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Estimating Aftershock Termination Time Using Statistical Decay Models: A Case Study of the March 22, 2024 Bawean Earthquake

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A B S T R A C T

An earthquake struck Bawean Island on March 22, 2024 with a magnitude of 6.5 followed by a series of aftershocks. In this study, the decay of aftershocks in the Bawean region was analyzed from March 22 to March 31, 2024 using the Omori Method, Mogi I Method, Mogi II Method, and Utsu Method. The purpose of this research is to determine the duration of aftershock decay in Bawean and to identify the most suitable statistical method for predicting aftershock decay time in the region. The analyzed data were obtained from the BMKG earthquake repository. By applying the four methods, results were obtained in the form of aftershock decay duration and correlation coefficients for each method. The analysis shows that the most appropriate statistical methods for calculating aftershock decay time in Bawean are the Mogi I Method and the Utsu Method both producing a correlation coefficient of approximately -0.806 and an aftershock decay duration of 24 days consistent with the BMKG earthquake catalog data.

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1. INTRODUCTION

Indonesia is a country with a high potential for geological hazards, such as volcanic eruptions and earthquakes. This condition is primarily caused by its location along active tectonic belts, characterized by the presence of numerous active faults and subduction zones [1]. Indonesia is geographically located at the intersection of three major tectonic plates, the Indo-Australian, Eurasian, and Pacific plates. In the Bali-Nusa Tenggara region, the tectonic setting becomes increasingly complex due to the subduction of the Australian Plate beneath the Nusa Tenggara Islands, forming an opposing arcuate structure [2].

The Bali–Nusa Tenggara region is also well known for its high seismic activity, particularly in the northern part. The elevated level of seismicity in this area is strongly influenced by the presence of the Flores Backarc Thrust, an active fault zone that frequently generates large earthquakes, such as the Lombok earthquake on August 5, 2018 [3]. Following a mainshock, seismic activity is typically accompanied by a sequence of aftershocks over a certain period of time [4].

The aftershock phenomenon can be explained by the Elastic Rebound Theory which describes earthquakes as a process of stress release toward a new equilibrium state along a fault following a mainshock [5]. During this adjustment process, the frequency of aftershocks gradually decreases and eventually ceases once the fault reaches a stable condition. This decreasing trend in aftershock frequency is referred to as aftershock decay [6].

To estimate the termination time of aftershock sequences, statistical approaches such as the Omori, Mogi I, Mogi II, and Utsu methods are commonly applied. Each method exhibits different levels of suitability depending on the study area which can be evaluated using the correlation coefficient (r) with values approaching 1 or -1 indicating a strong fit. Previous studies have reported varying results. For example, a study on aftershock decay following the Sunda Strait earthquake on May 23, 2021 concluded that the Mogi I method provided the best fit to BMKG data [7]. Meanwhile, the Mogi I and Utsu methods were found to be suitable for application in the Lombok region [8].

On March 22, 2024, a significant earthquake with a magnitude of 6.5 occurred near Bawean Island resulting in damage to approximately 4,300 buildings. The mainshock was followed by 878 aftershocks recorded between March 22 and June 12, 2024 based on analyses conducted by the Malang Geophysical Station [9]. This seismic activity is associated with the offshore Muria Fault which had previously been considered inactive [10][11]. This offshore fault differs from the active Muria Fault located on the Muria Peninsula which has been documented in the 2017 Indonesian Active Fault Map published by the National Center for Earthquake Studies [12] .

This study aims to validate the results of previous research related to the March 22, 2024 Bawean earthquake. The estimated termination time of the aftershock sequence is expected to serve as a reference for disaster mitigation efforts in the Bawean region and its surroundings. In addition, this study is expected to provide further insight into the characteristics and patterns of seismic activity in the area.

2. RESEARCH METHOD

2.1 Data

The earthquake data used in this study were obtained from the BMKG earthquake repository website (https://repogempa.bmkg.go.id/eventcatalog). The observation period spans from March 22 to March 31, 2024, covering the Bawean region and its surroundings within the coordinate boundaries of 111.4°–113.7° E longitude and 5.2°– 6.8° S latitude. The spatial distribution of the study area is illustrated in Fig. 1.

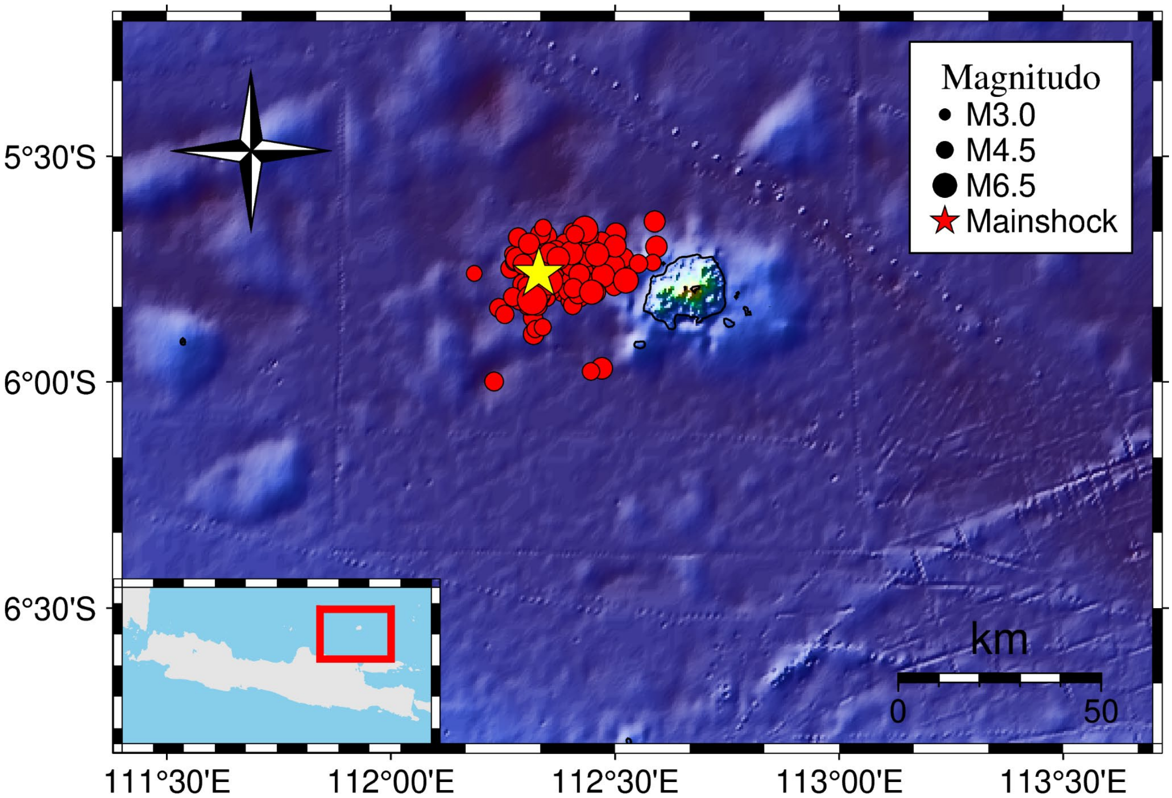


Fig. 1 Map of the study area boundaries in Bawean and its surroundings, showing the mainshock and aftershocks used as research data.

The acquired earthquake data were subsequently processed using Microsoft Excel to generate a daily earthquake frequency distribution graph for the study period. This graph was then analyzed using the Omori, Mogi I, Mogi II, and Utsu methods.

2.2 Omori Method

The Omori method describes the temporal decay of aftershock frequency as a function of time following the mainshock [13]. The mathematical expression of the Omori law is given by:

$$n(t) = k(c + t)^{-1} \quad (1)$$

Where:
$n(t)$: the aftershock frequency,
t : the time elapsed since the mainshock,
k and c :constants dependent on geological conditions.

2.3 Mogi I Method

The Mogi I method is applied to analyze aftershock sequences with durations longer than 100 days [13]. The formulation of this method is expressed as:

$$n(t) = a \cdot b^{t} \quad (2)$$

Where:
$n(t)$: the aftershock frequency,
t : the time elapsed since the mainshock,
a and b : constants influenced by the surrounding geological conditions

2.4 Mogi II Method

The Mogi II method is used for aftershock sequences with durations shorter than 100 days [13]. The mathematical expression is given by:

$$n(t) = a \cdot e^{-bt} \quad (3)$$

Where:
$n(t)$: the aftershock frequency,
t : the time elapsed since the mainshock,
a and b : constants influenced by the surrounding geological conditions

2.5 Utsu Method

The Utsu method is a development of the Omori method and is more suitable for describing aftershock frequency per unit time [13]. The equation for the Utsu method is written as:

$$n(t) = k(t + c)^{-p} \quad (4)$$

Where:
$n(t)$: the aftershock frequency,
t : the time elapsed since the mainshock,
k and p :constants dependent on geological conditions

2.6 Correlation Analysis

Since several methods are used to estimate the termination of aftershock activity, a comparative analysis is required to determine the most suitable method. The best-performing method is selected by comparing the correlation coefficient (r) between the observed data and the calculated results. The correlation coefficient is computed using the following equation:

$$r = \frac{n\sum x_i y_i - (\sum x_i)(\sum y_i)}{\sqrt{(n\sum x_i^2 - (\sum x_i)^2)(n\sum y_i^2 - (\sum y_i)^2)}} \quad (5)$$

Where:
r : the aftershock frequency,
x : the time elapsed since the mainshock,
y : constants dependent on geological conditions
n : the total number of data points.

3. RESULT AND DISCUSSION

The frequency distribution of aftershocks following the M6.5 Bawean earthquake on March 22, 2024, is shown in Figure 2. Based on the BMKG earthquake catalog, a total of 94 aftershocks were recorded between March 22 and March 31, 2024.

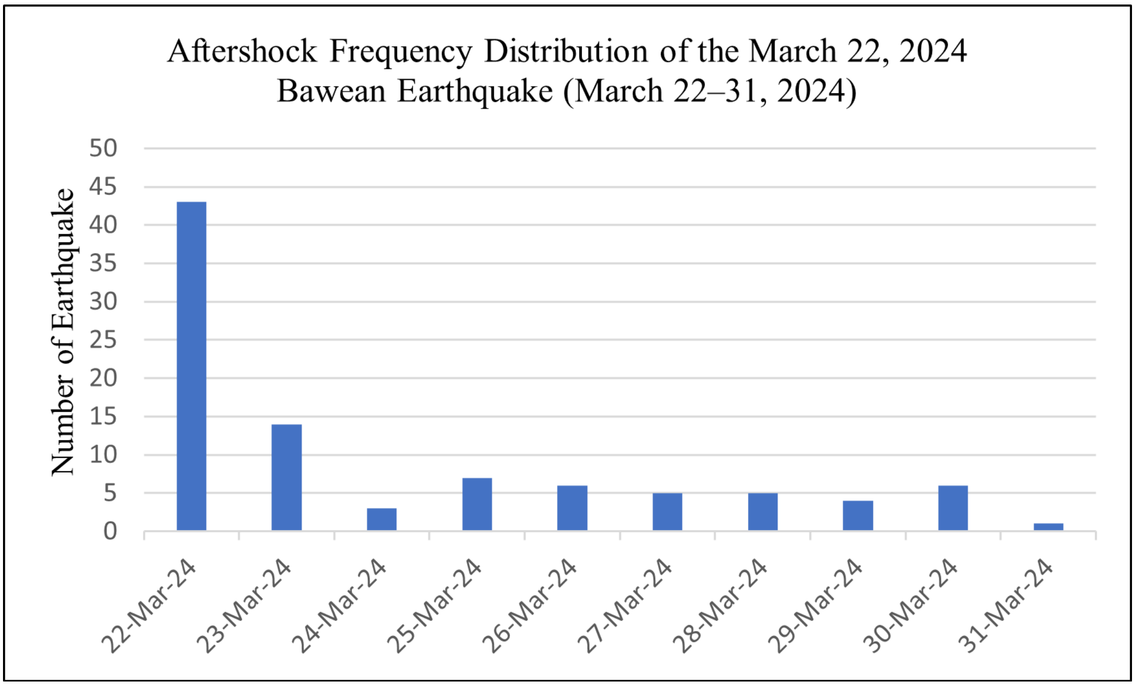
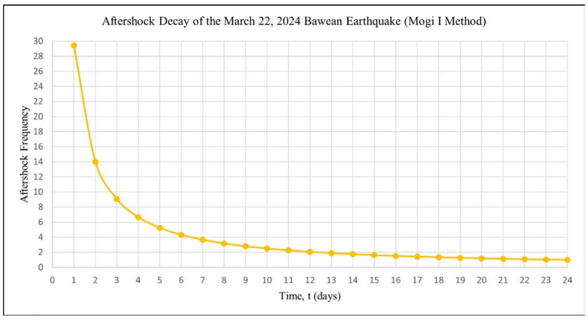


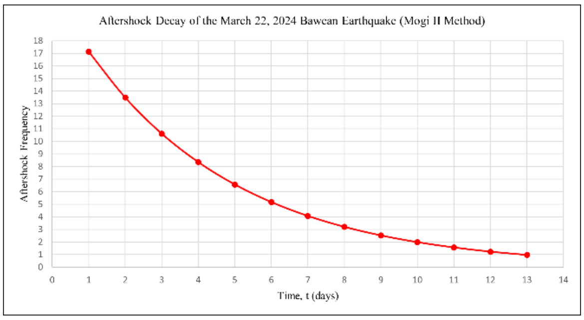
Fig. 2 Aftershock frequency distribution from March 22 to March 31, 2024.

The highest aftershock frequency occurred on the first day, March 22, 2024 with a total of 43 aftershocks. On the second day, the aftershock frequency decreased significantly to 14 events. Subsequently, the frequency fluctuated from the third to the tenth day following the mainshock.

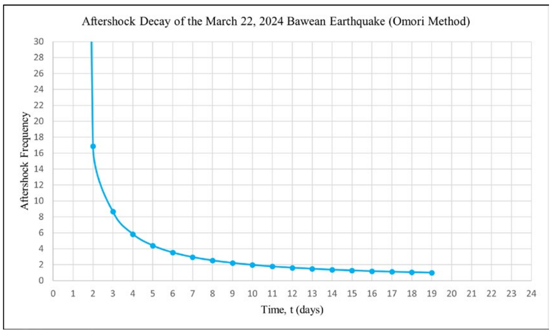
Using statistical approaches based on the four aftershock decay methods discussed previously, the aftershock frequency distributions, correlation coefficients, and aftershock decay durations were obtained. Aftershock decay is considered to occur over time when the correlation coefficient has a negative value, as the relationship between aftershock frequency and time is inversely proportional. A correlation coefficient value closer to -1 indicates a stronger inverse relationship [16].



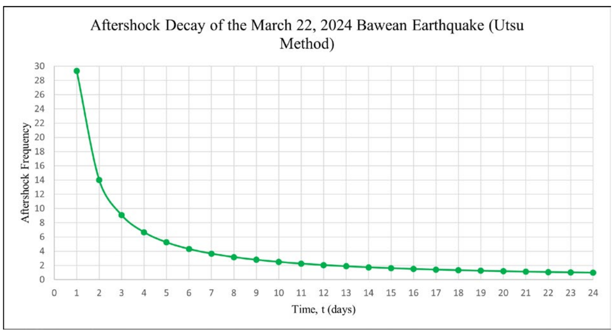
(a)



(b)



(c)



(d)

Fig. 3 Aftershock decay curves of the March 22, 2024 Bawean earthquake using (a) Mogi I, (b) Mogi II, (c) Omori, and (d) Utsu methods.

The estimation of aftershock decay duration was conducted using the Omori, Mogi I, Mogi II, and Utsu methods, as illustrated in Figure 3. The decay curves indicate that the aftershock frequency decreases with time. The final analysis results, including the correlation coefficients, decay durations, and estimated termination dates of aftershock activity, are presented in Table 1.

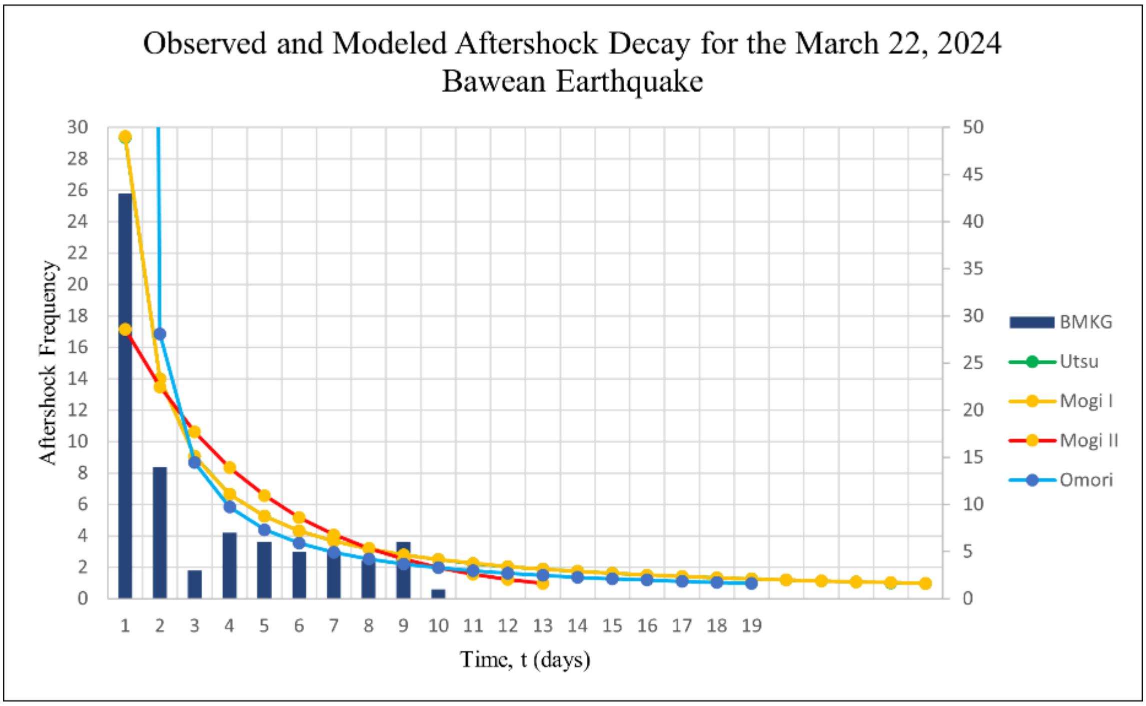


Fig. 4 Observed daily aftershock frequency and fitted statistical decay models (Omori, Mogi I, Mogi II, and Utsu) for the March 22, 2024 Bawean earthquake. The histogram represents the observed BMKG aftershock catalog while the curves indicate the theoretical decay functions of each model.

Each method yields different results in terms of decay patterns, correlation coefficients, and aftershock durations. The Omori method produces a correlation coefficient of 0.628, with the aftershock sequence estimated to end on the 19th day, corresponding to April 9, 2024. The Mogi I method yields a correlation coefficient of −0.806, estimating the aftershock termination on the 24th day, April 14, 2024. The Mogi II method produces a correlation coefficient of −0.745, with the aftershock sequence ending on the 13th day, April 3, 2024. Similarly, the Utsu method results in a correlation coefficient of −0.806, with an estimated aftershock termination on the 24th day, April 14, 2024.

Figure 4 shows the comparison between the observed daily aftershock frequency and the theoretical decay curves derived from the Omori, Mogi I, Mogi II, and Utsu models. The histogram represents the observed aftershock occurrences obtained from the BMKG earthquake catalog while the curves illustrate the expected temporal decay behavior predicted by each statistical model. As shown in the figure, the aftershock frequency decreases with time following the mainshock, indicating a typical decay pattern of aftershock activity.

The correlation coefficients and aftershock decay functions $n(t)$ derived from the four methods show noticeable differences. The Mogi I, Mogi II, and Utsu methods yield negative correlation coefficients indicating an inverse relationship between the independent variable (time) and the dependent variable (aftershock frequency). A negative correlation implies that as time increases, the aftershock frequency $n(t)$ decreases [11][17][18].

Table 1. Estimated termination time of aftershock activity following the March 22, 2024 Bawean earthquake

Method	Correlation Coefficient	Day	Estimated Termination Date
Omori	0,627622094	19	April 09,2024
Mogi I	-0,806582947	24	April 14,2024
Mogi II	-0,744988914	12	April 03,2024
Utsu	-0,806362935	24	April 14,2024

Based on the BMKG earthquake catalog, no seismic activity was recorded on April 14, 2024. This observation is consistent with the results obtained using the Mogi I and Utsu methods. Both methods also produce strong correlation coefficients, indicating good agreement with the observed data. Therefore, it can be concluded that the most appropriate statistical methods for estimating aftershock decay in the Bawean region are the Mogi I and Utsu methods. These two methods yield nearly identical correlation coefficients (-0.806) and aftershock decay durations with the aftershock sequence estimated to last for 24 days and terminate on April 14, 2024. As shown in the BMKG earthquake catalog (Figure 5), no aftershock activity was recorded on the 24th day following the mainshock.

EQ Repository | Requested Data

No	Event ID	Date time	Latitude	Longitude	Magnitude	Mag Type	Depth (km)	Phase Count	Azimuth Gap	Location	Agency
1	bmg2024hqks	2024-04-18T14:20:46.000721Z	-5.777413368225098	112.35114288330078	3.3164708819801976	M	5	35	218.12582397460938	Java Sea	BMKG
2	bmg2024hode	2024-04-17T08:15:06.022261Z	-5.751312255859375	112.3438949584961	4.972398040082093	M	10	134	35.356359481811523	Java Sea	BMKG
3	bmg2024hgkk	2024-04-13T02:49:14.511042Z	-5.733510971069336	112.39298248291016	3.426603945104656	M	10	24	229.34959411621094	Java Sea	BMKG
4	bmg2024hfwc	2024-04-12T19:35:37.588224Z	-5.670433521270752	112.3717269897461	3.258673138559679	M	10	36	240.0229797363281	Java Sea	BMKG
5	bmg2024hfmm	2024-04-12T14:43:41.242323Z	-5.740666389465332	112.55815887451172	4.032386473010134	M	10	90	76.98638916015625	Java Sea	BMKG
6	bmg2024hehv	2024-04-11T23:14:35.979355Z	-5.715095520019531	112.51365661621094	4.370323574430225	M	10	85	99.1903018951416	Java Sea	BMKG

Fig. 5 BMKG earthquake catalog showing no recorded aftershocks on April 14, 2024.

4. CONCLUSION

In this study, the estimation of the termination time of aftershock activity following the March 22, 2024 Bawean earthquake indicates that the Mogi I method provides the highest correlation coefficient with a value of -0.806582947. Based on this method, the aftershock sequence is estimated to have ended on the 24th day corresponding to April 14, 2024. Similar results are obtained using the Utsu method which yields a correlation coefficient of -0.806362935 and predicts the same aftershock termination date, namely the 24th day (April 14, 2024).

These findings are consistent with the BMKG earthquake catalog which shows no recorded seismic activity in the study area on April 14, 2024. Therefore, the Mogi I and Utsu methods can be considered reliable for accurately estimating the termination time of aftershock sequences associated with the March 22, 2024 Bawean earthquake.

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