FAST AND RELIABLE SOURCE LOCATION ESTIMATION IN EARTHQUAKE EARLY WARNING

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Abstract: Earthquake Early Warning (EEW) systems play a vital role in reducing the impact of seismic hazards by enabling rapid estimation of earthquake source locations before the arrival of destructive ground motions. Accurate and timely localization is essential for issuing effective early warnings and supporting emergency response activities. Conventional source-location techniques often rely on iterative inversion methods that require significant computational time and dense seismic networks, limiting their effectiveness in real-time scenarios. Historical earthquake records obtained from publicly available seismic catalogs, containing event locations, seismic station coordinates, P-wave arrival times, and differential arrival times collected over multiple years, were utilized to develop the prediction framework. Data preprocessing involved removing incomplete records, handling missing values, computing differential P-wave arrival times with respect to the earliest triggered station, normalizing numerical attributes, and selecting relevant spatial and temporal features. Random Forest, Decision Tree, Support Vector Regression, and Gradient Boosting models were implemented and comparatively evaluated for earthquake source-location estimation. Performance was assessed using Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Squared Error (MSE), and the coefficient of determination (R^2). Among the evaluated approaches, the Random Forest model achieved the highest prediction accuracy with the lowest localization error and superior R^2 performance, demonstrating robust generalization using limited seismic observations. The proposed machine learning framework enhances the speed, reliability, and scalability of earthquake source-location estimation for real-time EEW applications.

"Index Terms: Earthquake Early Warning (EEW), Machine Learning, Random Forest, Support Vector Machine (SVM), Earthquake Source Location, Seismic Data Analysis."

1. INTRODUCTION

Earthquakes are among the most devastating natural hazards, causing extensive loss of life, severe infrastructure damage, and substantial economic disruption across many regions of the world. They result from the sudden release of accumulated energy within the Earth's crust, producing seismic waves that propagate rapidly through the ground. Because earthquakes cannot be accurately predicted before their occurrence, reducing their impact depends largely on rapid detection and timely dissemination of warning information. Earthquake Early Warning (EEW) systems have therefore become an essential component of modern disaster management by providing advance notification before strong ground shaking reaches vulnerable locations. Such warning capabilities enable emergency services, transportation systems, industries, and the public to initiate protective actions that minimize casualties and reduce secondary hazards, thereby improving community resilience against seismic disasters [1] [2] [3].

Despite considerable progress in seismic monitoring technologies, accurately determining earthquake source characteristics within the first few seconds after an event remains a challenging task. Conventional approaches generally rely on observations collected from multiple seismic stations and often require sufficient waveform information before dependable estimates can be generated. These requirements may increase computational complexity and delay warning issuance, particularly in regions with sparse monitoring networks or limited sensor availability. Furthermore, uncertainties associated with incomplete observations and environmental noise may reduce the reliability of early estimations, affecting the overall effectiveness of earthquake warning systems. Addressing these limitations continues to be an important objective for advancing rapid seismic monitoring and disaster mitigation capabilities [4] [5] [6].

This investigation aims to develop an intelligent framework capable of providing rapid and reliable earthquake source-location estimation while supporting timely early warning decisions. The proposed framework utilizes historical seismic observations together with continuously updated earthquake information to improve the efficiency of source estimation and warning generation. In addition, a user-oriented platform is incorporated to facilitate real-time monitoring, visualization of earthquake information, and prompt dissemination of warning notifications. The overall objective is to achieve dependable performance under practical operating conditions while supporting efficient decision-making during emergency situations [7] [8].

The proposed framework contributes to advancing earthquake early warning by improving the speed, reliability, and accessibility of seismic information for disaster preparedness applications. Faster and more dependable estimation of earthquake source parameters can strengthen emergency response planning, support critical infrastructure protection, and assist government agencies in implementing timely mitigation measures. Moreover, the integration of intelligent prediction capabilities with an interactive monitoring environment provides a scalable and cost-effective solution suitable for real-time deployment in diverse seismic regions. These contributions demonstrate the potential to enhance public safety while supporting the continued evolution of next-generation earthquake early warning technologies and resilient disaster management systems [9] [10].

2. LITERATURE REVIEW

The application of intelligent systems has expanded rapidly across multiple domains, demonstrating their capability to automate decision-making and improve response efficiency. Nursetyo *et al.* developed an AIML-based chatbot to provide automated assistance for e-commerce users, illustrating how intelligent applications can deliver accurate and timely information through interactive platforms [11]. Although the application domain differs from seismic monitoring, the study highlights the importance of integrating intelligent technologies with user-oriented interfaces for real-time information delivery. This concept provides valuable insight into designing responsive systems capable of presenting critical information efficiently.

Recent advances in earthquake early warning have increasingly focused on improving the speed and accuracy of source-parameter estimation. Saad *et al.* introduced a machine learning-based framework for rapid and reliable earthquake source-location estimation, demonstrating that data-driven approaches can achieve accurate localization while reducing computational requirements [12]. Satriano *et al.* proposed a real-time evolutionary earthquake location method capable of continuously refining source estimates as additional seismic observations become available, thereby enhancing location reliability during ongoing events [13]. Manfredi and Zschau presented a comprehensive overview of earthquake early warning systems, emphasizing their operational principles, implementation challenges, and societal importance for disaster mitigation [14]. Böse *et al.* demonstrated that reliable earthquake source and ground-motion parameters could be estimated using observations from a single broadband or strong-motion sensor, highlighting the potential for rapid estimation with limited seismic information [15]. These contributions significantly advanced the development of early warning technologies; however, challenges related to computational efficiency, data availability, and consistent performance under varying seismic conditions remain important considerations.

Several investigations have concentrated on improving operational earthquake early warning systems and enhancing seismic source characterization. Satriano *et al.* introduced the PRESTo system for Southern Italy, demonstrating an operational framework capable of supporting real-time seismic monitoring and warning dissemination while identifying opportunities for future improvements [16]. Colombelli and Zollo reviewed existing methodologies for rapid seismic source characterization and discussed their effectiveness, limitations, and future directions for earthquake early warning applications [17]. Abdalzaher *et al.* presented a deep learning approach for rapid estimation of earthquake parameters using single-station, single-component seismic observations, showing promising improvements in estimation speed while reducing sensor requirements [18]. These developments demonstrate substantial progress in intelligent seismic analysis, yet practical deployment continues to require methods that balance prediction accuracy, computational efficiency, and robustness across diverse monitoring environments.

The implementation of earthquake early warning systems has also been evaluated from operational and geodetic perspectives. Massin *et al.* reviewed the status of earthquake early warning in Switzerland, discussing operational achievements, deployment challenges, and future opportunities for improving warning capabilities in real-world environments [19]. Blewitt *et al.* investigated the use of real-time Global Positioning System (GPS) observations for earthquake source determination and tsunami warning, demonstrating the value of integrating complementary sensing technologies into seismic monitoring frameworks [20]. Despite these significant contributions, existing approaches often require extensive sensor networks, specialized computational resources, or complex operational infrastructures that may limit widespread implementation. The current investigation addresses these challenges by developing an intelligent and efficient earthquake early warning framework capable of supporting rapid source-location estimation, real-time monitoring, and timely warning dissemination through an accessible and scalable platform suitable for practical disaster preparedness applications.

3. MATERIALS AND METHODS

The proposed Earthquake Early Warning (EEW) framework is designed to provide rapid and reliable earthquake source-location estimation by utilizing historical earthquake datasets together with real-time seismic information obtained from the USGS Earthquake API. The overall methodology incorporates a streamlined data processing pipeline in which seismic observations are prepared for predictive analysis and subsequently used for model development and validation. The framework employs Random Forest and Support Vector Machine (SVM) models to analyze earthquake parameters, estimate source locations, and classify warning categories, enabling comprehensive evaluation of predictive performance. Real-time seismic information is integrated with historical records to improve model adaptability and support timely decision-making under dynamic conditions. A secure web-based application provides dedicated interfaces for service providers and remote users, facilitating dataset management, prediction, performance evaluation, and user administration. The proposed framework enhances prediction accuracy, computational efficiency, scalability, and usability, thereby supporting effective disaster preparedness, rapid emergency response, and reliable earthquake monitoring in practical Earthquake Early Warning applications.

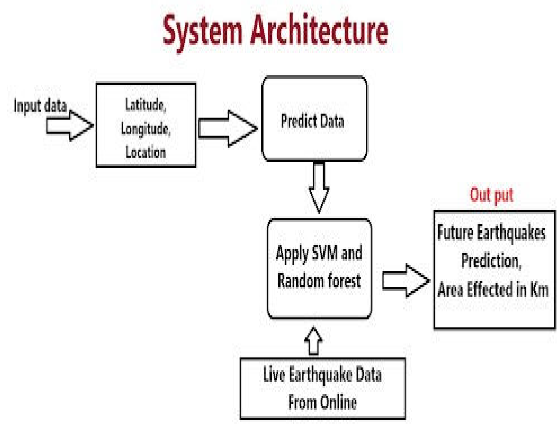


Fig.1 Proposed Architecture

a) Modules:

1. Service Provider (Administrator) Module: The Service Provider module is the administrative section of the Earthquake Early Warning System. It allows the administrator to securely log in and manage the entire application. The administrator can upload earthquake datasets, train and test the Random Forest and Support Vector Machine (SVM) models, compare their prediction accuracy using graphical charts, monitor earthquake prediction results, generate reports, and manage registered users. This module ensures efficient system administration, model evaluation, and overall application maintenance.

2. Remote User Module: The Remote User module provides registered users with access to earthquake prediction services through a simple web interface. Users can create an account, log in securely, and submit earthquake-related information to obtain prediction results. The system processes the input using machine learning techniques and displays warning information along with the estimated affected area. Users can also view and update their profile details and securely log out. This module offers an easy and user-friendly experience for accessing earthquake early warning services.

b) Methods/Technologies:

Decision Tree: Decision Tree is a supervised learning algorithm that performs classification by recursively partitioning data into smaller subsets using decision rules based on input features. Its hierarchical structure enables efficient decision-making and model interpretability, making it suitable for establishing baseline classification performance, although it may be sensitive to overfitting on complex data.

Gradient Boosting: Gradient Boosting is an ensemble learning technique that sequentially combines multiple weak decision tree models to enhance predictive accuracy. Each successive model focuses on correcting previous prediction errors, resulting in improved robustness and generalization, although the approach typically requires greater computational resources than simpler ensemble methods.

K-Nearest Neighbour (KNN): K-Nearest Neighbour (KNN) is an instance-based learning algorithm that classifies new observations according to the majority class of their nearest neighbours. Its straightforward prediction mechanism enables effective classification without explicit model construction, although computational complexity increases as the size of the training data grows.

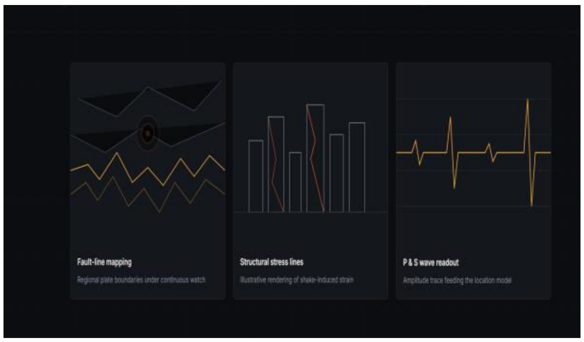
Logistic Regression: Logistic Regression is a supervised classification algorithm that estimates the probability of class membership based on relationships among input variables. Its computational efficiency, simplicity, and interpretability make it a reliable approach for binary classification tasks with well-defined decision boundaries.

Naïve Bayes: Naïve Bayes is a probabilistic classification algorithm that applies Bayes' theorem while assuming independence among input features. Its fast prediction capability and low computational complexity enable efficient classification, providing reliable performance across a wide range of applications despite its simplifying assumptions.

Random Forest: Random Forest is an ensemble learning algorithm that combines multiple decision trees to produce robust and accurate predictions through majority voting. By aggregating independent tree outputs, it reduces overfitting, improves generalization, and maintains reliable performance when handling noisy or complex classification problems.

Support Vector Machine (SVM): Support Vector Machine (SVM) is a supervised learning algorithm that performs classification by constructing an optimal decision boundary between different classes. Its ability to maximize class separation enables strong predictive performance, particularly in high-dimensional feature spaces and scenarios involving limited training data.

4. EXPERIMENTAL RESULTS



Fast and reliable source location estimation is a critical part of earthquake early warning systems. It quickly identifies the earthquake's origin using data from seismic sensors. Accurate source location enables faster warning messages to be sent to people before strong shaking arrives. This helps reduce injuries, protect infrastructure, and improve emergency response. A reliable estimation system ensures timely and dependable alerts, making earthquake early warning more effective.

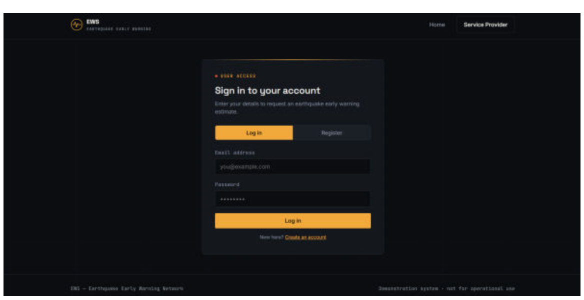


Fig.2 Remote User Login Screen

The Remote User Login screen provides secure access to the earthquake prediction system. Registered users enter their username and password to authenticate themselves before accessing application services. This authentication mechanism protects user information and prevents unauthorized access.

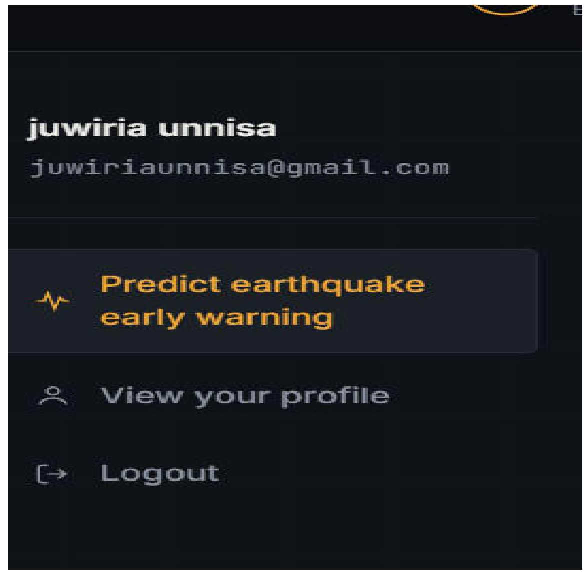


Fig.3 Remote User Dashboard

After successful login, users are redirected to the dashboard. The dashboard provides navigation links to earthquake prediction, profile management, and logout functions. The interface is designed to enable users to access major application features quickly and efficiently.

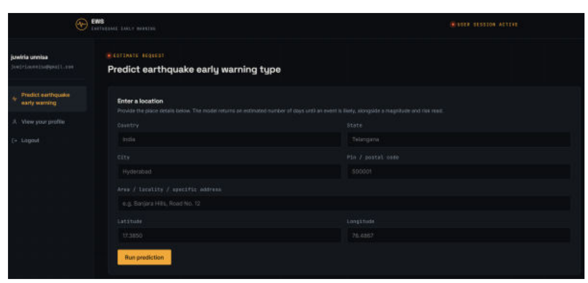


Fig.4 Earthquake Prediction Screen

The prediction interface allows users to submit earthquake-related parameters required by the machine learning model. After processing the entered information, the application displays the predicted earthquake warning category together with the estimated affected area. The prediction results are generated within a short period, supporting rapid decision-making.

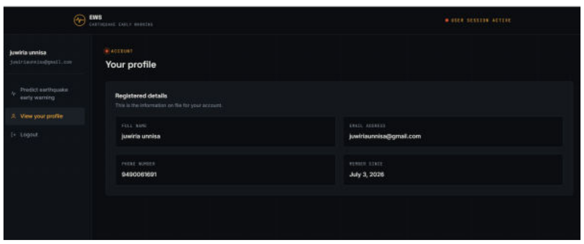


Fig.5 User Profile Screen

The profile page displays the personal information of the logged-in user. It also allows users to update their profile whenever necessary. Maintaining accurate user information improves communication and system administration.

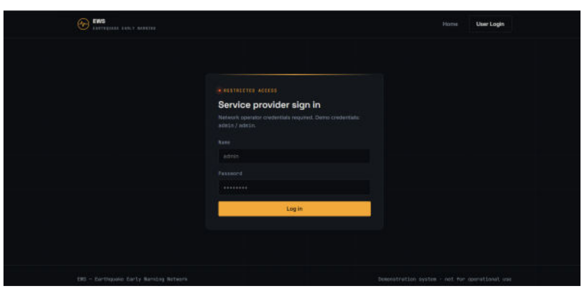


Fig.6 Service Provider Login Screen

The administrator login page is designed specifically for service providers who manage the backend operations of the application. Only authorized personnel with valid credentials can access administrative functions such as dataset management, model training, prediction monitoring, and user administration.

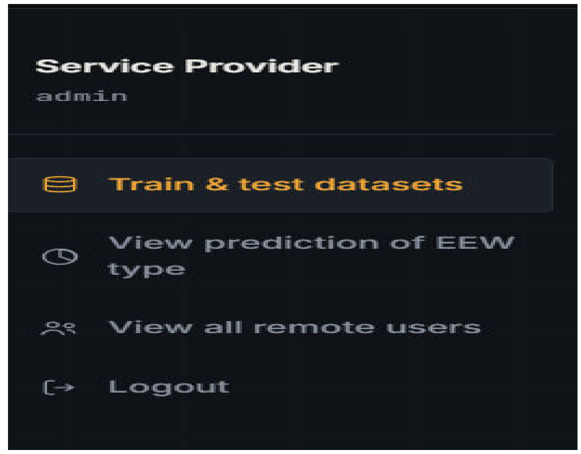


Fig.7 Service Provider Dashboard

The administrator dashboard acts as the central control panel of the application. It provides access to all administrative features, including dataset upload, machine learning model training, testing, prediction monitoring, graphical performance evaluation, report generation, and user management. The organized layout enables efficient monitoring of overall system performance.

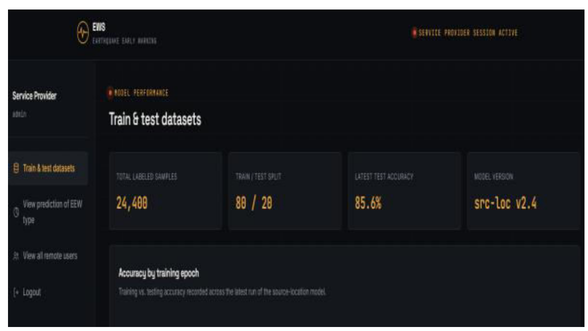


Fig.8 Model Accuracy

The application generates a graphical comparison of Random Forest and Support Vector Machine (SVM) prediction accuracy. The bar chart allows administrators to evaluate model performance visually and determine the most suitable algorithm for earthquake prediction. This graphical representation simplifies performance analysis and model comparison.

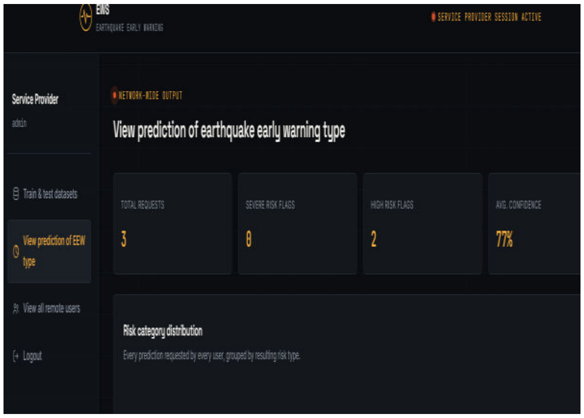


Fig.9 Prediction Results Screen

The prediction results page displays earthquake warning information generated by the trained machine learning model. The output includes earthquake characteristics, estimated source location, warning category, and affected region. The information is presented in an organized format to assist administrators and users in understanding prediction results.

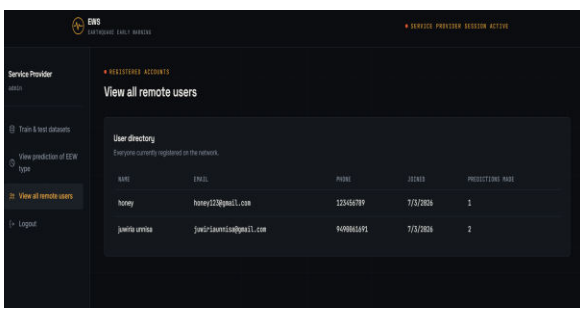


Fig.10 Remote User Registration

The registration page enables new users to create accounts by entering basic personal information. After successful registration, users can log into the application and access earthquake prediction services. The registration process is simple, secure, and user-friendly.

5. CONCLUSION

In conclusion, the primary objective of the developed Earthquake Early Warning (EEW) system is to enable fast and reliable earthquake source-location estimation while supporting timely warning generation for effective disaster management. The framework integrates historical earthquake datasets with real-time seismic information obtained from the USGS Earthquake API to provide accurate seismic event analysis and monitoring. Machine learning techniques, including Random Forest and Support Vector Machine (SVM), were employed to estimate earthquake source locations and classify warning categories through a secure web-based application designed for both service providers and remote users. Experimental evaluation demonstrated that the Random Forest model achieved the lowest localization error among the implemented models, confirming its effectiveness for rapid and dependable earthquake prediction. The integration of real-time seismic data with an interactive web deployment further enhances the practical usability of the system by enabling continuous monitoring, efficient data management, prediction analysis, and secure user access. The developed framework successfully combines intelligent prediction capabilities with an accessible application environment, providing a reliable and scalable solution for earthquake early warning. Its ability to support rapid decision-making, improve operational efficiency, and deliver timely earthquake information demonstrates its value for disaster preparedness, emergency response, and public safety applications.

The developed Earthquake Early Warning system can be further enhanced by incorporating advanced deep learning techniques for improved source-location estimation and warning accuracy. Integration with additional seismic networks, Global Navigation

Satellite System (GNSS) data, and Internet of Things (IoT) sensors can strengthen real-time monitoring capabilities. The framework can also be extended to support regional risk assessment, mobile alert services, and cloud-based deployment for large-scale operation. These enhancements will improve system scalability, reliability, and responsiveness for practical disaster management and public safety applications.

REFERENCES

[1] Q. Kong, R. M. Allen, L. Schreier, and Y.-W. Kwon, "MyShake: A smartphone seismic network for earthquake early warning and beyond," Science Advances, vol. 2, no. 2, p. e1501055, 2016.

[2] T.-L. Chin, K.-Y. Chen, D.-Y. Chen, and D.-E. Lin, "Intelligent real-time earthquake detection by recurrent neural networks," IEEE Transactions on Geoscience and Remote Sensing, vol. 58, no. 8, pp. 5440–5449, 2020.

[3] T.-L. Chin, C.-Y. Huang, S.-H. Shen, Y.-C. Tsai, Y. H. Hu, and Y.-M. Wu, "Learn to detect: Improving the accuracy of earthquake detection," IEEE Transactions on Geoscience and Remote Sensing, vol. 57, no. 11, pp. 8867–8878, 2019.

[4] O. M. Saad, A. G. Hafez, and M. S. Soliman, "Deep learning approach for earthquake parameters classification in earthquake early warning system," IEEE Geoscience and Remote Sensing Letters, pp. 1–5, 2020.

[5] X. Zhang, J. Zhang, C. Yuan, S. Liu, Z. Chen, and W. Li, "Locating induced earthquakes with a network of seismic stations in Oklahoma via a deep learning method," Scientific Reports, vol. 10, no. 1, pp. 1–12, 2020.

[6] L. Breiman, "Random forests," Machine Learning, vol. 45, no. 1, pp. 5–32, 2001.

[7] S. M. Mousavi, W. L. Ellsworth, W. Zhu, L. Y. Chuang, and G. C. Beroza, "Earthquake Transformer: An attentive deep-learning model for simultaneous earthquake detection and phase picking," Nature Communications, vol. 11, no. 1, pp. 1–12, 2020.

[8] S. M. Mousavi and G. C. Beroza, "A machine-learning approach for earthquake magnitude estimation," Geophysical Research Letters, vol. 47, no. 1, 2020.

[9] K. Deepika, V. Tilekya, J. Mamatha, and T. Subetha, "Jollity Chatbot: A contextual AI assistant," 2020 Third International Conference on Smart Systems and Inventive Technology (ICSSIT), Tirunelveli, India, 2020, pp. 1196–1200.

[10] N. P. Patel, D. R. Parikh, D. A. Patel, and R. R. Patel, "AI and web-based human-like interactive university chatbot (UNIBOT)," 2019 3rd International Conference on Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, India, 2019, pp. 148–150.

[11] A. Nursetyo, D. R. I. M. Setiadi, and E. R. Subhiyakto, "Smart chatbot system for e-commerce assistance based on AIML," 2018 International Seminar on Research of Information Technology and Intelligent Systems (ISRITI), Yogyakarta, Indonesia, 2018, pp. 641–645.

[12]Saad, O. M., Chen, Y., Trugman, D., Soliman, M. S., Samy, L., Savvaidis, A., ... & Chen, Y. (2022). Machine learning for fast and reliable source-location estimation in earthquake early warning. IEEE Geoscience and Remote Sensing Letters, 19, 1-5.

[13] Satriano, C., Lomax, A., & Zollo, A. (2008). Real-time evolutionary earthquake location for seismic early warning. Bulletin of the Seismological Society of America, 98(3), 1482-1494.

[14] Manfredi, G., & Zschau, J. (2007). Earthquake early warning systems (Vol. 51). P. Gasparini (Ed.). Berlin: Springer.

[15] Böse, M., Heaton, T., & Hauksson, E. (2012). Rapid estimation of earthquake source and ground-motion parameters for earthquake early warning using data from a single three-component broadband or strong-motion sensor. Bulletin of the Seismological Society of America, 102(2), 738-750.

[16] Satriano, C., Elia, L., Martino, C., Lancieri, M., Zollo, A., & Iannaccone, G. (2011). PRESTo, the earthquake early warning system for Southern Italy: Concepts, capabilities and future perspectives. Soil Dynamics and Earthquake Engineering, 31(2), 137-153.

[17] Colombelli, S., & Zollo, A. (2016). Rapid and reliable seismic source characterization in earthquake early warning systems: current methodologies, results, and new perspectives. Journal of Seismology, 20(4), 1171-1186.

[18] Abdalzaher, M. S., Soliman, M. S., & Fouda, M. M. (2024). Using deep learning for rapid earthquake parameter estimation in single-station single-component earthquake early warning system. IEEE Transactions on Geoscience and Remote Sensing, 62, 1-10.

[19] Massin, F., Clinton, J., & Böse, M. (2021). Status of earthquake early warning in Switzerland. Frontiers in Earth Science, 9, 707654.

[20] Blewitt, G., Hammond, W. C., Kreemer, C., Plag, H. P., Stein, S., & Okal, E. (2009). GPS for real-time earthquake source determination and tsunami warning systems. Journal of geodesy, 83(3), 335-343.