Wind-Wave Interaction in Sengguruh Reservoir and The Effect to Riprap Material

J Fidari

1Water Resources Engineering Department, Faculty of Engineering, Universitas Brawijaya, Malang, 65145, Indonesia

*Corresponding author: jadfan@ub.ac.id

Abstract. The Sengguruh Dam is one of the large dams managed by Jasa Tirta I Public Company. This reservoir has been operating for more than 38 years (operating since 1982 and the latest data is for 2020). This research was conducted to determine the effect of wind and the interaction of wind on the water in the Sengguruh Dam. Most of the interaction of water and wind is mostly carried out on coastal structures but rarely investigated in the upstream area of the river basin. Investigations were carried out to obtain an overview and characteristics of the influence of the two variables of wind and water on the hydraulics of the reservoir storage, sedimentation in the water column, and side effects of the embankment material in the riprap dam. This study will provide an overview of the condition of the Sengguruh Dam which is full of sediment and shows the wind and water interaction that occurs in the reservoir as well as the potential hazards that are quite large for the management of water resources and disasters in the surrounding community if there is a high risk or threat that occurs if these conditions do not meet dam safety standards in Indonesia.

Keywords: coastal structures, potential hazards, wind

1. Introduction

Recent field observations and large-eddy simulations have shown that the impact of fast swell on the marine atmospheric boundary layer (MABL) might be stronger than previously assumed. For low to moderate winds blowing in the same direction as the waves, swell propagates faster than the mean wind [1]. Wind-wave interaction phenomenon in a coastal area can be determined by model and observations. The model assumes a stationary momentum and turbulent kinetic energy balance and uses the dampening of the waves at the surface to describe the momentum flux from the waves to the atmosphere [1].

The primary research of wind-water interactions was focused on coastal areas along the shores of world oceans and seas because a basic understanding of coastal meteorology is an important component in coastal and offshore design and planning [2]. On other hand, dams and reservoirs play an important role in the control and management of water resources. Undoubtedly, mitigating floods, securing water supplies, and providing hydropower have benefited human societies in many ways, allowing for improved human health, expanded food production, and economic growth [3].

Base on that, similar principles of water wave mechanics are considered in conditions of water reservoirs [2]. The energy transferred to the water surface by wind generates a range of wave heights and periods that increase as the waves travel across the available fetch length [4]. The impact of wind-induced waves on the reservoir bank begins to arouse the concern of some researchers [5]. Compared with other factors, such as rainfall and fluctuations in reservoir water levels, the long-term effect of waves on the reservoir bank may be more critical [6].

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In this research Sengguruh Dam has been getting problems with the accumulation of sediment, flood, and riprap structure stability. That wind-wave interaction will give direct impact and indirect impact to Sengguruh Dam riprap material.

2. Material and Method
The wave characteristic most significant to riprap design is the wave height, which is influenced by wind velocity, duration, and fetch distance [6]. Based on the influence of wind speed, duration, and fetch distance, to obtain the phenomenon and the influence of this variable, we use 15 years of climate data from ECMWF data, and then it calibrates with climate data from the Sengguruh Dam station. For calibration, we use 2 years of climatology data observation from Sengguruh Dam Station. In the first part, we extract the wind variable at 10 m high ($u_{10}$) hourly for 15 years of historical data.

![Figure 1. $u_{10}$ and $v_{10}$ in Sengguruh Dam at 2019 using ECWMF climate data](image1)

![Figure 2. $u_{10}$ and $v_{10}$ in Sengguruh Dam at 2020 using ECWMF climate data](image2)

Figure 1 and Figure 2 are the wind fluctuation in the Sengguruh Dam catchment area. We use 2019 and 2020 wind data to compare data from observation data stations. Wind direction from ECWMF data was also analyzed. During the rainy season (start from November to December) wind blows with a range of 12%–28% and the majority from the south wind. The changing of wind direction monthly (start from January to December) at Sengguruh Dam can be seen in Figure 3.
Figure 3. The wind direction in Sengguruh Dam using ECWMF climate data
After obtaining wind data (wind speed vector and direction) the boundaries of the Sengguruh Dam area are also to be checked to ensure that the waves could form properly and could generate waves.

**Figure 4.** The Sengguruh boundary area and fetch possibility distance

Figure 4 shows the Sengguruh Dam boundary area, which line indicates the possibility of fetch distance. On line 1 (the red line) the line length is 1.84 km, on line 2 (blue color) the line length is 0.55 km, on line 3 (pink) the line length is 1.23 km. To check the majority influence of the distance it uses the Stevenson formula \[ H_w = 0.34 \sqrt{F} + 0.76 - \frac{2}{\sqrt{F}} \] (1)

Where:
\( H_w \): Heigh of wave (m)
\( F \): Fetch distance (m)

After wind data and climate data were get, the condition of the Sengguruh was also checked. The other major problem for the Sengguruh Dam that already operates 38 years old is high sedimentation from Semeru Mountain (debris flow) and from the river itself.

Figure 5 shows us the condition of Sengguruh Dam in the dry season and the rainy season. Panel (A) is the condition of Sengguruh Dam in the dry season and at the lowest water level; (B) panel is the condition of Sengguruh Dam in the rainy season with fully loaded with sediment material and debris flow from Semeru Mountain; (C) panel is excavating and removing sediment material in the dry season to maintain the Sengguruh Dam reservoir.
Figure 5. The Condition of Sengguruh Dam (A) Condition at low water level in the dry season; (B) Condition at rainy season; (C) Reservoir condition at the dry Season.

With several variables in that location, the riprap of the Sengguruh Dam also need to be checked. The material in riprap is suspected will get deflation with coupled variables. America Agriculture Soil Service [8] explains the failure of the riprap. The failure of the riprap has several types, it can be seen in Figure 6. In Figure 6 (A) riprap failure with sliding material but the base material is still in place and the filter blanket can be seen. In Figure 6 (B) riprap failure have a more complex condition with displacement at the rock material and the displacement penetrate until base material, the failure makes the radius of displacement (R).

Figure 6. (A) Riprap failure only in surface material; (B) failure penetrate until base material.

Source: Design of Riprap Revetment (USBR Report; 1989)
3. Result and Discussion

3.1. Fetch Condition.
Zhao [9] explain how fetch can get from spatial data, by divide reservoir area with reservoir width. Zhao explanation can be seen in Figure 7 panel (A), while the condition of Sengguruh Dam can be seen in Figure 7 panel (B) where the Sengguruh Dam area is 757.396 m$^2$, and the width is 4.655 m$^2$, so roughly the fetch can be fully developed according to Zhao explanation is about 162.71 m. With that condition, the fetch distance is also simulated base on the Sengguruh Dam area and river morphology. Start from the main dam until 3 km long, the possibility of the longest fetch distance is 1.23 km from the main dam. The simulation of wave height base on fetch can be seen in Figure 8. Base on that trend wave height will be reduced to 3.5 km long but it will increase rapidly if the distance was extended to 100 km (can be seen in Figure 8 (B)).

![Figure 7. A) Zhao Criteria for Fetch; B) Sengguruh Fetch using Zhao explanation.](image-url)
Figure 8. Wave Height simulation according to Fetch distance (A) until 3.3 km from The Main Dam; (B) The Fetch distance prolongs until 100 km long.

3.2. Wind-wave effect to riprap deflation

According to the United States, Bureau of Reclamation [10] Several factors that influence the occurrence of landslides caused by wind include soil erodibility (Is), climatological factors caused by wind (C’), soil roughness (K’), wind erosion speed (V’), land length (L’). It can be shown by the following equation:

\[ E = f(I_s, C', K_r', V', L') \]  

(2)

Woodruff [11] explain Soil erodibility (Is) can get from the table, C’, also should be computed on a monthly or seasonal basis to permit better evaluation of short-time, highly erosive periods, C’ also called a climatic factor, L’ is field length along the prevailing wind erosion direction, and V is equivalent quantity of vegetative cover.

Table 1. Deflation in Sengguruh Dam base on Wind-wave interaction in Reservoir

| Year | Month | E (Monthly average) | Ratio with Earth Dam Fill |
|------|-------|---------------------|---------------------------|
|      |       | Top (kg/m²) | Bottom (kg/m²) | Top | Bottom |
| 2019 | Jan   | 6.53 | 5.66 | 0.03% | 0.03% |
|      | Feb   | 4.50 | 3.90 | 0.02% | 0.02% |
|      | Mar   | 4.67 | 4.05 | 0.02% | 0.02% |
|      | Apr   | 4.50 | 3.90 | 0.02% | 0.02% |
|      | May   | 11.44 | 9.92 | 0.05% | 0.05% |
|      | Jun   | 8.64 | 7.49 | 0.04% | 0.03% |
|      | Jul   | 14.52 | 12.58 | 0.07% | 0.06% |
|      | Aug   | 19.23 | 16.66 | 0.09% | 0.08% |
|      | Sep   | 11.39 | 9.87 | 0.05% | 0.05% |
|      | Oct   | 17.19 | 14.90 | 0.08% | 0.07% |
|      | Nov   | 12.85 | 11.14 | 0.06% | 0.05% |
|      | Dec   | 6.98 | 6.05 | 0.03% | 0.03% |
| 2020 | Jan   | 5.05 | 4.38 | 0.02% | 0.02% |
|      | Feb   | 5.05 | 4.38 | 0.02% | 0.02% |
|      | Mar   | 5.73 | 4.97 | 0.03% | 0.02% |
|      | Apr   | 6.20 | 5.37 | 0.03% | 0.02% |
|      | May   | 6.76 | 5.85 | 0.03% | 0.03% |
|      | Jun   | 10.45 | 9.06 | 0.05% | 0.04% |
|      | Jul   | 14.46 | 12.53 | 0.07% | 0.06% |
|      | Aug   | 14.67 | 12.72 | 0.07% | 0.06% |
|      | Max   | 19.23 | 16.66 | 0.09% | 0.08% |
|      | Min   | 4.50 | 3.90 | 0.02% | 0.02% |
Using equation (2) procedure we can get the result as in table 1. The deflation will be higher in August and it will be decreased significantly in February. The ratio also shows us, that in August 0.09% of riprap material will be eroded.

4. Conclusion
This result of the wind-wave interaction and the effect on the riprap material shows us, that wind and wave also give influence to the riprap material. The result also gives us an explanation of the phenomenon of wind-induced waves and the aspect to make waves fully developed. To make waves fully developed in the reservoir at least the fetch must be around 100 km roughly. In the Sengguruh Dam Case, waves cannot be fully developed because of several variables such as river meander, sediment decomposition, and drag coefficient in the surface water boundary layer. If wind calculates hit directly to the main dam structure the deflation will happen. If we compare directly with the main dam heap the ratio will be small, almost nothing. But if we calculate accumulate annually it will show a lot of material has been sliding gradually in the earth-fill dam.

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