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Enhancing Seismic Monitoring Capabilities of Bogazici University Kandilli Observatory and Earthquake Research Institute Through Integrated AI Modules

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INTRODUCTION AND MAIN RESULTS

KOERI is upgrading its monitoring system with AI modules for phase picking, association, magnitude estimation, and also integrating GNSS data for early warning.

Initial results show improvements in detection, precision, and location accuracy over traditional methods.

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Introduction

The Kandilli Observatory and Earthquake Research Institute (KOERI), responsible for maintaining high-quality seismic monitoring to issue a tsunami alert message in this region, is implementing state of the art artificial intelligence modules to enhance its operational capabilities.

The monitoring system will also be extended to incorporate Global Navigation Satellite System data for early warning capabilities. We present a comprehensive upgrade to the monitoring system through the integration of specialized neural network architectures designed for phase picking, phase association and location-magnitude estimation. These AI modules are engineered to work collaboratively, forming an automated workflow that significantly improves catalog completeness and accuracy.

Initial performance metrics demonstrate substantial improvements in phase picking precision, event detection capabilities and location accuracy compared to traditional methods. This modernization of the Kandilli Observatory's monitoring system represents a significant step forward in providing high-quality seismic data for the scientific community, particularly in a region of profound importance for earthquake studies.

AI Models and Architectures

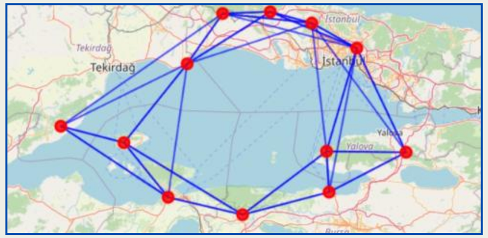

Fig 1: Stations Graph that is used in Graph Neural Network model

The pipeline integrates multiple AI models, each specialized for a stage of earthquake monitoring, and systematically combines their outputs to improve reliability.

Phase Picking: (PhaseNet, PhaseNO, EQCCT, EQTransformer): PhaseNet and PhaseNO use deep convolutional networks to extract local waveform features, while EQTransformer and EQCCT employ transformer-based attention mechanisms to capture longer-range temporal patterns. Using multiple architectures together improves the detection of P and S phases across varying waveform qualities.

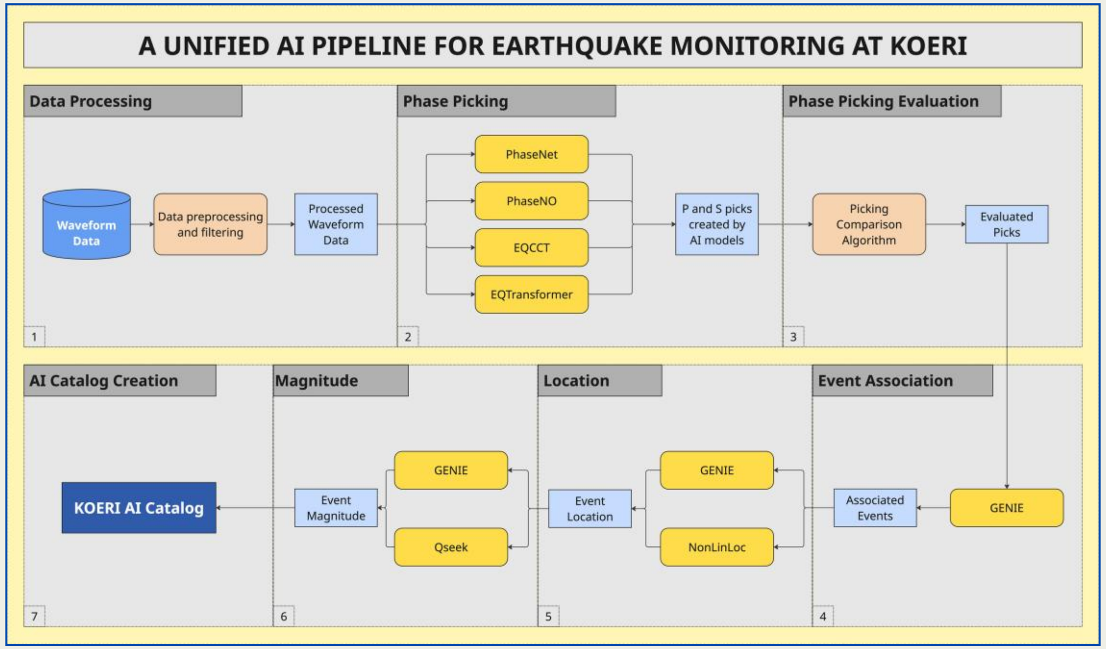

Fig 2: KOERI AI Pipeline Summary Diagram

Event Association:
GENİE (Graph Earthquake Neural Interpretation Engine) performs phase association with a Graph Neural Network (GNN) designed for seismic monitoring. Each graph node represents a (source, station) pair, with features encoding phase pick probabilities. While individual nodes may carry weak or ambiguous evidence, the message-passing mechanism aggregates information across stations, enabling validation or rejection of sources, separation of overlapping events, and inference of consistent spatio-temporal arrival patterns across the network.

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AI Models and Architectures

Event Location and Magnitude Estimation:

(GENİE, NonLinLoc, Qseek)

GENİE provides initial event locations and magnitude estimates using graph-based pick patterns. Locations are refined by NonLinLoc, a nonlinear probabilistic locator, while magnitudes are enhanced by Qseek, a feedforward network leveraging waveform features. This AI-traditional hybrid improves overall accuracy and operational reliability.

The integration of multiple models at each stage allows their strengths to complement one another, overcoming individual limitations and significantly improving the accuracy and robustness of KOERI's earthquake monitoring operations.

Implementation Process

The integration of AI models into KOERI’s earthquake monitoring involves four key stages: Model Training, Hyperparameter Optimization, Testing and Validation, and Operational Integration.

1) Model Training: GENİE is trained using synthetic travel-time data generated from uniformly distributed sources around the station network shown in Figure 1. The graph structure is constructed based on this fixed set of stations, and the model learns to associate source-station pairs using synthetic labels. Picks from AI-based phase pickers are used only during inference, not during training.
2) Hyperparameter Optimization: After initial training, hyperparameters are carefully fine-tuned separately for each region. This optimizes the models for local seismicity and network configurations.
3) Testing and Validation: AI model outputs are compared with KOERI’s existing catalogs, and events are manually reviewed to assess pick quality, association accuracy, and event locations. Systematic biases are identified and used to guide further model refinement.
4) Operational Integration (Ongoing): The full AI pipeline is being adapted for real-time use at KOERI, focusing on fast processing, seamless integration with existing systems, and reliable operation during periods of high seismic activity.

Fig. 3: 2023 Gemlik Earthquakes
*(**Orange**: Only in AI catalog, **Blue**: Only in KOERI catalog, **Green**: In both catalogs)*

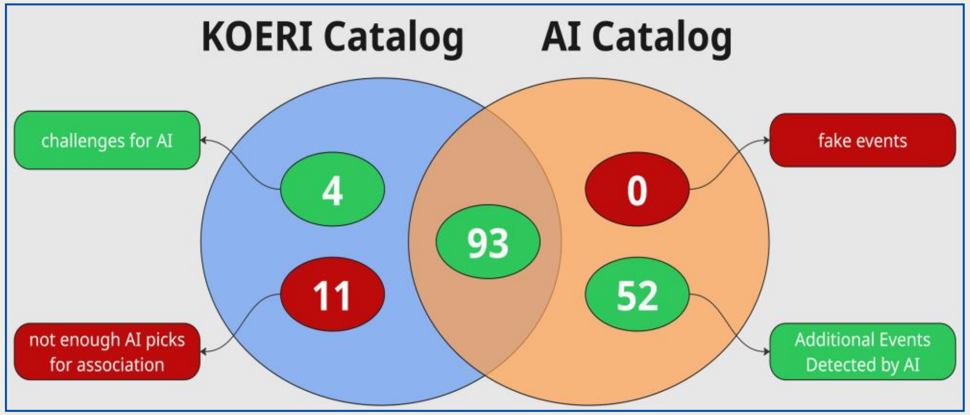

Fig. 4: KOERI Catalog vs AI Catalog for 2023 Gemlik Earthquakes

The first tests of the AI pipeline were conducted using data from the December 4, 2023 Bursa Gemlik Bay earthquake sequence, in which the largest event had a magnitude of 5.1. In this sequence, the existing KOERI catalog recorded 108 earthquakes, providing a suitable dataset to evaluate the pipeline’s event detection and association performance.

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Tests

The diagram shows that 93 events were common to both catalogs. The AI pipeline detected 52 additional real events, indicating improved sensitivity. Of the 15 events found only by KOERI, 11 were likely misassociated due to insufficient picks for AI models, while 4 true events detected by KOERI but missed by AI are categorized as "Challenges for AI."

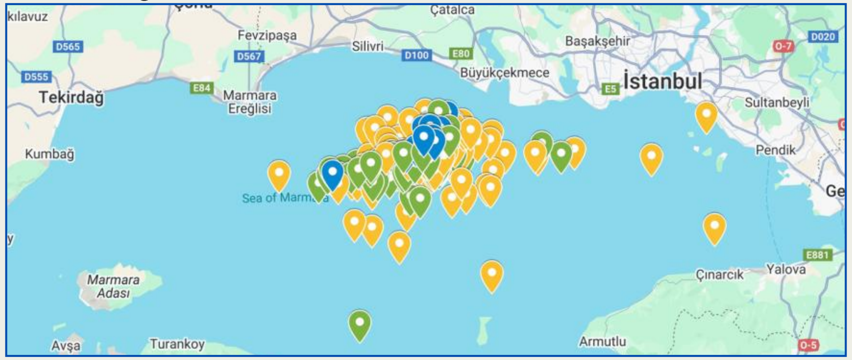

Fig. 5: April 23, 2025 Istanbul Earthquakes

These challenges mainly arise when signals from different sources occur close together in time, as illustrated in Figure 7, where three potential events happen within one minute. Addressing this requires careful adjustment of the variances used for label generation and node features in the GNN: smaller variances improve the model's ability to separate nearby events but reduce the overall number of associations by enforcing stricter travel-time consistency. Consequently, the accuracy of the underlying velocity model becomes critically important. As future work, a 3D velocity structure will be incorporated into the GNN model.

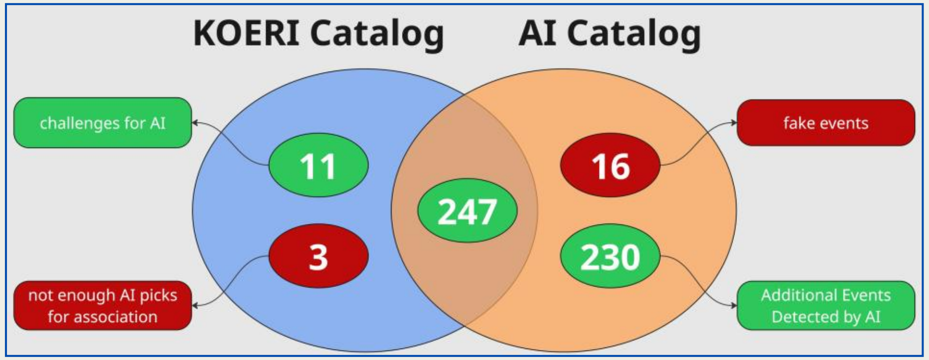

Fig. 6: KOERI Catalog vs AI Catalog for April 23, 2025 Istanbul Earthq.

The second application of the AI pipeline focused on the April 23, 2025 Istanbul earthquake sequence, which included the Mw 6.2 mainshock and its aftershocks. The corresponding KOERI catalog reported a total of 261 events (247 overlapping with AI detections and 14 unique to KOERI). The GNN model demonstrated strong performance by associating and locating an additional 230 events beyond the catalog, of which only 16 remain uncertain.

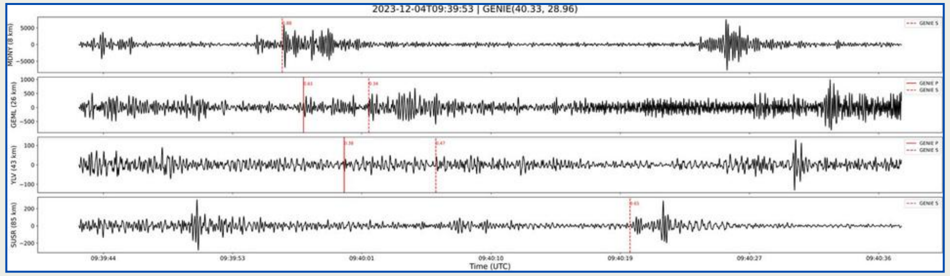

Fig. 7: Challenges for AI

In Figure 7, two or three earthquakes occurred in close succession. The AI pipeline successfully detected one event but missed the second. Finding optimal settings that generalize across all conditions remains a significant challenge.

Results

Comparison with KOERI's existing catalog showed that the AI pipeline detected a higher number of events. Manual review revealed that many of the additional events identified by the AI models were real earthquakes that had not been detected in the KOERI catalog. These were often smaller events that the traditional workflow missed but were confirmed upon closer examination.

There were also events present in the KOERI catalog but missing from the AI catalog. A significant proportion of these were found, after review, to be misassociated events, often due to insufficient pick numbers for reliable association, especially for AI models. However, some true events were detected by KOERI but missed by the AI. These cases are categorized as "Challenges for AI" and are under investigation to further improve model performance.