et al., 2007; Kian et al., 2015).

The Haydarpasa port (29.01E, 41N) is Turkey's third biggest port and located at southern entrance of Bosphorus in Istanbul. It is an important cargo port, terminal for ro-ro containers and passengers. This port serves the most industrialized and economized region of Turkey. There are two breakwaters with 3km length in total. The annual handling capacity of the Port is 144,000 twenty-foot equivalent units (TEU). In addition to the open storage area of 313,000 m² and covered area of 21,000 m², there exists a container land terminal outside the port in Göztepe district of Istanbul for stocking the empty containers which covers a holding capacity of 52,800 TEU. The total annual cargo volume in the area exceeds six million metric tons (MT). The motion of long waves inside the Haydarpasa port and the amplification of water level and current speed are investigated by using numerical tools NAMI DANCE. The resonance oscillations, periods of free oscillations and flow pattern of long waves in Haydarpasa port under the actions of long waves are investigated using numerical model (NAMI DANCE).The details of numerical modeling tool are given in the following together with the results and discussions (Yalciner et al., 2007; Kian et al., 2015).

Simulation in Haydarpasa port are performed by inputting different impulses inside the port and the motion of the wave, amplification of the water level and current velocities are monitored. In the simulations, the computational domain is selected to be bounded between 28.995E and 29.025E in E-W direction and 40.987N and 41.015N in S-N direction which covers 2km in S-N direction and 1.6km in E-W direction of Haydapaşa port. The bathymetry is obtained from GEBCO with 30sec resolution in deep sea carefully enhanced by digitization of the navigational charts inside and nearby the port. The numerical grid size is used as 2.4m and the time step is selected as 0.005s for a 60min real time simulation of any impulse inside the harbor. The amplification of water level and current speed are monitored by storing the time series of water level and current speed at 47 gauge points with especial focus on four numerical gauge points located at the corners or sides of a rhombohedral shape of a basin inside the port and then using them for spectrum analysis.

Three different impulses are applied to Haydarpasa Port in three different simulations to calculate the period of free oscillations in Haydarpasa port. Those impulses are i) dome shape circular static source with 5m wave amplitude and 80m diameter (R1), ii) E-W direction, line crested sinusoidal shape time dependent (dynamic) 10 sec period impulse with 1m wave amplitude (R2), iii) S-N direction line crested sinusoidal shape time dependent (dynamic) 10 sec period impulse with 1m wave amplitude (R3). The locations of these impulses and the selected numerical gauge locations (1-4) are shown in Figure 4.1 Time history of wave propagation for (R1) is shown in Figure 4.2.

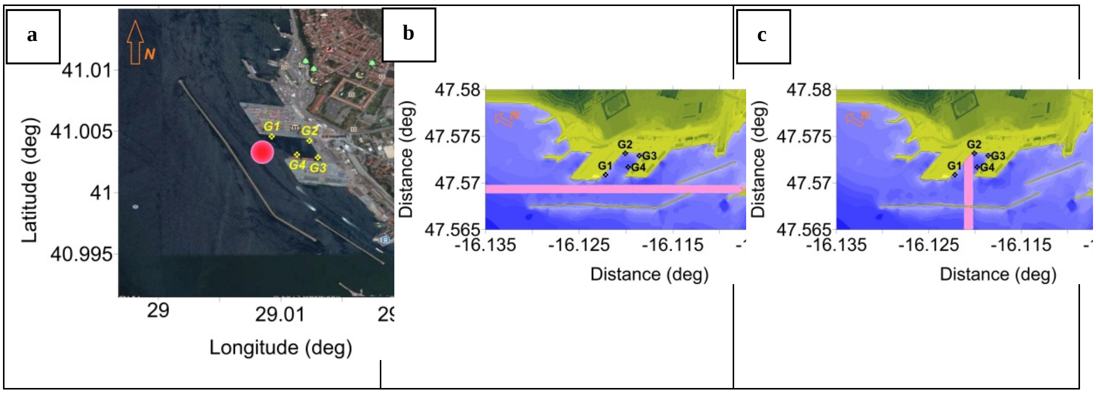

Fig. 4.1 The location of impulse a) dome shaped source (R1), b) sinusoidal line source parallel to the main breakwater (R2), c) sinusoidal line source perpendicular to the main breakwater (R3), at numerical gauge locations G1, G2, G3, G4. (Redrawn from: Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

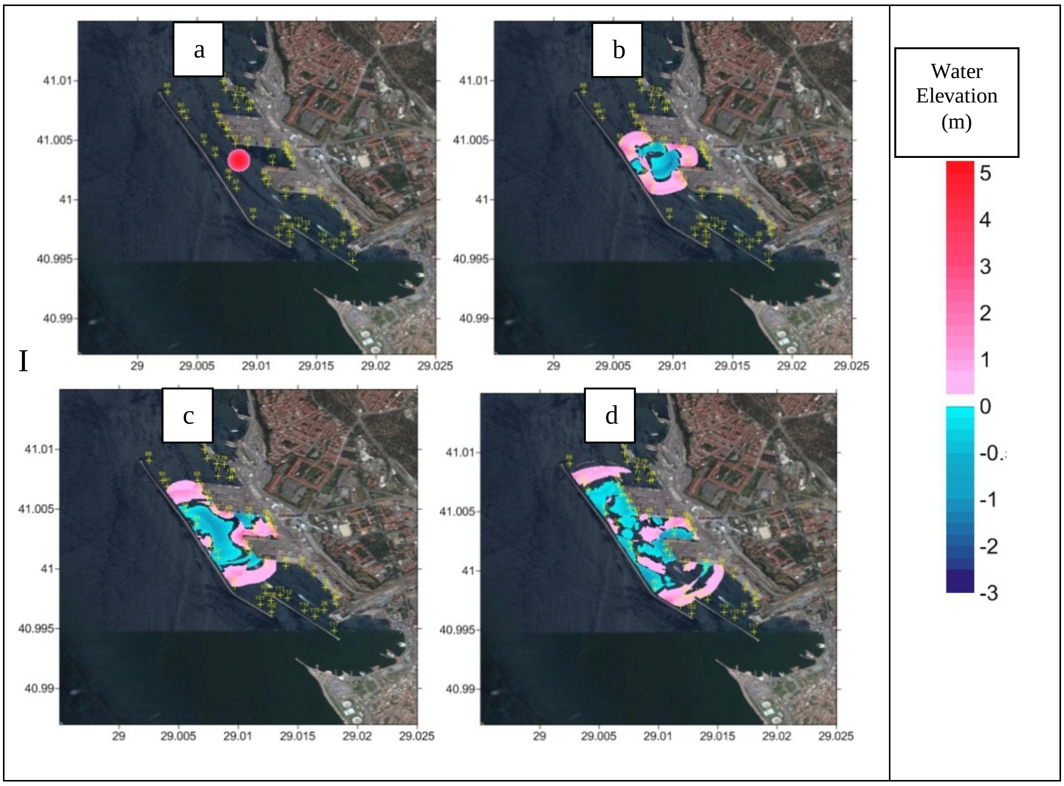

Fig. 4.2 Dome shaped wave(5m amplitude) propagation as time history in a) $t = 0$*, b)* $t = 10s$*, c)* $t = 30s$*, c)* $t = 60s$ *by the simulation (R1) of dome shaped. (Redrawn from: Kian et al., Wave amplification and resonance in enclosed basins; A case study in Haydarpasa Port of Istanbul, 2015)*

In order to determine the level of tsunami hazard and measure the level of the resilience of the study area, it is important to compute and evaluate the effects of main tsunami hydrodynamic parameters in shallow zone and at land. Among important parameters mentioned former, the spatial distribution of maximum water elevation, maximum current velocity, and the momentum flux computed by the simulations according to different initial impulses are also plotted (Figure 4.3).

The time history of wave propagation for (R2) is shown in Figure 4.4 and for (R3) in Figure 4.6. The spatial distribution of maximum water elevation, maximum current velocity, and the momentum flux for (R2) and (R3) are shown in Figures 4.5 and 4.7 respectively.

It is seen from Figure 4.3 and Figure 4.5 and Figure 4.7 that the highest amplifications of maximum water elevations, current velocities and momentum fluxes occur at the concave (G2 and G3) and convex (G1 and G4) corners comparing to other locations inside the inner rhombohedral shaped basin of the port. Figure 4.8 shows the time histories of the water levels and Figure 4.9 shows the time histories of the current velocities at numerical gauge locations 1-4 computed by the simulations (R1, R2 and R3). It is seen from Figure 4.8 that the water level is amplified more at the convex corners (G2 and G3) than the concave corners (G1 and G4). It is seen from Figure 4.9 that the current velocity is amplified more at the points (G1 and G3) than the points (G2 and G4).

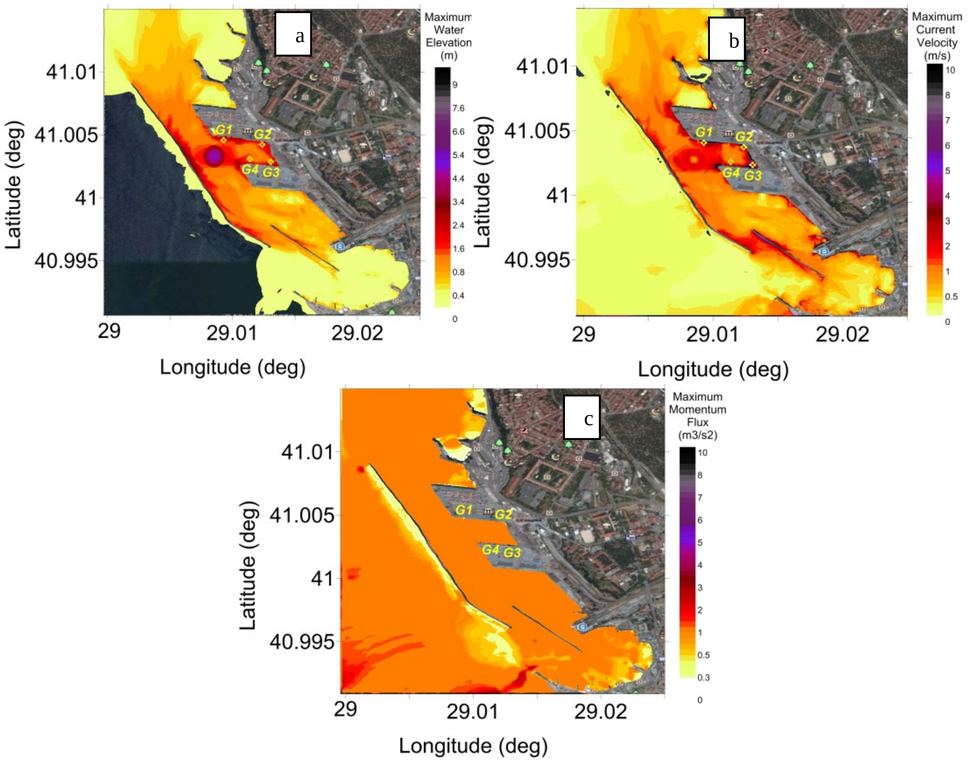

Fig. 4.3 The spatial distribution of maximum water surface elevation, maximum current velocity, and the maximum momentum flux computed by the simulation (R1) of dome shaped source (Redrawn from: Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

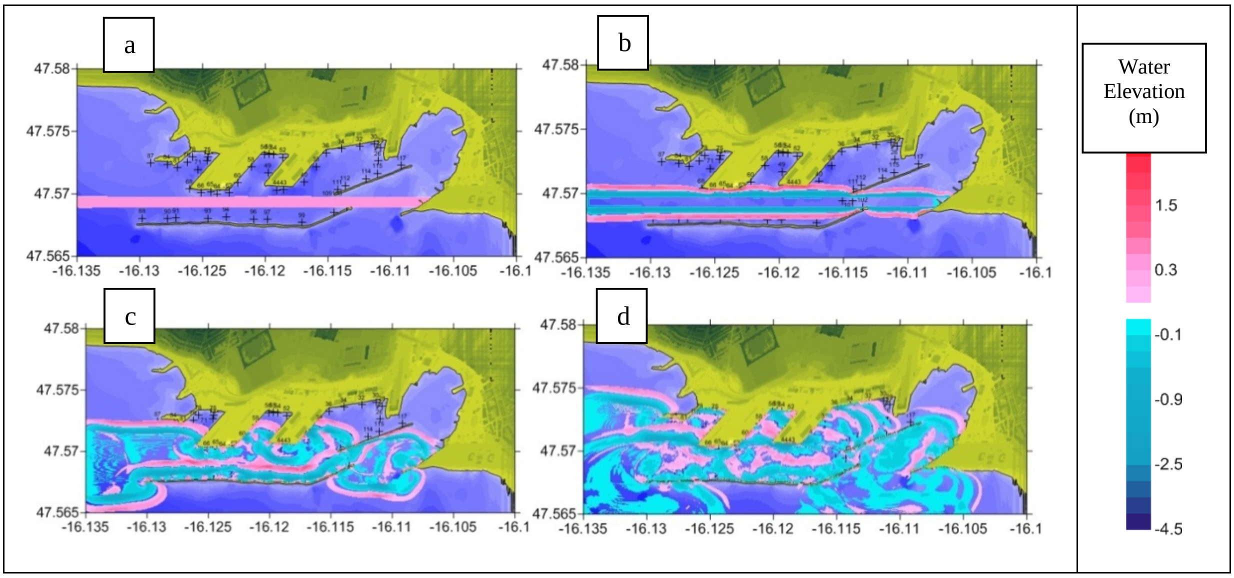

Fig. 4.4 Line impulse in sinusoidal shape (1m amplitude) with crest line parallel to the main breakwater axis in x direction propagates as time history in a) $t = 0$, b) $t = 10s$, c) $t = 30s$, d) $t = 60s$, by the simulation (R2). (<u>Redrawn from:</u> Kian et al., Wave amplification and resonance in enclosed basins; A case study in Haydarpasa Port of Istanbul, 2015)

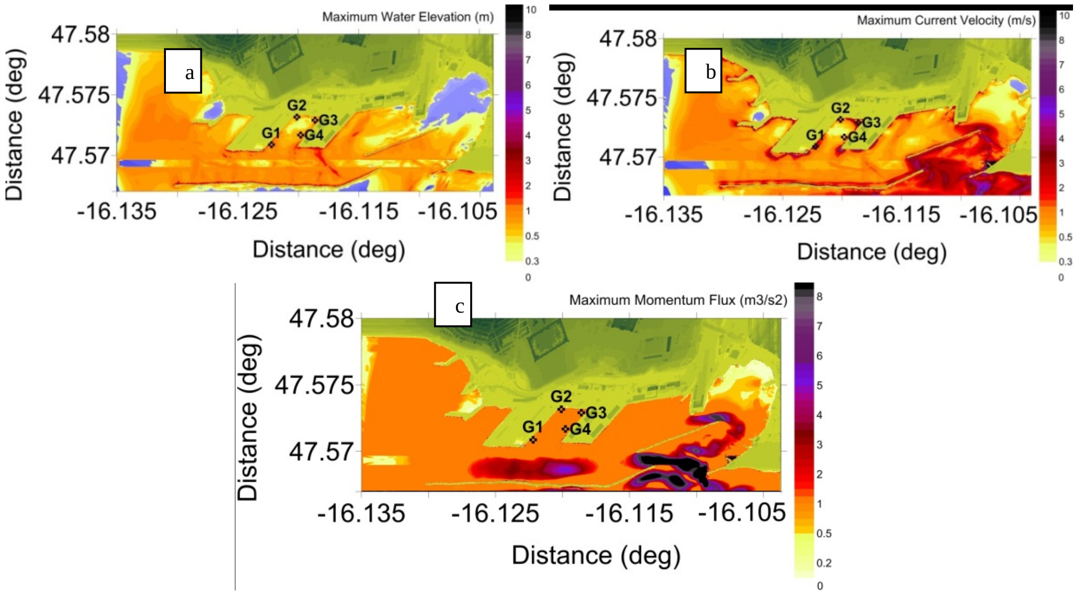

Fig. 4.5 The spatial distribution of maximum water surface elevation, maximum current velocity, and the maximum momentum flux computed by the simulation (R2) of sinusoidal shaped line source with the crest parallel to the main breakwater. (<u>Redrawn from:</u> Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

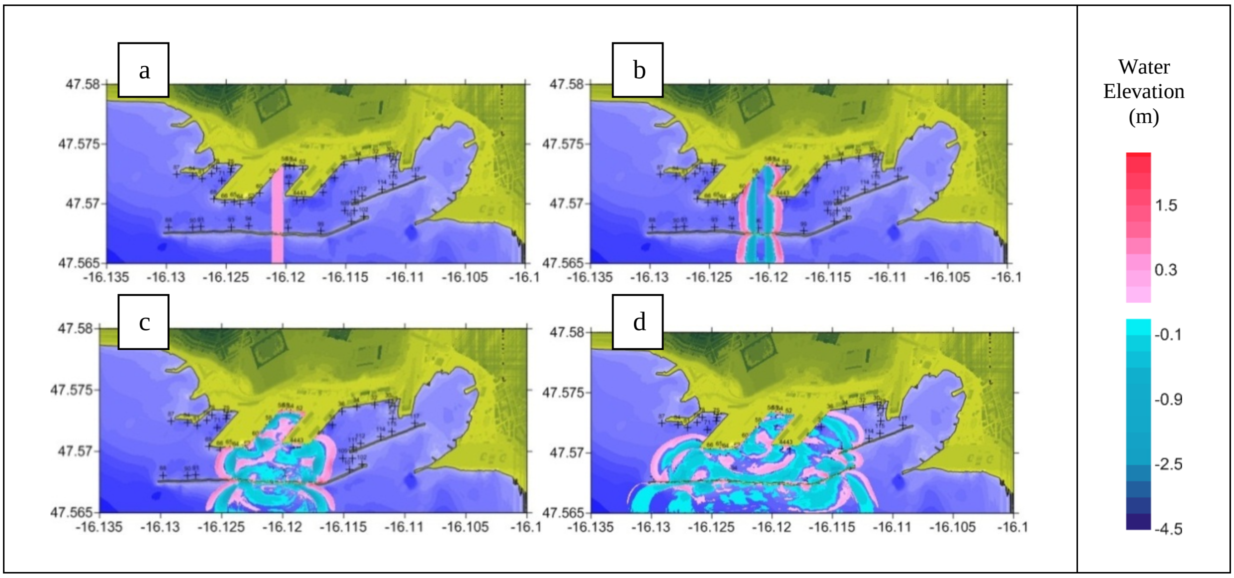

Fig. 4.6 Line impulse in sinusoidal shape (1m amplitude) with crest line prependicular to the main breakwater axis in x direction propagates as time history in a) $t = 0$, b) $t = 10s$, c) $t = 30s$, d) $t = 60s$, , by the simulation (R3). (<u>Redrawn from:</u> Kian et al., Wave amplification and resonance in enclosed basins; A case study in Haydarpasa Port of Istanbul, 2015)

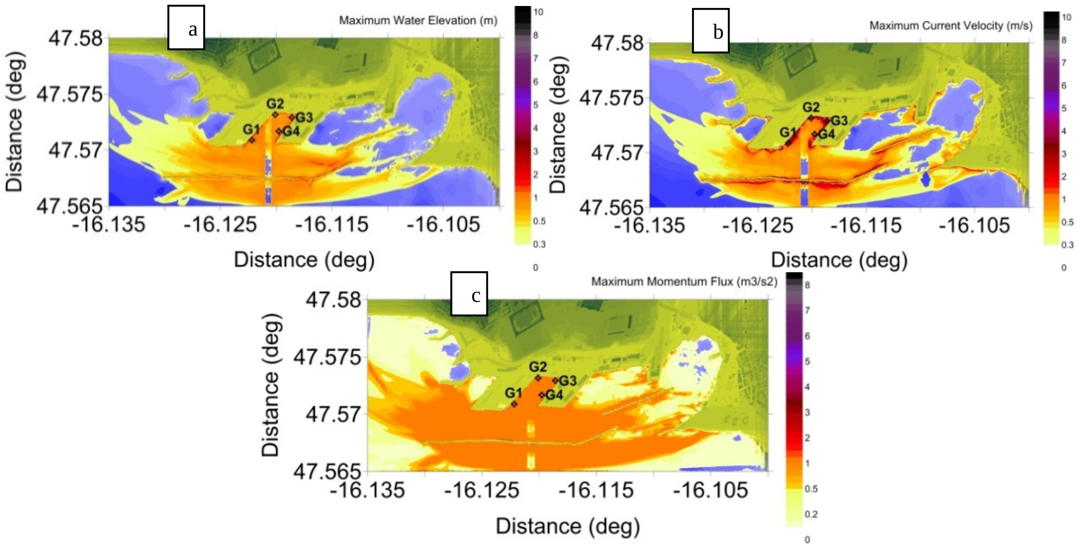

Fig. 4.7 The spatial distribution of maximum water surface elevation, maximum current velocity, and the maximum momentum flux computed by the simulation (R3) of sinusoidal shaped line source with the crest perpendicular to the main breakwater. (<u>Redrawn from:</u> Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

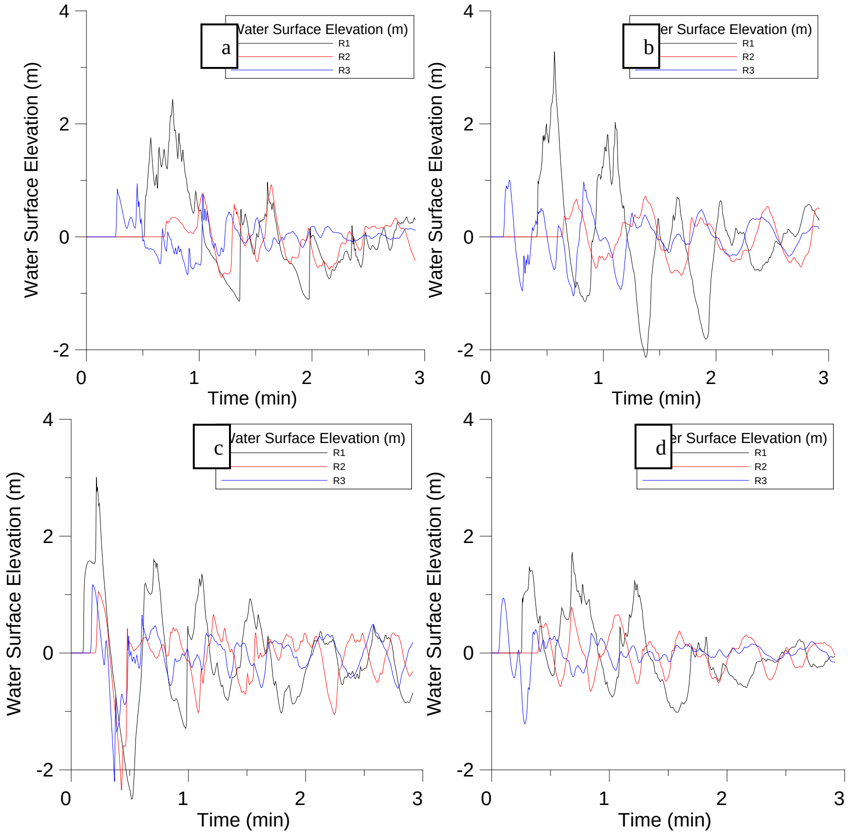

Fig. 4.8 The time histories of water level at numerical gauge locations 1-4 (a-d respectively), computed by the simulations (R1, R2 and R3). (Redrawn from: Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

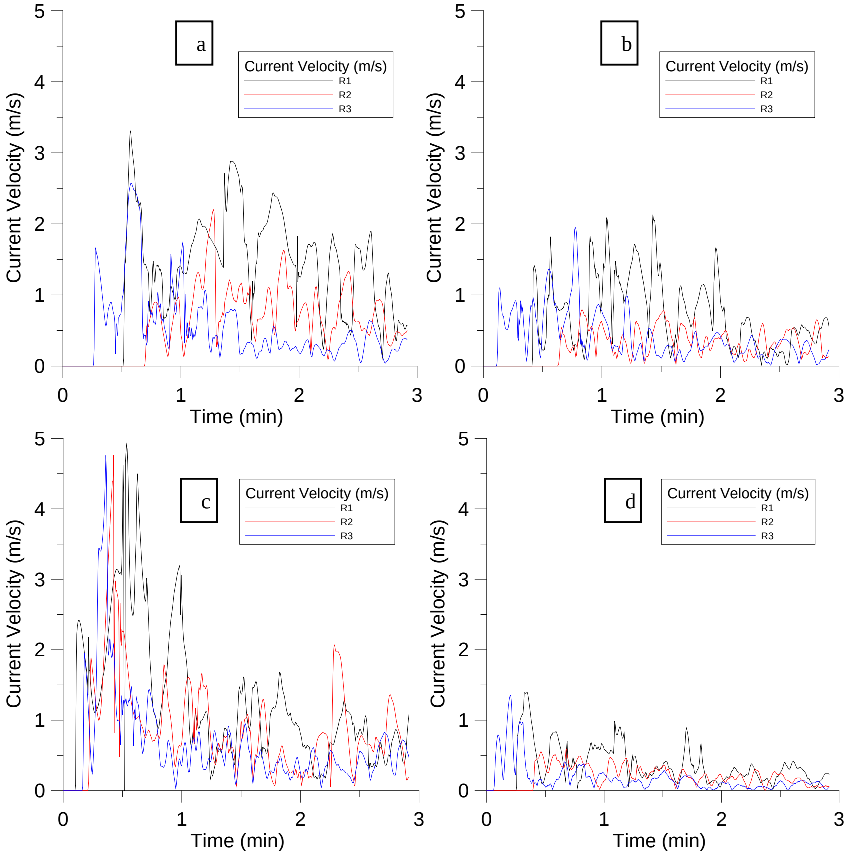

Fig. 4.9. The time histories of current velocities at numerical gauge locations 1-4 (a-d respectively), computed by the simulations (R1, R2 and R3). (Redrawn from: Yalciner et al., Harbors and tsunami threat; A case study in the Sea of Marmara, 2015)

The most common periods coincide with the peaks of spectrum curves (for different initial impulses) are shown in Table 4.1. These periods are selected from the list of periods where the spectrum curve show peak for majority of the gauge locations where the time series are analysed as given in Section 3. Any possible tsunami or long wave approaching to Haydarpasa port will cause higher agitation if the period of the incoming wave coincides with the periods given in Table 4.1. These results are case specific for Haydarpasa Port.

Table 4.1 Periods (s) of Free Oscillations in Haydarpasa Port. Crest Line Impulses are in Parallel (First Column) and Perpendicular (Second Column) Directions to the Main Breakwater with 1m Amplitude and 10sec Period of Sınusoidal Wave and Static Dome shape Wave with 5m Amplitude (Third column). (Redrawn from: Kian et al., Wave amplification and resonance in enclosed basins; A case study in Haydarpasa Port of Istanbul, 2015)

Mode no.	*Line impulse parallel to main breakwater*	*Line impulse perpendicular to main breakwater*	*Initially static Dome shape uplift of water surface with $100m$ diameter*
1	476.4	1311	1311
2	150	374.4	374.4
3	111.6	218.4	154.2
4	66.6	154.2	114
5	55.2	109.2	67.2
6	45.6	69	54.6
7	40.2	54.6	44.4
8	33.6	44.4	40.2
9	28.2	40.2	33.6
10	25.2	34.2	28.2
11	20.4	28.2	25.8
12	17.4	25.8	20.4
13	16.2	23.4	17.4
14	12	20.4	16.2
15		17.4	12
16		16.2	
17		12	

5 Summary and Concluding Remarks

Resilience of harbors and coastal utilities against marine hazards is an important issue. Tsunamis may cause significant damages on ports and may result malfunctioning of the ports during recovery and rescue operations after disasters. Therefore the resilience of ports is one of the important requirements at post disaster conditions. In a closed basin, waves are trapped and last in longer time than semi-enclosed basins. The energy decay is affected by friction, rather than dissipation through an opening. Resonance inside harbors due to tsunami waves can exacerbate the damages by amplifying the water level changes, currents and momentum fluxes. An example of assessing possible amplifications due to resonance in Haydarpasa port is selected as a case study. The results are given in this deliverable.

The study related to this report has been mainly focused on the assessment of spatial distribution of water level and current velocity amplifications due to the long wave motion inside Haydarpasa Port. In the study the inundation of wave has not been considered, however the model is capable to compute inundation. One of the noticeable facts is that the difference in spectral peaks among several gauge records is declarative of effect of basin geometry. The regular (e.g. rhombohedral shaped) basins having fully reflective boundaries (such as in Haydarpasa port) can cause resonance and hence amplification of the waves, since the energy inside harbour cannot diminish and may be focused at some locations.

The size, shape and depth of the basin affect the wave amplification according to the period of incident wave when the period coincides with one of the periods of free oscillations of the basin. In general, stronger oscillations occur in long and narrow inlets due to the low rate of energy dissipation and focusing. Inlets with rapid and severe shoal and abrupt contraction are susceptible, when the wave is forced to slow down with decrease in water column depth and the height grows (NOAA2014).

The data and experience gained from the simulations and their results indicate that the amplification of water level and current should be expected at corners of the inner basins as shown in the Haydarpasa port case. The regular shaped inner basins with reflective boundaries can also become critical regions such as the case in Haydarpasa port (Kian et al., 2015; Yalciner et al., 2015).

The resonance periods of the Haydarpasa port are computed as 1311, 374, 154, 111.6, 67.2, 54.6, 44.4, 40.2, 33.6, 28.2, 25.8, 20.4, 17.4, 16.2, 12 seconds (Table 4.1). These results indicate that additional amplifications may be expected in the port if the period of incident waves coincide with one of these values. The periods of tsunamis in the sea of Marmara may fit some of these periods. Moreover, the periods of waves generated in extreme storms may also be long enough to fit one of these resonance periods.

Wave energy dissipaters (absorbing boundaries) at critical locations inside the basin are one of the options to control the unexpected wave amplifications inside the harbors under extreme conditions and hence become one of the mitigation measures.

6 References

Altinok, Y., Alpar, B., Ersoy, S. and Yalciner, A.C. (2000) Tsunami generation of the Kocaeli Earthquake (August 17th 1999) in the Izmit Bay: coastal observations, bathymetry and seismic data. Turkish Journal of Marine Sciences, Institute of Marine Sciences and Management, University of Istanbul. December, 1999.

Altinok, Y., Ersoy, S., Yalciner, A. C., Alpar B., Kuran U. (2001) Historical tsunamis in the Sea of Marmara. International Tsunami Symposium ITS 2001, Seattle, August 7-9, 2001, 527-535.

Admire, A.R., Dengler, L.A., Crawford, G.B., Uslu, B.U., Borrero, J.C., Greer, S.D., and Wilson, R.I. (1982) Long-period motions of a moored ship induced by harbor oscillations, Coast. Eng. Japan, 25, 261-275.

Djumagaliev, V.A., Kulikov, E.A., and Soloviev, S.L. (1993) Analysis of ocean level oscillations in Malokurilsk Bay caused by tsunami of 16 February 1991. Science Tsunami Hazards, 11 (1), 47-58.

Girolamo, P. D. (1996) An experiment on harbour resonance induced by incident regular waves and irregular short waves. Coastal Engineering, 27, 47-66.

Henry, R.F. and Murty, T.S. (1995) Tsunami amplification due to resonance in Alberni Inlet: Normal modes. In: Y. Tsuchiya and N. Shuto (eds.) Tsunami: Progress in Prediction, Disaster Prevention and Warning. Kluwer Acad. Publ., Dordrecht, The Netherlands, 117-128.

Honda, K., Terada, T., Yoshida, Y., and Isitani D. (1908) An investigation on the secondary undulations of oceanic tides. J. College Sci., Imper. Univ. Tokyo, 108 pp.

Kian, R. Yalciner, A. C., and Zaytsev, A. (2014) Evaluating the performance of tsunami propagation models. Bauhaus summer school in Forecast Engineering, Weimar, Germany, 17-29 Aug, 2014.

Kian, R. Yalciner, A. C., and Zaytsev, A. (2015) Wave Amplification and Resonance in Enclosed Basins; A Case Study in Haydarpasa Port of Istanbul. IEEE/OES Eleventh CWTM, St.Petersburg, Florida, USA, 2-6 Mar. 2015 (submitted).

Korgen, B.J. (1995) Seiches. American Scientist, 83, 330-341.

Lynett. P. J. (2010) Modeling of Tsunami Currents in Harbors. American Geophysical Union, Fall Meeting 2010.

MarCom Working Group 53 (2009) Tsunami Disasters in Ports due to the Great East Japan Earthquake. Mitigation of Tsunami Disasters in Ports, PIANC.

MarCom Working Group 122 (2014) Tsunami Disasters in Ports due to the Great East Japan Earthquake. Mitigation of Tsunami Disasters in Ports. PIANC.

Mei, C.C. (1992) The applied dynamics of ocean surface waves. World Scientific, London, 740 pp.

Miles, J. and Munk, W. (1961) Harbor paradox. J. Waterways Harbor Division, ASCE, 87, 111-130.

Miller, G.R. (1972) Relative spectra of tsunamis. Hawaii Inst. Geophys. HIG-72-8, 7 pp.

Munk, W.H. (1962) Long waves in The Sea. J. Wiley, New York, 647-663.

Murty, T.S. (1977) Seismic Sea Waves - Tsunamis. Bull. Fish. Res. Board Canada 198, Ottawa, 337 pp.

NAMI DANCE Manual (2010) Developed by Zaytsev, C., Yalciner, A.C., Pelinovsky, E., and Kurkin, A. Tsunami Simulation/Visualization Code NAMI DANCE versions 4.9. http://www.namidance.ce.metu.edu.tr (Reviewed on July 3, 2014).

NOAA Technical Report NOS CO-OPS 079 (2014) An Examination of the June 2013 East Coast Meteotsunami Captured By NOAA Observing Systems. Silver Spring, Maryland, November 2014.

Okal, E. A., Borrero, J. C., and Synolakis, C. E. (2006) Evaluation of tsunami risk from regional earthquakes at Pisco, Peru. Bull. Seismol. Soc. Am. 96, 1634–1648, doi: 10.1785/0120050158.

Ozer, C., Karakus, H., and Yalciner, A.C. (2008) Investigation of Hydrodynamic Demands of Tsunamis in Inundation Zone. Proceedings of 7th International

Conference on Coastal and Port Engineering in Developing Countries, Dubai, UAE, February 24-28.

Ozer, C. and Yalciner, A.C. (2011) Sensitivity Study of Hydrodynamic Parameters during Numerical Simulations of Tsunami Inundation. Pure Appl. Geophys. 2083-2095.

Ozer, C., Yalciner, A. C., Zaytsev, A., Penilovsky, P. (2011) Tsunami hydrodynammics in coastal zones. European Geosciences Union, Vienna, Austria, 3-8 April, 2011.

Rabinovich, A.B. (1997) Spectral analysis of tsunami waves: Separation of source and topography effects. J. Geophys. Res. 102 (C6) 12,663-12,676.

Rabinovich, A.B., Thomson, R.E., and Stephenson, F.E. (2006) The Sumatra tsunami of 26 December 2004 as observed in the North Pacific and North Atlantic oceans. Surveys in Geophysics, 27, 647-677.

Rabinovich, A.B. and Thomson, R.E. (2007) The 26 December 2004 Sumatra tsunami: Analysis of tide gauge data from the World Ocean Part 1. Indian Ocean and South Africa. Pure Appl. Geophys. 164 (2/3), 261-308.

Rabinovich, A. B. (2008) Seiches and Harbour Oscillations. In: Kim, Y.C. (ed.) Handbook of Coastal and Ocean Engineering. World Sci., Singapore.

Raichlen, F. (1966) Harbor resonance. In: Ippen, I.T. (ed.) Estuary and Coastline Hydrodynamics. McGraw Hill Book Comp., New York, 281-340.

Sawaragi, T. and Kubo, M. (1982) Long-period motions of a moored ship induced by harbor oscillations. Coast. Eng. Japan, 25, 261-275.

Shimamoto, T., Tsutsumi, A., Kawamoto, E., Miyawaki, M., and Hiroshi, S. (1995) Field survey report on tsunami disasters caused by the 1993 Southwest Hokkaido earthquake. Pure Appl. Geophys. 144 (3–4), 665–691.

Titov, V.V., Rabinovich, A.B., Mofjeld, H., Thomson, R.E., and González, F.I. (2005) The global reach of the 26 December 2004 Sumatra tsunami. Science 309, 2045-2048.

Tsutsumi, A., Shimamoto, T., Kawamoto, E., and Logan, J. (2000) Nearshore flow velocity of Southwest Hokkaido earthquake tsunami. J. Waterw., Port, Coastal, Ocean Eng. 126 (3), 136–143.

Uslu, B. (2008) Deterministic and probabilistic tsunami studies in California from near and far field sources. PhD Thesis, University of Southern California.

Van Dorn, W.G. (1984) Some tsunami characteristics deducible from tide records. J. Phys. Oceanogr. 14, 353-363.

Wiegel, R.L. (1964) Tsunamis, storm surges, and harbor oscillations. Ch. 5 in Oceanographical Engineering, Prentice-Hall, Englewood Cliffs, N.J., 95-127.

Wilson, B. (1972) Seiches. Advances in Hydrosciences 8, 1-94.

Yalciner, A.C., Alpar, B., Altinok,Y., Ozbay, I., Imamura, F. (2002) Tsunamis in the Sea of Marmara: Historical documents for the past, models for the future. Marine Geology 2002, 445-463.

Yalciner, A.C. and Pelinovsky, E. (2007) A short cut numerical method for determination of resonance periods of free oscillations in irregular shaped basins. Ocean Engineering 34, Issues 5–6, 747-757.

Yalciner, A.C., Ozer, C., Karakus, H., Zaytsev, A., and Guler, I. (2010) Evaluation of coastal risk at selected sites against eastern Mediterranean tsunamis.

Proceedings of 32nd International Conference on Coastal Engineering (ICCE 2010), Shanghai, China.

Yalciner, A. C., Gulkan, P., Dilmen, D. I., Aytore, B., Ayca, A., Insel, I., and Zaytsev, A. (2014) Evaluation of tsunami scenarios for western Peloponnese, Greece. Bollettino di Geofisica Teorica ed applicata 55, n.2, pp. 485-500.

Yalciner, A. C., Kian, R., Aytore, B., and Zaytsev, A. (2015) Harbors and tsunami threat; a case study in the Sea of Marmara. 36th IAHR World Congress, Delft, Netherland, 28 Jun-3 July 2015 (submitted).

Zaitsev, A., Yalciner, A.C., Pelinovsky, E., Kurkin, A., Ozer, C., Insel, I., Karakus, H., Ozyurt, G. (2008) Tsunamis in Eastern Mediterranean, histories, possibilities and realities. Proceedings of 7th International Conference on Coastal and Port Engineering in Developing Countries, Dubai, UAE, February 24-28, 2008.

Review and reference page

Document information		
Document title Deliverable D6 - Numerical Modelling of Tsunamis in Harbours and Bays		***Document No.*** 20120768-06-R
Type of document Report	***Distribution*** Limited	***Date*** 3 March 2015 ***Rev. No & date*** 1 / 1 May 2015
Client CONCERT-Japan Joint Call Secretariat		
Keywords		

Geographical information	
Country, County	***Offshore area***
Municipality	***Field name***
Location	***Location***
Map	***Field, Block No.***
UTM-coordinates	

Document control

***Quality assurance according to* NS-EN ISO9001**

Rev.	Reason for revision	Self review by:		***Colleague review by:***		***Independent review*** by:		***Inter-disciplinary review by:***	
0	Original document								

Document approved for release	Date	Sign. Project Manager
	1 May 2015	Carl B. Harbitz

NGI

PARI

Middle East
Technical University
Civil Engineering
Department

Technische
Universität
Braunschweig

CONCERT JAPAN
Connecting and Coordinating
European Research and Technology Development with Japan

concertjapan.eu