Numerical Simulation to Determine the Effectiveness of Groynes and Breakwaters as Protective Structures for Gandoriah Beach, Pariaman City

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Abstract. This research is about numerical simulation to determine the effectiveness of groynes and breakwaters as protective structures for Gandoriah Beach in Pariaman City (West Sumatra - Indonesia) using an existing program. The effectiveness of the protective structure can be seen based on the bathymetry that is formed as a result of this structure performance. In the simulation of the present research, the direction of the incoming waves at the offshore boundary condition is the dominant direction, namely the west direction, with two wave conditions, namely during normal and stormy times. Simulations of morphological changes are carried out in six scenarios. The first three scenarios are for wave simulations under normal conditions with no shore protective structures (scenario 1), with groynes (scenario 2) and with breakwaters (scenario 3). Meanwhile, the second three scenarios are for wave simulation in storm conditions with no shore protective structures (scenario 4), with groynes (scenario 5) and with breakwaters (scenario 6). The simulation results for the 20 days state show that in normal wave conditions, the breakwaters have a fairly good performance for the formation of sedimentation behind the structures so that it is estimated that the formation formed is tembolo. Meanwhile, groyne is only effective to restrain the sedimentation rate along the structures. In the wave simulation during stormy time, there is a dominant current along the nearshore. In this case the performance of the groynes is better than the breakwaters because the groynes can inhibit the rate of erosion along the shore. Due to the use of breakwaters there is erosion behind the structures. Based on the simulation results without shore protective structures, both in normal and storm waves, abrasion and erosion processes occur, so that Gandoriah Beach needs handling.

1. Introduction

Gandoriah Beach (figure 1) is a tourist beach located in Pariaman City, Central Pariaman Sub-District. Almost all sub-districts in Pariaman City (except for East Pariaman Sub-District) have a beach area that is directly opposite the Indonesian Ocean. Pariaman City has a shoreline length of ± 12 km while its land area is only ± 73.36 km\textsuperscript{2} [1]. This means that Pariaman City only has a land area of ± 6 km wide. The shore protection that have been built along Gandoriah Beach are a series of groynes. Within a few years these buildings have changed the hydrodynamic pattern of the waters, but at present conditions appear to be ineffective in reducing the rate of abrasion [2]. These ineffective shore protective structures cause the condition of Gandoriah Beach along ± 1.5 km (from the Navy Monument to the ASEAN Monument) as if it does not get a shore protective structure. Meanwhile, there are many landmarks along Gandoriah Beach that must be protected from the threat of abrasion.
The present study objectives are to determine the effectiveness of groynes as commonly used shore protective structures and breakwaters as alternative structures to protect Gandoriah Beach from abrasion due to the ferocious waves of the Indonesian Ocean by numerical simulations. The more effective shore structures will be identified by comparing the formed bathymetry. Numerical simulations are carried out with the CMS Wave and CMS Flow modules. The CMS Wave is a steady module, while the CMS Flow is an unsteady module. Even though these two modules are different, they are integrated with each other as a single unit in the Coastal Modeling System, which is included in the Surface Water Modeling System program package.

The (steady) CMS Wave module is used for wave modeling, while the (unsteady) CMS Flow module is used for modeling currents and elevations, sedimentation and morphological changes. The CMS Wave is based on averaged phase waves and its governing equation is a wave action balance equation which was modified by Mase in 2001 by adding the energy dissipation factor at the time of the wave breaking and the wave diffraction factor [4]. As a boundary condition for offshore, the spectral wave density $E(\sigma, \theta)$ is calculated using the parametric spectrum model. The governing equation in the CMS Wave is solved by using the finite difference method, by dividing the domains into rectangular grids with variable sizes. The output of the CMS Wave module is the height, period and direction of the waves on each grid which has taken into account the wave transformation processes such as refraction, diffraction, reflection and breaking waves.

The CMS Flow module is a 2D hydrodynamic and sedimentation model, based on depth averaged. This means that the flow velocity and sediment transport in the vertical direction are not taken into account [5]. The numerical method used in CMS Flow is the finite volume method, and in SMS version 10.1 only an explicit scheme is available. The governing equation for hydrodynamics is derived from the depth averaged shallow water equations in Cartesian coordinates [5]. The boundary in the present study is the water level.

The principle of sediment transport in CMS Flow is the concept of bed shear stress that occurs due to currents, waves and wind. So that the coefficient of friction is very influential in determining sediment transport. The present study considers sediment transport to be an equilibrium bed load and a non-equilibrium suspended load, where only the bed load is in balance, while the floating sediment is not. The elevated sediment transport is calculated using the advection-diffusion (AD) equation, while the basic sediment transport is calculated using the Lund-CIRP equation. The sediment continuity equation for morphological change is AD equation [6]. Nam et al. simulated the sedimentation rates of five series of specimens with different sediment transport formulas [7]. The results of their study indicate that the AD formula for elevated sediments and Lund CIRP for bottom sediments provides the best predictions for longshore sediment transport, compared to the use of other formulas.

2. Materials and methods

2.1. Data collection

Secondary data used in the present study are Batimetri Nasional (Batnas) data, daily maximum wind data for 10 years of observation (2010 - 2019) by BMKG Minangkabau Airport station and tide elevation data for a period of 20 days (from 15 May to 3 June 2020) obtained from Badan Informasi dan Geospasial (BIG). Due to limited measurement data, the influence of the river mouth of Batang Pariaman which is located in the northern Gandoriah Beach and the river mouth of Batang Jirak which is in the southern part is not taken into account in the present study.

2.2. Data processing

The Batnas data processing is carried out using ArcGis to obtain contours with an elevation difference of 1 m. Wind data are processed in two stages. The first stage is to classify daily wind data for 10 years of observation in the form of wind rose diagram to determine the percentage of wind events with a certain speed. Furthermore, the second stage is to predict wave height in deep water based on the dominant direction using the procedure of the Sverdrup MunkBretschneider (SMB) [8, 9].
2.3. Determination of the simulation domain for the Coastal Modeling System

Numerical set-up for CMS Wave and CMS Flow using bathymetry as the basic data, followed by making a grid, inputting boundary conditions and other parameter data. Basically the simulation is carried out in two stages. The first is to simulate waves without interaction with currents (CMS Wave only) on a parent domain (parent grid), and the second is to simulate wave-current interactions on a child domain (child grid) by coupling the two modules (CMS Wave and CMS Flow) (figure 2).

The first stage simulation with CMS Wave on parent domain. The bathymetry at the research site is relatively complex because in front of Gandoriah Beach there are three small islands which are quite influential on the wave diffraction process. Meanwhile, CMS Flow v.3.75 is only intended for small domains and cannot cover domains that are too large for grid cells with relatively small dimensions. In order for the wave transformation process on the bathymetry to be simulated well, in this study, the simulation was carried out in two stages. In the first stage, the waves are simulated in the parent domain, without current interaction. The simulation is carried out in two conditions, namely normal waves and storm waves. The purpose of the first stage simulation is to get a wave output from the parent domain to be forwarded as a wave input in the child domain. The focus of our research is on the child domain, where groynes and breakwaters are located. The parent domain measures 8080 m x 7680 m with a grid cell size of 40 m x 40 m. The input to the boundary conditions in the deep sea is the height and period of the waves generated based on wind data. The spectrum used is the JONSWAP spectrum for fetch limited conditions.

The second stage simulation with coupling CMS Wave and CMS Flow on the child domain. Simulations on the child domain are carried out in six scenarios: (1) simulation of normal waves in existing conditions (without shore protective structures); (2) simulation of normal waves with the addition of groynes; (3) simulation of normal waves with the addition of breakwaters; (4) simulation of storm waves in existing conditions; (5) simulated storm waves with the addition of groynes; and (6) simulation of storm waves with the addition of breakwaters. Simulations of morphological changes due to the interaction of waves and currents were carried out for 20 days (480 hours) for each scenario with a state time interval of 6 hours for wave simulation. This 6 hour duration
was chosen because of the consideration that the type of tide at Gandoriah Beach is semi-diurnal. The second consideration is the incapable of our computer memory capacity with a duration smaller than that.

Figure 2. Parent domain (parent grid) and child domain (child grid)

In a child domain, the coupling process is carried out between CMS Wave and CMS Flow. The data will be forwarded in two directions according to the time increment increase of simulation (Δt). The CMS Wave will be processed first, after that the wave data from the CMS Wave will be forwarded to the CMS Flow as input. CMS Flow output in the form of water level elevation, current, sediment transport and morphological changes that occur have taken into account the influence of the waves. The CMS Flow output is forwarded back to the CMS Wave as input in the next increment of time (Δt). In such a way, changes in water level and current are taken into account in the wave simulation performed by CMS Wave, including bathymetry updates due to changes in morphology, and so on until the end of the specified simulation time.

The addition of groynes in the simulation is in the second and fifth scenarios, and the addition of breakwater structures in the simulation is in the third and sixth scenarios. The groyne used is type I. The length of the groyne is determined based on the theory proposed by Horikawa [9], which is between 40% and 60% of the average width of the surfzone with the distance between groynes being one to three times the length of the groyne. The surfzone width is known from the simulation output of the parent domain. The breakwater is expected to form a salient formation so that the sedimentation formed behind the breakwater does not obstruct sediment transport along the nearshore. The comparison between the length of the breakwater and the distance of the breakwater to the shoreline between 0.5 and 0.67 as suggested by Dally and Pope in [10], the gap width between the breakwaters is determined based on the empirical diagram of several breakwaters in the USA put forward by Pope and Dean in [10].
The size of the child domain is 3000 m x 3600 m with a grid cell size of 20 m x 20 m. As a boundary condition for CMS Wave is the simulated output wave from the parent domain. The spectrum used is TMA (Texel, Marsen and Arsloe) for shallow water. While the boundary requirement for CMS Flow is the tide elevation during the period 15 May 2020 to 3 June 2020 (20 days) (see figure 3).

![Tide elevation along 15 May to 3 June 2020](image)

**Figure 3.** Tide elevation from 15 May to 3 June 2020

Input data for simulations in the child domain can be seen in tables 1 and 2.

**Table 1.** Input data for the CMS Wave in the child domain

| Wave                      | Normal          | Storm           | Notes: |
|---------------------------|-----------------|-----------------|--------|
| Bathimetry                | Existing        | 0.025           | [8], [9], [11] |
| Coefficient of Refraction | 0.3             | 0.3             |        |
| Coefficient of Diffraction| 1               | 2               | [4]    |
| Manning resistance-coefficient | 0.025          | 0.025           |        |

The reflection coefficient for the structureless condition is determined based on the slope angle of the coast (θ = 5°) [11] using the Battjes diagram (1974) in [8]. Meanwhile, the reflection coefficient for the rubble mound structure is determined based on [9]. The diffraction coefficient in CMS wave is determined based on [4].

**Table 2.** Input data for the CMS Flow

| Parameters                   | Input Data | Notes          |
|------------------------------|------------|----------------|
| D50                          | 0.2        | Fine sand [12] |
| Manning resistance-coefficient| 0.025      | [12]           |
| Water density                | 1025 kg/m³ |                |
| Soil density                 | 2650 kg/m³ |                |
| Porosity                     | 0.4        |                |
| Hydrodynamic time step (Δt)  | 1 s        |                |

3. Results and Discussion

3.1. Wind wave generation
Based on the wind rose in figure 4, the dominant wind originates from the west with a percentage of 38.72%.

![Wind rose from 2010 to 2019](image)

Figure 4. Wind rose from 2010 to 2019

The final result of wave generation by wind is shown in table 3. Wave height \( H \) in normal conditions is \( H \) significant or the average height of 33.33% of the highest value of wave data. Wave height \( H \) during the storm is the maximum wind occurrence from the west on June 12, 2014. The wave data in table 3 is then used as boundary conditions for the parent domain CMS Wave.

| Incident Wave | Normal | Storm |
|---------------|--------|-------|
| Angle (°)     | 0      | 0     |
| Height, \( H \) (m) | 3.02   | 5.73  |
| Periode, \( T \) (s) | 8.5    | 10.57 |

3.2. First stage simulation

The first stage of the simulation is carried out on the parent domain only with the CMS Wave module only. Simulations are carried out twice. The first is in normal wave conditions, where the offshore boundary condition is normal waves. The second simulation is in a storm surge condition, where the offshore boundary condition is a storm wave. Both simulations use existing bathymetry. So, in these simulations there is no shore protection structures in the parent domain. The wavefront profiles for normal wave and storm wave conditions are shown in figure 5.

The output of the simulation in the parent domain such as height and wave period at the location shown by the red line in figure 5 (left and right) will be passed as boundary conditions for the
simulation input in the child domain. The output of the parent domain used as input for the child domain is shown in table 4.

The dimensions of groyne and breakwater for simulations in the child domain are as shown in table 5.

![Wavefront profile in normal wave conditions (left) and in stormy wave conditions (right). At this stage, no shore protection structures have been added to the parent domain.](image)

**Figure 5.** Wavefront profile in normal wave conditions (left) and in stormy wave conditions (right). At this stage, no shore protection structures have been added to the parent domain.

**Table 4.** Wave output from the CMS waves in the parent domain.

| Incident Wave       | Normal | Storm |
|---------------------|--------|-------|
| Angle (°)           | 4.53   | 6.26  |
| Height, $H$ (m)     | 2.9    | 4.93  |
| Period, $T$ (s)     | 8.3    | 10    |

**Table 5.** Groyne and breakwater dimensions for simulations in the child domain.

| Structures          | Groins | Breakwaters                   |
|---------------------|--------|-------------------------------|
| Length (m)          | 60     | 80                            |
| Distance between them (m) | 100 - 120 | 40 (gap width) |
| Width (m)           | 20     | 20                            |
| Top elevation       | 0.2 m above MSL | 0.5 m below MSL (Submerged) |
| Quantities          | 8      | 8                             |

3.3. **Second stage simulation**

The second stage simulation is only carried out on the child domain by combining the CMS Wave module with the CMS Flow module. The existing morphological conditions with no structure, with groynes and with breakwaters are shown in figure 6.
Figure 6. Existing morphology: (a) without structures, (b) with groynes and (c) with breakwaters

Normal wave conditions (scenarios 1, 2 and 3). In normal wave conditions, sediment transport is influenced by waves and currents along the nearshore which predominantly move from north to south. Morphological changes that occur due to normal waves can be seen in figure 7.

Figure 7. Morphological changes after 480 hours simulation with normal wave: (a) without structures, (b) with groynes and (c) with breakwaters.

Morphological changes due to normal waves in detail are shown in the cross sections as shown in figure 8.
The simulation results with storm wave conditions can be seen in figure 7 (a), where there has been a significant increase in depth along A0 to A1. Erosion that occurs in detail can be seen in sections I-I (figure 8 left) and II-II (figure 8 right). In the I-I section (figure 8 left), additional depth begins to occur at a distance of 10 m from the shoreline, with a depth difference of 0.5 m from the initial bathymetry. The more it goes offshore, the additional depth that occurs reaches 1 m. From A0 to A1, along ± 500 m, it is a fairly prone location along Gandoriah Beach because of the deep depth, for normal waves the area of breaking waves occurs almost near the shoreline, so the wave conditions near the shore are quite high. In section II-II (figure 8 right), the condition without structure does not really affect the erosion process. This is estimated because at the location of the II-II (A1-A2) section there is silting bathymetry towards the sea as shown in figure 6 (a), namely the existing bathymetry conditions, so that at this location the high and the wave energy reaching the shore is weak.

The results of the second scenario (namely the simulation results of normal waves propagating on the child domain with groynes), the effect of groynes can be seen in figure 7 (b). Erosion occurs between the first, second and third groynes along A0 to A1. From the I-I section (figure 8 left) it can be seen that despite erosion, groynes can provide protection compared to the condition without structure. The increase in depth that occurs from the shoreline to 60 m (along the groyne structures) to the sea is a maximum of 0.5 m.

The results of third scenario (namely the simulation results of normal waves propagating in the child domain with breakwater protection), the effect of adding breakwaters (substitute for groynes) on morphological changes can be seen in figure 7 (c). Sedimentation occurs behind the breakwater which is connected to the shoreline, so it is estimated that the formation formed is tembolo, even though the initial planning used the requirements for salient formation. Details can be seen in cross sections of I-I and II-II. Sedimentation formed by the breakwater can increase the elevation of the existing conditions.

Storm surge conditions (scenarios 4, 5 and 6). The simulation results with storm wave conditions show an anomaly. During a storm, the wave height and its energy towards the shore decrease, because some of the waves have broken further from the shoreline. Mera [13] defined that the occurrence of breaking waves caused by depth, starting when the ratio of wave height $H$ and water depth $h$ becomes greater than a certain size. The CMS Wave generally gives the value ratio $(H/h)$ for random waves is 0.64 and uses a more detailed equation with the extended method by Goda [4]. The storm surge 4.93 m high reached the breaking point at a considerable distance from the shore. When a wave breaks, a current occurs which causes the transport of sediment from the location of the breaking wave. Simulated storm waves every 6 hours continuously cause sedimentation to form in the breaking wave area at the offshore boundary, which begins to form on the 5th day of the simulation. Sedimentation that forms blocks the flow of currents from offshore to the shore, so what happens is current forces
due to the depth flowing from north to south at very high speed (3 to 5 m / s). These currents are the dominant cause of erosion processes along the nearshore. The dominant morphological changes influenced by currents in storm wave conditions can be seen in figure 9.

![Figure 9](image_url)

**Figure 9.** Morphological changes after 480 hours simulation with storm waves: (a) without structure, (b) with groynes and (c) with breakwaters.

Morphological changes due to the storm surges can be seen in more detail in the cross sections shown in figure 10.

![Figure 10](image_url)

**Figure 10.** Morphological changes due to the storm surges at sections I-I (left) and II-II (right).

The results of the fourth scenario (namely the simulation results of storm waves propagating on the child domain without the shore protective structures) show that erosion has occurred along the nearshore due to currents, especially at locations A0-A1 as shown in figure 9 (a). The I-I section (figure 10 left) shows that the results of the fifth scenario (namely the simulation results of storm waves that propagate on the child’s domain with groynes), the performance of the groynes look better than the conditions without structures (scenario 4) and with the addition of breakwaters (scenario 6). Likewise, in section II-II (figure 10 right) starting from the shoreline up to 60 m towards the offshore (along the structures), the groynes are able to withstand sediment transport along the nearshore so that there is no significant increase in depth from the existing conditions. In the sixth scenario, the I-I section, starting from the shoreline up to 40 m towards the offshore, shows that the morphological changes due to the breakwaters are the same as those without structure, so it is estimated that the breakwater is unable to withstand the rate of erosion along the nearshore. The sedimentation behind
the breakwaters only formed until the 5th day of the simulation because the waves had weakly reached the shore. But after a dominant current occurs from north to south, the process that occurs is erosion along the nearshore, thus forming an irregular erosion pattern behind the breakwater as seen in section II-II.

4. Conclusions
Normal wave simulation results indicate that the sediment transport process is influenced by waves and currents. Breakwater is more effective in shore protection against abrasion. Sedimentation behind the breakwaters leads to the tombolo formation, although the initial setting uses the equation for salient formation. Groin is only effective in holding sediment transport along the nearshore as wide as ± 60 m from the shoreline. In addition, groin also does not function to reduce incoming wave energy. There is a significant erosion process on Gandoriah Beach if it is not protected by shore protective structures.

The results of the storm wave simulation show that the dominant process that occurs is erosion along the nearshore due to currents, so that the role of groin is more dominant than the breakwater. This is because the main function of the breakwater is to weaken the incoming wave energy perpendicular to the shore, while the groin functions well to hold sediment transport along the nearshore.

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