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Analysis of Waikelo Port Breakwater Failure through 2D Wave Model

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Abstract. Waikelo Port is located in South West Sumba of East Nusa Tenggara. The port facilities are protected by breakwater with a vertical wall construction and it was built in a relatively deep ocean at -15m of Low Water Sea Level (LWS). On 21st of January 2012, an earthquake with magnitude of 6.3 Richter scale occurred around Sumba Island and it caused cracking in the concrete wall of breakwater. Then, 4 days after on 25th January 2012, a heavy wind of 20–23 knots generated a high wave around 4.0–5.0m in Sumba strait. These high waves caused a critical damage on the west part of the breakwater. The damage of port facilities were getting worse when a storm called Lua hit on March 2012. This study was conducted to observe the effect of the extreme event in the failure of breakwater. The result of two-dimensional (2D) wave model shows that the wave heights in the area of breakwater are varied 3.80 to 4.0m. It is quite greater than the wave design of 50 years return period (= 2.00m) which was used in breakwater design and calculation. This observable fact confirms that the failure of breakwater was caused by the continuous extreme events that exceed the design criteria.

Keywords: Waikelo port, breakwater failure, extreme event, 2D wave model

1. Introduction

The reasons for breakwater failures can be classified in three major categories (a) reasons relate to the structure itself, (b) reasons relate to the hydraulic and loads conditions, and (c) reasons relate to the foundation and seabed change [1]. The possibility causes in term of the hydraulic and load conditions type are exceedance of design wave condition, concentration of wave action at certain zones along breakwater, breaking wave and impact loads and wave overtopping.

Waikelo Port is located in North West Sumba, the Province of East Nusa Tenggara and it is used for inter island transportation. This port was established in 2011 and placed by the Waikelo Sea Port. The Waikelo Port is equipped a movable bridge and protected by a vertical wall construction breakwater. The breakwater itself was constructed in -15m of LWS and calculated based on the design wave of 50 years return period which was equal to 2.00m

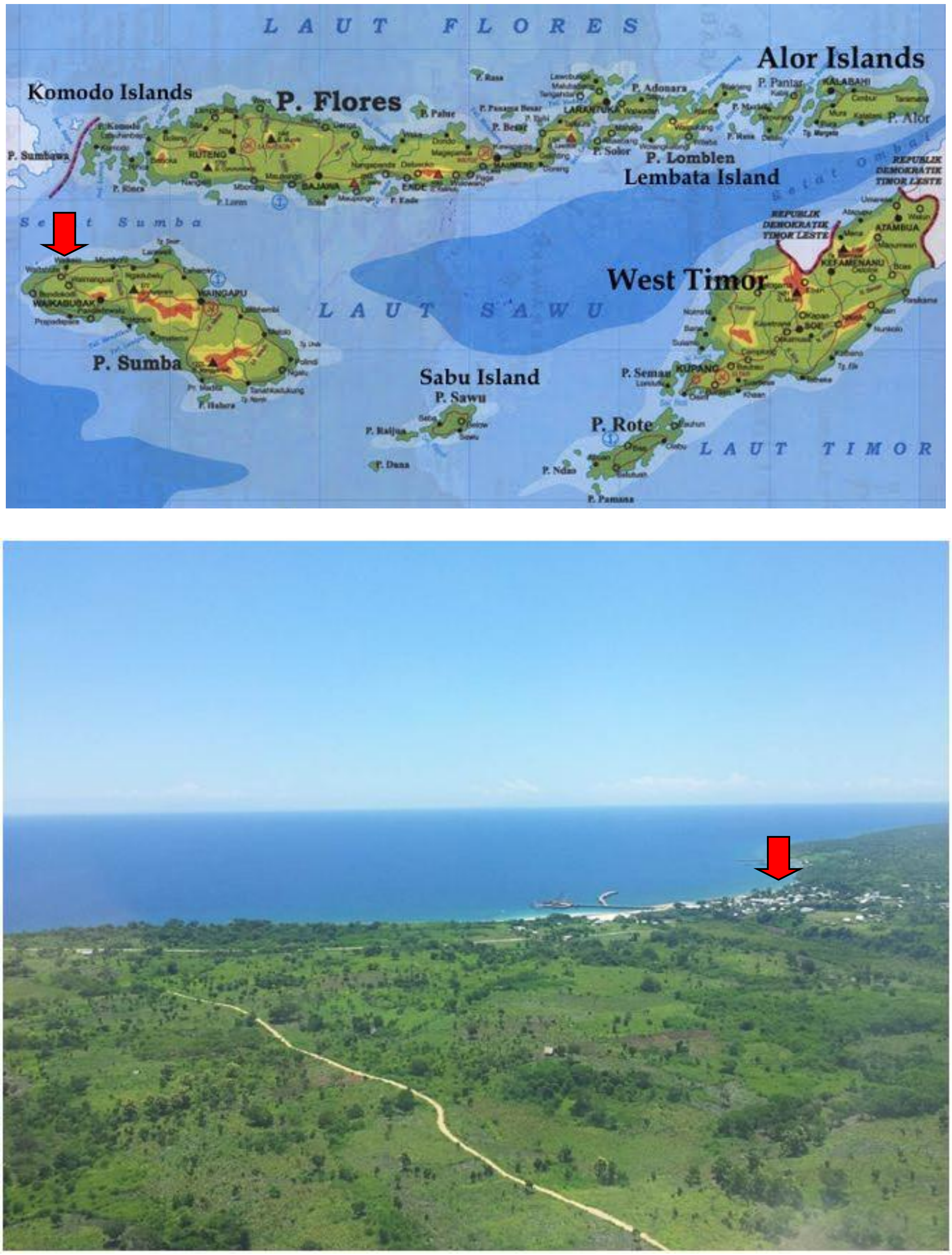

Figure 1. Location of study, Waikelo Port, South West Sumba, East Nusa Tenggara

The consecutive extreme events hit Waikelo Port was started on January 21st, 2012, when 6.3 Richter scale earthquakes occurred around Sumba Island. This earthquake caused the breakwater to crack in the concrete wall as displayed in Figs. 2, 3. Then, the next 4 days, the second severe events occurred. A heavy wind of 20–23 knot generated a huge wave around 4.0–5.0m and struck Waikelo Port and also its facilities. This high wave caused the west part of the breakwater around 24.95m length fail. The next massive events happened on March 2012; a storm called Lua blew Waikelo Port in 5 days continuously and caused crucial damage in the port facilities as shown in Figs. 4, 5. By considering the chronologic extreme events as menti0ned before, the main objective of this present study is to analysis and review the breakwater failure through 2D wave propagation model.

Figure 2. Cracking on breakwater concrete wall after an earthquake on January 21st, 2012.

Figure 3. Significant damage of breakwater due to high wave on January 25th, 2012

Figure 4. Major damage of port facilities after Lua storm on March 2012.

Figure 5. Major damage on movable bridge after Lua storm on March 2012.

2. Wave Generation and Propagation

Heavy winds blow above the sea with enormous fetches acting for lengthy durations, possibly generating high and huge sea waves. Wave storms are usually described as events of significant wave height, H_s, overreaching a predetermined threshold (critical H_s) with a short duration.

2.1. Wind Wave Generation

The height, length and period of wind waves in the open ocean are generated by the fetch, the wind speed, the duration of the wind blows, the distance of the wave travels and the water depth. General speaking, increasing in fetch length, wind speed and or duration will be generating a huge wind waves. Then, in term of the water depth, when it is sufficiently shallow, it will also determine on the size of wave propagation. The wind simultaneously creates waves of various heights, lengths and periods as it blows above the sea.

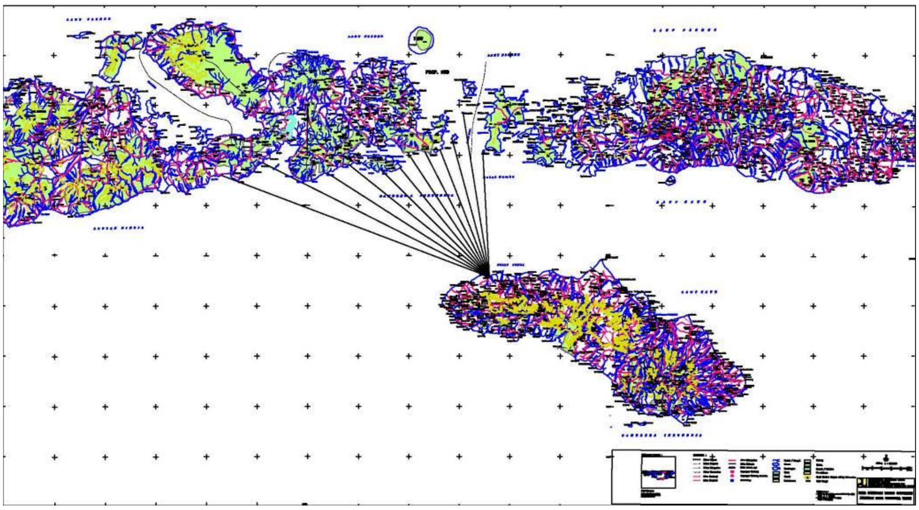

Figure 6. Mapping scheme for fetch length calculation of Waikelo Port

Data used in this present study was obtained from Indonesia Meteorological, Climatological and Geophysical Agency (BMKG) which has located in Kupang. Based on BMKG record, it has increased significantly of wind speed and wave height during 10 days since 21st to 31st of January 2012 in Sumba Strait. BMKG recorded data informed that on January 25th, 2012 wind speed blew at 20–23 knots from North West direction with the significant wave height, H_s, was at 2.50–3.00m and the maximum wave height, H_{max}, reached 4.0–5.0m. In order to verify recorded significant wave height data, subsequently, the wind wave heights on January 21st–31st, 2012 was calculated by considering fetch length as displayed and tabulated in Fig. 6 and Tabel 1.

Table 1. Calculations of Waikelo Port fetch length

Direction		North West (= 315°)	
α	cosα	Xi (km)	Xi × cosα
42	0.743	69.310	51.507
36	0.809	91.338	73.894
30	0.866	77.510	67.126
24	0.914	74.966	68.485
18	0.951	77.255	73.474
12	0.978	81.628	79.844
6	0.995	77.128	76.705
0	1.000	81.476	81.476
-6	0.995	96.492	95.963
-12	0.978	105.134	102.837
-18	0.951	138.176	131.413
-24	0.914	154.359	141.014
-30	0.866	2.891	2.504
-36	0.809	2.351	1.902
-42	0.743	2.050	1.523
Σcosα :	13.511	Σxi × cosα :	1049.667

Based on the calculation result as written in Table 1, the effective fetch ($fetch_{eff}$) can be obtained by using a simple formula as written below,

$$fetch_{eff} = \frac{\Sigma(Xi \times \cos\alpha)}{\Sigma\cos\alpha} = \frac{1049.667}{13.511} = 77.690 \text{ km}$$

Then, recorded wind speed (U) was 23 knot or equal to 11.832m/s, thus wind stress factor (U_A) = $0.71U^{1.23}$ = 14.830m/s and the significant wave height (H_s) = 1.616 x 10^{-2} U_A $fetch_{eff}^{0.5}$ = 2.112m. This calculated significant wave height is near to BMKG recorded data at 2.50–3.00m. Furthermore, maximum wave height can be calculated using simple and practical equation proposed by Goda [2] that $H_{max} = 1.8H_s$ = 3.80m. This value is also close to BMKG recorded data at 4.0-5.0m.

2.2. 2D Wave Model

Two-dimensional spectral wave model with energy dissipation and diffraction terms was used in this current study. It simulates a steady-state spectral transformation of directional random waves simultaneous with ambient currents in the coastal area. 2D Wave model in here is based on the wave-action balance equation [3].

$$\frac{\partial(C_x N)}{\partial x} + \frac{\partial(C_y N)}{\partial y} + \frac{\partial(C_\theta N)}{\partial \theta} = \frac{\kappa}{2\sigma}\left[\left(CC_g \cos^2\theta N_y\right)_y - \frac{CC_g}{2}\cos^2\theta N_{yy}\right] - \varepsilon_b N - S \quad (1)$$

where:

$$N = \frac{E(\sigma,\theta)}{\sigma} \quad (2)$$

is the wave-action density as a function of frequency σ and direction θ. $E(\sigma,\theta)$ is spectral wave density representing the wave energy per unit water surface area per frequency interval. Execution of the numerical scheme of those governing equation are explained in some literatures [3, 4]. C_x, C_y and C_θ are the velocity characteristic with respect to x, y, and θ direction; N_y and N_{yy} symbolize the first and second derivatives of N with respect to y; C and C_g are wave celerity and wave group velocity; then, κ is an empirical factor which depicted the magnitude of diffraction; ε_b is the energy dissipation during wave breaking parameter; S means additional sources such as: bottom friction loss, wind strength and interaction of nonlinear wave.

2.2.1. Wave diffraction. The first term on the right side of equation 1 is the wave diffraction term derived from a parabolic approximation wave theory [3]. In application practice, values of κ are in between 0 with no diffraction to 4 for strong diffraction. A value of κ = 2.5 was used by [3, 4, 5] to model wave diffraction for both narrow and wide gaps between breakwaters. κ value = 4 is recommended for wave diffraction at a semi-infinite long breakwater or at a narrow gap case with the opening equal or less than one wavelength. In the case of a fairly wider gap with an opening greater than one wavelength, the value of κ is equal to 3.

2.2.2. Wave reflection. The wave energy reflected at a shoreline is computed in assumptions of the incident and reflected wave angles are proportional to the shore normal direction and the reflected wave N_r is assumed to be linearly relative to the incident wave N_i:

$$N_r = K_r^2 N_i \quad (3)$$

where K_r is a coefficient of reflection, K_r = 0 for no reflection and K_r = 1 for full reflection. K_r is defined as the ratio of reflected to incident wave height [6].

Refraction diffraction analysis were made using two dimensional 2D wave model at steady state condition with model grid 5 x 5m^2 as displayed in Fig. 7. 2D wave model analysis in here used BMKG data recorded on January 25th, 2012 when the wave height was varied from 4.0m–5.0m and strong wind blew from North West direction. Two scenarios of wave model have been developed to simulate wave height in surround breakwater. There are 4 (four) examination points (A, B, C, D) to observe wave height generation due to significant wave height, H_s, of 4.00m and 5.00m as displayed in Fig. 8.

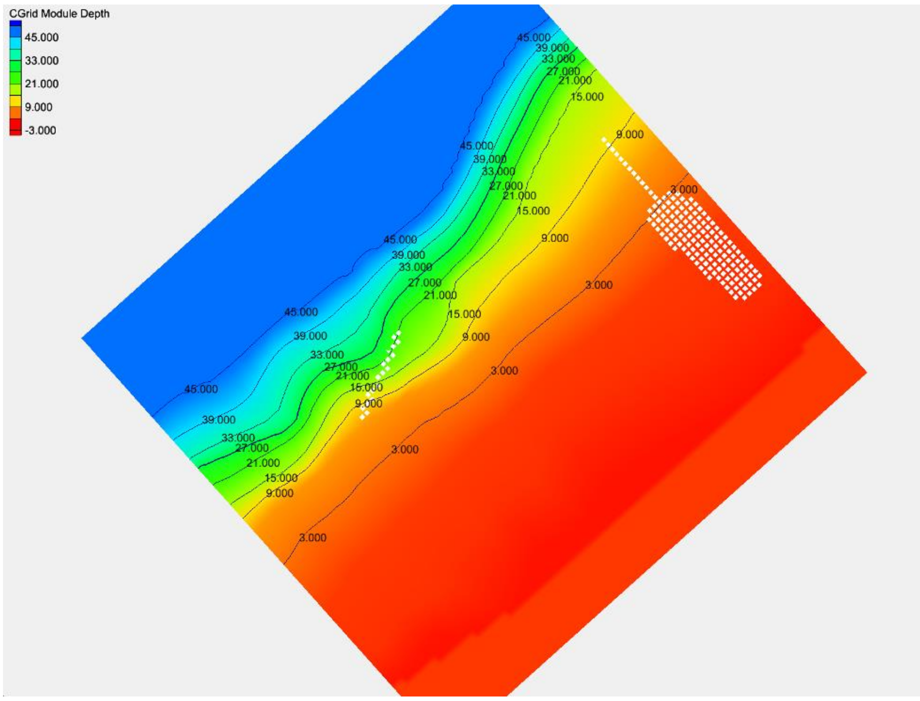

Figure 7. Numerical model bathymetry grid for 2D wave model of Waikelo Port

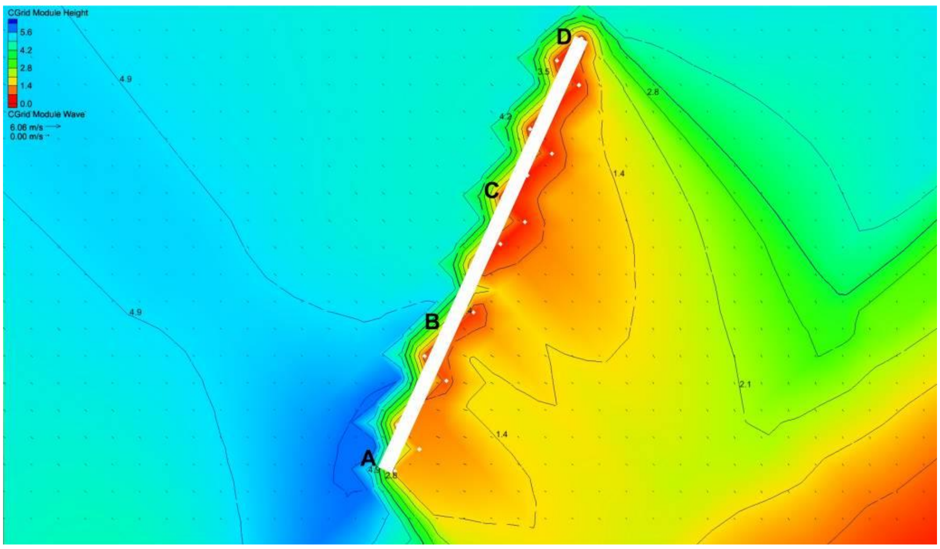

Figure 8. Examination points (A, B, C, D) of 2D wave model simulation in surround breakwater

3. Result and Discussion

The simulation result of developed 2D wave model from 2 of significant wave height scenarios at 4.0 and 5.0m are displayed in Figs. 9, 10, 11, and 12.

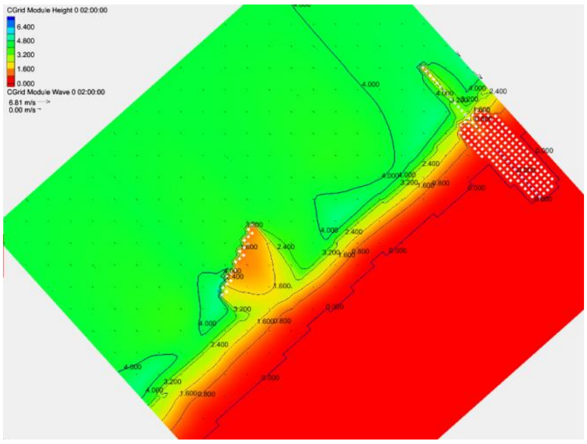

Figure 9. Simulated wave propagation due to 4.0m of significant wave height (H_s).

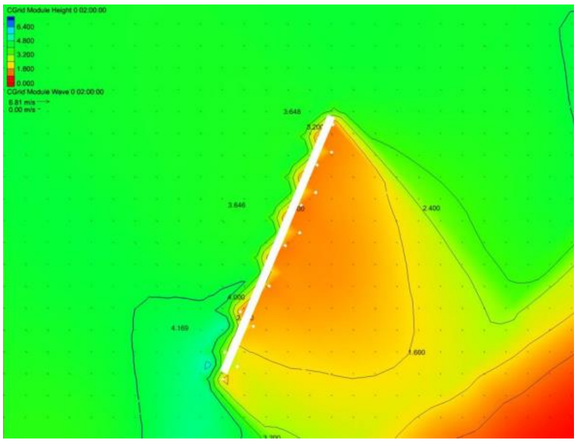

Figure 10. Distribution of wave height in surround breakwater due to H_s = 4.0m.

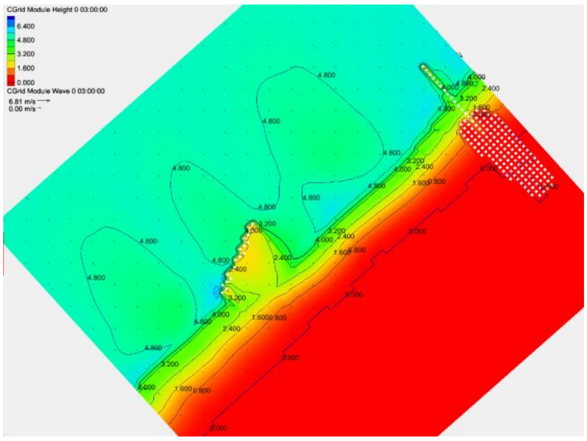

Figure 11. Simulated wave propagation due to 5.0m of significant wave height (H_s).

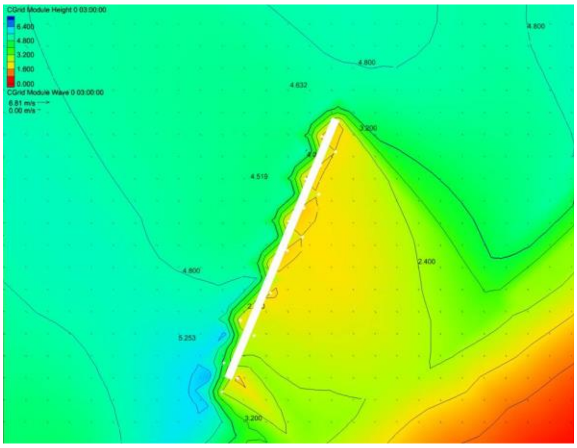

Figure 12. Distribution of wave height in surround breakwater due to H_s = 5.0m.

Based on the result of 2D wave model as shown in Figs. 9, 10, 11 and 12 above, it can be seen clearly the variation of wave height in 4 examination points (A, B, C, D) in front and back side of breakwater. The details are summarized in Table 2.

Table 2. Simulated wave height in surround breakwater

Examination points	H_s = 4.0 m		H_s = 5.0 m	
	Front side (m)	Back side (m)	Front side (m)	Back side (m)
A	4.31	2.22	5.87	2.73
B	4.14	1.55	4.79	1.72
C	3.82	1.53	4.65	1.64
D	3.80	1.83	4.75	1.73

From the diffraction and refraction analyses inform that the wave height in front side of breakwater is varied from 3.80m to 5.87m. This value is much higher than 50 years return period of wave design (2.00 meters) which is used as a calculation reference of breakwater structure.

4. Conclusions

Calculation of wave generation based on wind speed on January 25th, 2012 at 23 knot, produce significant wave height 2.11m and maximum wave height 3.80m. Those calculation results are quite close to recorded data by BMKG. Based on the result of 2D wave model simulation, it can be concluded that the wave height in surround breakwater is higher than wave design of 50 years return period which is used in design and calculation of breakwater structure. The reasons of Waikelo Port breakwater failure can be classified in reasons relate to the hydraulic and loads conditions: exceedance of wave condition and it can be categorized also in force majeure type.

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