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A 3D Numerical Study of Cyclone Gonu Waves Impact on Ramin Port

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ABSTRACT

In this paper the TELEMAC-3D model has been hired to simulate and study the high waves' interaction with coastal structures. Therefore a special arrangement of TELEMAC-3D has been prepared in this study to simulate wave generation, coastal processes, wave set-up and overtopping over coastal structures. Experimental data has been used to verify this arrangement of the model. Thereafter, the model has been used to simulate the interaction of waves induced by Cyclone Gonu and Ramin Port breakwaters. Visually comparisons between images provided by Iran Fisheries Organization during the Gonu event and the TELEMAC3D results conclude that the numerical model could simulate the interaction of Gonu induced wave and Ramin breakwaters with a good accuracy. Different kind of results like inundation area, wave overtopping discharge over the breakwaters and wave penetration in port were obtained in this simulation.

1. Introduction

Cyclone Gonu (Fig. 1), June 2007, is the strongest cyclone among all tropical cyclones recorded in Arabian Sea since 1945, the year which recording began in this region. Most of tropical cyclones generated in Indian Ocean tend to travel to Oman in the West or Pakistan and India in the North and only their swell waves reach to Iranian Coasts, therefore Gonu was exceptional. It killed 49 people in Oman and 23 people in Iran [1] in spite of on time warning systems' public awareness and early evacuation; otherwise much more lives could be lost.

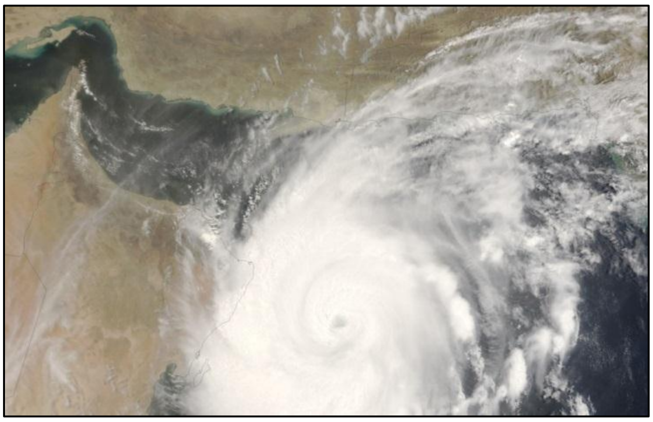


Figure 1. Cyclone Gonu (https://visibleearth.nasa.gov)

The maximum wind speed during Gonu on the Iranian Coast reached 58 km/h and about 4.5 m significant wave height was recorded outside of Chabahar bay in depth of 30 m, [1, 2].

After the Cyclone, The maximum watermark detected in the field observations was about 4 m above mean sea level in mud flats of Chabahar Bay [3]. On the other hand, on the Omani coast the inundation height reached up to 5 m [4].

Gonu is not the only powerful Cyclone reached to the Iranian Coasts; there are other evidences about strong cyclone crashing Iranian coasts before Gonu. The India Meteorological Department compiled an extensive summary of cyclonic storm tracks for the period from 1877 to 1970. Reviewing those tracks, four severe storms were identified to enter Oman Sea including storms happened in June 1889, June 1890, May 1898 and April 1901. However the "Best track" data of these events were weakened as they approached Iranian Coast. One might concluded that the Cyclone patterns has been changed due to climate change and made Gonu reach to Iranian Coast at a very strong situation [2].

Therefore strong Cyclone like Gonu may attack Iranian Coasts again in the future. That's why it is essential to estimate the effect of high waves induced by tropical cyclones on the Iranian coastal structures to check the design of existing structures and design the future structures.

This made many researchers to study the effect of cyclone Gonu on Iranian and Omani coastlines. Most of the studies were on the Gonu storm surge and inundation in both countries. Fritz et al. [4] observed the high water marks and inundation along Omani side in 2007 while Shah-hosseini et al [3] measured the water marks in Iranian side in 2008.

Khalilabadi and Mansouri [5] analyzed the hourly sea level recorded by tide gauges of the National Cartographic Center (NCC) at Jask and Bandar-Abbas to calculate the non-tidal sea level change during Gonu in Persian Gulf. Golshani and Taebi [1] numerically simulated Gonu and its resulting waves in the southern Iran using a time-dependent radius cyclone field and used the computed waves for extreme value analysis. Mashhadi et al. [6] also simulated the storm surges and wave characteristics during Gonu employing the SWAN and GETM models. However, to the authors' knowledge, there is no study on the effect of the Gonu induced wave on the coastal areas and structures.

Therefore in this this research, TELEMAC-3D has been hired to simulate wave generation, shoaling, refraction, diffraction, penetration as well as wave overtopping over coastal structures. The model has been verified based on Hsiao and Lin [7] experiments on solitary waves imping a seawall. After that, the interaction of high waves induced by the Cyclone Gonu with Ramin port breakwaters was simulated. The results then have been compared visually with the photos taken during the Cyclone in Ramin port. Ramin fishing port is located in the east of Chabahar, in the Southeast of Iran (Fig. 2). Its breakwaters were damaged by wave overtopping over them during Gonu event; however their stability was preserved (Fig. 3).

Figure 2. Aerial view of Ramin Port

Figure 3. Damaged in Ramin Port breakwaters resulted by wave overtopping during Gonu Cyclone

2. Numerical Model

2.1. Mathematical formulation

The TELEMAC-3D open source software is part of the TELEMAC modeling system developed and managed by a consortium of core organizations e.g. Artelia (France), Electricité de France R&D (EDF, France), and HR Wallingford (United Kingdom). TELEMAC-3D solves the RANS equations by the finite elements method through the vertical integration of the continuity equation and momentum equations [8].

$$\frac{\partial U_j}{\partial x_j} = 0 \qquad (1)$$

$$\frac{\partial U_j}{\partial t} + U_i \frac{\partial U_j}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} - g_j + \upsilon \Delta\left(U_j\right) + F_j \qquad (2)$$

U_i and U_j are velocity component in ith and jth coordinate directions (for three dimensional equations i and j =1, 2, 3), p is pressure, g_j= gravity acceleration in jth direction, ν_t kinetic eddy viscosity, ρ is water density. To simplify the solvation process, the pressure considered as the sum of hydrostatic pressure and a dynamic pressure term:

$$p = p_{atm} + \rho_0 g\left(\eta - z\right) + \rho_0 g \int_z^{Z_s} \frac{\Delta\rho}{\rho_0} dz + p_d \qquad (3)$$

Here, p_{atm} and p_d are the atmospheric and the dynamic pressure, η is the free surface elevation, ρ_0 is the reference water density. The turbulent viscosity can be estimated from a k-ε turbulence model. Thereafter the governing equations are:

$$\frac{\partial k}{\partial t} + U_j \frac{\partial}{\partial x_j} k = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + p - G - \varepsilon \qquad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + U_j \frac{\partial}{\partial x_j}\varepsilon = \frac{\partial}{\partial x_j}\left[\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}\left[P + \left(1 - C_{3\varepsilon}\right)G\right] - C_{2\varepsilon}\frac{\varepsilon^2}{k} \qquad (5)$$

$$P = \nu_t \frac{\partial \overline{U_i}}{\partial x_j}\left[\left(\frac{\partial \overline{U_i}}{\partial x_j} + \frac{\partial \overline{U_j}}{\partial x_i}\right)\right] \qquad (6)$$

$$G = -\frac{\nu_t}{\mathrm{Pr}_t}\frac{g}{\rho}\frac{\partial \rho}{\partial z} \qquad (7)$$

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \qquad (8)$$

where k is the turbulence kinetic energy, ε is the kinetic energy dissipation rate. P is a turbulence energy production term and G is a source term due to the gravitational forces. C_μ, Pr_t, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k and σ_ε are k-ε model contestants.

2.2. Model Verification

Since there was no nearshore wave measurement near the Ramin port during the Cyclone, the model has been verified against Hsiao and Lin [7] experiments on solitary waves imping a trapezoidal seawall on a sloped bed (Fig. 4). The physical characteristics of the selected experiment for the verification are summarized in Table (1). In this simulation, the bed and seawall act as rough wall. Slip boundary condition is used for the side walls and a variable free surface condition is placed as the wave generator in the inlet boundary.

After the simulation, the calculated water free surface configuration over the seawall has been compared with measurement data in four different stages of wave transmission over the seawall and illustrated in Fig. (5); as could be seen in the figure, TELEMAC-3D results have an acceptable accuracy. After testing the TELEMAC-3D accuracy in simulation of wave runup and overtopping over coastal structures, the model has been hired to simulate the runup and overtopping of Cyclone Gonu induced waves over Ramin port breakwaters.

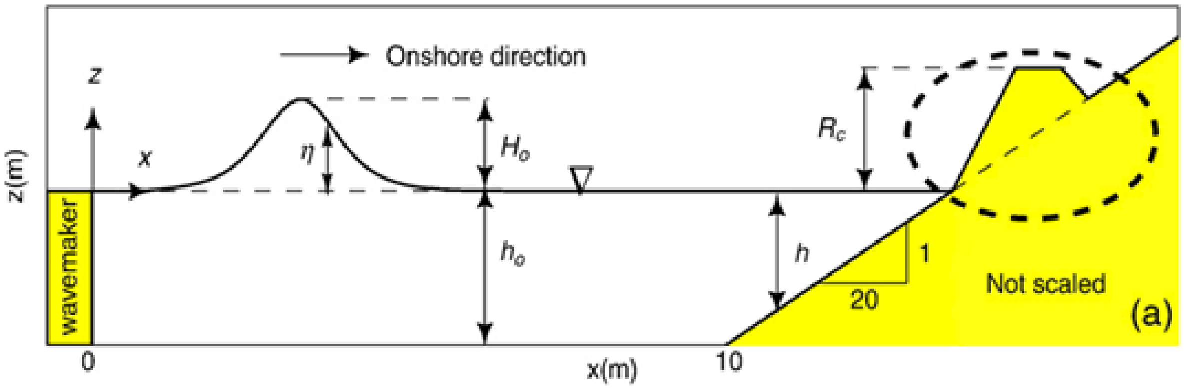


Figure 4. Sketch of wave flume layout [7]

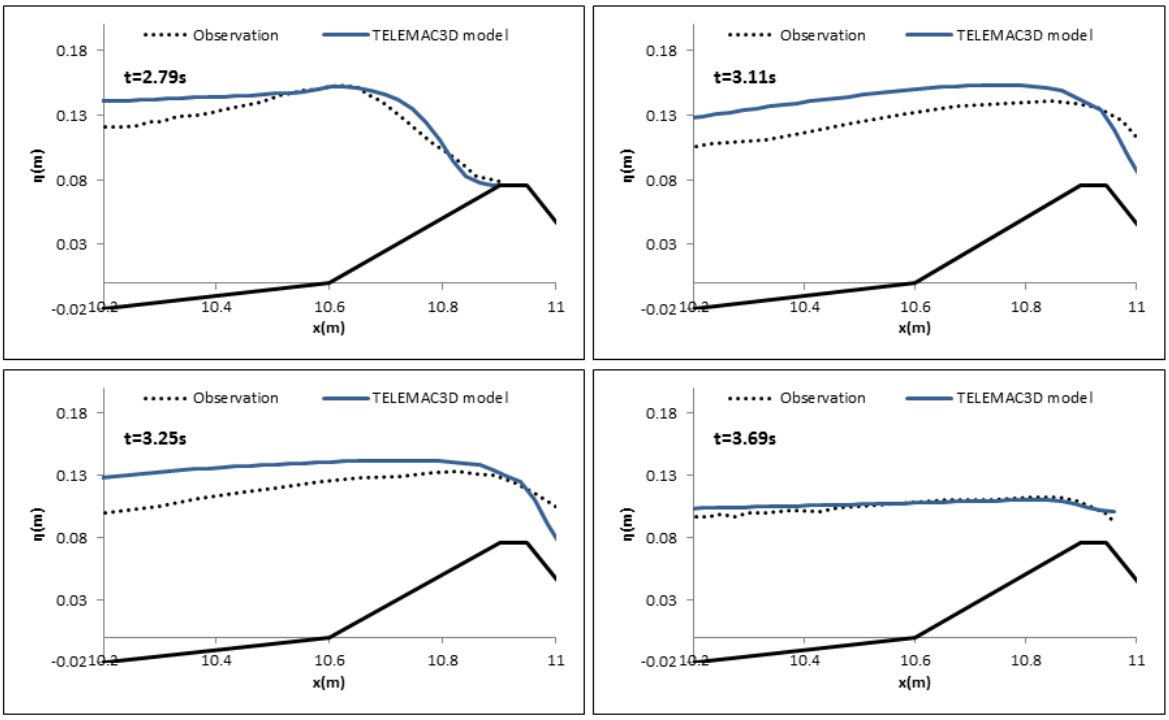


Figure 5. Comparison between numerical results and Hsiao and Lin (2010) experimental measurements

Table 1. The simulation characteristics based on Hsiao and Lin [7]

h_0 (m)	H_0 (m)	$\varepsilon = h_0/H_0$	R_C (M)
0.2	0.07	0.35	0.056

2.2. Model Setup

To run the model, the local bathymetry and free surface elevation in addition to wave condition near the offshore boundary are necessary. For bathymetry data, Ramin port hydrography provided by Iran Fisheries Organization in 2005 has been used. The numerical domain was discretized to triangular mesh with mean side length about 10 m. To achieve higher accuracy, the mesh size decreased to about 1 m around the breakwaters (Fig. 6). As if it's a 3D domain, it is divided to 5 layers in vertical direction. This number of layer was chosen based on try and error. More layers increase computation time without meaningful changes in the results; while fewer layers couldn't calculate the wave propagation and transmission well.

The East and West boundary are introduced as slip boundary condition. In the South, the inlet boundary, a wave generator should be defined by introducing a time varying free surface elevation at the inlet boundary. At the time of Gonu event, an AWAC current and wave profiler had been installed in 25.261° N and 60.650° E in 30 m depth as a part of measurement tools installation during the project MONITOR SB&B by Ports and Maritime Organization of Iran. Fig.7 shows the time series of significant wave height, peak period and wave direction measured during Gonu event.

The AWAC was located about 9 km from the South boundary of the numerical domain used in this research and in the same depth, therefore its measurements was suitable enough to be used as the offshore boundary condition of this simulation. The simulations of Mashhadi et al. [6] also showed that the wave height in the location of the AWAC and the south boundary of our numerical domain was almost the same in different time steps of Gonu event. Therefore we have chosen these measurements as the input waves for the south boundary condition.

To start the simulation we also need the free surface elevation covering tide and storm surge effects. As long as there was a tide gage installed inside Ramin port at the time, there was no difficulty to obtain the free surface variations. Fig. 8 shows the water free surface variations during Gonu event. For the simulation, one of the most extreme situations has been considered which was observed in 2006/06/06; table 2 summarized the hydrodynamic parameters of this situation. In this table $\Delta\eta$ is the difference between mean sea - $\bar{\eta}$ - level and the free surface influenced by tide and storm surge. Considering the mean sea level equal 2.9 m based on the Ramin port design studies (Fig. 9) we have:

$$\eta=\bar{\eta}+\Delta\eta=2.9+1.5=4.4\text{ m} \qquad (9)$$

Table 2. The hydrodynamics parameters for the simulation of Gonu induced wave crash on Ramin port breakwaters

$\Delta\eta$ (m)	*dir* (degree)	T_p (s)	H_s (m)
1.5	175	12.0	5.0

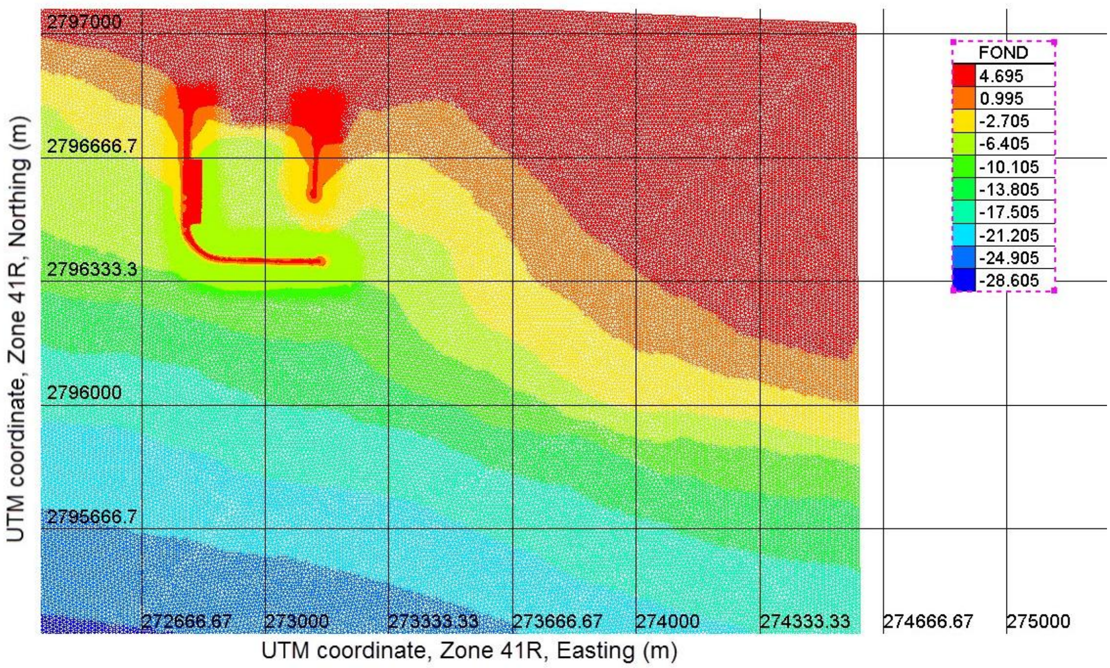


Figure 6. Computational grid for TELEMAC-3D based on Ramin port geomorphology

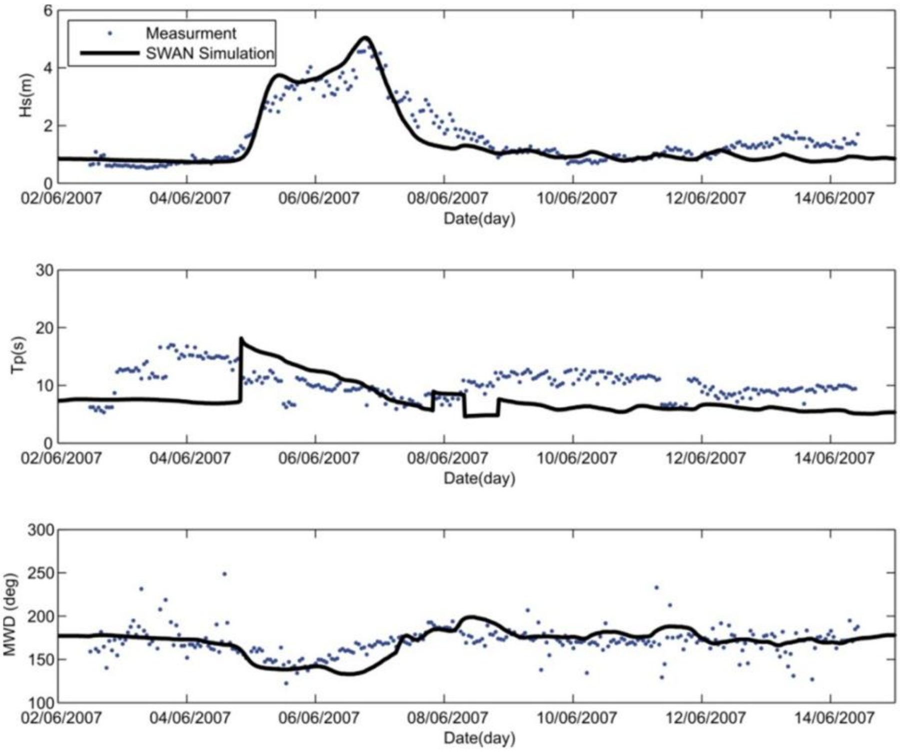


Figure 7. Significant wave height, peak wave period and mean wave direction measured by AWAC2 during Gonu event [6]

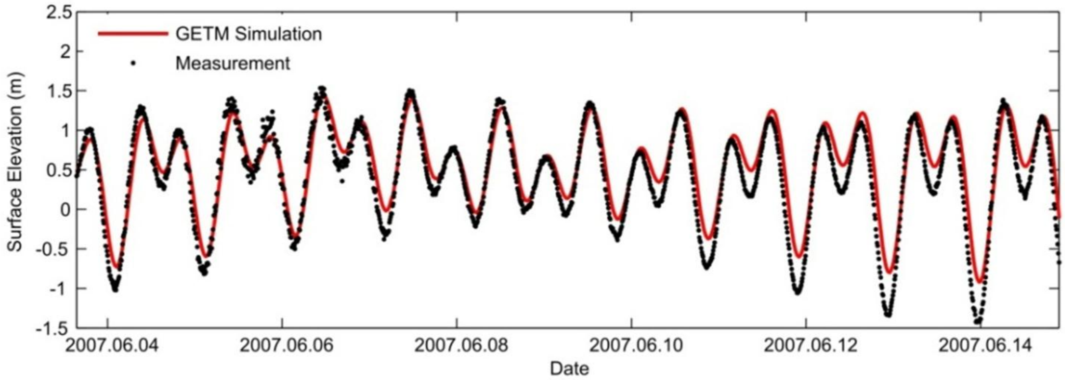


Figure 8. Free surface variation during Gonu event in Ramin port [6]

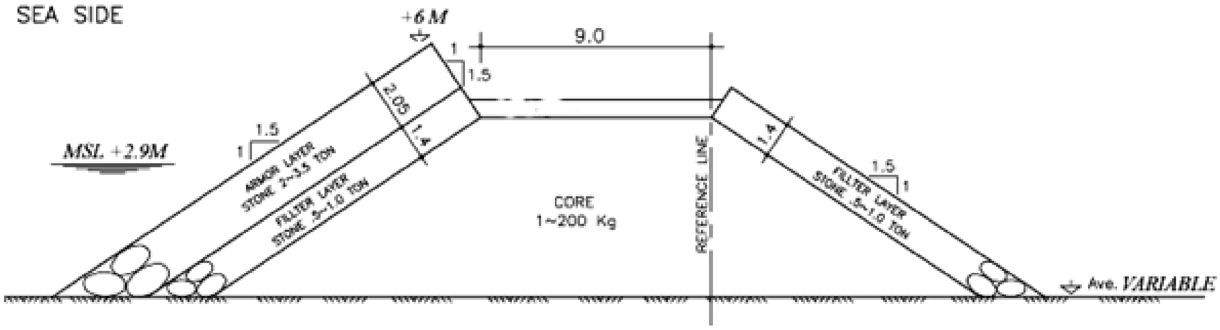


Figure 9. Ramin port breakwater sections versus sea levels

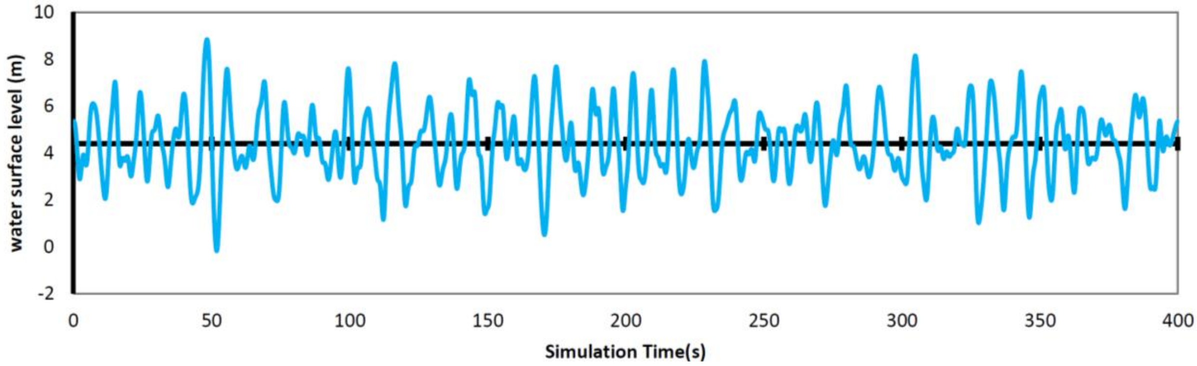


Figure 10. Free surface input time series

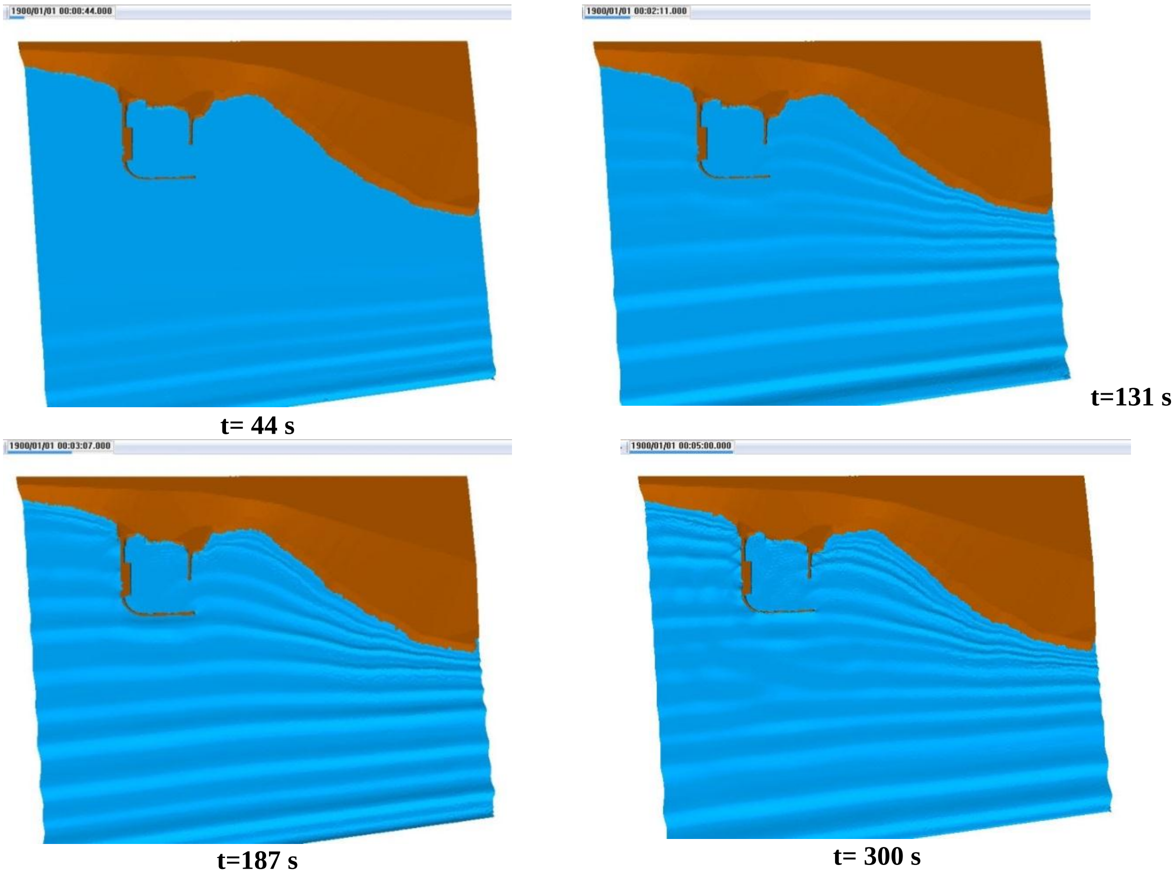


Figure 11. Wave propagation inside the numerical domain

Based on table 2 a wave time series based on JONSWAP wave spectrum was generate using WAFO module in MATLAB, this time series then has been used to introduce a time varying free surface boundary condition at the South boundary as illustrated in Fig. (10). At the bottom, a rough bed boundary condition has been considered.

The simulation start from still water condition which means the free surface elevation is set to mean water level. In addition zero velocities and hydrostatic pressure is considered in the entire domain as initial conditions.

4. Results and Discussion

The simulation was carried out for 5 minutes of the worst situation in Ramin port during the Gonu incident. Waves generated at the South boundary propagate inside the numerical domain. Fig. (11) shows us 3D views of free surface results in four different time steps of the simulation. As illustrated in the figure, waves start to response to the bed hydrography as they approaching the shoreline. At t= 187 s, wave diffraction is observed around the main breakwater tip. Also wave penetration inside the port basin is clear. At t=300, wave overtopping over the main breakwater is also recognizable.

To study the interaction of waves and breakwaters four different sections were selected in the simulation domain (Fig. 12). The maximum and minimum of the water line in the shore area is illustrated in this figure with two black continues lines. The maximum line can be considered as the inundation line. The variation of free surface can be extract in any location needed. For example Fig. 13 shows the free surface variation at Transect 2, Stations 1 to 6. As it could be seen in the figures, starting from Station 1 to Station 3, waves height reduces considerably during the reducing water depth, but as for Station 4, the water surface variations starts to get stronger as a result of interaction between waves and the main breakwater. In some points, water level exceeded 5.7 m which is the breakwater crest level. Station 5 is located inside the port basin, as one can see in the figure, the wave heights are less than 0.3 m there which show that the port remained almost calm during the simulation.

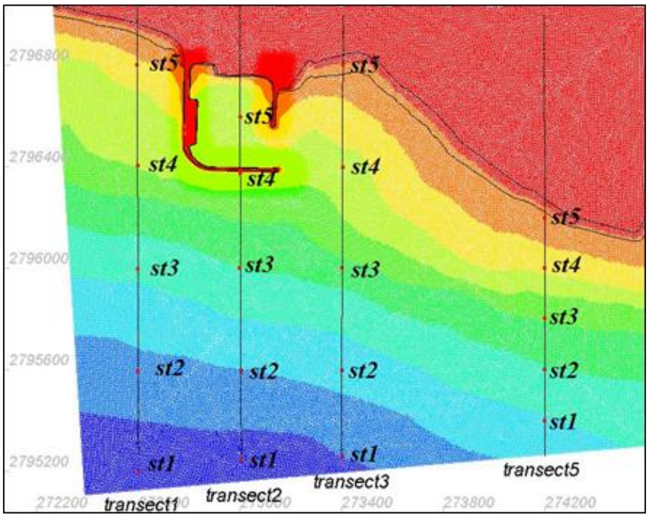
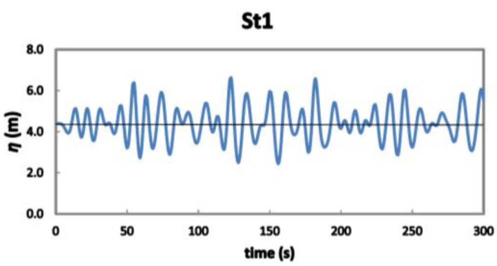


Figure 12. The selected sections for extracting outputs

Fig. (14) shows the maximum and minimum free water surface in front of the main breakwater at Transection 2. The wave overtopping over the breakwater can be observed clearly in this figure. The overtopping discharge can be estimated by multiplying average flow velocity and thickness of the water jet over the breakwater in each section. Fig. (15) shows this discharge for Transection 2. The maximum discharge reaches to 1.5 m^2/s in this section during the simulation.

Fig. 16 a and b show a comparison between 3D view of wave overtopping over the main breakwater and the photos taken by Iran Fisheries Organization; as it could be seen in this figure, the model results visually agree with the wave overtopping filmed in the port.



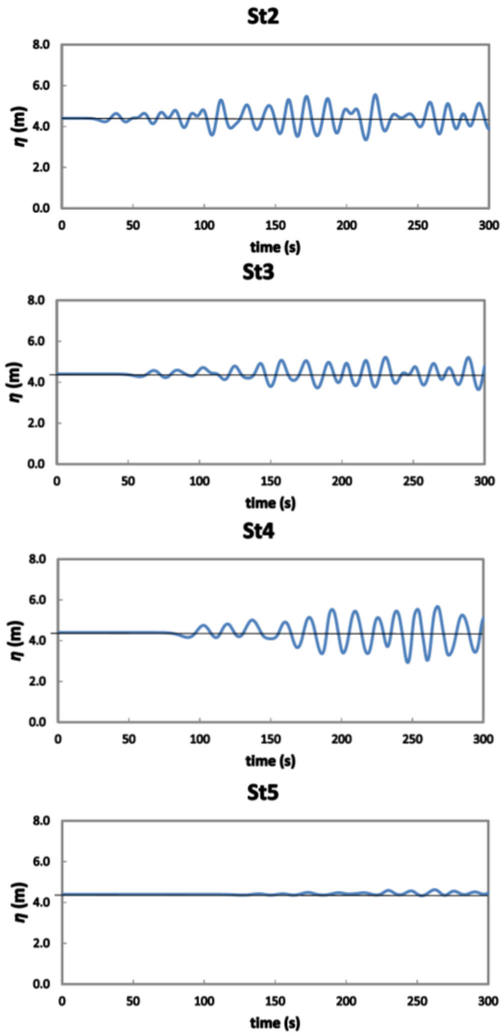


Figure 13. free surface variation in transection 2

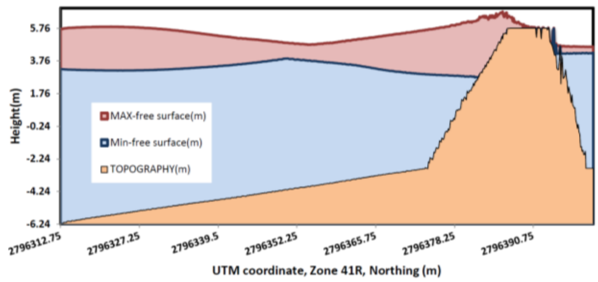


Figure 14. Maximum and Minimum free surface level in front of the breakwater, Transection 2

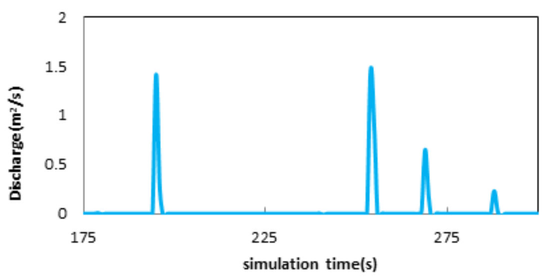


Figure 15. Overtopping discharge over the main breakwater, Transection 2

b

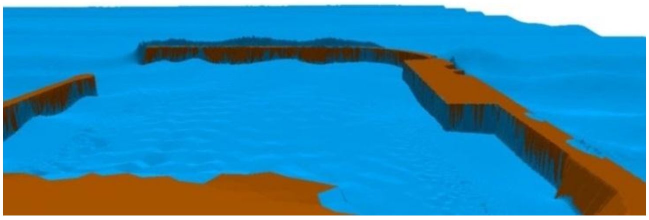


Figure 16. Comparison between a) real image of wave overtopping during the Gonu incident and b) the numerical results

5. Conclusions

TELEMAC-3D model has been hired for the first time to simulate high wave crash on coastal structures. For this simulation, Ramin port breakwaters were considered during Cyclone Gonu. The model was first verified versus Hsiao and Lin [7] experimental results because there wasn't any nearshore measurement during the cyclone. The simulation inputs were hydrography of Ramin port area, a variable free surface boundary condition as a wave generator in the South boundary and the free surface affected by storm surge. The 3D results show that the model was successful in simulating coastal process like wave shoaling, refraction and the diffraction at the tip of the breakwater.

Some wave overtopping was observed during the simulation which is in agreement with the videos taken by Iran Fisheries Organization videos during Gonu event. The overtopping discharge can be obtained from this simulation. It was also observed that in spite of wave diffraction and overtopping, the port basin was almost safe. According to this simulation, TELEMAC-3D could be hired in modeling of waves and coastal structure interactions as well as wave penetration inside ports and coastal process; however wave and current measurement are needed to verify and calibrate this model.

List of Symbols (Optional)

C_μ, Pr_t, $C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k and σ_ε	k-ε model contestants
g	Gravity acceleration
G	Source term due to the gravitational forces
k	Turbulence kinetic energy
p	Pressure
p_{atm}	Atmospheric pressure
p_d	Dynamic pressure
P	Turbulence energy production term
U_i	Fluid velocity in i^{th} direction
x, y, z	Coordinate directions
$\Delta\eta$	Difference between mean sea level and the free surface
ε	Kinetic energy dissipation rate
η	Free surface elevation
ν_t	Kinetic eddy viscosity
ρ	Water density
ρ_0	Reference water density

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