Reliability Analysis of Revetments near Canti Pier, South Lampung

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Abstract. Canti pier is located in Southern Lampung and faces the Sunda strait water areas. Locals use this pier sailing to Sebesi island, and tourists need it as the closest starting point from the mainland to explore Krakatoa’s natural reserve. As a volcano tsunami occurred last December of 2018, Canti was one of the affected locations. Previous study shows measured wave height of 3-7 m in Way Muli and Kahai beach, located around 10 km from Canti. Field observation clearly shows the damaged concrete structure of the T-shaped Canti pier’s end tip due to the tsunami. This research focuses on analyzing the reliability of the north and south revetments of the Canti pier that still exists using statistic and probability methods. Van der Meer’s rock stability formula is adopted as the basis of determining the Limit State Function (LSF). For the reliability method, the FORM (First Order Reliability Method) is applied and produces the probability of failure of the revetment’s system during particular designed service times. The result shows that the northern revetment is relatively more robust than the southern revetment as its probability of failure is slightly lower. The expected failure probabilities are acceptable during regular operation for both revetments (less than 15%). If there is a stormy condition, the chance of collapse south revetment is relatively higher. One could also foresee the total collapse of revetments if tsunami waves attack. This condition also describes the 2018 tsunami wave height in Canti is much lower than in Way Muli since this area is sheltered by some islands, such as Sebuku and Sebesi. To conclude, considering the normal wave condition, the revetments’ reliability is noticeably low or even unreliable (tsunami waves).

Keywords: reliability analysis, FORM, revetment, Canti pier

1. Introduction

The 2018 Sunda Strait tsunami occurred due to a flank collapse of Mount Anak Krakatoa [1,2]. [1,3,4] surveyed the damaged areas along the coast of Java and Sumatera island due to the waves. [1] measured the inundation wave height (ranging 3-7 m) in some areas in Southern Lampung and destroyed public infrastructures, including the pier and revetments.

The tsunami destroyed the end tip of T-shaped Canti pier in South Lampung Province. Fortunately, the whole structure remains and functional (see Figure 1a). The revetment structures in the northern and southern parts of
the Canti pier were not collapsed, although we observed the breaching process on the structure’s seaward side (see Figure 1b and 1c). There is a need to assess these revetment structure’s failure probability to see their reliability and plan the maintenance.

![Figure 1. a) The broken end tip of T-shaped Canti pier structure; b) breaching process in north revetment; c) breaching process in south revetment](image)

Risk assessment of built coastal structures due to extreme waves is challenging. [5] introduced the role of reliability in the design phase of coastal structures. [6] applied and improved the analysis of coastal structures in Turkey. They also pointed out the robustness of van der meer’s equation in reliability analysis of coastal structure’s design. [7] researched Vietnam’s coastal structures reliability analysis, and [8] did for the case of Korea’s breakwaters. This research paper presents the reliability analysis of revetments in Canti (South Lampung) after facing the extreme waves event (tsunami) in the last 2018 in Sunda Strait.

2. Risk Assessment and Probabilistic Design

In the risk assessment model, the safety of coastal structures was evaluated by modeling random design variable (z) with probability distributions at their limit state, called Limit State Function (LSF). An LSF (z) is a function of the strength/resistance (R) and the load (S) for a particular failure mode,

\[ z(x) = R(x) - S(x) \] (1)

the probability of failure \( P_f \) considering two statistically independent variables of R and S is shown as follow,

\[ P_f = \int \int f_R(r)f_S(s) \, dr \, ds \text{ where } R \leq S \] (2)

First-Order Reliability Method (FORM) approximates the failure surface by a tangent hyperplane (Burcharthur, 1993). The van der meer’s rock stability equations [9] as an LSF in the design phase are as follows,

\[ z = 6.2 \, P_{0.18} \, \Delta \, D_{n50} \left( \frac{S}{\sqrt{N}} \right)^{0.2} \xi^{-0.5} - H_s \text{ where } \xi = \tan \alpha \sqrt{s} \text{ for plunging waves} \] (3)

\[ z = 1.0 \, P_{-0.13} \, \Delta \, D_{n50} \left( \frac{S}{\sqrt{N}} \right)^{0.2} \sqrt{\cot \beta} \xi^P - H_s \text{ for surging waves} \] (4)
in which:

- $P$ = notional permeability
- $D_{n50}$ = nominal diameter = $\frac{M_{50}}{\rho_s}$ (kg); in which $M_{50}$ is 50% finer
- $S$ = damage level
- $N$ = number of waves
- $\Delta = \frac{\rho_s - \rho_w}{\rho_w}$
- $\rho_s$ = rock density (kg/m$^3$)
- $\rho_w$ = seawater density (kg/m$^3$)
- $s$ = wave steepness = $\frac{H_0}{L_0}$; in which $H_0$ and $L_0$ respectively are wave height and wavelength in deep water
- $\tan \alpha$ = beach slope

Each variable in van der meer’s equation involves uncertainty either in its measurement or its definition. Therefore, defining the relevant statistical distribution for the variables is essential in reliability analysis. To determine the probability of failure in design lifetime ($P_{fn}$), Poisson’s distribution is used. Reliability in design lifetime ($r_n$) is the opposite of the probability of failure.

$$P_{fn} = 1 - \left(1 - P_f\right)^n$$

where $n$ is the design lifetime of the structures

$$r_n = 1 - P_{fn}$$

3. Methodology

This research assesses the revetments structure by performing FORM as a reliability analysis tool in van der meer’s rock stability equation. Some parameters were collected from field observation, and others were from secondary data collection (see Figure 2a). Hydrodynamics conditions are designed in scenario analysis to describe mild, medium, and harsh situations.

Canti itself is one of the villages in South Lampung province and geographically located in 105° 35’ 34.18” E and 5° 47’ 48.58” S. Field observation chose 6 points along the revetment structures to represent north (points 1-3) and south (points 4-6) revetments (see Figure 2b). The length of north and south revetment respectively are 168 m and 221 m. Structural data of revetments were measured and input to reliability analysis, while hydrodynamics data were interpreted from related references.
4. Results and Discussion

The research proposes three scenarios describing hydrodynamics loads faced by revetments in Canti. Significant wave height is assumed to be low in normal condition (0.8 m), and in storm conditions, significant wave height is much higher (2 m). Wave height in tsunami condition is taken based on a post-tsunami survey by [1] in Way Muli to Kahai beach of inundation wave heights were 3.97 to 6.83 m. Those areas are located 10 km from Canti; in the model, the input values for the mean and standard deviation of tsunami wave height are 5 m and 0.5 m, see column 2 of table 1 for more detail about the scenarios.

Figure 3 presents the distribution of LSF for all scenarios in which the negative side defines the yearly exceedance probability/probability of failures (Pf) (see also Table 1, column 4th). In normal and stormy waves scenarios for both revetments (see Figures 3a-3d), the negative values of LSF are much less, which representing low yearly exceedance probabilities. In the tsunami scenario (see Figures 3e for north and 3f for south revetments), the yearly probability of failures is relatively high, reaching 100% for south revetment (see also Table 1, column 6th and 7th).
Figure 3. Limit State Function (LSF) or $z = 0$ (x-axis) and Monte Carlo’s frequency (y-axis) for all scenarios in the model: a) normal condition for north revetment; b) normal condition for south revetment; c) storm condition for north revetment; d) storm condition for south revetment; e) tsunami condition for north revetment; and f) tsunami condition for south revetment.

In the long run (25 years and 50 years design lifetime), the north revetment’s reliability is higher than the south revetment in all scenarios (see Table 1, columns 6th and 7th). These results also confirm that the rate of breaching areas observed in the south is more extensive than in the north (see Figure 1b & 1c again). In normal conditions, both revetments have considerably good reliability, and the future probability of failures is less than 15%. In stormy conditions, the north revetment’s probability of failure is also acceptable; however, the south revetment is
considerably high, reaching 40% in 50 years of design lifetime. If tsunami waves attack the revetments, the probability of both structure’s failures is extremely high (more than 90%). Field observation shows that revetment structures do not experience structural collapse after the 2018 Sunda Strait tsunami. One possible explanation for this is that the tsunami waves of Way Muli were not reached the Canti area since it is sheltered behind some islands, such as Sebesi, Sebuku, and some small islands. However, this thesis has to be validated by the hydrodynamic simulation of the tsunami.

**Table 1. Reliability analysis of revetments in Canti**

| No | Scenarios                  | Revetments | $P_t$ | $\beta$ | $P_{f}$ 25 yrs | $P_{f}$ 50 yrs | Highest alfa |
|----|----------------------------|------------|-------|---------|----------------|----------------|--------------|
| 1  | Normal Condition (Hs: 0.8 m and stdev.: 0.2) | North      | 5.516 x 10^{-4} | 3.263    | 1%             | 3%             | $d_{a50}$, P, N, and Hs |
|    |                            | South      | 2.854 x 10^{-3} | 2.764    | 7%             | 13%            |
| 2  | Storm Condition (Hs: 2.0 m and stdev.: 0.2)  | North      | 2.314 x 10^{-3} | 2.832    | 6%             | 11%            | $d_{a50}$, Hs |
|    |                            | South      | 9.773 x 10^{-3} | 2.335    | 22%            | 39%            |
| 3  | Tsunami (H: 5 m and stdev.: 0.5 m)              | North      | 3.572 x 10^{-2} | 1.803    | 60%            | 84%            | $d_{a50}$ and P |
|    |                            | South      | 9.298 x 10^{-2} | 1.323    | 91%            | 99%            |

*a stdev.: standard deviation

The model also shows the alfa values for each van der meer’s equation variable (see Table 1, column 8th). This alfa parameter’s high absolute value represents the contribution of the relevant variable’s uncertainty to the final result. For all scenarios, the nominal diameter ($D_{a50}$) of revetment’s armor comes in the top, followed by other variables (notional permeability $P$, number of waves $N$, and wave height $H$) alternately. Two of the major challenges in assessing built coastal structures are indeed defining the rock dimension and adjusting notional permeability.

5. Conclusion and Future Research

First-Order Reliability Method (FORM) is successfully applied to analyze the reliability of revetment in Canti, especially after the tsunami attack. In the long run, the north revetment is more robust than the south revetment in normal waves condition. However, if we consider the stormy situation, the south revetment’s reliability is relatively lower; therefore maintenance plan of this revetment is highly recommended. The 2018 Sunda Strait tsunami waves did not severely damage the revetments as is modeled; this is presumably due to Canti’s sheltered location behind some islands.

In the future, the results need to be elaborated in the fault-tree failure system that incorporated probabilities of every failure mechanism of the structures. It is also recommended to detailing an action plan for maintenance of the revetment regarding future reliability.

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References

[1] Takabatake, T et al., 2019. Field survey and evacuation behaviour during the 2018 Sunda Strait tsunami. Coastal Engineering Journal. ISSN: 2166-4250 (Print) 1793-6292 (Online). DOI: 10.1080/21664250.2019.1647963

[2] Grilli, S. T. et al., 2019. Modelling of the tsunami from the December 22, 2018 lateral collapse of Anak Krakatau volcano in the Sunda Straits, Indonesia. Nature Scientific Reports (2019) 9:11946. [https://doi.org/10.1038/s41598-019-48327-6]
[3] Muhari, A et al. 2019. The December 2018 Anak Krakatau Volcano Tsunami as Inferred from Post-Tsunami Field Surveys and Spectral Analysis. Pure Appl. Geophys. 176 (2019), 5219–5233. https://doi.org/10.1007/s00024-019-02358-2

[4] Syamsidik et al., 2020. The December 22, 2018 mount Anak Krakatau volcanogenic tsunami on Sunda strait coast, Indonesia: tsunami and damage characteristics Nat. Hazards Earth Syst. Sci., 20, 549–565, 2020. https://doi.org/10.5194/nhess-20-549-2020

[5] Burchart, H. F. 1993. Reliability Evaluation and Probabilistic Design of Coastal Structures. International Seminar on Hydro-Technical Engineering for Future Development of Ports and Harbours (Unyusho Kowan Gijutsu Kenkyujo) Tokyo, 1993

[6] Balas, C. E & Ergin, A. 2002. Reliability-Based Risk Assessment in Coastal Projects: Case Study in Turkey. J. Waterway, Port, Coastal and Ocean Engineering. ISSN 0733-950X. Vol. 128, No. 2, March 1, 2002. 52-61

[7] Cong-Mai, V. et al. 2009. Probabilistic Design and Reliability Analysis of Coastal Structures – A Vietnam Case. Proceedings of the 5th International conference on Asian and pacific coasts 2009. ISBN: 978-981-4297-97-5. World Scientific. Pg.: 201-210

[8] Kim, S-W & Suh, K-D. 2010. Reliability Analysis of Breakwater Armor Blocks: Case Study in Korea. Coastal Engineering Journal, Vol. 52, No. 4 (2010) 331–350. DOI: 10.1142/S0575818910002208

[9] van der Meer, J. S. 1988. Rock slopes and gravel beaches under wave attack. Doctoral Thesis, Delft University of Technology.