Wave Model for the Design of Sustainable Coastal Infrastructures at an Industrial Site in Tuban, East Java

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Abstract. This study focuses on the use of computational model in the design of a breakwater structure, which aims to determine the propagation pattern of the long-term ocean waves, in order to understand their propagation from the deep waters, and to determine the distribution of their energy around a proposed breakwater construction site. The method used is computational simulation of the wave model using the 2D Boussinesq Wave (BW) Module of MIKE21 software. The simulation used an incoming wave of 4.6 m high, which corresponds to the 100 years return-period value. The results show that the existing breakwater layout can protect the harbour by reducing the incoming wave height by up to 75%. At the proposed design condition, the propagation pattern of the incoming wave slightly differs from the existing condition. The presence of the slopes on both sides of the channel changes the wave direction outwards due to shoaling effects, and consequently, larger concentration of wave energy occurs at some parts of the proposed breakwater design. Results from the model are useful for the design of the new breakwater structures, which is designed according to the predicted wave energy distribution.

Keywords: breakwater design, numerical model, ocean wave, Tuban

1. Introduction

1.1. Background

An industrial facility in Tuban, East Java, is facing problems with the shoaling of its navigation channel and the damaged breakwater which protects its harbour and ports. Along with the planned revitalisation of the PT Trans-Pacific Petrochemical Indonesia (TPPI) ports and navigation channel, a new breakwater structure is to be developed to strengthen an existing and aging breakwater consisting of cellular cofferdam, as illustrated in figure 1. It is desirable to understand the distribution of wave forces acting on the new structure compounds, so that an efficient and safe design of the new structure can be achieved. The presence of the proposed deeper navigation channel is also of great importance to be investigated, with respect to its effect on the incoming wave behaviour and the impact on the harbour and the ports in the area [1,2,3]. As one of the design considerations for the design of the new TPPI port rubble mound breakwater, the magnitude of the incident wave must be determined, especially in extreme conditions [4]. In this case, wave propagation from the deep sea towards the
The coastal area, especially the TPPI and surrounding areas, must be modeled. The wave propagation model must be able to show the phenomenon of shoaling, refraction of the direction of propagation due to variations in bathymetry, diffraction by natural barriers or structures (buildings), and reflection by coastlines or structures (buildings). Numerical models are powerful tools to assist in estimating the wave transformation and deformation in engineering practice [5]. Mathematical or numerical modeling of the ocean waves have been widely used in the design of coastal structures [6] [7]. The Boussinesq model, in particular, was used to characterize the long wave agitation in the ports [8].

![Image](a)

![Image](b)

**Figure 1.** Illustration of two problems faced by PT TPPI Tuban (a) and the proposed solutions (b).

This study aims to model the long-term (100 years) return-period ocean waves, to understand their propagation from the deep waters to the coasts, and to determine the distribution of wave energy in terms of significant wave heights around the planned breakwater construction site, which is of rubble mound type [9].

1.2. **Location of study: TPPI industrial site, Tuban, East Java**

The location of the study is situated around PT. TPPI Tuban, Tuban district, in the northern part of East Java (6.77° S, 111.95° E). The area comprises of a foreland (tanjung Awar-awar), with sandy beaches at some parts and characterized by the presence of TPPI Industrial site. The dominant current in the area flows to and from the west-northwest, at an average speed of 0.15 m/s. The dominant wind direction throughout the year is from the east and the west [10]. The seabed of Tuban waters consists mainly clay, varying from very soft to soft and becoming firm at depth [11]. This study is mainly based on the field data and results of numerical modeling. Field survey was conducted at the location on January 2019 [12], while the modeling activities were carried out at the Computing Test Laboratory, Port Infrastructure Technology and Coastal Dynamics (BTIPD) - BPPT in Yogyakarta [13]. The domain (area) of the study is shown in the following figure.

![Image](a)

**Figure 2.** Location of study: TPPI industrial site, Tuban, East Java (6.77° S, 111.95° E).
1.3. MIKE21 Boussinesq Wave (BW) module

MIKE 21 BW (Boussinesq Wave) Module is part of MIKE software package developed by DHI. MIKE 21 BW is capable of reproducing the combined effects of all important wave phenomena of interest in port, harbour and coastal engineering which includes shoaling, refraction, diffraction, wave breaking, bottom friction, moving shoreline, and partial reflection and transmission. A major application area of MIKE 21 BW is determination and assessment of wave dynamics in ports and harbours and in coastal areas. Applications related to the 2D MIKE21 BW module include determination of wave disturbance caused by wind-waves [14] and propagation of long wave into a port [8]. Misra (2011) demonstrated the use of MIKE21 BW to investigate wave interaction with deep-draft navigation channels [2].

2. Method

2.1. Work Stages

Methods of the study include field data collections and analysis such as sea water level, bathymetry and coastline measurements. Wind and wave data are gathered from other sources. Computational simulation of the wave model is carried out using the 2D Boussinesq Wave (BW) Module of MIKE21 software from DHI (Danish Hydraulic Institute). The existing condition and one layout of the proposed design of breakwater structure were tested, each of which were simulated and analysed against an incoming wave from the Northwest of 4.6 m high, which corresponds to the 100 years return-period value. The study stages are summarised as:

- secondary data collection of regional wind and wave data
- secondary data collection of bathymetry
- digitization of coastline data from Google Earth
- field survey: bathymetry and tide data of the TPPI area.
- sea wave data analysis and determination of wave heights and wave periods for return periods of 100 years.
- simulation using the Boussinesq Wave (BW) module of MIKE21 software from DHI.
- analysis of results

2.2. Governing Equations

The equations used to describe this wave propagation in MIKE21 Boussinesq Wave (BW) modeling are as follows [14]:

Continuity

\[
n \frac{\partial \xi}{\partial t} + \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} = 0
\]  

(1)

X momentum

\[
n \frac{\partial P}{\partial t} + \frac{\partial}{\partial x} \left( \frac{P^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{h} \right) + \frac{\partial R_{xx}}{\partial x} + \frac{\partial R_{xy}}{\partial y} + F_x
\]

\[
n^2 gh \frac{\partial \xi}{\partial x} + n^2 P \left[ \alpha + \beta \frac{P^2 + Q^2}{h} \right] + gP \sqrt{P^2 + Q^2} \frac{h^2 C^2}{n^2} + n \Psi_1 = 0
\]

(2)

Y momentum

\[
n \frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{PQ}{h} \right) + \frac{\partial R_{yy}}{\partial x} + \frac{\partial R_{xy}}{\partial y} + F_y
\]

\[
n^2 gh \frac{\partial \xi}{\partial y} + n^2 Q \left[ \alpha + \beta \frac{P^2 + Q^2}{h} \right] + gQ \sqrt{P^2 + Q^2} \frac{h^2 C^2}{n^2} + n \Psi_2 = 0
\]

(3)

where the Boussinesq dispersion terms \( \Psi_1 \) dan \( \Psi_2 \) are defined by...
\[ \psi_j = -\left( B + \frac{1}{3} \right) d^3 \left( \frac{P_{,,x,x} + Q_{,,x,y}}{x_{,x} + x_{,y,y}} \right) - n B d^3 \left( \frac{P_{,,x,x} + Q_{,,x,y}}{x_{,x} + x_{,y,y}} \right) \]

\[ - dd_x \left( \frac{1}{3} P_{,,x} + \frac{1}{6} Q_{,,x} + n B d \left( 2 \frac{x_{,x} + x_{,y,y}}{x_{,x} + x_{,y,y}} \right) \right) - dd_y \left( \frac{1}{6} Q_{,y} + n B d \frac{x_{,y}}{x_{,x} + x_{,y,y}} \right) \]

\[ \psi_j = -\left( B + \frac{1}{3} \right) d^3 \left( Q_{,y} + P_{,x} \right) - n B d^3 \left( \frac{x_{,y}}{x_{,x} + x_{,y,y}} \right) \]

\[ - dd_x \left( \frac{1}{3} Q_{,y} + \frac{1}{6} P_{,x} + n B d \left( 2 \frac{x_{,x} + x_{,y,y}}{x_{,x} + x_{,y,y}} \right) \right) - dd_y \left( \frac{1}{6} P_{,y} + n B d \frac{x_{,x}}{x_{,x} + x_{,y,y}} \right) \]

Subscript \( x, y \) and \( t \) denotes partial differentiation with respect to space and time respectively.

Symbol List

- \( P \): flux density in the x-direction, m\(^3\)/m/s
- \( Q \): flux density in the y-direction, m\(^3\)/m/s
- \( B \): Boussinesq dispersion factor
- \( F_x \): Horizontal stress term in x-direction
- \( F_y \): Horizontal stress term in y-direction
- \( x, y \): Cartesian co-ordinates, m
- \( t \): time, s
- \( h \): total water depth (= \( h + \xi \)), m
- \( d \): still water depth, m
- \( g \): gravitational acceleration (\( = 9.81 \) m/s\(^2\))
- \( n \): porosity
- \( C \): Chezy resistance number, m\(^{0.5}\)/s
- \( \alpha \): resistance coefficient for laminar flow in porous media
- \( \beta \): resistance coefficient for turbulent flow in porous media
- \( \xi \): water surface level above datum, m

2.3. Model setup and scenarios

The setup and scenario to model the incoming waves at extreme conditions (100 years return period) were done to ensure that the model can show the phenomenon of shoaling, refraction in the direction of propagation due to variations in bathymetry, diffraction by natural barriers or structures (buildings), and reflection by coastlines or structures [14]. The following points describe the model specifications and modeling scenarios (see Figure 3):

a. Model domain is a rectangle measuring 4.2 km x 3.2 km.

b. 2 model geometries were tested: current conditions (existing) and developed (design) conditions. The existing geometry includes the current condition of the coastline, the current structure of existing breakwater, and the current condition of bathymetry of the port and navigation channel. The developed (design) condition is the present condition with the addition of a new rubble mound breakwater and dredged navigation channel to \(-13 \) m.

c. The model domain is discretized (divided) into a computational cell (grid) matrix of 905x675 elements, each sized at 5 meter.

d. Bathymetry data from GEBCO and field surveys are interpolated in the computational domain.

e. The input wave is an incoming 100 years return period wave coming from the Northwest or 315 degrees, which is 4.6 m high and 8.7 sec period [10] as shown in table 1.

**Table 1. Return period waves in Tuban region**

| Return Period (years) | Wind Speed \( U_{10,10} \) (m/s) | Wave Height \( H_s \) (m) | Wave Period \( T_{H_s} \) (s) |
|-----------------------|-----------------------------|-----------------------------|-----------------------------|
f. The water level is assumed to be at HWL (high water level) conditions, which is +0.96 meters from MSL (mean sea level) according to survey results by BTIPDP [12].

g. The incoming wave is assumed to occur in the western monsoon (early January), where the dominant direction of the wave is from the Northwest [10].

h. Sponge layer (damping layer) is applied to the outer boundaries (open boundaries) of the model domain, while the porosity layer is defined on the coastline and coastal structures such as breakwater and docks.

i. Data extraction and analysis is carried out at several points (locations) so that the wave height at the return-period condition can be determined, as well as the amount of wave energy reduction by the existing coastal structure and the proposed (designed) structures.

3. Results and discussion

3.1. Existing conditions

Figure 4 below shows the variation of water surface elevation at one moment in time, for existing configuration under an incoming extreme wave of 4.6m, which corresponds to the height of the wave that occurs approximately once in 100 years. The wave propagation patterns for existing conditions are shown in the Figure, where the color scale shows the water level.

The water level variation in figure 4 shows the propagation pattern of the incoming wave. The presence of refraction (changes in direction) due to variations in bathymetry, as well as reflection by breakwater structures and other structures at the TPPI port can be seen clearly from the results of the
modeling. At some locations, especially on the outer side of the breakwater structure, superposition between incoming and reflected waves produces waves that reinforce or reduce each other, depending on the phase difference between the incident wave and the reflected wave.

Figure 5. Waveheight distribution at the harbour and ports of TPPI for existing conditions.

Figure 5 shows the energy distribution in terms of significant wave height. The color scale shows the significant wave height (Hs), which is clarified by the label on the contour. This figure also illustrates the effectiveness of breakwater in reducing wave energy to maintain the tranquility of the harbour. In this figure some significant wave height (Hs) values are shown at several important locations around the harbour, breakwater and SWI (sea water intake) for the 100 years return period wave. Significant wave heights at the 3 ports (docks) account for around 1.1 to 1.7 meters.

3.2. Developed (design) conditions
The propagation patterns of the 100-yearly wave for the proposed design conditions are shown in Figure 6. The color scale shows the water level. The results show that there is refraction due to variations in bathymetry on both sides of the navigation channel where there is persistent slope starting from the harbour towards the open waters. It also shows the reflection by the breakwater structure and other structures in the TPPI port. In the gap (passageway) between the existing and the new breakwater structures, the wave height gradually decreases. The presence of a sediment control structure also dampens the waves approaching the sea-water intake (SWI) pool.

Figure 6. Water level variation for developed (design) conditions.

The following figure shows the significant wave height (Hs) distribution and illustrates the effectiveness of breakwater in reducing wave energy into the harbour. It is clear that the presence of abrupt changes in bathymetry on the sides of the proposed navigation channel causes concentration of
wave energy. This affects the wave that penetrates into the harbour, where bigger waves are measured at the three main ports of TPPI, varying from 1.6 to 2.1 m.

**Figure 7.** Waveheight distribution at the harbour and ports of TPPI for developed conditions.

The results for the developed (design) conditions with the presence of deep navigation channel show that there is concentration of wave on both sides of the channel (where there is abrupt change in the bathymetry along the sides of the channel). Unfortunately, this concentrated wave energy propagates towards the entrance of the harbour and consequently, larger waves are noted throughout the harbour including the 3 main ports, where there is an increase of waveheight by 25 to 30% compared to existing conditions (see figure 8). The non-linear Mike21 BW model shows the non-linear effect of the navigation channel with significant consequence on the wave penetration into the harbour. The slopes on both sides of the channel create diffraction and refraction which result in wave focusing effect, which also conform with the results obtained by Gruwez et al [6].

**Figure 8.** Wave energy concentration on both sides of navigation channel.

Due to the changes in wave propagation patterns in the proposed (design) condition, especially near the navigation channel, the outline of the toe of the breakwater was modified as described in the picture [9]. Figure 9 shows the detailed waveheight (Hs) distribution around the head of the proposed rubble mound breakwater. The waves strike the front part of the new rubble mound breakwater structure at different waveheights as observed at several points. The peak Hs value occurs at the tip at around 4.9m. The wave energy, as represented by the wave height, varies along the sides of the breakwater, thus the minimum strength that is needed at different parts of the breakwater also varies accordingly. This must be taken into consideration when selecting the appropriate armor unit for the safe and cost-effective breakwater. In other words, the weights and sizes of the armor units can be varied for efficiency.
4. Conclusions
It has been shown that the Boussinesq Wave (BW) module of MIKE 21 is capable of providing good estimation on the propagation pattern and wave energy distribution, which is useful in the design of a coastal structure such as breakwater. The non-linear BW model has taken into account phenomena such as refraction, diffraction and reflection due to interaction of the waves with the coastline and coastal structures. Distribution of significant wave height (Hs) for 100 years return-period wave is obtained at the harbor, ports, and around the proposed coastal structure. For an incoming wave of 4.6 m high, the existing breakwater can reduce the wave height in the harbor to about 10-15% of the original value. However, the results for the new (proposed) design shows that slightly bigger waves penetrate the harbor due to wave energy concentration along the navigation channel, which agrees with the results from previous studies. Waveheight around the proposed breakwater varies, where the maximum value of about 5 m occurs at the front part. The sea-side of the mid-section is subject to 2.7 to 3 m wave, while on the harbour-side can be as low as 0.5 m. This variation of waveheights around the structure can be used as guidelines in determining the required strength at different parts of the structure. Therefore, modeling of ocean wave has proved to be an essential stage in the design of coastal structures such as breakwaters, in order to achieve efficient design.

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Acknowledgment
This material is based on work executed at Port Infrastructures & Coastal Dynamics Laboratory (BTIPDP-BPPT) in co-operation with PT TPPI Tuban, East Java in 2019. In that respect, the authors wish to thank those involved in the field survey for providing valuable data for the model. We would also like to thank the reviewers in BTIPDP for their comments and suggestions.