Submerged breakwater effectiveness based on wave spectrum changes in Panjang Island, Jepara

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Abstract. Jepara government took the initiative to construct submerged breakwaters to reduce wave force. Development planning of submerged breakwater need to analyze the reduction of wave spectrum (H and T) around the breakwaters. On this research we applied two variances of structure. Analysis of wave spectrum used 2D hydro-dynamic mathematical model. Data that has been used for input model there are bathymetry data, wind data along 2009-2019, tide data, and coastline data. Wave height and wave period data was obtained by wind data along 2009-2019 which was calculated using DNS method. Model simulation of wave height and period applied in two formation at 5 wind direction (North, Northeast, East, Southeast, and South). Effectiveness is known by the changes of Hmax and T while passing the structure. Based on simulation model, highest wave height found during southeast wind and reduce after passing the breakwaters. Breakwaters with 4 structure (formation 2) has higher reduction percentage. Incoming wave height values decrease after passing submerged breakwater.

1. Introduction

Coastline morphology is easier to change due to several processes such as erosion, sedimentation and coastal zone utilization [1]. Coastal erosion that creates change of coastline occurs by several natural factors like wave erosion, longshore current, wind [2], volcanic and tectonic activity [3]. Ocean wave are dominant factor that effects coastal erosion. Coastal erosion can be occurs by coastal sediment transport and the growth effects by wave height (H).

Moving shoreline that caused by wave force has been occurred at eastern side in Panjang island. Panjang Island located in western side of Kartini Port, Jepara and it is used for tourism and religious activities [4]. Coastal erosion induces land subsidence and it is makes damage to beach buildings. This erosion is affected by wave force that formed by ship activities and strong wind blows. During east monsoon (July-September) strong wind blows from east to west, it is created higher wave and has been dominant factor to coastal erosion [5]. Ocean wave is one of parameters that effects to coastal and ocean zone changes in addition to current or tidal [6]. This erosion needs to mitigate before it is cause more complex problem to environment.

Jepara government took initiative to develop mitigation for coastal erosion in Panjang Island. In this case, the government will develop breakwaters that can be wave force reduction. The types of breakwaters that will be located at eastern side Panjang Island are submerged breakwater [5]. Submerged breakwater is a breakwater that the top of the structure is below to Low Lowest Water Level (LLWL) [7]. Some literature looks at the widespread use of LCB in various countries such as the USA, UK, Japan, and Italy [8]. in Japan the use of LCB is becoming very popular and is more widely used than conventional breakwaters [9]. This breakwater has a structural form like artificial reefs that can be equal to wave reduction by coral reefs [10]. Submerged breakwater is widely used in many countries. The submerged breakwaters are becoming a favourite in defending the shoreline erosion, build artificial
beach to reduce the need of sand supply [11], retained aesthetic value, and assure water circulation to maintain good water quality for bathing purpose [12,13].

Development planning of submerged breakwater needs to analyze the effectiveness of the structures. Purpose of this research is to calculate the effectiveness of the structures. Structure effectiveness is known by the change of wave spectrum (H and T) after passing the breakwaters.

2. Methodology

2.1. Scope

Structure effectiveness analyze are needed to calculated percentage of reduction. On this research, we made two variance breakwater formations. Both formations have a different length, same gap, same width, and located in same depth (Figure 1).

![Figure 1. Illustration of two variance formations structure](image)

Two dimensional (2D) hydro-dynamic mathematical model is applied for wave simulation on two variance breakwater formations. Effectiveness of the structure is known by changes of wave height (H) and wave period (T) after passing the breakwaters.

![Figure 2. Study area Panjang Island, submerged breakwater located at eastern side of the island (yellow filled)](image)

2.2. Data collection

Model simulation with 2D hydro-dynamic mathematical model needs several hydro-oceanography data input. Bathymetry data obtained by measurements with echosounder instrument on October, 2018 and March, 2019 and bathymetry data obtained from ocean topography map (Table 1). Tide data collected from Meteorology and Climatology Agency during bathymetri data measurement.
Tide data are used for correcting bathymetry data. Consideration of obtained tide data from Meteorology and Climatology Agency in Semarang by reason of it has same constituent harmonic value.

Wind data for input model along 2009-2019 every 3 hours were obtained from www.ogimet.com. This wind data has been analyze with DNS method [14] to calculate wave height (H) and wave period (T).

Table 1. Data collection for input model

| No | Data          | Obtain                                                                                          | Description                                           |
|----|---------------|-------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| 1  | Bathymetry    | • Measurement with Garmin Echosounder 585 instrument  
              | • Ocean topography map by Hydro and Oceanography Service | Ocean bathymetry used for input model                 |
| 2  | Tide          | • Tide data from Meteorology and Climatology Agency, Semarang  
              | | Tide data on October 2017 and March 2018 are collected to correcting measurement result of bathymetry data |
| 3  | Wind Data     | • Wind data that is speed and direction along 2009-2019  
              | | Wind data is collected for forecasting and input model                           |
| 4  | Coastline Data| • Obtained from Geographic Information Agency  
              | | Coastline data used for input model                                               |

2.3. Wave forecast data analysis

Wind data that has been collected along 2009-2019 from www.ogimet.com, analyzed with DNS method [14] to calculated wave height (H) and wave period (T). The equation of DNS method [14] given below:

\[
H_s = 0.0016 U^2 + 0.0406 U \\
T_s = 0.15 U + 2.892
\]

Where \(H_s\) is wave height significant; \(T_s\) is wave period significant; and \(U\) is wind speed. This wave forecast method is a development from darbyshire wave forecast method.

2.4. Mesh model

Data input that needed to built model mesh is bathymetry and coastline data. Wave model simulation on this research used 2 kind of mesh. First is major domain mesh with 2 km² area. Second is minor area mesh that appropriated with submerged breakwater study area. Quadrangular mesh are applied at minor domain mesh (Figure 2).

Figure 3. a). Study area with major domain mesh and; b). Study area with minor domain mesh

2.5. Spectral wave simulation model

Wave model simulation on this research used 2D hydro-dynamic mathematical model. Wave forecast with DNS method has been used for input data model. Wave height and wave period forecast data as input model are chosen at 5 effective conditions of wind direction, there are from north, northeast, east, southeast, and south (Table 2). This condition selection based on location of submerged breakwater that faced with 5 wind directions.
Table 2. Wave forecast results for input model

| No | Wind       | H (m) | T (s) | Direction |
|----|------------|-------|-------|-----------|
| 1  | North      | 1.25  | 5.6   | 360       |
| 2  | Northeast  | 1.89  | 6.5   | 45        |
| 3  | East       | 2.13  | 6.79  | 90        |
| 4  | Southeast  | 2.52  | 7.24  | 135       |
| 5  | South      | 1.25  | 5.6   | 180       |

On this model, controller equation is wave force balance equation both in cartesian and spherical coordinates formulated by \[15\]

- **Cartesian coordinate**

\[
\frac{\partial \vec{N}}{\partial t} + \vec{v} \cdot (\vec{v} \cdot \vec{N}) = \frac{S}{\sigma} \tag{3}
\]

Where:
- \(N(\vec{x}, \sigma, \theta, t)\) : force dense
- \(t\) : time
- \(\vec{x} (x, y)\) : cartesian coordinate
- \(\vec{v} (c_x, c_y, c_\sigma, c_\theta)\) : propagation group speed of four dimensional wave
- \(S\) : source

- **Spherical coordinate**

\[
\vec{N} = NR^2 \cos \phi = \frac{ER^2 \cos \phi}{\sigma} \tag{4}
\]

Where:
- \(\vec{N}(\vec{x}, \sigma, \theta, t)\) : force dense
- \(\vec{x} (\phi, \lambda)\) : spherical coordinate, where \(\phi\) : latitude and \(\lambda\) : longitude
- \(E\) : Normal energy dense
- \(R\) : earth radian

- **On polar coordinate**, equation of wave force balance can be write as:

\[
\frac{\partial \vec{N}}{\partial t} + \frac{\partial}{\partial \phi} c_\phi \vec{N} + \frac{\partial}{\partial \lambda} c_\lambda \vec{N} + \frac{\partial}{\partial \sigma} c_\sigma \vec{N} + \frac{\partial}{\partial \theta} c_\theta \vec{N} = \frac{S}{\sigma} \tag{5}
\]

Where:
- \(\vec{N}(\vec{x}, \sigma, \theta, t) = SR^2 = \) total source and sink function

- **Energy source**, \(S\), shown source function superposition from various physic phenomenon.

\[
S = S_{in} + S_{nl} + S_{ds} + S_{bot} + S_{surf} \tag{6}
\]

Where:
- \(S_{in}\) : Formed of energi by wind
- \(S_{nl}\) : Wave energy transfer caused by non linier wave-wave interaction
- \(S_{ds}\) : wave energy disipasion caused by whitecapping
- \(S_{bot}\) : Disipasion caused by bottom friction
- \(S_{surf}\) : wave energy disipasion caused by depth-induced breaking

To calculate changes of wave height and wave period before and after passing breakwater, on this model used 4 latitudinal and 2 longitudinal cross section (Figure 3 and 4).
3. Results and Discussion

3.1. Wave spectrum reduction

Based on simulation model of wave spectrum using two dimensional Spectral Wave (SW) module that has been applied in two variance formations shown in xy graph given below:
Figure 6. Changes of wave height due to submerged breakwater at condition of wave direction from north. a). Wave height reduction at cross section 1; b). Wave height reduction at cross section 2; c). Wave height reduction at cross section 3; d) Wave height reduction at cross section 4.

Figure 7. Changes of wave height due to submerged breakwater at condition of wave direction from northeast. a). Wave height reduction at cross section 1; b). Wave height reduction at cross section 2; c). Wave height reduction at cross section 3; d) Wave height reduction at cross section 4.
Figure 8. Changes of wave height due to submerged breakwater at condition of wave direction from east. a). Wave height reduction at cross section 1; b). Wave height reduction at cross section 2; c). Wave height reduction at cross section 3; d) Wave height reduction at cross section 4.

Figure 9. Changes of wave height due to submerged breakwater at condition of wave direction from southeast. a). Wave height reduction at cross section 1; b). Wave height reduction at cross section 2; c). Wave height reduction at cross section 3; d) Wave height reduction at cross section 4.
Figure 10. Changes of wave height due to submerged breakwater at condition of wave direction from south. a). Wave height reduction at cross section 1; b). Wave height reduction at cross section 2; c). Wave height reduction at cross section 3; d) Wave height reduction at cross section 4.

Figure 11. Changes of wave height due to submerged breakwater at cross section 5 and 6. a). Wave height reduction at condition of wave direction from north; b). Wave height reduction at condition of wave direction from northeast; c). Wave height reduction at condition of wave direction from east; d) Wave height reduction at condition of wave direction from southeast; e). Wave height reduction at condition of wave direction from south.

Reduction of wave spectrum has been calculated in every cross section and two variance formations. Wave height that came from open seas (distance 0m) decrease after passing the breakwater. Decreasement of wave height shown that submerged breakwater effects to wave transformation (refraction, diffraction and reflection). Wave refraction occurs due to changes of water depth (Gamito & Musgrave, 2002) [16]. In this case, submerged breakwater has a role to changes of water depth. Refraction has bigger effects to wave height, wave direction, and wave energy distribution along coastline [17]. Wave that hits a barrier will be reflected partly or all of it, this called wave reflection.
On this model simulation has been put observation point every 2m along latitudinal and longitdinal cross section (40 point at latitudinal cross section and 100 point at longitudinal cross section) to calculated changes of wave height. Model simulation shown that formation 2 has a bigger percentage of reduction (Table 3). This results indicated that structures length and more gap effect to wave redution. Based on Pilarczyk [18], low crested structure efficiencies and shoreline response depending on characteristic of wave transmission and structure design.

Table 3. Reduction percentage at latitudinal cross section between two formations.

| Wind direction | Cross section 1 | Cross section 2 | Cross section 3 | Cross section 4 |
|----------------|----------------|----------------|----------------|----------------|
|                | Form. 1 | Form. 2 | Form. 1 | Form. 2 | Form. 1 | Form. 2 | Form. 1 | Form. 2 |
| North          | 26.04% | 29.63% | 28.32% | 33.94% | 25.18% | 32.25% | 11.71% | 12.56% |
| Northeast      | 37.21% | 37.65% | 38.48% | 44.80% | 35.31% | 42.62% | 33.74% | 39.36% |
| East           | 37.07% | 37.65% | 37.99% | 42.52% | 36.06% | 40.92% | 39.90% | 40.45% |
| Southeast      | 41.30% | 42.01% | 35.72% | 44.90% | 40.28% | 44.63% | 44.60% | 45.03% |
| South          | 19.23% | 19.40% | 28% | 30.75% | 18.31% | 25.54% | 27.50% | 27.02% |

Note: Values in bold show higher reduction percentage.

Spatial models of wave spectrum have been apllied on this reasearch. Spatial models used for analyzed wave distribution around submerged breakwater and analyzed maximum wave height distribution between five conditions of wind direction. Based on models, maximum wave height distribution shown during wind blows from southeast (Figure 15). During east monsoon strong wind blows and it creates higher wave force. Along 2009-2019, maximum wave height from southeast is 2.52m and maximum wave period is 7.24s. Protection zone has been formed at behind of submerged breakwater, it shown at all of spatial models. Protection zone indicates a lower wave and it is important to protect coastline from erosion.

Wave difraction has shown at the edge of the structure. According to Triadmodjo [17], Fenton [19], and Jian et al. [20], if the incoming wave is blocked by a barrier such as a breakwater or island, the wave will turn around the edge of the barrier and enter the protected area behind it. This phenomenon called wave difraction. For a single barrier (breakwater), the height of the wave somewhere in the protected area depends on the distance of the point to the edde of the barrier \( r \), the angle between the barrier and the line connecting the point to the barrier edge \( \beta \), and the angle between the direction of propagating the wave and the barrier \( \theta \).Formation 1 has bigger wave difraction, wave height that has been formed by difraction has a higher wave height. It creates lower reduction percentage at formation 1.

![Figure 12. Spatial distribution of wave height at condition of wave direction from north.](image-url)
Figure 13. Spatial distribution of wave height at condition of wave direction from northeast.

Figure 14. Spatial distribution of wave height at condition of wave direction from east.

Figure 15. Spatial distribution of wave height at condition of wave direction from southeast.
4. Conclusions

Two-dimensional hydro-dynamic mathematical model analysis used for calculating effectiveness between two variance formations which is known by reduction percentage. Based on research results, wave height values decrease after passing submerged breakwater with reduction percentage of 18.31% - 45.03%. Wave direction from southeast has maximum wave height distribution with highest wave value in the cross section is 3.21m and reduce to 1.91m. Based on simulation model, formation 2 has a bigger reduction percentage eventhough both formation shown a little difference of reduction percentage.

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