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Tsunami Vulnerability Analysis of Makran Subduction Zone through Fuzzy Logic

Adil Rehman[1] and Huai Zhang[1,2,3]

[1]Key Laboratory of Computational Geodynamics, College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
[2]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519080, China
[3]Beijing Yanshan Earth Critical Zone National Research Station, University of Chinese Academy of Sciences, Beijing 101408, China

Corresponding author: adil.geologist5@gmail.com
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Abstract - Tsunamis are among the most terrifying natural hazards, causing significant loss of life and property and impacting our society's human, economic, and social aspects. Given their destructive nature, developing effective techniques for tsunami observation and demolition reduction is crucial. This study proposes a novel tsunami detection and alert system utilizing fuzzy logic to mitigate these impacts. The primary objective of this research is to develop and implement a fuzzy logic-based tsunami prediction system that generates alerts indicating the likelihood of a tsunami-categorized as definite, certain, average, or rare. In the present study, we employ the fuzzy logic technique in MATLAB, using various defuzzification techniques available in the MATLAB fuzzy logic toolbox. The calculated values for the tsunami alert system in the Makran Subduction Zone are as follows: rare (1.91), average (4.75), certain (6.75), and definite (8.8). The designed tsunami alert system and model can predict tsunamis automatically and manually, potentially saving many lives more effectively than previous methods. The research objectives of this study are to (1) develop a fuzzy logic-based model for tsunami prediction, (2) implement the model using MATLAB, and (3) evaluate the model's performance in generating accurate tsunami alerts.

Keywords: Fuzzy logic system, tsunami warning, tsunami vulnerability, defuzzification techniques

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Introduction

The Makran subduction zone is formed by the Arabian Plate moving beneath the Eurasian Plate at approximately 4 cm/year. It is separated by two fault systems: the Minab faults connecting the western Makran with the Zagros fold-thrust belt in Iran, and the Chaman-Ornach-Nal fault in the east (Regard *et al*., 2010). The zone is unique for its slow subduction rate and low seismicity compared to other regions (Mokhtari *et al*., 2008; Heidarzadeh *et al*., 2008).

Several seismic events have been recorded in the area, as shown in Figure 1. Tsunamis, or "harbor waves," are destructive waves triggered by disturbances on the sea's surface, representing a significant global risk (National Oceanic and Atmospheric Administration, 2018). Earthquakes are the primary cause of tsunamis, though other sources, such as landslides and volcanic eruptions, can also contribute (Heck, 1947).

Tsunamis are also referred to as shallow water waves (Truong, 2012). Their wavelength can exceed 500 km, with periods ranging from 10

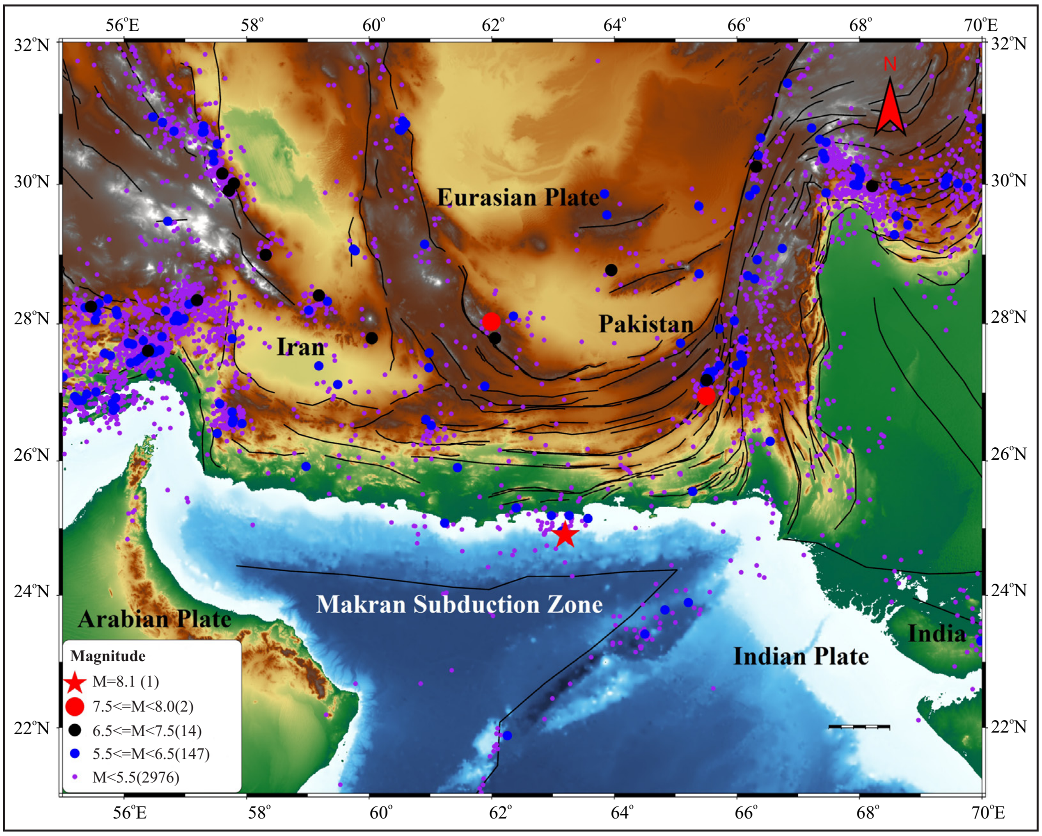

Figure 1. Map illustrating seismic activity in the Makran Subduction Zone (MSZ), delineating the interaction between the Indian, Arabian, and Eurasian Plates.

minutes to 2 hours (Tayal, 2014). This research aims to (1) develop a fuzzy logic-based model for tsunami prediction, (2) implement the model using MATLAB, and (3) evaluate its performance in generating accurate tsunami alerts. Fuzzy logic techniques, widely used in various fields, are applied here to design a tsunami alert system for the study area. Previous tsunami prediction methods relied on recorded earthquake data, but with technological advancements, fuzzy logic systems have been introduced for tsunami forecasting and alert design (Cherian, 2010; Tayal, 2014). Smith *et al*. (2013) propose a probability of 8.7 to 9.2 magnitude earthquakes in the Makran subduction zone. A review by Rashidi *et al*. (2020) indicates the potential for megathrust earthquakes up to magnitude 9.0, posing significant tsunami risks to the coastal regions of Iran, Pakistan, and Oman due to the large seismogenic zone and high coupling ratio. Salah *et al*. (2021) emphasize the need for effective early warning systems, citing the risk of large-magnitude earthquakes generating tsunamis in these regions. Palomero *et al*. (2022) highlighted significant advancements in fuzzy-based models for time series forecasting, while Nalluri *et al*. (2023) examined the role of fuzzy scales in multi-criteria decision-making during COVID-19. Baral *et al*. (2023) explored the use of Fuzzy TOPSIS for improving decision accuracy in multi-criteria problems.

Onar *et al*. (2023) review fuzzy multi-criteria decision-making in earthquake supply chain management, emphasizing its role in handling complexities during disasters. Ghadamode *et al*. (2022) applied remote sensing, GIS, AHP, and fuzzy logic for tsunami vulnerability mapping in the Andaman region, showcasing the integration of spatial analysis in disaster management. Sadrykia *et al*. (2017) introduced a GIS-based fuzzy decision-making model to assess seismic vulnerability in areas with incomplete data, integrating AHP, fuzzy sets, and TOPSIS for managing uncertainties in seismic risk.

For tsunami alert area identification, fuzzy logic processes input parameters, including magnitude, b-value, and slab velocities (Vd, Vo, Vb), through various schemes. Three steps in the fuzzy logic method are fuzzification, inference, and defuzzification. Fuzzification maps the input value from the system being controlled according to the fuzzy set membership function. After that, the inference process of fuzzification will be determined using statistical data from the expert and presented logically. After processing the input variables, the combination of these variables' rules is adjusted to produce the output level of tsunami risk in this case. This process is called defuzzification. The value of input-output parameters and linguistic variables utilized in this case for tsunami alert system design are given below.

- The magnitude variable has four linguistic values: small, medium, large, and very large.
- The downgoing slab velocity variable has four syntax values: Low, Medium, High, and Very High.
- The overriding slab velocity variable has four syntax values: Low, Medium, High, and Very High.
- The rollback velocity variable has four syntax values: Low, Medium, High, and Very High.
- B-value has four syntax values: Low, Medium, High, and Very High.
- Tsunami alert has four linguistic values: rare, certain, average, and definite.

Input Parameters

The first thing was the challenge of taking appropriate parameters. So, the best and most effective possible parameters were selected, which are adequate and helpful for accurate prediction and warning of tsunamis. The input parameters are discussed below.

a) Magnitude – earthquakes generate tsunamis under the ocean. The earthquake-released energy is measured by different magnitude scales, such as moment magnitude (Mw), used in this paper. The general observation shows that earthquakes with magnitude 6.5 or greater cause a generation of tsunamis Tayal (2014). So, Magnitude, as the essential component, has been chosen as an input parameter.
b) Downgoing slab velocity - When two tectonic plates collide, one plate becomes subducted, and another is unsubducted. The subducting plate is called the downgoing plate or the subducting slab. So, the Arabian Plate is downgoing in the Makran subduction zone, and this slab's velocity is 4.65 cm/yr (Huang, 1997).
c) Overriding slab velocity –The unsubducted plate is called the overriding slab. So, the Eurasian slab is overriding in the Makran subduction zone. The velocity of this plate is 0.95 cm/yr (Huang, 1997).
d) Rollback velocity of the slab – the rollback phenomena of the plate take place in the downgoing plate through different slab interactions in convergence, shown in the seaward migration fore-arc area. So, the rollback component has also been included in the argument of Arabian and Eurasian plate interaction. Makran rollback rates that may be negative but are not statistically distinguishable from zero (Jarrard, 1986).
e) B-value – b-value is considered one of the fundamental seismological parameters in the Gutenberg-Richter relationship—the b-value changes from place to place with time. Essentially, the active tectonic zone's b-value is close to one 1. Whenever the b-value is low, the stress in that region will be high and produce a greater Magnitude of earthquake, and we know that earthquake is the most common cause of tsunami generation. So, the b-value as the integral component has been opted as an input parameter.

Methods and Materials

Mamdani fuzzy inference system (MFIS) has been utilized for the present research work. The most extensively understood fuzzy inference system is the Mamdani system. This system was presented by Mamdani (1976). It can be built using a command window available in Matlab (MathWorks, n.d.). The MFI system utilized in the current work is shown in the Figure 2.

The primary uses of fuzzy inference systems (FIS) are to resolve and simplify complex systems and computations through input-output parameters by establishing rules.

1) Membership Function Editor
   In this portion, values and shapes are assigned to all membership functions.
2) Rules Editor
   In this portion, rules are added to check the system's behavior.
3) Rule Viewer
   In this portion, one can see the active or not rules.
4) Surface Viewer
   In this portion, one can see that input and output are generated as a map. By applying the process in MFIS, a tsunami alert model has been developed. The input variables used are Magnitude, b-value, downgoing slab velocity, overriding slab velocity, and rollback velocity, and the only output variable used is tsunami alerts. After setting input parameters, fuzzy inference rules were established for the given output parameter in Figure 3. The FIS rules depend on one understanding of the system by performing contrast experimentation. In any fuzzy set, Vagueness appears because of its membership functions. There are distinct forms of membership function, such as triangular and trapezoidal. One can select any shape of membership function based on their understanding and information. The current work chose the trapezoidal membership function based on Tan and Chua (2007). Defuzzification is the process of representing a fuzzy set with a crisp number. As the output in FIS is also fuzzy, it requires transformation into a crisp value for its practical use.

Different defuzzification techniques have been used for the same output functions, such as the centre and bisector of area. The Centroid

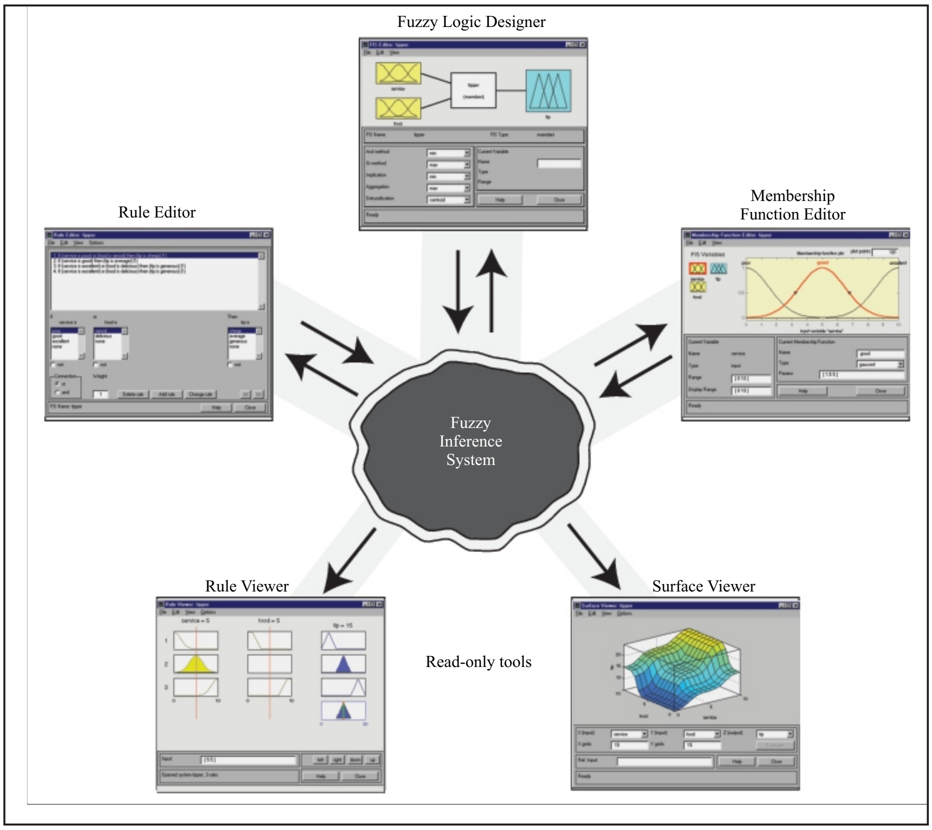

Figure 2. Fuzzy Inference System components and their interactions (MathWorks, n.d.).

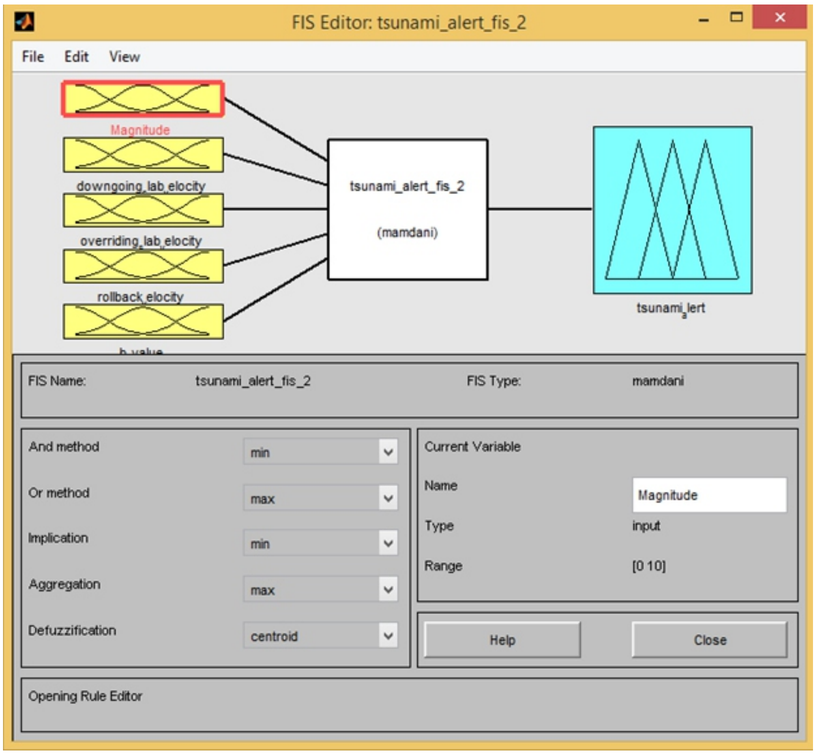

Figure 3. FIS Editor showing input variables (Magnitude, Downgoing slab, Overriding slab, and Rollback velocity) and the output variable (tsunami alert) with Mamdani FIS settings.

Technique is the most widely used because of its simple operation.

Fuzzification

Fuzzification is a phenomenon in which mathematical values are given to the input variable. Classification data is characterized into linguistic values based on every variable value—membership function values of the input and output, as shown in Table 1.

Fuzzification Schemes and Rules Utilization

One can subsequently decide the rule, i.e., when the Magnitude is small, the b-value is very high, downgoing slab velocity is very high, overriding slab velocity is low, and rollback velocity is very high, tsunami alert will be rare. We are getting the accurate output value, though we are giving several distinct numerical values to the output.

In Rule Viewer, one can see how much the rule he has given to his system is active. Figure 4 demonstrates the rule viewer for distinct input values.

Table 1. Input-Output Parameters Membership Functions with Their Assigned Values

Parameters	Values
Magnitude (Mw)	• 0 to 4 -> small • 3.5 to 6 -> medium • 5.5 to 8 -> large • 7.5 to 10 -> very large
Down-going slab velocity (Vd)	• 0 to 3 -> low • 2.5 to 4.65 -> medium • 4.0 to 7.65 -> high • 6.0 to 10 -> very high
Overriding slab velocity (Vo)	• 0 to 0.95 -> low • 0.85 to 4.55 -> medium • 4.0 to 6.0 -> high • 5.5 to 10 -> very high
Rollback velocity (Vb)	• 0 to 2 -> low • 1.5 to 4.5 -> medium • 4.0 to 6.5 -> high • 6.0 to 10 -> very high
Tsunami alert system	• 0 to 4 -> rare • 3.5 to 6 -> average • 5.5 to 8 -> certain • 7.5 to 10 -> definite

a) Rule viewer for definite alert of tsunami

The input value when a tsunami is definite is given below. When we provide the below input value, the outcome we get is 8.8. The result shows the value in a definite order. The input value when the tsunami is definite is given below.

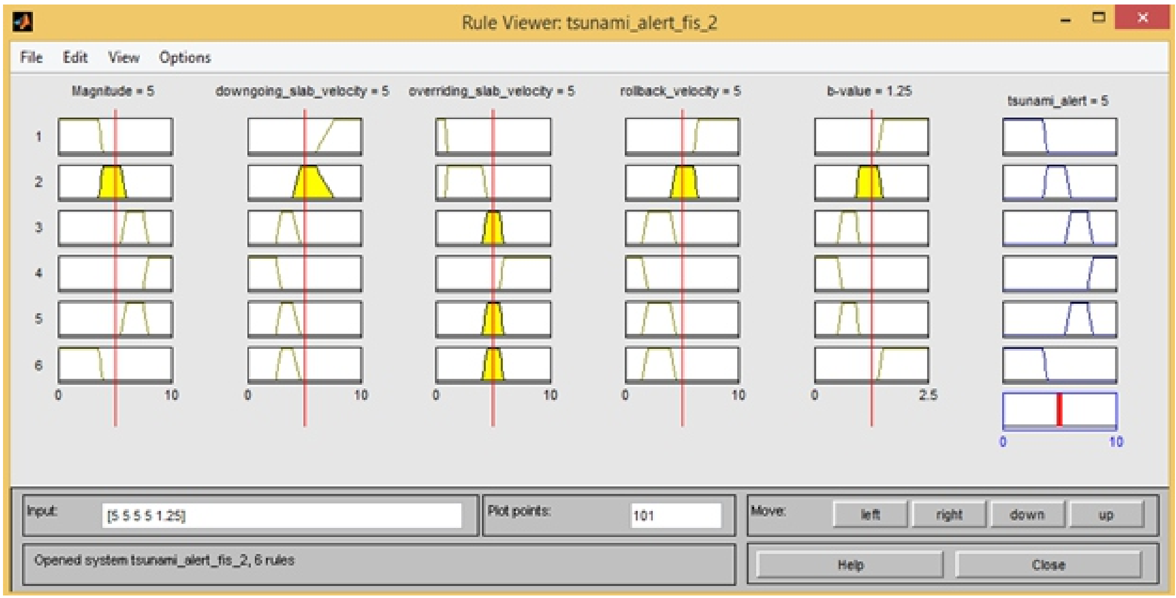

Figure 4. Rule Viewer for tsunami alert with inputs variables.

- Magnitude: 7.51
- Down-going plate velocity: 1.067
- Overriding plate velocity: 6.789
- Rollback velocity: 1.742
- b-value: 0.496

b) Rule viewer for certain alerts of tsunami
The input value when a tsunami is certain is given below. When we provide the below input value, the outcome we get is 6.75. The result shows the value in a certain order. The input value when the tsunami is certain is given below.
[7.697 2.528 5.225 2.416 0.5452]

c) Rule viewer for average alert of tsunami
The input value when the tsunami is average is given below. When we provide the below input value, the outcome we get is 4.75. The result shows the value in average order. The input value when the tsunami is average is given below.
[5.67 6.64 2.56 5 1.104]

d) Rule viewer for rare alerts of tsunami
The input value when a tsunami is rare is given below. When the below input value is provided, the outcome obtained is 1.91. The result shows the value in rare order. The input value for when the tsunami is rare is given below.
[3.76 3.88 5.22 2.42 1.449]

Comparative Analysis of Defuzzification System

Individual defuzzification techniques have been utilized in the current work. These defuzzification techniques are center of area, bisector of area, middle of maximum, smallest of maximum, and largest of maximum, respectively. The center of area technique is one of the extensively utilized defuzzification techniques. Tables 2-5 show distinct defuzzification technique output values.

Table 2. Contrast Different Defuzzification Techniques When Parameters are in Definite Range

Method	Output Value	Tsunami Alert
Centroid	8.8	Definite
Bisector	8.8	Definite
MOM	8.8	Definite
LOM	10	Definite
SOM	7.6	Definite

Table 3. Contrast Different Defuzzification Techniques Utilized When Parameters are in A Certain Range.

Method	Output Value	Tsunami Alert
Centroid	6.75	Certain
Bisector	6.7	Certain
MOM	6.75	Certain
LOM	7.9	Certain
SOM	5.6	Certain

Table 4. Comparison of Different Defuzzification Methods Utilized When Parameters are in the Average Range.

Method	Output Value	Tsunami Alert
Centroid	4.75	Average
Bisector	4.8	Average
MOM	4.75	Average
LOM	5.6	Average
SOM	3.9	Average

Table 5. Comparison of Different Defuzzification Methods Utilized When Parameters are in Rare Range.

Method	Output Value	Tsunami Alert
Centroid	1.91	Rare
Bisector	1.9	Rare
MOM	1.85	Rare
LOM	3.7	Rare
SOM	0	Rare

Result and Disscusion

In this study, a fuzzy logic-based tsunami alert system was developed for the Makran Subduction Zone using the fuzzy logic toolbox in MATLAB. The primary objective was to create a system capable of generating tsunami alerts, categorizing the likelihood of a tsunami into four levels: rare, average, certain, and definite. This fuzzy logic model accounts for the inherent uncertainties in tsunami prediction by integrating multiple geological parameters, including magnitude, downgoing slab velocity, overriding slab velocity, rollback velocity, and b-value, which are essential for evaluating tsunami risk.

To achieve this, the Mamdani technique was applied, and six rules were defined based on different combinations of the input parameters. These rules are central to determining the tsunami alert level, as outlined below:

1. If the magnitude is small, and down-going slab velocity is very high, and overriding slab velocity is low, and rollback velocity is very high, and the b-value is very high, then a tsunami alert is rare.
2. If the magnitude is medium, and down-going slab velocity is high, and overriding slab velocity is medium, and rollback velocity is high, and the b-value is high, then the tsunami alert is average.
5. If the magnitude is large, and down-going slab velocity is medium, and overriding slab velocity is high, and rollback velocity is medium, and the b-value is intermediate, then the tsunami alert is certain.
6. If the magnitude is very large, and down-going slab velocity is low, and overriding slab velocity is very high, and rollback velocity is low, and the b-value is low, then the tsunami alert is definite.
7. If the magnitude is large, and down-going slab velocity is medium, and overriding slab velocity is high, and rollback velocity is medium, and the b-value is intermediate, then the tsunami alert is certain.
8. If the magnitude is small, and down-going slab velocity is medium, and overriding slab velocity is high, and rollback velocity is medium, and the b-value is very high, then a tsunami alert is rare.

These fuzzy rules are implemented using the trapezoidal membership function, which represents each input's fuzzy set. This approach allows the system to effectively handle uncertainty and imprecision, which is typical in natural disaster prediction, making it suitable for tsunami alert generation.

Several defuzzification techniques were tested to convert the fuzzy outputs into crisp values, necessary for determining the tsunami alert levels. The methods tested included:

- Largest of Maximum
- Smallest of Maximum
- Centroid

The application of each technique produced distinct output values:

- Largest of Maximum resulted in an output value of 10, corresponding to a definite tsunami alert.
- Smallest of Maximum yielded 5.6, indicating a certain tsunami alert.
- The Smallest of Maximum method, applied again, provided 3.9, corresponding to an average tsunami alert.
- Applying the Smallest of Maximum technique once more resulted in 0, signifying a rare tsunami alert.

These results confirm the robustness of the fuzzy logic system, as the different defuzzification techniques provided consistent and reliable outcomes. The variation between techniques highlights the flexibility of fuzzy logic in adapting to different decision-making criteria, allowing the system to accommodate a wide range of preferences while maintaining accuracy in the output.

The fuzzy logic-based model's ability to produce distinct tsunami alerts, ranging from rare to definite, demonstrates its practical application for tsunami risk assessment. This system offers a significant advantage over traditional methods that often rely on earthquake data alone, providing a more comprehensive assessment by integrating multiple geological factors. The reliability of the model is further reinforced by its consistent results across different defuzzification techniques, making it a valuable tool for early tsunami warnings.

This approach can be adapted to other tsunami-prone regions, such as coastal areas of Iran, Pakistan, and Oman, where the potential for large-magnitude earthquakes and associated tsunamis poses a substantial risk to human lives and property. By providing timely alerts, the system could contribute significantly to disaster preparedness and mitigation efforts, ultimately saving lives.

Conclusion

Many reports about the Makran Subduction zone show the possibility of medium to large earthquakes in the region, which cause tsunami events. To know about the possibility of a great earthquake occurring in the area, fuzzy input techniques such as Magnitude, b-value, down-going slab velocity, overriding slab velocity, and rollback velocity provide information about the stability and stress rate in the given region. The calculated value obtained from fuzzy logic techniques shows the possibility of great earthquake occurrences in the area. With the increasing rate of seismicity of the Makran Subduction Zone of the Eastern and Western segments, the mega-thrust of Western Makran is locked, and as this locked zone is breached, it will produce a greater Magnitude of earthquakes. The different values calculated for the tsunami alert system of Makran Subduction zone occur in the range of rare is 1.91, average 4.75, certain 6.75, and definite is 8.8. So, it is suggested that if the overriding and Subducting plate of the Makran Subduction zone starts movement directly at a faster speed and moves in one turn, it will produce an earthquake and tsunami of greater magnitudes, i.e., 8.8 magnitudes. Fuzzy logic proposes additional ways to indicate linguistic and particular characteristics of real-world computation. The calculation obtained from fuzzy logic techniques allows us to calculate the tsunami risk for the study area. We can minimize the risk by applying the methods we used in the present study.

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