Wave transformation around breakwater (case study: tourism harbour, Eastern Bali, Indonesia)

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Abstract. An essential aspect in the sustainable design of breakwater is the determination of the design wave condition. It is predicted by utilizing severe wave conditions of the past 10 to 20 years. The tourism harbor at eastern Bali, Indonesia, is located where extreme wave condition occurs. Therefore, this research studies the wave height before and after constructing a breakwater in the harbor area. The wave height was simulated using numerical modeling. The methodology was performed by using the coastal modeling software of the SMS-CGWAVE model. The result shows the highest design wave height value of 3.9 m in the direction from the southeast. The design breakwater can reduce wave height up to 0.9 m or a 75.5% reduction. Further study is needed to simulate the extension of breakwater length to meet the criterion design of wave height in the harbor basin.

1. Introduction

When the waves approach the shoreline, a wave transformation occurs due to shoaling, refraction, and diffraction. Shoaling occurs when the water depths are less than half of the wavelength and causes a reduction of wave velocity. Refraction is a change of the direction of the wave that occurs when the wave velocity is reduced and the wave becomes more aligned with the depth contours. Diffraction occurs when a wave propagates into an obstacle such as breakwaters and travels to the area behind it [1,2]. The extreme wave condition at tourism harbor, eastern Bali, disrupts passengers' loading and unloading and has a safety concern. A breakwater facility can protect the harbor area by reducing the extreme wave height [3]. Many studies have been conducted about breakwater reducing a wave height by different location studies and different types of breakwater specifications. Each study has its limitations [4,5,6], while an analysis facing directly to the Indonesian Ocean with a double non-overtopping breakwater is not much studied earlier. This study aims to analyze the reduction of the extreme wave condition at the harbor area at eastern Bali by creating a wave simulation with the condition before and after the breakwater construction. A CGWAVE model can simulate the characteristics of waves coming towards
the shoreline and breakwater [7]. Therefore, this study used a Surface Modelling System (SMS), CGWAVE model, to create wave simulation for analyzing the wave characteristic around the breakwater. The result of this study is the wave height that occurs at the harbor area and the percentage of wave height reduction after the construction of the breakwater.

2. Methodology

2.1. Research stages
The study starts with literature studies and research planning regarding wave characteristics and hydrodynamic references. The data used for this research were obtained from [8] and [9]. The wave characteristic was 50 years of predicted wave conditions with a significant wave height (Hs) of 3.9 m and a significant period (Tp) of 8.13 s. Other parameters being utilized are wave rose data as a reference for the direction of the dominant waves (east, northeast, and southeast), bathymetry, topography, and breakwater design layout. The bathymetry and the breakwater design layout can be seen in Figure 1. After the required data has been collected, the next step is to create a 2D wave modeling. Wave modeling was created with two conditions; the first condition was created in the existing condition or without the breakwater structure. Second, the model is created with the design conditions in the presence of a breakwater structure. Then after the running of the model is completed, data analysis can be done by comparing the existing condition data with the breakwater condition data by making an observation line profile. After collecting the wave height data from the model, the percentage of wave reduction that occurs in both conditions is analyzed.

2.2. Wave modeling
This study provides two-wave model conditions, existing and breakwater conditions with the incident wave from three directions, northeast (45°), east (90°), and southeast (135°) using a CGWAVE model. The analysis begins with the input geometry model, creating boundary area, creating a mesh, and solving the simulation. The bathymetry model is used to create a mesh model. The size of the mesh model depends on the wavelength data [10]. In this study, the significant period (Tp) is 8.13 s. A wavelength calculation was carried out to determine the size of the mesh [11].

\[ L_0 = 1.56 T^2 \]
\[ L_0 = 1.56(8,13)^2 \]
\( L_0 = 103.11 \text{ m} \)

Where:
\[
L_0 = \text{Wavelength at deep sea (m)} \\
T = \text{Wave period at deep sea (s)}
\]

The mesh size must have a minimum of 200 vertices along the shoreline to make the wave model output more accurate. The shoreline observed in this study is around 2 km. A 10 m mesh size is needed to create 200 vertices. Therefore, the equation that used to create a mesh in the CGWAVE modeling are:

- Wavelength = Period x Celerity
- Celerity = \((\text{gravity} \times \text{depth})^{0.5}\)
- Mesh size = Wavelength/10

The following is a view of model layout at existing conditions for this study. Figure 2 shows the mesh layout that have over 200 mesh of elements with a 10 m size and a mesh model layout with a water depth information.

**Figure 2.** Wave mesh model boundary, before (a) and after (b) the modeling process.

**Figure 3.** Wave from northeast direction modeling results of existing condition (a) and with breakwater structure (b).
After a boundary mesh is created, the wave amplitude (wave height/2) of 1.95 m, wave period of 8.13 s, and dominant wave angle direction from the northeast, east, and southeast is entered at CGWAVE’s model control. The wave mesh element needs to be adjusted to ensure there are no zero or minus at depth values before running the model. The comparison between the existing and breakwater condition model is shown in Figure 3 to Figure 5.

3. Results and discussion

3.1. Wave reduction result
The wave height reduction analysis is done by making an observation line to compare the results between the existing conditions model and the condition of the breakwater model. The layout of the observation sections layout to analyze the wave reduction can be seen in Figure 6. Section A-A’ is observing the harbor entrance channel to determine the wave reduction that occurs. The graph in Figure 7 shows that the wave height at the observation point of the existing condition A-A’ section of the design harbor basin is about 2.4 m. Meanwhile, in conditions with a breakwater, the wave height drops to 1.8 m. From the east, the current wave height is around 1.1 m, and it drops to 0.1 m with a breakwater. From the southeast, in the existing condition, the wave height reaches 2.4 m, then it drops to 0.2 m with the breakwater. Section C-C’ is observing the harbor entrance channel to determine the wave reduction that occurs.
Figure 6. Observation wave height sections layout

The graph in Figure 8 shows that the wave height at the observation point of the existing condition A-A’ section of the design harbor basin is about 2.4 m. Meanwhile, in conditions with a breakwater, the wave height drops to 1.8 m. From the east, the current wave height is around 1.1 m, and it drops to 0.1 m with a breakwater.

Figure 7. Wave reduction section A-A.

Figure 8. Wave reduction section C-C.
From the southeast, in the existing condition, the wave height reaches 2.4 m, then it drops to 0.2 m with the breakwater. The previous study shows the same pattern of wave reduction graph [12]. For more details, the percentage of wave height reduction is shown in Table 1.

**Table 1.** Percentage of wave height reduction between existing and breakwater conditions.

| Wave Direction | Wave Height Existing Condition (m) | Wave Height Breakwater Condition (m) | Wave Reduction (%) |
|----------------|------------------------------------|--------------------------------------|--------------------|
| Northeast      | 2.4                                | 1.8                                  | 26.4               |
| East           | 1.1                                | 0.1                                  | 87.0               |
| Southeast      | 2.4                                | 0.2                                  | 90.6               |
|                |                                    | Section B-B'                         |                    |
| Northeast      | 1.9                                | 1.3                                  | 32.8               |
| East           | 1.9                                | 0.2                                  | 90.2               |
| Southeast      | 0.7                                | 0.2                                  | 74.3               |
|                |                                    | Section C-C'                         |                    |
| Northeast      | 1.3                                | 0.5                                  | 61.7               |
| East           | 2.5                                | 0.2                                  | 93.4               |
| Southeast      | 1.9                                | 0.2                                  | 90.7               |
|                |                                    | Section D-D'                         |                    |
| Northeast      | 1.6                                | 0.4                                  | 75.5               |
| East           | 1.6                                | 0.1                                  | 90.8               |
| Southeast      | 1.6                                | 0.2                                  | 88.4               |
|                |                                    | Section E-E'                         |                    |
| Northeast      | 0.8                                | 0.8                                  | 0.0                |
| East           | 0.8                                | 0.3                                  | 65.1               |
| Southeast      | 0.8                                | 0.3                                  | 55.1               |

It shows that the wave reduction due to the breakwater has the most significant percentage reduction in wave height in the A-A' sections coming from the southeast, reaching a value of 90.6%, and the minor percentage reduction in wave height coming from the northeast with a value of 26.4%. It indicates that the breakwater design cannot protect the harbor basin from the northeast wave. The previous study shows that an alternative breakwater design is analyzed by extending the breakwater layout that can reduce the incoming wave height compared to the previous breakwater [13].

### 3.2 Analysis of alternative breakwater layout

In this section, an analysis of alternative breakwater layout is planned by modifying the addition of the length of the right side of the breakwater.

*Figure 9. Modeling results of alternative breakwater conditions with northeast wave direction.*
The alternative breakwater only modifies the south or right side of the breakwater by extending the breakwater length by a breakwater head diameter, which is 50 m, by still maintaining the minimum standard for two lanes for a ship, which is 86.6 m. To analyze the reduction by alternative breakwater layout, wave modeling was created the same way as before with a significant wave input of 3.9 m and a significant period of 8.13 s. The model result for the alternative breakwater with the wave coming from the northeast is shown in Figure 9. The model showed that the red color is dominant, which means have a low wave height at the harbor basin, unlike Figure 4, which shown that the orange color is more dominant at the harbor basin.

Table 2. Percentage of wave height reduction between existing and alternative breakwater conditions.

| Wave Direction | Existing Wave Height (m) | Alternative Breakwater Wave Height (m) | Maximum Wave Height for Vessel GT50 0.3 m | Wave Reduction (%) |
|----------------|--------------------------|----------------------------------------|------------------------------------------|---------------------|
| Northeast      | 2.4                      | 0.3                                    | Ok                                       | 89.4                |
| East           | 1.1                      | 0.3                                    | Ok                                       | 74.8                |
| Southeast      | 2.4                      | 0.3                                    | Ok                                       | 88.9                |
| Northeast      | 1.9                      | 0.2                                    | Ok                                       | 91.2                |
| East           | 1.9                      | 0.3                                    | Ok                                       | 86.4                |
| Southeast      | 0.7                      | 0.2                                    | Ok                                       | 66.5                |
| Northeast      | 1.3                      | 0.1                                    | Ok                                       | 88.9                |
| East           | 2.5                      | 0.1                                    | Ok                                       | 95.4                |
| Southeast      | 1.9                      | 0.1                                    | Ok                                       | 92.7                |
| Northeast      | 1.6                      | 0.1                                    | Ok                                       | 92.1                |
| East           | 1.6                      | 0.1                                    | Ok                                       | 94.2                |
| Southeast      | 1.6                      | 0.1                                    | Ok                                       | 91.0                |
| Northeast      | 0.8                      | 0.3                                    | Ok                                       | 66.9                |
| East           | 0.8                      | 0.3                                    | Ok                                       | 62.4                |
| Southeast      | 0.8                      | 0.2                                    | Ok                                       | 74.3                |

From Table 2, it is shown that the highest percentage of wave reduction occurs in the east wave direction reaching 95.4% at the C-C' section, while the smallest wave reduction percentage occurs in the east wave direction at the E-E' section. The wave height from the northeast, which was previously reduced to only 26.4% in the initial A-A' breakwater section, can be reduced to 89.4%. Reduction of wave height tends to increase with alternative breakwaters. However, there is a decrease in minor wave height reduction, namely in the A-A' section from the east wave direction; in the initial breakwater layout, the percentage of wave reduction reaches 87%. However, in the alternative breakwater layout, the percentage of wave reduction drops to 74.8%. It can be caused by the influence of wave reflections that are getting bigger due to the addition of the breakwater length. The previous study shows the same percentage wave reduction pattern result by extending the breakwater layout [12]. However, further research is needed by considering cost and material factors in making alternative breakwater designs that can reduce wave height for east, northeast, and southeast wave directions.
4. Conclusion

4.1. Conclusion
Based on conducted study, it can be concluded that:

With a wave height in breakwater conditions with an observation point in the harbor pool from southeast reaching 2.4 m, from east reaching 2.4 m and from northeast reaching 2.5 m, the Sanur Harbor area is not protected from the threat of incoming waves;

With the breakwater structure, the wave height at the observation point at the Sanur Harbor breakwater is reduced from the east to 0.1 m with the largest reduction value of 90.8%, from the southeast it reaches 0.2 m with a reduction value of 90.7%, from the northeast reached 0.4 m with a reduction of 75.5%;

In the A-A' section with the direction of the northeast wave with a breakwater condition, the wave reduction is still relatively small with a value of 26.4% with a wave height of 1.8 m;

The breakwater design cannot protect the harbor pool with the high waves coming from the northeast with the vessel's design requirements of a critical wave height of 0.3 m, but the wave height is still high with a magnitude of 1.8 m from the northeast;

To optimize the protection of the harbor from northeastern waves, a new breakwater layout is needed by extending the south side of the breakwater by 50 m which is the diameter of the breakwater head;

Based on the alternative breakwater layout modeling with the addition of the right breakwater length of 50 m, the percentage of wave reduction in the northeast direction reaches 0.1 m with the largest reduction value of 92.1%, from the east it reaches 0.1 m with a reduction value of 95.4%, from the southeast it reached 0.1 m with a reduction of 92.7%. The alternative breakwater layout can protect the harbor pool from the threat of wave height coming from the northeast, east and southeast.

4.2. Suggestion
Based on results of this study, it is suggested to do further research by considering cost and material factors in making alternative breakwater designs that can reduce wave height for east, northeast and southeast wave directions.

Acknowledgement
This work is supported by Research and Technology Transfer Office, Bina Nusantara University as a part of Bina Nusantara University’s International Research Grant, with contract number: No.017/VR.RTT/III/2021.

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