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# Visualization of the Relationship Between Magnitude and Depth of Earthquakes in Southern Indonesia Through Curve Interpolation

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## Abstract

Indonesia in the southern latitudes is one of the tectonically active regions that often experiences earthquakes due to plate subduction activity. This activity causes the accumulation of energy in the subduction zone that can be released at any time in the form of earthquakes with various levels of depth and strength. This study aims to visualize the relationship between depth and magnitude of earthquakes in the region using curve interpolation techniques. Earthquake data was obtained from the BMKG catalog over a period of time, covering a wide range of earthquake events with a fairly wide variation in magnitude and depth. Through this analysis, the general pattern of the relationship between the depth of the earthquake source and the resulting magnitude can be observed, which is then visualized to facilitate interpretation. The visualization results show that there are certain trends that indicate how changes in depth can affect earthquake strength, where earthquakes that occur at a certain depth do not show a tendency that results in greater or smaller magnitudes. This approach is expected to contribute to the understanding of the seismic characteristics of the region.

**Keywords:** computational physics, curve interpolation, plate subduction, visualization

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## INTRODUCTION

Indonesia is located in a zone where five major tectonic plates meet: the Eurasian Plate and Philippine Plate in the north, the Indo-Australian Plate in the south, the Indian Plate in the west, and the Pacific Plate in the east. As a result of this convergence, most of Indonesia is located in a subduction zone characterized by frequent tectonic and volcanic earthquakes, and Indonesia is located in the volcanic or ring of fire (Morante-Carballo et al., 2024).

Earthquakes are natural phenomena that occur due to the shifting or collision of tectonic plates, fault activity, volcanic eruptions, and rockfalls beneath the earth's surface (Buszta et al., 2023). These events are destructive and can occur in a short period of time but have a significant impact. In Indonesia, which is located at the meeting point of three major tectonic plates, earthquakes occur almost evenly, with intensities ranging from low to extremely destructive (Supendi et al., 2022). Earthquake-prone areas in Indonesia are widespread, especially in the southern latitudes of Indonesia, covering Sumatra, Java, Bali, Nusa Tenggara, parts of Sulawesi, the Maluku Islands, and Papua.

Each earthquake event provides a seismic image in the form of a wave signal recording that has been processed manually or non-manually to become phase reading data (Kandris et al., 2020). The seismic image in the form of an earthquake parameter, namely magnitude, is a quantity that describes the amount of energy released when an earthquake occurs (Ghosh, 2020). The magnitude scale is often expressed in the Richter scale (SR), which was first proposed by K. Wadati and C. Richter around 1930. The epicenter or earthquake source is the point located vertically above the earthquake point below the earth's surface. The epicenter location is determined using a geographic coordinate system expressed in latitude and longitude.

In seismic studies, several key parameters are analyzed to understand the characteristics of an earthquake, including magnitude, depth, location, and time of occurrence. Of these parameters, magnitude and depth play an important role in determining the impact of an earthquake. The depth of an earthquake indicates how deep the hypocenter is from the earth's surface; shallow earthquakes (<70 km) generally cause stronger tremors on the surface than deep earthquakes. Several studies also show that depth affects the distribution pattern of aftershocks and reflects the mechanical properties of tectonic plate interfaces (Cubas et al., 2022).

Since 2000, there have been various natural disasters in Indonesia. Based on Indonesian Disaster Information Data (2019), many have been recorded as national disasters, including the 2004 earthquake and tsunami in Aceh, the 2006 earthquake in Yogyakarta and Bantul, the 2006 tsunami in Pangandaran, the 2009 earthquake in Padang and Padang Pariaman, the 2010 eruption of Mount Merapi in Central Java, the 2018 earthquake and tsunami in Palu and Donggala, the 2018 tsunami in the Sunda Strait caused by the eruption of Anak Krakatau, the 2019 flash floods and landslides in Papua, the 2021 earthquakes in Mamuju and Majene as well

as in East Nusa Tenggara, The eruption of Mount Semeru in 2021, and most recently, the earthquake in Sumur District, Pandeglang-Banten in 2022.

The rapid development of computational technology has encouraged the application of computational thinking in analyzing complex geophysical phenomena (Lore et al., 2023), including seismic activity. Computational thinking enables researchers to break down complex problems into manageable components, identify patterns within datasets (Berikan & Özdemir, 2020), and design computational models to systematically visualize relationships between variables. In the context of natural disasters, particularly earthquakes, this approach plays an important role in processing and interpreting seismic data that often exhibit nonlinear characteristics and large data volumes (Ibrahim & Al-Bander, 2024). Southern Indonesia is recognized as one of the tectonically active regions due to the interaction between the Indo-Australian and Eurasian plates, resulting in frequent earthquakes with varying magnitudes and depths. Therefore, computational-based analytical methods are required to better understand and visualize the relationship between earthquake magnitude and depth (Maneerat & Rungskunroch, 2024). One approach that can be utilized is curve interpolation, which allows the construction of mathematical representations of the relationship between these variables, thereby facilitating clearer visualization and interpretation of seismic data (Dick et al., 2025).

Based on this explanation, understanding the relationship between depth and earthquake magnitude is important in identifying seismic patterns and characteristics in a region. Data visualization through a curve interpolation approach can be an effective tool in interpreting the correlation between these two parameters. Therefore, this study aims to visualize the relationship between depth and earthquake magnitude in southern Indonesia based on data from the Meteorology, Climatology, and Geophysics Agency (BMKG), through the application of polynomial and spline interpolation methods, thereby enriching scientific analysis of earthquake characteristics in the region.

## METHOD

This study uses quadratic polynomial interpolation and cubic spline interpolation methods to analyze the relationship between the magnitude and depth of earthquakes in southern Indonesia. Interpolation is the process of calculating and finding the value of a function, where the graph passes through a set of given points. These points can be the results of a known function or experimental data from an experiment. The main purpose of interpolation is to obtain an approximation polynomial that can replace the original complex function with a simpler function. One of the functions commonly used as an approximation function is the polynomial function (Weng et al., 2025).

There are various interpolation methods, but in this study, quadratic polynomial interpolation and cubic spline interpolation were used. Earthquake data was obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG), then processed through

cleaning and filtering stages to ensure data quality. Quadratic polynomial interpolation was used to form a simple relationship model between magnitude and depth, while cubic spline interpolation was applied to produce a smoother and more continuous curve. According to Dong et al. (2022), cubic spline is an approximation method that performs interpolation on xxx points located between two data points, assuming that the function is a third-degree polynomial. The interpolation results are visualized in graph form, then analyzed to identify patterns of relationships between variables and compare the effectiveness of the two interpolation methods.

### Problem Statement

To visualize the relationship between depth and magnitude of earthquakes in southern Indonesia so that the pattern of correlation between the two can be identified and analyzed more easily.

### Mathematical Equation

#### Quadratic Polynomial

$$\begin{aligned}f_2(x) &= a_0 + a_1x + a_2x^2 \\a_0 &= b_0 - b_1x_0 + b_2x_0x_1 \\a_1 &= b_1 - b_2x_0 - b_2x_1 \\a_2 &= b_2 \\b_0 &= f(x_0) \\b_1 &= \frac{f(x_1) - f(x_0)}{x_1 - x_0} \\b_2 &= \frac{\frac{f(x_2) - f(x_1)}{x_2 - x_1} \frac{f(x_1) - f(x_0)}{x_1 - x_0}}{x_2 - x_0}\end{aligned}$$

## Cubic Spline

Point  $n + 1$  to be interpolated:

$$g_i(x) = a_i(x - x_i)^3 + b_i(x - x_i)^2 + c_i(x - x_i) + d_i, \quad i = 0, 1, \dots, n - 1$$

Global interpolation function

$$g(x) = g_i(x), \text{ for } x_i \leq x \leq x_{i+1}$$

## Algoritma

### 1.1 Initial Data

1.1.1 Start

1.1.2 Import the libraries to be used, namely:

3.1.1.2.1 numpy for numerical processing

3.1.1.2.2 pandas for data processing

3.1.1.2.3 matplotlib.pyplot for data visualization

3.1.1.2.4 interp1d and CubicSpline from scipy.interpolate as the interpolation used

1.1.3 Reading the data file 'clean\_data\_report.csv' using pd.read\_csv() with encoding 'latin-1'.

1.1.4 Taking the 'DEPTH (KM)' column as array x.

1.1.5 Taking the 'MAGNITUDE (M)' column as array y.

1.1.6 Displaying:

1.1.6.1 Text "=== Depth (X) and Magnitude (Y) Data ===".

1.1.6.2 The first 10 data points.

1.1.6.3 Fill the x array and the y array.

1.1.7 Using a counter to check for duplicate values in x.

1.1.8 Print duplicate depths along with the number of occurrences.

1.1.9 Finished

### 1.2 Polynomial Interpolation

1.2.1 Start

1.2.2 Sort the x and y arrays based on x in ascending order. using np.argsort().

- 1.2.3 Remove duplicates from `x` with `np.unique()`, adjust `y`.
- 1.2.4 Create interpolation function `degreetwo` using `interp1d(x_unique, y_unique, kind='quadratic')`.
- 1.2.5 Create a new array `x_new` with 500 data points evenly spaced between the minimum and maximum values of `x` using `np.linspace()`.
- 1.2.6 Calculate the polynomial interpolation results for all `x_new`.
- 1.2.7 Done

### 1.3 Spline Interpolation

- 1.3.1 Start
- 1.3.2 Sort the `x` and `y` arrays based on `x` in ascending order using `np.argsort()`.
- 1.3.3 Remove duplicates from `x` using `np.unique()`, adjust `y`.
- 1.3.4 Create the interpolation Cubic Spline using `Cubic Spline(x_unique, y_unique)`.
- 1.3.5 Create a new array `x_new` with 500 data points evenly distributed between the minimum and maximum `x` values using `np.linspace()`.
- 1.3.6 Calculate the spline interpolation results for all `x_new`.
- 1.3.7 Done

### 1.4 Spline Interpolation

- 1.4.1 Start
- 1.4.2 Sort the `x` and `y` arrays based on `x` in ascending order using `np.argsort()`.
- 1.4.3 Remove duplicates from `x` using `np.unique()`, adjust `y`.
- 1.4.4 Create the interpolation Cubic Spline using `Cubic Spline(x_unique, y_unique)`.
- 1.4.5 Create a new array `x_new` with 500 data points evenly distributed between the minimum and maximum `x` values using `np.linspace()`.
- 1.4.6 Calculate the spline interpolation results for all `x_new`.
- 1.4.7 Done

### 1.5 Quadratic Interpolation Visualization

- 1.5.1 Start
- 1.5.2 Plot points on the `x` coordinate array and `y` coordinate array
- 1.5.3 Plot a line on the `x_quad` coordinate array and the `y_quad` coordinate array
- 1.5.4 Plot points on the `x_unique` and `y_unique` coordinate arrays

1.5.5 Display the plot on the screen

1.5.6 Finish

### 1.6 Cubic Spline Interpolation Visualization

1.6.1 Start

1.6.2 Plot points on the x coordinate array and y coordinate array

1.6.3 Plot a line on the x\_spline coordinate array and the y\_spline coordinate array

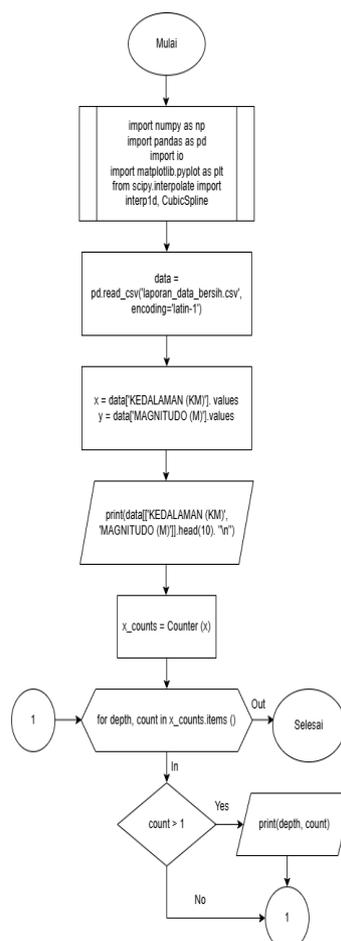
1.6.4 Plot points on the x\_unique and y\_unique coordinate arrays

1.6.5 Display the plot on the screen

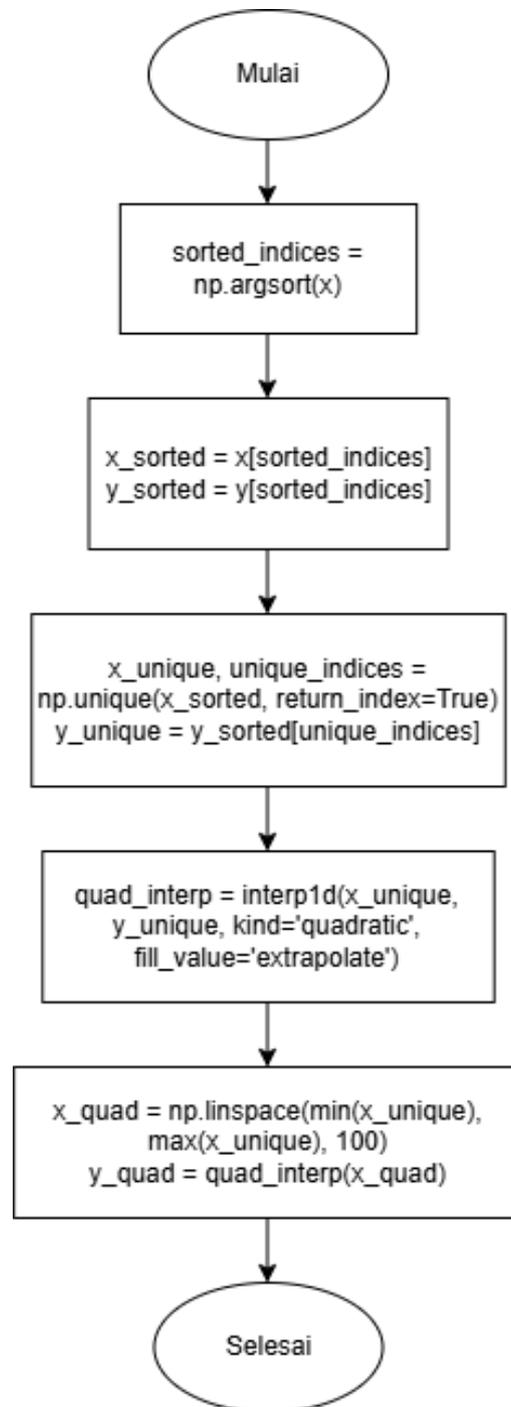
1.6.6 Finish

## Flowchart

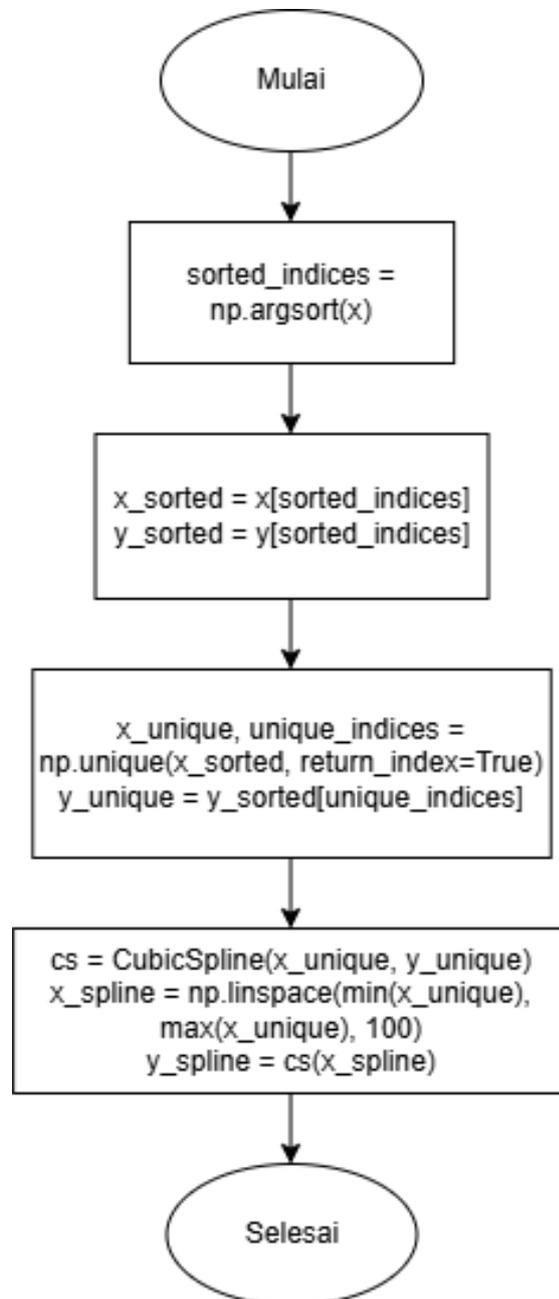
### 1.1 Initial Data



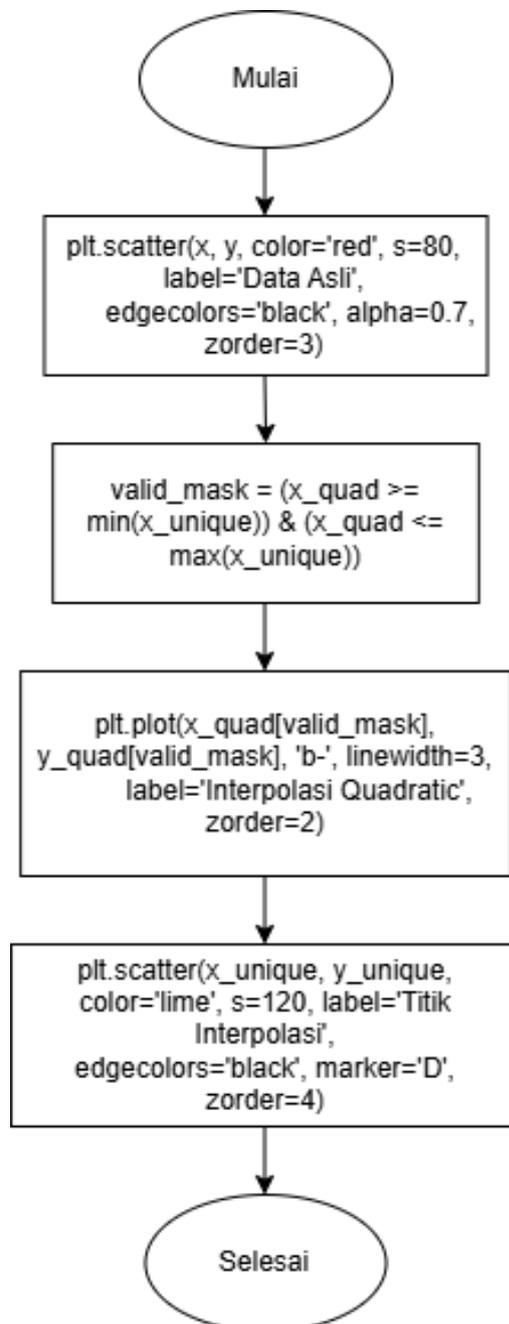
## 1.2 Polynomial Interpolation



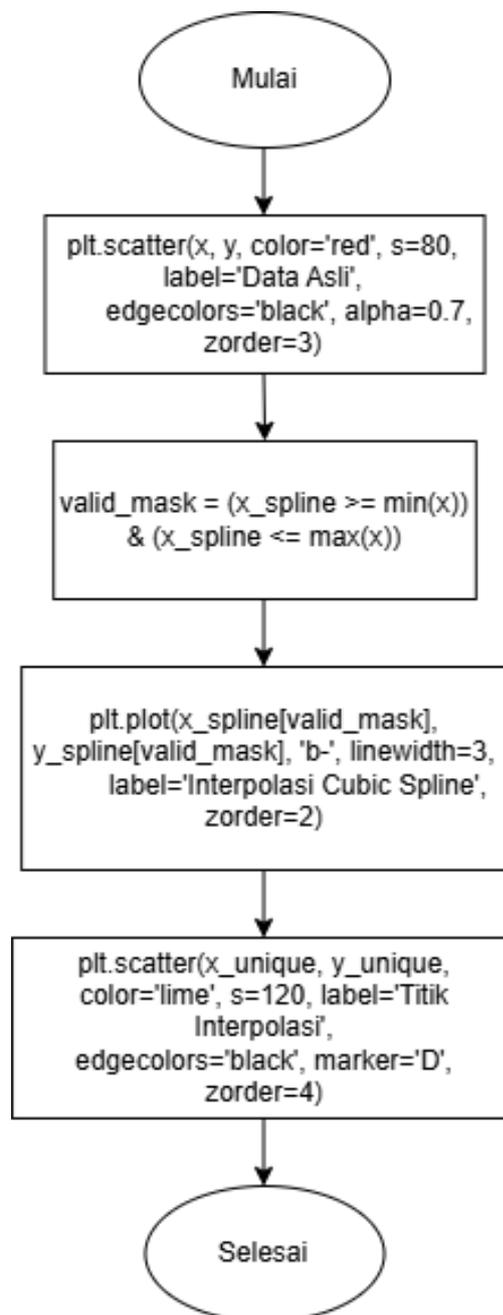
### 1.3 Spline Interpolation



### 1.4 Spline Interpolation



### 1.5 Quadratic Interpolation Visualization



## RESULTS AND DISCUSSION

This study uses quadratic interpolation in the visualization of earthquake depth data (in kilometers) against magnitude (on the M scale). The original data, shown as red dots, reveals a fairly varied distribution, especially at depths of less than 100 km, where there are sharp fluctuations in magnitude. Quadratic interpolation, represented by the blue curve, provides a smoother approximation of the data variation than linear interpolation. The interpolation curve shows several

peaks and valleys that follow the data trend, such as an increase in magnitude at a depth of around 180–300 km and a decrease thereafter. The interpolation points (green diamonds) show that the quadratic model is able to approximate the original data quite well at certain points.

The *output* obtained from *the source code* is as follows

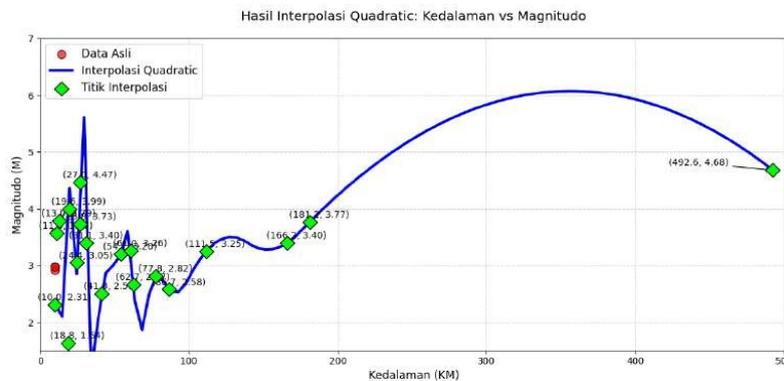
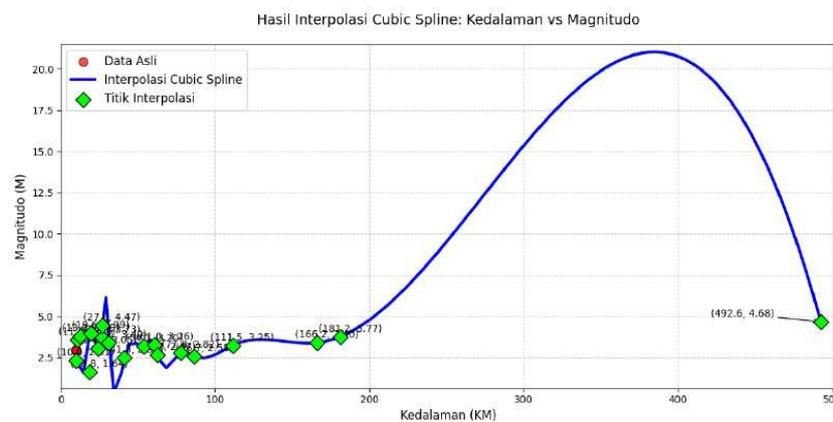


Figure 1. Quadratic Interpolation Results

Quadratic interpolation was chosen because this method can describe changes in data direction (up and down) simply but effectively. Compared to linear interpolation, quadratic interpolation provides a more natural curve shape and reduces the impression of rough cuts between data points. However, it should be noted that quadratic interpolation has limitations, especially for data with extreme fluctuations or noise, where the risk of overshooting may increase. Therefore, for data with many points and complex variations such as this data, cubic spline interpolation may be a better alternative because it produces a smoother curve and reduces local errors.

Overall, quadratic interpolation in this study has successfully described the general pattern of the relationship between depth and earthquake magnitude, although for further analysis and improved accuracy, the use of spline-based interpolation methods or higher-order polynomial fitting may be considered.

The *output* results obtained from *the source code* are as follows



**Figure 2.** Cubic Spline Interpolation Results

In this study, the cubic spline interpolation method was used to model the relationship between earthquake depth (km) and magnitude (M). The original data, shown by the red dots, has a fairly fluctuating distribution, especially at depths of less than 100 km. The cubic spline interpolation results, represented by the blue curve, show a much smoother pattern than the quadratic interpolation. This curve is able to follow changes in the data direction more flexibly, resulting in continuous transitions between each segment of data points. The green points show the interpolation results at specific depths, which closely approximate the original data.

In this graph, cubic spline interpolation appears to handle small data fluctuations quite well, without extreme overshooting, except at the beginning (depth less than 50 km) where there is a significant deviation. After a depth of 100 km, the interpolation curve forms a more consistent pattern, showing an upward trend in magnitude until it peaks at a depth of about 400 km, then declines again. Compared to quadratic interpolation, cubic spline provides a more realistic fit to local changes in the data because it considers the first and second derivatives at each node, resulting in a more natural curve and reducing interpolation errors between data points.

The use of cubic spline interpolation has proven to be more effective for datasets with complex variations such as this, because this method is able to reduce the risk of excessive fluctuations that commonly occur in high-degree polynomial interpolation (Flajs, 2020). In addition, cubic splines produce more stable and accurate estimates when predicting magnitude values at depths not available in the original data (Rae et al., 2025). With these advantages, cubic spline interpolation is recommended as a superior method compared to quadratic interpolation in modeling the relationship between depth and earthquake magnitude.

Based on the data visualization results, it can be seen that the area with the greatest depth and magnitude of the earthquake is located at coordinates latitude -7.23 degrees and longitude 125.33235 degrees. This area is East Nusa Tenggara (NTT), with an earthquake depth of reaching 492.6 km and a magnitude of 4.68 M. NTT is known as one of the earthquake-prone regions in Indonesia. This data is in line with the findings in a journal written by Ni Made Rysnawati and her colleagues, which

states that NTT is an area with a fairly high level of earthquake vulnerability. This is due to the geographical location of NTT, which is located between two earthquake-prone zones. In the south, there is a subduction zone where the Eurasian Plate and the Indo-Australian Plate meet and collide. Meanwhile, in the north, this region is influenced by a back-arc thrust fault. These conditions make NTT highly vulnerable to the dangers and risks of earthquakes. Based on these facts, it can be concluded that East Nusa Tenggara is indeed a region with high earthquake vulnerability due to its geological position between two earthquake-prone zones.

Based on the data obtained, the relationship between earthquake depth and magnitude does not show a completely consistent pattern. In general, earthquakes that occur at great depths do tend to have higher magnitudes than shallow earthquakes. However, variations are still apparent, such as in an earthquake with a depth of 27 km that had a magnitude of 4.47, while at a depth of 31.1 km, the magnitude was smaller, at 3.4. This difference shows that depth is not the only factor that determines the magnitude, but there are other factors such as rock conditions, earthquake source mechanisms, and geological characteristics around the fault zone.

Based on the results of research and data visualization, although there is a tendency for earthquakes at greater depths to produce higher magnitudes, the relationship between depth and magnitude is not absolute or linear. The available data shows that shallow earthquakes can also produce large magnitudes, and earthquake depth is not always accompanied by very high magnitudes. Therefore, the relationship between depth and magnitude is complex and influenced by many factors other than depth itself. Other factors such as earthquake source mechanisms, rock types, and local geological conditions can also affect earthquake magnitude.

## **CONCLUSION**

Thus, this study visualizes the relationship between depth and earthquake magnitude in the southern latitudes of Indonesia using quadratic interpolation and cubic spline methods. The visualization results show that both methods are capable of identifying general trends between earthquake depth and the resulting strength (magnitude), albeit with their own characteristics. Quadratic interpolation provides a fairly good approach in describing data fluctuations, but tends to experience limitations when dealing with complex variations, as it can produce curve shapes that are too sharp or deviate from the actual data pattern. Meanwhile, cubic spline interpolation proved to be superior in modeling fluctuating data because it produces smoother, more continuous, and realistic curves. Another finding was the identification of East Nusa Tenggara as the region with the greatest earthquake depth and magnitude in the dataset, reinforcing the understanding that this region has a high level of seismic vulnerability due to its location between two earthquake-prone zone.

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