2-D Coastal Hydrodynamic Model to Evaluate the Performance of the Abu Dhabi Shore Protection System

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Abstract. The main shoreline of the Abu Dhabi City Main Island is facing the Arabian (Persian) Gulf from the north-west side and is exposed to continuous current wave action. Therefore, a shore protection system was developed on this side from the Main Island. The shore protection system consists of onshore and offshore breakwaters, huge volumes of damped sand, and an artificial island known as the Lulu Island. In this study, the performance of the current shore protection system of Abu Dhabi City Main Island was evaluated using the Costal Graphical Wave (CGWAVE) 2D-hydrodynamic model. The model can simulate the characteristics of the waves when they approach the breakwaters or the shoreline. Our study has shown that the breakwaters manage to dissipate most of the wave energy before the waves reach the Lulu Island, whereas this island protects the Abu Dhabi City shoreline by creating an elongated sea area between the island and the shoreline that is devoid of any wave action. The constructed shore protection system was also efficient in controlling beach erosion and flooding by damping the wave energy.

1. Introduction

Abu Dhabi City consists of a main natural island surrounded by several small natural and artificial islands. The artificial islands were developed along with the breakwaters to protect the main island from beach erosion due to the wave action. The main shoreline, the Corniche, of Abu Dhabi City Main Island is facing the Arabian (Persian) Gulf from the north-west side and is exposed to continuous current wave action. Therefore, a shore protection system was developed on this side from the Main Island. The general design criteria and guidelines for shore protection systems have been documented in many textbooks and manuals [1-4]. The development of the shore protection system of Abu Dhabi City Main Island went through three stages: 1) reshaping the shoreline by degrading and damping huge amounts of natural sand; 2) constructing onshore and offshore breakwaters; and 3) developing an artificial island, Lulu Island. The developed shore protection system of Abu Dhabi City is shown in Figure 1B.

The objective of this article is to evaluate the design of the current shore protection system of Abu Dhabi City Main Island. Due to the complex geometry of the shoreline protection system, a 2D-hydrodynamic coastal model was used in the evaluation of the design. The Costal Graphical Wave (CGWAVE) was used to simulate wave characteristics when these approach the shoreline and breakwaters. Two scenarios were simulated: scenario (1) of the Abu Dhabi City shoreline prior to 1970, when neither the breakwaters nor Lulu Island had been constructed (Figure 1A). Under this condition, the waves were approaching the shoreline without any diffraction causing washout of the sand and hence beach erosion. Historical records have documented that due to extreme wave and tidal...
action the beach area near the shoreline of the Main Island was occasionally flooding with the seawater extending for a few kilometers inside the island. Scenario (2) simulated the shoreline conditions after 2003, where the Abu Dhabi City shoreline was reshaped and protected by onshore and offshore breakwaters, and Lulu Island (Figure 1B). The Lulu Island assumed to provide additional protection to the Abu Dhabi City shoreline by diffracting the wave energy. Another function of the Island was to hide the offshore breakwaters and be used as a recreational area providing an aesthetic appeal for the shoreline.

2. Model description
The Costal Graphical Wave (CGWAVE) developed by the US Army Corps of Engineers [5] was used to simulate wave characteristics near the breakwaters and the shoreline. CGWAVE is a finite-element model that simulates surface gravity waves in coastal areas by solving the differential form of the two-dimensional elliptic mild-slope wave equation. This equation can be written as:

\[ \nabla \cdot \left( C_g \nabla \hat{\eta} \right) + \frac{C_g}{C} \sigma^2 \hat{\eta} = 0 \]  

(1)

where \( \hat{\eta}(x, y) \) is a complex surface elevation function, from which the wave height can be estimated, \( \sigma \) is the wave frequency under consideration (in radians/second), \( C(x, y) \) is the phase velocity \( s/k \), \( C_g(x, y) \) is the group velocity defined as \( \frac{\partial \sigma}{\partial \mathbf{k}} = nC \) in which \( n = \frac{1}{2} \left( 1 + \frac{2kd}{\sinh 2kd} \right) \), and \( k(x, y) \) is the wave number, defined as \( 2\pi/L \), and related to the local depth \( d(x, y) \) through the linear dispersion relation \( \sigma^2 = gk \tanh(kd) \), where \( L \) and \( g \) are the wave length and acceleration due to gravity, respectively.

Equation (1) simulates wave refraction, diffraction, and reflection (i.e. the general wave scattering problem) in coastal domains of arbitrary shape. The equation was modified as follows to include the effects of frictional dissipation:
\[ \nabla \cdot (CC_s \nabla \hat{\eta}) + \left( \frac{C_s}{C} \sigma^2 + i \alpha \omega + i C_s \sigma \gamma \right) \hat{\eta} = 0 \]  

(2)

where \( \alpha \) is a friction factor and \( \sigma \) is a wave breaking parameter. The following forms of friction factor and wave breaking parameter were used in CGWAVE:

\[ w = \left( \frac{2n \sigma}{k} \right) \left( \frac{2f_r}{3\pi} \left( \frac{ak}{2kd + \sinh 2kd} \right) \sinh kd \right) \]  

(3)

\[ \gamma = \frac{\chi}{d} \left( 1 - \frac{\Gamma^2 d^2}{4a^2} \right) \]  

(4)

where \( a \) is the wave amplitude, defined as one-half the wave height \( H/2 \); \( f_r \) a friction coefficient, a function in the Reynolds number and the bottom roughness. Typically, values for \( f_r \) are in the same range as for Manning's coefficient, and \( \chi \) and \( \Gamma \) in Equation (4) are empirical constants.

In addition to the above mechanisms, nonlinear waves may be simulated in the mean sea elevation. This is accomplished by incorporating amplitude-dependent wave dispersion, which has been shown to be important in certain situations. The nonlinear dispersion relation used is

\[ \sigma^2 = gk \left( 1 + (ka)^2 F_1 \tanh (kd) \right) \tanh (kd + kaF_2) \]  

(5)

where

\[ F_1 = \frac{\cosh (4kd) - 2 \tanh^2 (kd)}{8 \sinh^4 (kd)} \quad \text{and} \quad F_2 = \left( \frac{kd}{\sinh (kd)} \right)^2. \]

In defining the boundary conditions for a domain, it was assumed that along rigid, impermeable vertical walls, no water flows normal to the surface, giving

\[ \frac{\partial \hat{\eta}}{\partial n} = 0 \]  

(6)

However, along coastlines or permeable structures, the following partial reflection boundary condition applies

\[ \frac{\partial \hat{\eta}}{\partial n} = \alpha \hat{\eta} \]  

(7)

where \( \alpha = \alpha_1 + i \alpha_2 \) is a complex coefficient which can be represented as

\[ \alpha = ik \frac{1 - K_r}{1 + K_r} \]  

(8)

where \( K_r \) is the reflection coefficient.

Along the open boundary where outgoing waves must propagate to infinity, the Sommerfeld radiation condition applies

\[ \lim_{kr \to \infty} \sqrt{kr} \left( \frac{\partial}{\partial r} - ik \right) \hat{\eta}_s \to 0 \]  

(9)

In Equation (9), \( \eta_s \) is the scattering wave potential defined as

\[ \hat{\eta}_s = \sum_{n=0}^{\infty} H_n(kr) (\alpha_n \cos n\theta + \beta_n \sin n\theta) \]  

(10)
where $H_\nu(kr)$ are Hankel functions of the first kind. The Hankel functions of the second kind do not satisfy the Sommerfeld radiation condition at infinity and are hence excluded from the previous equation. The form of Equation (10) requires that the exterior domain is of constant depth and that straight, collinear and fully reflective coastlines are in the exterior region. To overcome these problems, an alternative scheme was developed to deal with the open boundary condition [6]. This consists of using the following parabolic approximation along the open boundary:

$$\frac{\partial \hat{\eta}_s}{\partial r} + p \hat{\eta}_s + q \frac{\partial^2 \hat{\eta}_s}{\partial \theta^2} = 0$$

(11)

where $p = \frac{k^2 r^2 + k_0^2 r^2 + ik_0 r + 0.25}{2ik_0 r^2}$ and $q = \frac{1}{2ik_0 r^2}$, in which $k_0$ is the wave number corresponding to the averaged water depth along the open boundary $\Gamma$. Within the model domain $\Omega$, the mild-slope equation applies (Figure 2). The parabolic approximation of Equation (11) will be used only along the semi-circular arc $\Gamma$ as the open boundary condition.

**Figure 2.** Definition sketch of CGWAVE domain [5]. In the figure $A_1$ and $A_2$ are the end points of the semi-circular arc $\Gamma$. 

3. Results
Due to the complex geometry of the Abu Dhabi City shoreline protection system, a 2D-hydrodynamic coastal model was used in the evaluation of the design. The Coastal Graphical Wave (CGWAVE) developed by the US Army Corps of Engineers [5] was used to simulate the wave characteristics when they approach the breakwaters and shoreline. The model was calibrated by matching the model wave outputs at the Um Al Dalkh Wave Station, located in the south-west of the model domain, with the measured values at the station. This was done iteratively by changing the wave height at the boundary until the simulated wave height at the station matches the measured value.

Two cases were simulated using CGWAVE: scenario (1) of the Abu Dhabi City shoreline prior to 1970, where neither the breakwaters nor the Lulu Island had been constructed, and as mentioned previously with the waves approaching the shoreline without any diffraction causing washout of the sand and beach erosion. In this scenario, we have examined the tidal action in terms of wave height and water surface elevation. Scenario (2) examined the Abu Dhabi City shoreline after 2003, representing current shoreline conditions, where the shoreline had been reshaped and protected by onshore and offshore breakwaters, and the Lulu Island. The Lulu Island was assumed to provide additional protection to the Abu Dhabi City shoreline by diffracting the wave energy. In this scenario, we wanted to examine the effectiveness of the current shore protection system in providing sufficient protection of the Abu Dhabi City shoreline by damping wave energy.

Figures 3 and 4 show for the first scenario the CGWAVE simulations for the sea water elevation and wave height, respectively. The figures show the simulation for wind blowing from the west direction with a speed of 94 km/hr. Figure 3 shows that the sea surface elevation varies from -5.0 to 4.6 m. The wide variation in the sea surface elevation occurs in the deep water due to various combinations of wind effect, water currents, and oscillatory and tidal wave interaction. However, this variation diminishes in the shallow water near the shoreline due to disruption processes such as reflection, refraction, and diffraction. The negative sign indicates that the elevation of the ocean wave is below the mean sea level, while the positive sign indicates that the elevation of the ocean wave is above the mean sea level. Figure 4 shows that the wave heights vary from 0.1 to 3.0 m. It is true that the ocean waves lost part of their energy as they approached the shoreline, but the energy is still great enough for the waves to reach the shoreline at heights that allow them to cause beach erosion.

Figure 3. Predicted water surface elevation for scenario 1 of Abu Dhabi City shoreline
From Figures 5 and 6 of the second scenario, it can be seen that the offshore breakwaters dissipate most of the ocean wave energy before the waves reach Lulu Island and then the island completely hinders the waves from reaching the Abu Dhabi City shoreline. Figure 5 shows that some waves are still reaching the Abu Dhabi City shoreline from the openings on both sides of the island, but they have very little energy left in them. It is also evident that some areas behind Lulu Island are completely devoid of any wave action due to the offshore breakwaters; the water is almost completely still there. The wave heights along the shore and around the Lulu Island are almost zero as can be seen in Figure 6.
Figure 6. Predicted wave height for scenario 2 of Abu Dhabi City shoreline

4. Conclusion
The current article examines the design of the constructed shore system of Abu Dhabi City Main Island in terms of its efficiency to protect the Abu Dhabi shore from wave action and the consequent beach erosion. Two cases were investigated using a 2D-hydrodynamic coastal model, namely: Scenario (1) with the shoreline as it existed in its natural condition prior to 1970, where the breakwaters and an artificial island, the Lulu Island, did not exist; and Scenario (2), where the modified shoreline, after the 2003 interventions that included the constructed breakwaters and Lulu Island was modelled. Our study has shown that the breakwaters manage to dissipate most of the ocean wave energy before the waves reach Lulu Island, whereas this Island protects the Abu Dhabi City shoreline by creating an elongated sea area along the city’s shoreline that is devoid of any wave action. The simulations have also shown that the proposed design of the shore protection system was successful in controlling beach erosion and flooding by damping the wave energy.

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