Predicting Deep-Seated Landslide Displacements in Lushan Mountain through the Integration of Convolutional Neural Networks and an Age of Exploration-Inspired Optimizer

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Abstract

Deep-seated landslides have caused substantial damage to both human life and infrastructure in the past. Developing an early warning system for this type of disaster is crucial to reduce its impact on society. This research contributes to developing predictive early warning systems for deep-seated slope displacements by employing advanced computational models for environmental risk management. Our novel framework integrates machine learning, time series deep learning, and convolutional neural networks (CNN), enhanced by the Age of Exploration-Inspired Optimizer (AEIO) algorithm. Our approach demonstrates exceptional forecasting capabilities by utilizing eight years of comprehensive data—including displacement, groundwater levels, and meteorological information from the Lushan Mountain region in Taiwan. The AEIO-MobileNet model precisely predicts imminent slope displacements with a mean absolute percentage error (MAPE) of 2.81%. These advancements significantly enhance geohazard informatics by providing reliable and efficient landslide risk assessment and management tools. These safeguard road networks, construction projects, and infrastructure within vulnerable slope areas.

Keywords: deep-seated landslide; displacement forecasting; landslide risk assessment; early warning system; machine learning; time-series deep learning; convolutional neural network; metaheuristic optimization.

1. Introduction

Landslides are among the most devastating natural disasters (Huang and Fan, 2013), claiming an average of over 4,000 lives annually worldwide between 2004 and 2010 (Petley, 2012). Landslides represent a global hazard, particularly in developing countries, where rapid urbanization, population growth, and significant land use changes occur (Caleca et al., 2024). The identification, management, and monitoring of landslides are made difficult by the diversity of their types (shallow slides, deep-seated slides, rock falls, rock slides, debris flows) and the complexity of their categorization based on triggers, material composition, movement speed, and other characteristics (Das et al., 2022; Hungr et al., 2014). These issues are further exacerbated in countries with complex geological and climatic conditions.

A deep-seated landslide involves the gradual and persistent displacement of a substantial amount of soil and rock, which can escalate into a sudden and devastating event (Kilburn and Petley, 2003; Geertsema et al., 2006; Chigira, 2009). Unlike shallow landslides, which typically affect surface layers to a few meters, deep-seated landslides extend deeper, often exceeding 10 meters, and can involve the movement of underlying bedrock (Lin et al., 2013). Predicting these events is challenging and costly (Thai Pham et al., 2019). Therefore, extensive efforts have been made to predict such disasters throughout history. One method that has been employed involves thoroughly examining the physical and geological characteristics of the mountainous areas at risk of landslides (Cotecchia et al., 2020). Furthermore, the level of groundwater has been shown by numerous studies in the past to influence the mechanisms behind landslide formation significantly (Miao and Wang, 2023; Preisig, 2020).

In pursuing a generalized approach to landslide forecasting, researchers have determined that the critical factors associated with slope instability exhibit temporal variability, necessitating using time series data (Chae et al., 2017). This approach combines slope deformation data collected through sensors drilled deep into the slope bed with data on the natural conditions of the monitoring area, which is collected simultaneously. Upon establishing that the data pertinent to landslide prediction falls within the category of time series data, a formidable challenge in research related to this type of disaster is devising a predictive model capable of forecasting the likelihood of such catastrophes based on related factors.

One of the most effective solutions for constructing models to predict time series data involves applying data-driven techniques. The advancement of computational capabilities has driven the widespread adoption of data-driven machine-learning models over physics-based models. This shift is based on the premise that the data used for slope monitoring originates from nonlinear systems (Zhou et al., 2018). An increasing array of novel data-driven solutions is being developed to overcome the constraints of traditional machine-learning approaches. Among these data-driven solutions, convolutional neural networks (CNN) have emerged as one of the most effective methods. These CNN models, which excel at automated feature extraction, can enhance efficiency in analyzing complex datasets and improve the accuracy of prediction results (Alzubaidi et al., 2021).

Moreover, there is a noteworthy recent trend in employing metaheuristic optimization algorithms to fine-tune the hyperparameters of artificial intelligence (AI) models, thereby augmenting their efficiency. This approach has found application in geological and construction studies and other fields, showcasing substantial effectiveness. Consequently, the fine-tuning of hyperparameters represents a potent avenue for elevating the efficiency of AI models in research focused on predicting deep-seated displacements.

Leveraging the effective methodologies mentioned above, this study employs AI models optimized by an innovative metaheuristic optimization algorithm to predict deep-seated displacement on the northern slope of Lushan Mountain in Ren'ai Township, Nantou County. The geological characteristics of this area have undergone extensive research (Wang et al., 2015; Lin et al., 2020). Previous studies have identified varying depths of the shear plane. Specifically, Lin et al. (2020) determined the depth of the shear plane is 85m and 106m based on inclinometer data. This research paper is firmly grounded in empirical evidence meticulously collected over eight years from extensometers at depths of 70 and 40 meters. Our analysis also considers the cumulative impact of storms and heavy rainfall on groundwater levels, utilizing data from four stations measuring groundwater levels in the study area and other weather conditions that potentially trigger landslides. The objectives of our research were as follows:

1) To analyze the application of machine learning and deep learning methods to time series data to forecast short-term, deep-seated slope displacements across the Lushan Mountain area.
2) To identify the optimal model and hyperparameters for accurately forecasting deep-seated displacements in the study area.
3) To evaluate the role of metaheuristic optimization algorithms in fine-tuning the hyperparameters of AI models.

This study represents the first instance of AI models being utilized to predict deep-seated landslides in Lushan Mountain. Additionally, it marks the inaugural application of AEIO for fine-tuning AI models in landslide-related research. Our findings provide a valuable resource for civil engineers, contractors, and inspectors involved in the planning and monitoring of construction projects in landslide-prone areas. Predicting the likelihood of landslide events can help minimize property loss, guide schedule adjustments, improve work safety, and ensure smooth traffic flow during critical periods. Additionally, understanding internal displacements provides engineers with precise data to evaluate the resilience of structures and infrastructure in vulnerable areas, enabling the issuance of prudent warnings.

2. Literature Review

2.1 Groundwater Levels and the Forecasting of Deep-Seated Displacements

Landslide triggers can be attributed to loading, slope geometry, weather conditions, and hydrological conditions (Perkins et al., 2024; Van Natijne et al., 2023; Millán-Arancibia and Lavado-Casimiro, 2023; Jones et al., 2023). Among these, hydrological conditions, especially groundwater levels, have been one of the most critical elements considered in studies related to landslide prediction. Numerous studies have substantiated this point. For instance, research by Take et al. (2015) demonstrated that the distance and velocity of landslides triggered under high-antecedent groundwater conditions are significantly more significant compared to scenarios with drier conditions. Another study has shown that water accumulation at a soil-bedrock contact can develop positive pore water pressures, causing landslides (Matsushi and Matsukura, 2007) (see Figure 1). Moreover, studies on past landslide events have also demonstrated similar findings. Examples of this research include the Tessina landslide in northeastern Italy, where groundwater conditions triggered movement (Petley et al., 2005). Additionally, the study by

Keqiang et al. (2015) on water-induced landslides in the Three Gorges Reservoir project area highlights the significant impact of hydrological conditions on the likelihood of such disasters.

Similarly, Preisig (2020) developed a groundwater prediction model for analyzing the stability of a compound slide in the Jura Mountains. Additionally, Srivastava et al. (2020) explored machine learning algorithms to forecast rainfall and established thresholds for landslide probabilities. Although the research by Srivastava et al. did not directly rely on groundwater levels to predict landslides, it is evident that rainfall, a crucial factor in their study for landslide prediction, also influences hydrological conditions. Therefore, their research further underscores the importance of considering groundwater levels in landslide prediction.

The northern slope in the Lushan area of central Taiwan, the region investigated in this study, exhibits significant gravitational slope deformation, making it prone to landslides during typhoons or heavy rainfall events. Lin et al. (2020) conducted in-depth studies on the mechanisms of landslide occurrence based on the geological conditions of the area. While successfully providing valuable insights into the evolution of deep-seated gravitational deformations, their study focuses exclusively on employing traditional analytical methods in geological research, such as analyzing data from geotechnical instruments and conducting geological borehole analysis.

Our research aims to adopt a novel approach compared to previous landslide studies at Lushan Mountain by utilizing AI models and metaheuristic optimization algorithms. This research will utilize weather conditions and groundwater levels as inputs for AI models to predict deep-seated displacement, thus aiding in landslide forecasting in this region.

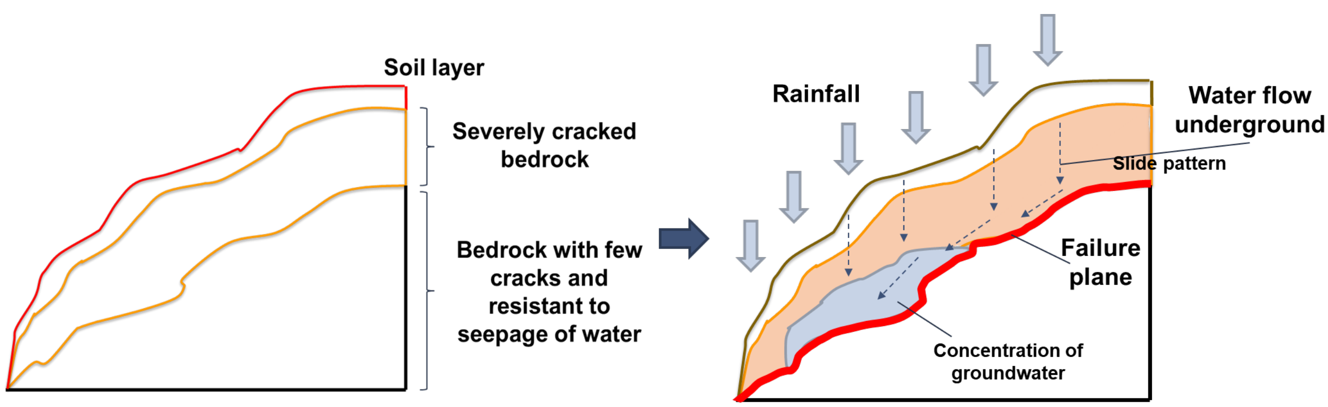

Figure 1. Schematic illustration showing the effects of groundwater on deep-seated slope failure

2.2 Forecasting Slope Displacements: Conventional Methods

Several conventional methods are commonly employed to predict deep slope displacement. These methods primarily involve simulating factors affecting slope stability in landslide-prone areas using data collected from ground-based monitoring devices. An early approach to predicting deep-seated slope movements is geotechnical mapping. This technique characterizes rock and soil's strength, density, and porosity.

For instance, Crosta and Agliardi (2003) analyzed the geology and rock mass behavior using Voight's semi-empirical failure criterion, incorporating time-dependent factors to generate velocity curves that indicate risk levels. Recently, Xu et al. (2018) utilized real-time remote monitoring systems to measure internal stress, deep displacement, and surface strain. This data was used to formulate forecasting models to assess slope stability, particularly in railway construction. However, a common challenge with this method is the instability and frequent changes in the terrain and geology of landslide-prone areas. This necessitates constant updates to the computational model, which can be time-consuming and labor-intensive.

Moreover, physical-based numerical and laboratory modeling methods are also gaining traction in landslide research. These methods aim to maintain forecasts using various data types while reducing human workload and ensuring high accuracy. For example, Mufundirwa et al. conducted a laboratory study to examine the effectiveness of the inverse velocity model in predicting rock mass destruction resulting from landslides at depths of 2m and 4m along the sliding plane. This study utilized historically recorded data from Asamushi, Japan, and the Vaiont reservoir in Italy (Mufundirwa et al., 2010). Meanwhile, Wu (2010) employed the numerical discontinuous deformation analysis method to simulate a blocky assembly's post-failure behavior, incorporating earthquake seismic data. Another study follows this trend by Jiang et al. (2011), who utilized the fluid-solid coupling theory to simulate displacement and capture the interaction between fluid and solid materials. However, both numerical models and laboratory modeling methods require substantial effort from researchers. These approaches demand deep expertise and the development of complex models. More importantly, they rely heavily on assumptions during the simulation process and may not accurately reflect real-world conditions, leading to significant errors.

Stability analysis is another commonly used method related to physics, which evaluates the forces acting on ~~a~~ slope behavior. Fu and Liao (2010) presented a technique for implementing the non-linear Hoek-Brown shear strength reduction, determining the correlation between normal and shear stress based on the Hoek-Brown criterion. Subsequently, the micro-units (microscopic components of the rock mass) instantaneous friction angle and cohesive strength under specific stress conditions are calculated. Although this approach effectively addresses cost and labor issues, it still heavily relies on the researcher's assumptions and is limited by the ability to utilize only a small portion of data from the research area.

However, in landslide studies, monitoring data is constantly updated, generating large volumes daily with a temporal relationship (Peternel et al., 2022; Corominas et al., 2014). As previously mentioned, using conventional methods in landslide research presents numerous challenges whenever data changes or gets updated. In contrast, AI models can overcome these difficulties by automatically learning to identify connections between input and output data. AI models can be updated to incorporate additional input variables and handle increasing amounts of data flexibly in response to real-world conditions. Therefore, AI models will be utilized in this research instead of conventional methods.

2.3 Forecasting Slope Displacements: Machine Learning and Deep Learning

In studies employing machine learning and deep learning models for landslide research, a plethora of research utilizes discrete data to train AI models to predict the probability of landslides or to construct maps depicting landslide susceptibility. For instance, Margarint et al. (2013) employed a logistic regression model to predict landslides based on discrete data in four regions of Romania. The logistic regression model yielded promising predictions, with an AUC value (area under the curve) ranging between 0.851 and 0.94 for the validation dataset. Subsequently, these results were utilized to construct a map of landslide susceptibility in the study area. In a similar study, Pham et al. (2016) used multiple AI models, including support vector machines (SVM), logistic regression (LR), Fisher's linear discriminant analysis (FLDA), Bayesian network (BN), and naïve Bayes (NB), for landslide susceptibility assessment in a region within the Uttarakhand state of India. The SVM model yielded the best prediction results among the models used.

In addition to discrete data, many landslide studies utilize time series data. When it comes to technical forecasting using time series data, machine learning regression prediction models, such as extreme learning machine (ELM) (Li et al., 2018), least squares support vector machine (LSSVM) (Liu et al., 2019), dynamic neural network (DNN) (Aggarwal et al., 2020), random forests (RFs) (Hu et al., 2021), SVM (Zhang et al., 2021), and Gaussian process regression (GPR) (Hu et al., 2019), have proven highly effective at yielding reliable results. These models also provide scalability and the ability to handle larger datasets. However, it is essential to note that machine learning models are sensitive to the white noise typical of time series features. This can pose challenges in capturing subtle behaviors and complex interrelationships, mainly when data availability is limited (Zhang et al., 2020). Finally, feature engineering (the process of selecting and transforming input variables to enhance the performance of the models) is computationally intensive and labor-intensive, limiting its applicability when rapid forecasting is required.

Alongside the aforementioned machine learning models, a range of neural network models, from simpler ones like Artificial Neural Networks (ANN) to more advanced approaches such as Deep Neural Networks (DNNs) and CNN, are also employed in research related to landslide (Kumar et al., 2017; Zheng et al., 2022). Notably, CNN models have become increasingly popular and are widely used in research related to this disaster. CNN models often yield superior predictive results than other models in landslide susceptibility assessment and displacement prediction (He et al., 2024).

Moreover, another research trend in landslide forecasting involves the use of time series deep learning models such as Recurrent Neural Networks (RNN), Long Short-Term Memory (LSTM), and

Gated Recurrent Units (GRUs), which use previous information to generate current outputs and provide state feedback (Yang et al., 2019; Xu et al., 2022; Yang et al., 2022; Zhang et al., 2022). These time-series deep learning models can effectively capture patterns of changes over time, making them highly suitable for time-series data in landslide-related studies. However, there has yet to be a comprehensive study that employs a combination of machine learning methods, time-series deep learning, and CNN models to compare and determine the most suitable model for predicting landslide displacement. Therefore, our research aims to address this gap.

Another noteworthy research trend involves using AI models to predict landslides based on spatial-temporal data. For instance, Dahal et al. (2024) utilized spatial-temporal data to pinpoint where landslides may occur and predict when they might happen and the expected landslide area density per mapping unit. The Ensemble Neural Network employed in this research yielded promising predictions, demonstrating its potential for forecasting landslides in Nepal's areas affected by the Gorkha Earthquake. However, our study only managed to gather temporal data. Consequently, the AI models developed in our research will be trained to learn and forecast time-series data.

2.4 Hybrid metaheuristic optimization algorithm and AI models in landslide prediction

In landslide-related research, numerous studies have employed hybrid models, wherein metaheuristic optimization algorithms optimize the hyperparameters of AI models. For example, Balogun et al. (2021) studied landslide susceptibility mapping in Western Serbia. This research collected 14 different condition factors to serve as input data for the Support Vector Regression (SVR) model to predict landslide occurrences. The study results indicate that SVR models, with hyperparameters fine-tuned by optimization algorithms such as gray wolf optimization (GWO), bat algorithm (BA), and cuckoo optimization algorithm (COA), all yielded better prediction results compared to using a single model.

Hakim et al. (2022) conducted a study utilizing CNN models optimized by the GWO and imperialist competitive algorithm (ICA) for landslide susceptibility mapping from geo-environmental and topo-hydrological factors in Incheon, Korea. This research demonstrates that GWO and ICA effectively fine-tuned the CNN model, resulting in a highly accurate landslide susceptibility map.

Jaafari et al. (2022) employed an AI model known as the group method of data handling (GMDH) for classification purposes, optimizing it using the cuckoo search algorithm (CSA) and the whale optimization algorithm (WOA). In northwest Iran, they aimed to predict landslides based on various factors, including topographical, geomorphological, and other environmental factors. After training and testing, the GMDH-CSA model produced superior prediction results compared to the GMDH-WOA and the standalone GMDH model.

It is evident from numerous past studies on landslides that the application of metaheuristic optimization algorithms significantly enhances the predictive effectiveness of AI models. Therefore, this study also incorporates this approach to ensure the model's accuracy in landslide prediction. This study will also employ a recently developed metaheuristic algorithm, including a clustering algorithm. This algorithm is promising in yielding favorable results in fine-tuning hyperparameters for AI models.

3. Methodology

3.1 Convolutional Neural Networks

In 1998, LeCun introduced a novel type of DNN known as the CNN, specifically designed for processing data with a grid-like structure, such as images. The complex, layered system of CNN facilitates the automated extraction of features without extensive preprocessing, making it ideal for object recognition, image classification, and segmentation tasks. The detailed mechanism of the CNN model can be found in Appendix A.

This study will use various CNN models to predict deep-seated slope displacement. The CNN models employed in this research include VGG (Simonyan and Zisserman, 2014), ResNet (He et al., 2016), Inception (Szegedy et al., 2015), Xception (Chollet, 2016), MobileNet (Howard et al., 2017), DenseNet (Huang et al., 2017), and NASNet (Zoph et al., 2018). To clarify, the term "standard CNN models" will refer to models with structures that can be user-defined, while "retrained CNN models" will denote those with architectures that have been researched and developed by other scientists and have been proven to be highly effective.

CNN models are typically used for image processing tasks. However, the input data for this study is in numerical and vector form. Therefore, several transformation steps are required to convert this numerical and vector data into image data suitable for CNN input. Detailed information about these transformation steps can be found in the study by Chou and Nguyen 2023 (Chou and Nguyen, 2023).

3.2 Deep Learning Models for Time Series

RNN was introduced by Elman in 1990 (Elman, 1990). This model makes predictions based on sequential data, crucial for language modeling, document classification, and time series analysis. The architecture of an RNN model can be found in Appendix B.

In this study, advanced models of RNN, such as LSTM [54] and GRU [55], are also utilized, and their effectiveness in predicting deep-seated landslides will be compared.

3.3 Machine Learning

In addition to the aforementioned deep learning models, as elucidated earlier, machine learning models will be employed to predict deep-seated slope displacements in this research. The machine learning models utilized will encompass the following: linear regression (LR) (Stanton, 2001), ANN (Mcculloch and Pitts, 2021), SVR (Drucker et al., 1996), classification and regression tree (CART) (Breiman, 1984), radial basis function neural network (RBFNN) (Han et al., 2010), extreme gradient boosting (XGBoost) (Chen; and Guestrin). These machine learning models will be used to make predictions and will be compared with other deep learning models.

3.4 Model Validation and Performance Metrics

3.4.1 Evaluation and Validation

To obtain reliable (i.e., generalizable) evaluation and validation results, it is crucial that the data used for testing does not include the data used for training. Therefore, a dataset must be divided into training, validation, and testing subsets before training the AI model. Training data is used to learn patterns; testing data is used to assess model performance and identify errors; and validation data is used to fine-tune the hyperparameters. In the current study, we opted to refrain from employing cross-validation, which tends to be time-consuming. Instead, we adopted the holdout approach to manage our large dataset with well-represented target variables (Figure 2). A 90:10 ratio is generally used to split datasets into learning and testing data (Di Nunno et al., 2023). When implementing the holdout method during hyperparameter optimization, 20% of the learning data is used for validation, and the remaining 80% is used for training.

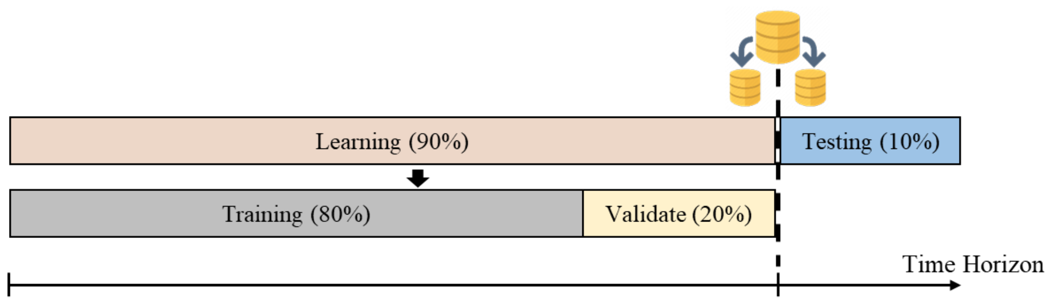

Figure 2. Data are splitting under the proposed Holdout scheme.

3.4.2 Performance Metrics

This study utilized four widely recognized performance measures to assess the model's effectiveness in prediction accuracy (Chou and Nguyen, 2023). The measures included mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean square error (RMSE).

MAE represents the mean of absolute errors, calculated as the average of the absolute differences between actual and predicted values. Its advantage lies in its simplicity, which provides a straightforward measure of average prediction error. However, a drawback of MAE is its insensitivity to more significant errors, so it may not effectively highlight differences between models when significant errors are present. It is defined as:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|y_i - \hat{y}_i| \quad (1)$$

where n is the number of predictions, y_i is the i^{th} forecasted value, and $\hat{y}_i$ is the corresponding i^{th} actual value.

MAPE quantifies the average absolute error ratio to the actual value derived from the differences between actual and forecasted values. It provides a clear metric in percentage terms, facilitating straightforward interpretation across various datasets. However, MAPE's limitation arises from its sensitivity to zero values in the actual data, which can become undefined or impractical to compute, limiting its utility in scenarios involving zero or near-zero actual values. The expression for MAPE is as follows:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \tag{2}$$

where n is the number of predictions, y_i is the i^{th} forecasted value, and $\hat{y}_i$ is the corresponding i^{th} actual value.

RMSE represents the square root of the average squared error between actual and forecasted values and is widely used for its ability to indicate the dispersion of errors. This method captures the magnitude and direction of errors, making it practical for assessing overall prediction accuracy. However, RMSE tends to be more sensitive to outliers and significant errors than MAE due to its squaring of errors during computation. This sensitivity can disproportionately affect its evaluation in datasets with extreme values. The expression for RMSE is as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{3}$$

where n is the number of predictions, y_i is the i^{th} forecasted value, and $\hat{y}_i$ is the corresponding i^{th} actual value.

3.5 Age of Exploration-Inspired Optimizer

This study employs a range of AI models to forecast deep-seated displacement in mountainous regions. To enhance the prediction accuracy of these AI models, the study incorporates a novel metaheuristic optimization algorithm known as the Age of Exploration-Inspired Optimizer (AEIO). Developed by Chou and Nguyen in 2024, this algorithm has demonstrated high effectiveness in fine-tuning the hyperparameters of AI models. This algorithm treats each particle in the search domain as an explorer. The movement of particles toward regions with higher fitness values parallels the exploratory activities of the Age of Exploration, where explorers sought ideal locations for establishing colonies. In this study, each particle represents a set of hyperparameters, with the ultimate goal of the search process being to identify the optimal particle or hyperparameter set that minimizes prediction error for AI models. Figure 3 illustrates the AEIO algorithm.

The strength of the AEIO algorithm lies in its ability to develop specific strategies for particles based on their positions, enabling faster convergence to the optimal point. Using density-based spatial clustering of applications with noise (DBSCAN) for particle clustering, the AEIO determines whether particles are in favorable or unfavorable positions, reminiscent of explorers during the Age of Exploration. The proximity (within clusters) allows explorers to gather information and move toward optimal locations, thereby enhancing their ability to establish new colonies. In contrast, explorers far apart (outside clusters) adopt different strategies, relying on limited peer guidance or general trends in their quest for new territories.

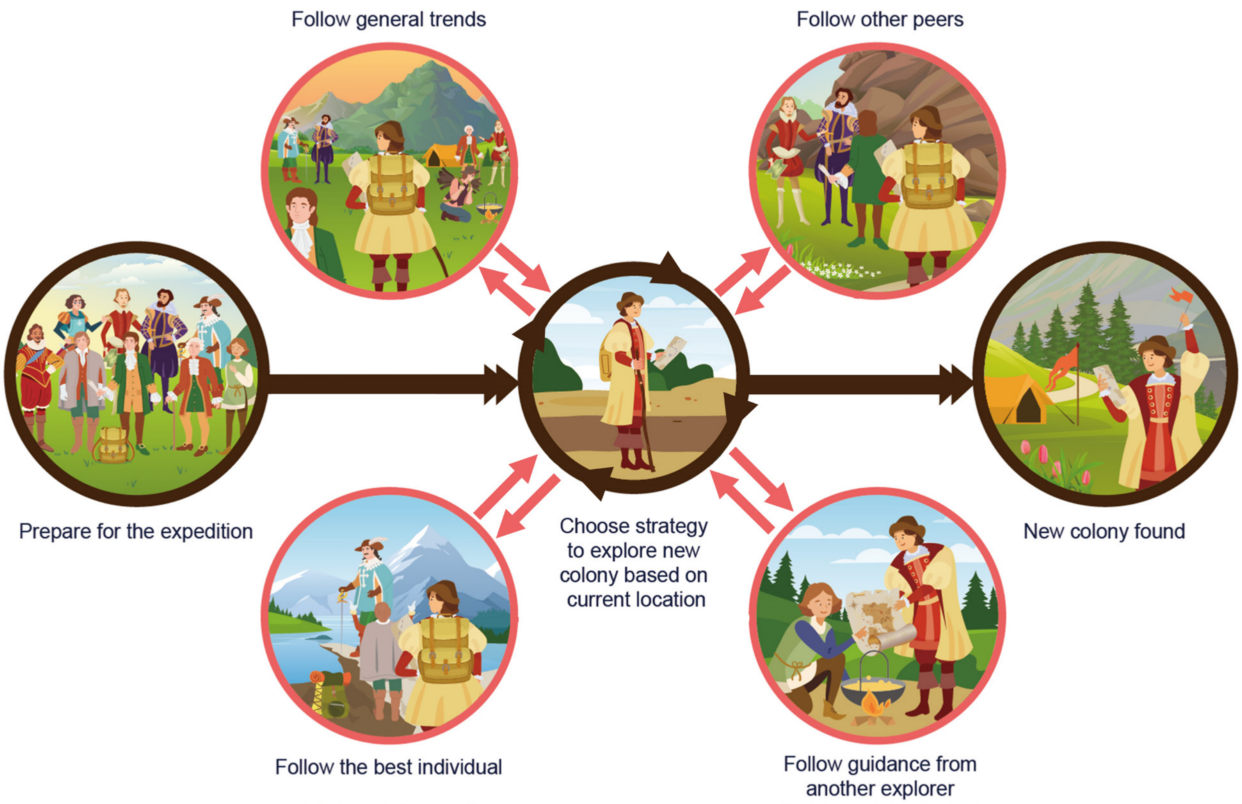

Figure 3. Illustration of Age of Exploration-Inspired Optimizer

In each iteration, explorers forecast their next move. If it promises a better position, they relocate. Otherwise, if the new spot is less favorable for colony establishment, they stay put and await the next iteration. The algorithm employs specific mathematical formulas to calculate the movement step of explorers or particles in the AEIO. The exploratory steps of an explorer in the AEIO algorithm will continuously iterate until the stop condition is satisfied.

- **Explorers follow general trends**

The explorer choosing this movement type will calculate the distance from their location $x_{i,d}(t)$ to the center of all other explorers ($Meanvl_d(t)$), then attempt to move towards that central point in the hope of finding a better location with the potential to establish a new colony. The following formula determines the explorer's position after the movement:

$$x_{i,d}(t+1) = x_{i,d}(t) + \alpha * \left(Meanvl_d(t) - x_{i,d}(t)\right) \times rand(0,1) \times R \quad (4)$$

$$Meanvl_d(t) = \frac{x_{1,d}(t)+x_{2,d}(t)+\cdots+x_{n_{Pop},d}(t)}{n_{Pop}} \quad (5)$$

where $d = 1,2, \dots D$; D is the number of dimensions; $i = 1,2, \dots n_{Pop}$; n_{Pop} is the total number of explorers; $t = 1,2, \dots MaxIt$ is the number of iterations; $MaxIt$ is the maximum value of iteration; α is a parameter for adjusting the particle's movement toward the centroid position (usually equals 3). $Meanvl_d(t)$ is the centroid of all particles in dimension d. $rand(0,1)$ is the random number in the range [0,1]. R: a number that equals 1 or 2 depending on the value of *rand*(0, 1) per the equation. $R = round(1 + rand(0,1) \times 1)$, $x_{i,d}(t)$ is the location of particle i in iteration t, $x_{i,d}(t+1)$ is the location of particle i in iteration $(t+1)$.

- **Explorers follow three other peers**

Explorers employing this movement method will calculate the average position of three randomly selected other explorers $\left(\frac{x_{1,d}(t)+x_{2,d}(t)+x_{3,d}(t)}{3}\right)$ and then move toward this newly calculated average position. The explorer's new position is computed using the following formula:

$$x_{i,d}(t+1) = x_{i,d}(t) + \left(\frac{x_{1,d}(t)+x_{2,d}(t)+x_{3,d}(t)}{3} - x_{i,d}(t)\right) \times rand(0,1) \times R \quad (6)$$

where: $x_{1,d}(t)$, $x_{2,d}(t)$ and $x_{3,d}(t)$ are three random explorers in dimension *d* at iteration *t*, $d = 1,2, \dots D$; D is the number of dimensions; $i = 1,2, \dots n_{Pop}$; n_{Pop} is the total number of explorers; $t = 1,2, \dots MaxIt$ is the number of iterations; $MaxIt$ is the maximum value of iteration.

- **Explorers follow the best one**

According to this strategy, the explorer ($x_{i,d}(t)$) will move closer to the position of another explorer currently holding the best position ($Best_d(t)$), as determined by the following formula:

$$x_{i,d}(t+1) = x_{i,d}(t) + \left(Best_d(t) - x_{i,d}(t)\right) \times rand(0,1) \times R \quad (7)$$

where: $Best_d(t)$ represents the position of the particle with the best fitness in dimension d at iteration t, the parameters d and t hold the same significance as defined in Equation 10.

- **Explorers follow guidance from another one**

Explorers in favorable positions with access to information can execute this movement strategy. In this scenario, explorers ($x_{i,d}(t)$) will consult with ~~each other~~ another explorer. The consulted explorer will compare their direction and distance to the best individual, who holds the most favorable position ($Best_d(t)$) and guide the inquirer. This algorithm assumes that the inquirer can be any explorer, i.e., a random explorer ($x_{1,d}(t)$). The following formula describes how to calculate the new position of the explorer following this strategy:

$$x_{i,d}(t+1) = x_{i,d}(t) + \left(Best_d(t) - x_{1,d}(t)\right) \times rand(0,1) \times R \quad (8)$$

where: $x_{1,d}(t)$ is a random explorer in dimension *d* at iteration *t*. the parameters d and t hold the same significance as defined in Equation 10.

- **Crowd control mechanism**

To enhance the efficiency of AEIO in transitioning between exploration and exploitation, a mechanism is employed to adjust the parameters of DBSCAN throughout each cycle, according to the following formula:

$$\varepsilon_d = \left(0.1 + \frac{t}{MaxIt}\right) \times (Meanvl_d(t) - Best_d(t)) \tag{9}$$

$$MinPts = round\left(1 + \frac{t}{MaxIt} \times 10\right) \tag{10}$$

The exploratory steps in the AEIO algorithm begin by classifying positions using the DBSCAN algorithm. Subsequently, the explorers update the crowd control mechanism according to equations (13) and (14), and move according to various strategies defined by equations (8), (10), (11), and (12). This process is conducted iteratively until the maximum number of iterations is reached.

To fine-tune the hyperparameters of AI models, the AEIO algorithm treats each hyperparameter as a variable. Furthermore, the objective function of the AEIO algorithm seeks to minimize the prediction error of AI models, which is quantified by an evaluation metric (MAPE). Figure 4 presents a flowchart illustrating the process by which the AEIO algorithm aids in fine-tuning hyperparameters for AI models.

3.6 Experiment Setup

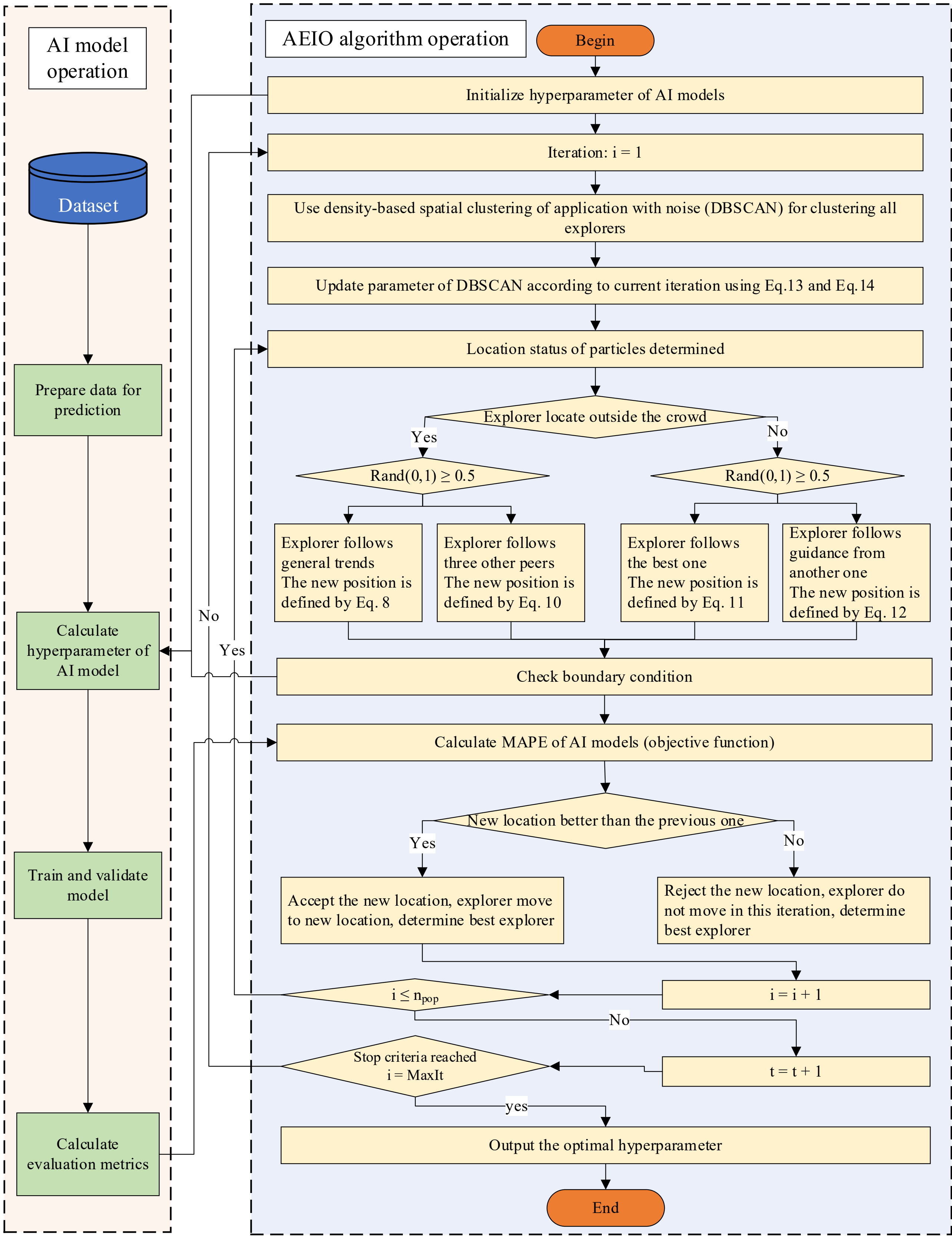

Figure 4. Flowchart of the fine-tuning process of AI models by the AEIO algorithm

3.6.1 Research Area

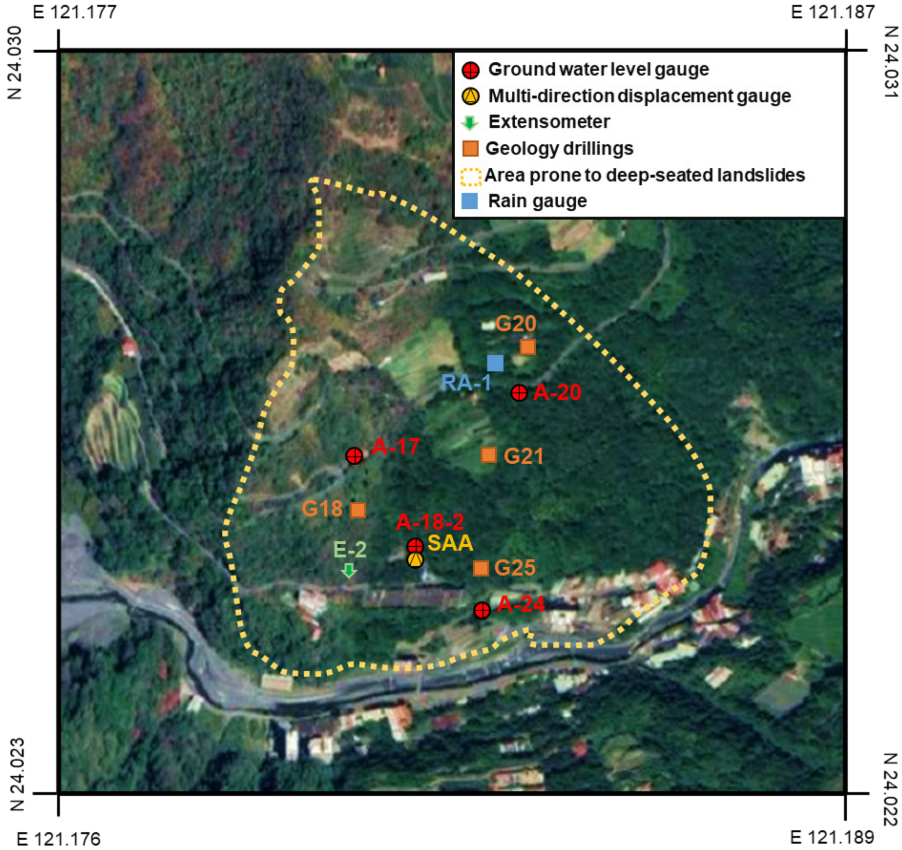

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Figure 5. Locations of measurement devices

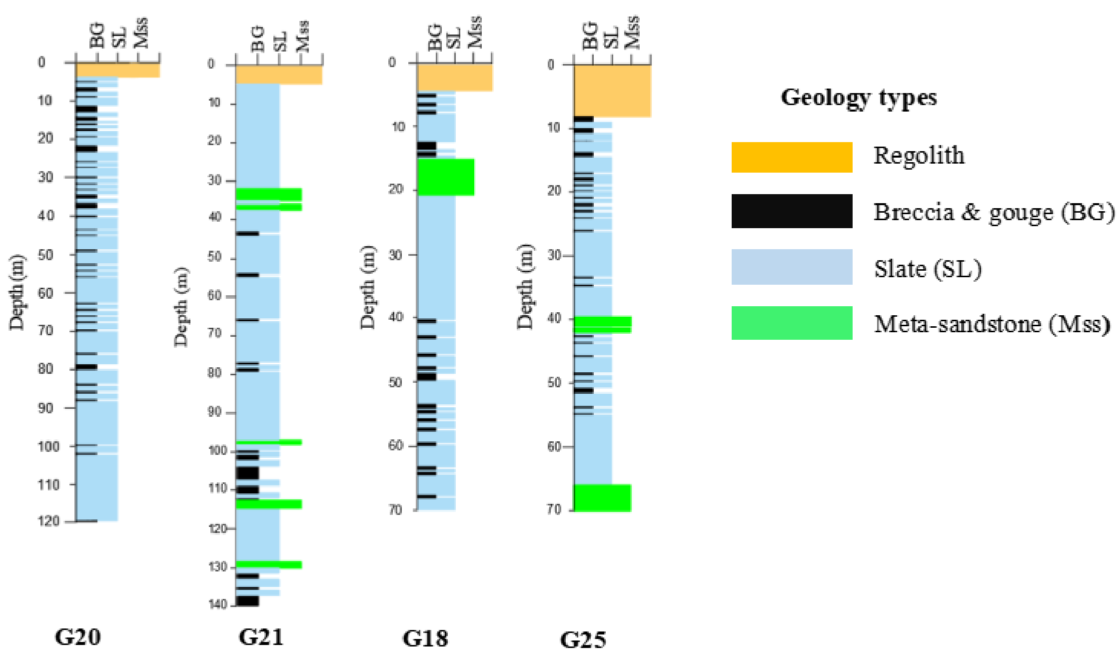


Figure 6. Illustration of geological drilling survey

The current study focuses on the northern slope of Lushan hot spring in Ren'ai Township, Nantou County (Figure 5), with Nenggao Mountain to the east, Hehuan Peaks to the north, Zhuoshe Mountain to the south, and Puli Basins to the west. The terrain features rugged mountain ranges, youthful valleys, and notable river erosion (Lee and Chi, 2011). Lushan Hot Springs is located below the hill, and the main access roads for nearby settlements and hot spring sites include Provincial Highway 14 and County Highway 87.

In an early study of deep landslides in this area, Lin et al. (2020) reported that the Lushan slope exhibits large-scale deep-seated gravitational slope deformation, characterized by a steep scarp, a gently inclined head, and a curving river at its base. Figure 6 illustrates the geological details of the research area and shows the distribution of four survey boreholes (G20, G21, G18, and G25) along the slope. Regolith, slate, and meta-sandstone are three distinct lithological units revealed through drilling. Additionally, the study by Lin et al. identified the depths of failure planes in these survey boreholes. Specifically, boreholes G18 and G25 did not record any failure planes, while boreholes G20 and G21 recorded failure planes at depths of 85 meters and 106 meters, respectively. These failure planes were identified based on inclinometer data from the corresponding study (Lin et al., 2020).

Initially, the thickness of the topmost regolith layer was found to be less than 10 meters. Secondly, slate predominated, exhibiting a notable presence with sporadic evidence of weathering that resulted in brecciated patterns. This composition frequently broke into breccia and gouges, particularly along cleavage planes and thin shear zones, indicating its susceptibility to collapse. This geological layer is identified as the area's primary cause of landslide risk. Finally, meta-sandstone appeared intermittent compared to the more prevalent lithological units, characterized by its fragility and fractures and occurring less frequently in the drilled samples.

Previous research has detected signs of brittle deformation in the area. These indications include chevron folds within cleavages, visible cracks, and intricate jigsaw puzzle-like patterns at the head of the rock formations. Overturned and flexural toppling cleavages are prevalent toward~~s~~ the toe of the slope. Additionally, kink bands are observable on fractures recently undergoing flexural folding along the eastern boundary. Notably, horizontal cleavages near the toe region also exhibit inter-cleavage gouges. Further details on this geological information can be found in the study by Lin et al. (2020). These instances highlight the potential for significant geological changes and landslide risk in this region.

3.6.2 Data Collection and Preprocessing

In this study, hourly data of deep-seated displacement and groundwater level were collected by the Department of Civil Engineering, College of Science and Technology, at the National Chi Nan University research group over eight years from July 2009 to June 2017, yielding 68,317 data points. The installation time points and locations are presented in Table 1 and Figure 5, respectively.

The data used in this study were collected using an in-hole telescopic gauge (E-2), a multidirectional shape acceleration array sensor (SAA) with an underground displacement gauge, and four groundwater level gauges (A-17, A-18-2, A-20, and A-24). The transmission, storage, and processing of data are described in detail in the research of Lau et al. (2023).

The operation of the in-hole extensometer entailed the installation of a borehole through the sliding surface. One end of a steel cable was anchored at the bottom, and a displacement gauge was placed at the free end to measure deformations automatically. The fixed stops for E-2 and SAA were situated at depths of 70 meters and 40 meters below the surface, respectively. In addition to groundwater level data, information regarding significant rainfall events in this area was also measured and is presented in Table 2.

Table 1. Device installation timepoints

<table>
<tr><td>Year</td><td>2008</td><td>2009</td><td>2010</td><td>2011</td><td>2012</td><td>2013</td><td>2014</td><td>2015</td><td>2016</td><td>2017</td></tr>
<tr><td rowspan="4">Groundwater level gauge</td><td colspan="10">A-17</td></tr>
<tr><td colspan="6">No data</td><td colspan="4">A-18-2</td></tr>
<tr><td>No data</td><td colspan="9">A-20</td></tr>
<tr><td>No data</td><td colspan="9">A-24</td></tr>
<tr><td rowspan="2">Extensometer</td><td>No data</td><td colspan="9">E-2</td></tr>
<tr><td colspan="3">No data</td><td colspan="7">SAA</td></tr>
</table>

Table 2. Heavy rainfall events in the study area

No.	**Rain onset (month/day/year hour: minute)**	**Rain end time (month/day/year hour: minute)**	**Accumulating rainfall (mm)**	**Drop rain hour (hr)**	**Event**
1	7/17/2008 14:00	7/19/2008 21:00	418	55	Kameiji typhoon
2	9/112008 16:00	9/15/2008 12:00	943.5	92	Pungentmusc typhoon
3	9/28/2008 1:00	9/30/2008 10:00	523.5	57	Rose honey typhoon
4	8/4/2009 3:00	8/12/2009 20:00	931	209	Mopull typhoon
5	6/8/2012 13:00	6/17/2012 16:00	1029	219	Torrential rain
6	7/30/2012 7:00	8/3/2012 11:00	370	100	Supull typhoon
7	5/10/2013 16:00	5/25/2013 1:00	597	345	Torrential rain
8	7/12/2013 19:00	7/15/2013 23:00	330	76	Suprofit typhoon
9	9/20/2013 22:00	9/23/2013 18:00	347	68	Usagi typhoon
10	5/9/2014 5:00	5/22/2014 3:00	326.5	310	Torrential rain
11	7/22/2014 14:00	7/24/2014 0:00	321.5	34	Madham typhoon
12	6/1/2017 11:00	6/4/2017 21:00	897	82	Torrential rain
13	6/11/2017 17:00	6/19/2017 3:00	638.5	178	Torrential rain

Based on the collected data, analyses have examined the correlation between groundwater levels and deep-seated displacement at Lushan Mountain. To observe this correlation, graphs illustrating the precipitation of recorded heavy rainfall (Figure 7A), variations in displacement (Figure 7B and Figure 7C), and groundwater levels (Figure 7D) over time have been plotted.

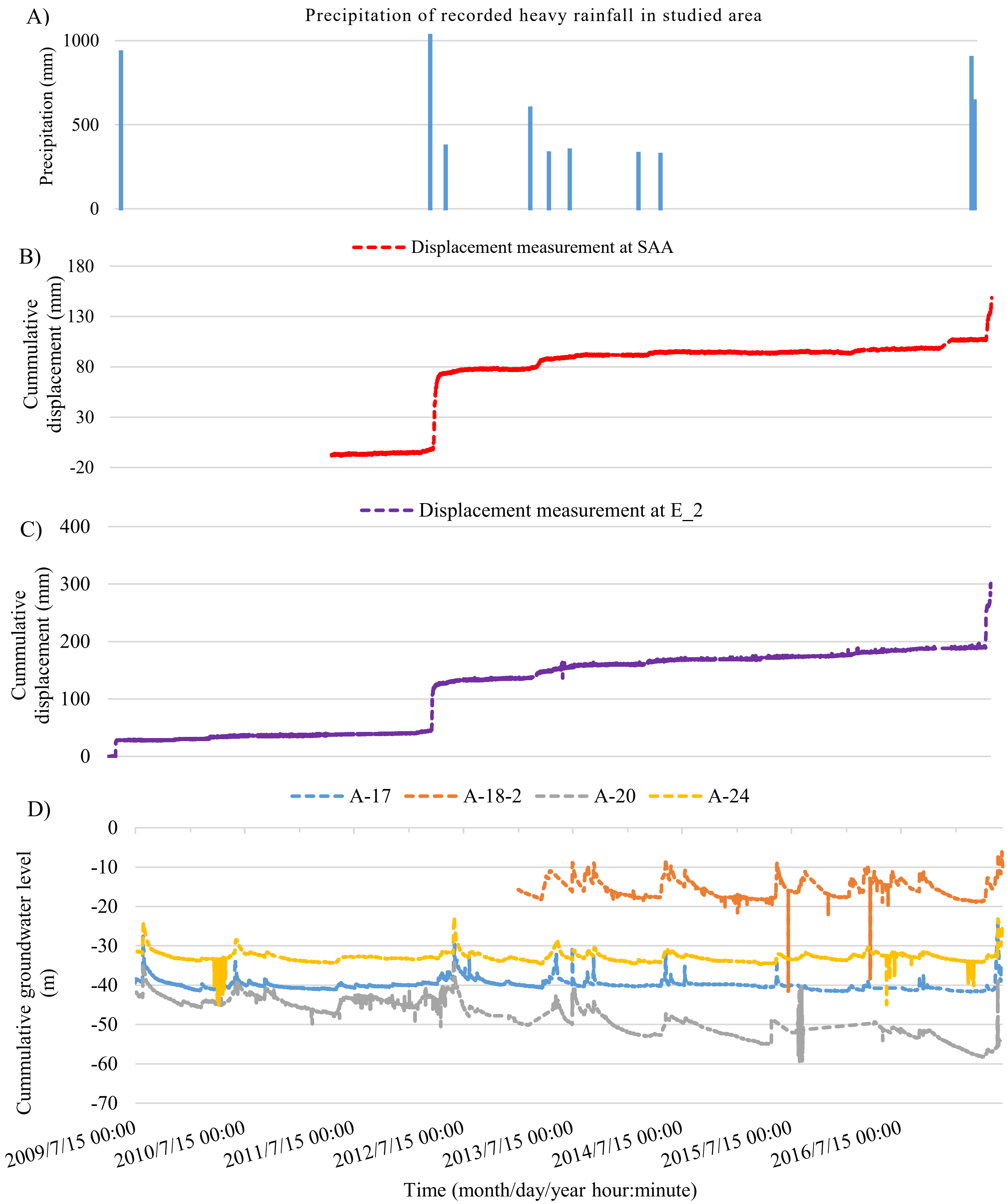


Figure 7. Unified timeline visualization of data in this study.

A) Precipitation of recorded heavy rainfall in the studied area; B) Measured displacements from extensometer SAA C) Measured displacements from extensometer E_2; D) Groundwater levels at stations A-17, A-18-2, A-20, and A-24.

The graphs above show that the displacement values at both stations often exhibit significant increases coinciding with periods of pronounced fluctuations in groundwater levels. Specifically, in June 2012, there was a notable surge in groundwater levels attributed to heavy rainfall from June 8, 2012, to June 17, 2012, totaling 1029 mm over 219 hours (as indicated in Table 2 and Figure 7A). The abnormal rise in groundwater levels caused a structural alteration in the area's soil, consequently amplifying deep-seated displacement at both stations, namely E_2 and SAA, as evidenced in Figure 7B and Figure 7C.

Similar events occurred in November 2017. Heavy rainfall totaling 638.5 mm over 178 hours during this period also caused a sudden alteration in groundwater levels, resulting in significant deep-seated displacement. Through comparison, it is apparent that there were up to 13 instances of anomalous heavy rainfall during the study period. However, not every example of heavy rain resulted in significant fluctuations in groundwater levels, leading to substantial displacement. Hence, data regarding groundwater level elevation will be used to predict deep-seated landslides rather than rainfall data.

In addition to groundwater level data, weather factors such as temperature and humidity are also utilized as input data for the prediction model. This study includes temperature as an input variable for AI models to predict deep-seated displacement due to its impact on soil structure. Elevated temperatures can cause thermal expansion of soil particles, which can increase pore water pressure and reduce effective frictional resistance forces (Pinyol et al., 2018). Additionally, previous research has shown a relationship between temperature and the likelihood of landslides in clay-rich soils, which are also present in the geological composition of Lushan Mountain (Shibasaki et al., 2017; Loche and Scaringi, 2023).

This study collected groundwater level and displacement data on-site using sensors. Furthermore, temperature and humidity data were obtained from the website https://power.larc.nasa.gov. This dataset is part of the Prediction of Worldwide Energy Resource (POWER) project, developed by the National Aeronautics and Space Administration (NASA) of the United States. The POWER solar data derives from satellite observations, which are used to infer surface insolation values. Meteorological parameters are sourced from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) assimilation model. The primary solar data is available with a global resolution of 1° x 1° latitude/longitude, while the meteorological data is provided at a finer resolution of ½° x ⅝° latitude/longitude. Users can download the data hourly, daily, or monthly through this website.

Table 3 displays the input and output variables for AI models to predict deep-seated displacement at Lushan Mountain. Two datasets will be generated: one for predicting displacement at the E_2 station and another for indicating displacement at the SAA station. Table 4 outlines the number of data points for each dataset and illustrates how the data is divided into training and testing sets.

Table 3. Input and output variables of a model predicting deep-seated displacement.

	Attributes group	Attributes	Variable ID	Dataset of E_2 station	Dataset of SAA station
Output variables	Deep-seated displacement measures	Displacement extensometer at station E_2 (mm)	Y1	✓	-
		Displacement extensometer at station SAA (mm)	Y2	-	✓
Input variables	Groundwater level data	Groundwater level at station A-17 (m)	X1	✓	✓
		Groundwater level at station A-18-2 (m)	X2	✓	✓
		Groundwater level at station A-20 (m)	X3	✓	✓
		Groundwater level at station A-24 (m)	X4	✓	✓
	Weather data	Temperature at 2 meters (°C)	X5	✓	✓
		Specific humidity at 2 meters (g/kg)	X6	✓	✓

Table 4. Number of data points

Quantity of data points	Dataset of the E-2 station	Dataset of SAA station
Total data samples	68312	51679
Count of training samples (90% of the total sample)	61477 (2009/07/15-2016/09/07)	46523 (2011/07/13 – 2016/11/16)
Count of testing samples (10% of the total sample)	6835 (2016/09/07-2017/06/20)	5156 (2016/11/16-2017/06/20)

3.6.3 Data Preprocessing

Firstly, the data in this study will undergo a normalization process to scale all features to a consistent range (typically between 0 and 1). This step is essential to ensure that the model considers the importance of each feature, thereby enhancing overall prediction accuracy (Han et al., 2006).

In the current study, the sliding window technique is implemented after data normalization to organize data according to a specific time frame. This involves using historical data from previous steps to predict the output for subsequent steps (Chou and Ngo, 2016). The forecasting horizon refers to the length of time into the future for which output forecasts are made.

The basic process of the sliding window technique is illustrated in Figure 8. To train AI models, this study opts for a window size of one week (equivalent to 168 hours). This fixed window size is utilized exclusively for single AI models. Subsequently, the hybrid model's AEIO algorithm and other hyperparameters will fine-tune the window size to determine the most suitable settings.

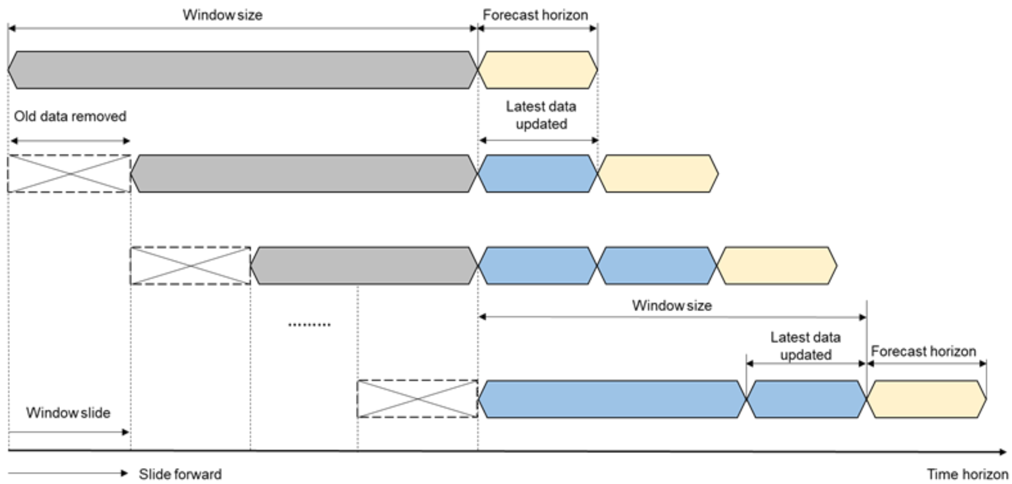


Figure 8. Sliding window technique

This study focuses on predicting deep displacement values at two distinct time intervals: 1 day ahead (+24 hours) and seven days ahead (+168 hours). These forecast horizons are strategically chosen to provide timely information, enabling management departments to make accurate decisions regarding evacuating people and assets from areas prone to landslides.

Specifically, for valuable assets and machinery that require time for relocation from landslide-prone areas, having advance knowledge of the landslide event one week ahead of relocation is crucial. Furthermore, for humans, animals, or other assets that can be evacuated more swiftly, predicting the landslide one day in advance is sufficient to ensure safety.

The predicted outputs are quantified in mm/day, facilitating decision-making for administrators according to the TGS-SLOPEM106 standard (Ruitang et al., 2017). Table 5 outlines suggested actions corresponding to different degrees of deep displacement as per the TGS-SLOPEM106 standard issued by the Taiwan government.

Table 5. Recommendations are taken from TGS-SLOPEM106 for addressing displacement values in the early stages of deep sliding.

Classification of the displacement value	**Attention value**	**Warning value**	**Action value**
Corresponding displacement value	2 mm/month	0.5 mm/day	10 mm/day

Classification of the displacement value	Attention value	Warning value	Action value
Condition of slopes	The slope started to slip or slowly move	The hill is undergoing constant-velocity descent.	The rate of slope movement is increasing, elevating the risk of collapse.
Recommendations on monitoring activities	- Inspect the monitoring system for any irregularities and consider increasing the frequency of visual inspections	- Enhance the frequency of the automated monitoring system	- Implement a rigorous monitoring system frequency
Countermeasures	- Conduct a slope stability investigation and assessment - Develop a reinforcement and improvement plan to enhance slope stability	- Execute emergency slope reinforcement procedures - Develop an emergency response plan for individuals and vehicles within the landslide area	- Evacuate people and vehicles from the landslide area

4. Model Establishment and Analysis Results

4.1 Model Establishment

Predicting deep-seated displacement at Lushan Mountain is undoubtedly highly challenging, given that such landslides depend on numerous factors. Therefore, multiple methods will be employed simultaneously to identify the optimal AI model for prediction. These methods include single machine learning, time series deep learning, CNN, and hybrid models.

This study will conduct a testing process to systematically identify the optimal model capable of accurately predicting deep-seated landslides. An illustration of this process can be found in Figure 9. Initially, the study will sequentially employ various single numerical AI models, such as machine learning models (LR, ANN, SVR, CART, RBFNN, XGBoost) and time series deep learning models (RNN, R-RNN, LSTM, R-LSTM, GRU, R-GRU), to forecast displacement.

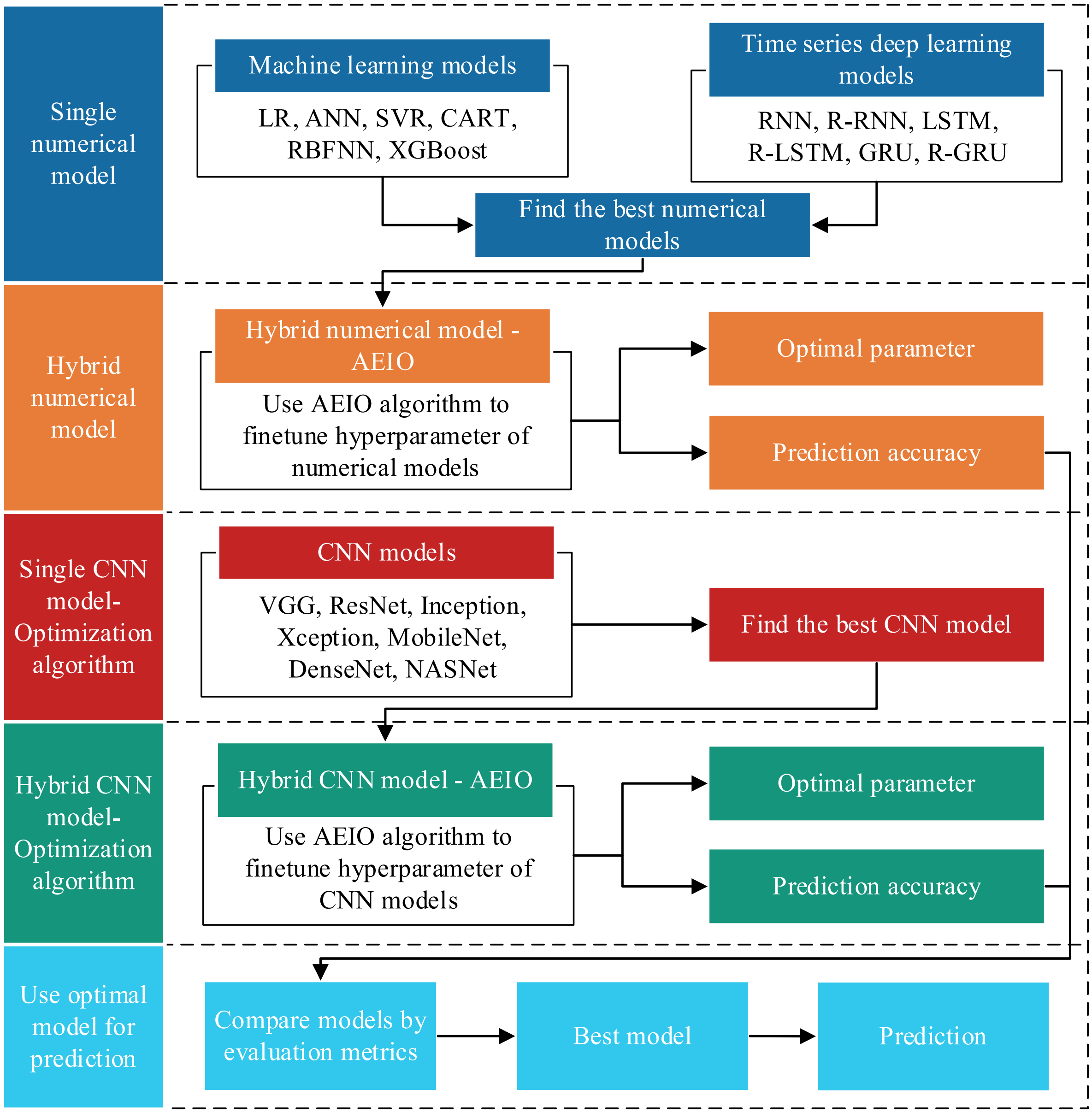


Figure 9. Diagram depicting the steps of choosing the optimal AI model to predict deep-seated displacement

Subsequently, the model with the highest prediction accuracy will be selected for integration with the AEIO algorithm, forming a hybrid model. In this hybrid model, the hyperparameters of the best numerical AI model will be fine-tuned by the AEIO algorithm to enhance prediction accuracy.

In addition to the numerical AI models, this study employs individual CNN models for predicting deep-seated displacement. Subsequently, similar to the approach above, the best CNN model with the highest displacement prediction capability will be fine-tuned by the AEIO algorithm within a hybrid model. In the final step, a comparison process between the two hybrid models— one comprising the best numerical model and the other involving the best CNN model fine-tuned by AEIO— will be conducted to select the optimal model for this study.

4.2 Analysis Results

This section will present the experimental results of the steps outlined in Figure 9, along with relevant metrics and analysis.

4.2.1 AI Models

a. Machine Learning Models

Initially, single machine learning models will be employed to predict deep-seated displacement. In this phase, machine learning models will utilize default hyperparameters, as detailed in the research of Chou and Nguyen (2023). The prediction results of these models at both E-2 and SAA stations are displayed in Table 6. These results show that most machine learning models demonstrate a relatively good predictive capability for displacement, particularly the XGBoost model, which exhibits MAPE values ranging from 8.14% to 9.58%. Following closely, CART also produces favorable prediction results, with MAPE ranging from 8.53% to 9.76%. Regarding prediction accuracy, XGBoost and CART models outperform LR, ANN, SVR, and RBFNN models.

Table 6. Performance results of machine learning models for predicting deep-seated displacement.

Model	MAPE (%)		MAE (mm)		RMSE (mm)		Time (s)	
	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead
E-2-station								
LR	10.70	11.22	22.61	21.32	28.17	31.96	0.0001	0.003
ANN	12.31	13.31	22.19	24.92	26.56	32.54	129.80	212.83
SVR	12.46	12.47	21.98	22.56	26.27	28.05	162.55	174.44
CART	8.53	8.67	15.67	16.87	25.16	27.81	1.50	2.57
RBFNN	15.13	15.19	23.81	22.56	28.42	31.96	2.32	4.10
XGBoost	**8.14**	**8.36**	14.80	14.68	23.07	23.92	1.58	3.28
SAA-station								
LR	11.18	12.11	11.51	11.64	17.26	16.07	0.01	0.01
ANN	10.91	10.93	9.43	10.45	16.55	15.92	116.78	190.69
SVR	10.55	10.94	10.87	9.18	15.64	13.42	136.01	346.30
CART	10.57	10.76	7.11	7.30	13.51	10.63	0.91	1.59
RBFNN	14.51	14.95	11.38	12.68	17.13	19.06	4.20	8.76
XGBoost	**9.17**	**9.58**	8.43	7.83	16.36	16.97	1.12	2.29

Moreover, the results in Table 6 also indicate that there is not a significant difference in the prediction errors of the machine learning models at both E-2 and SAA stations, as the error values for both stations are nearly equal across all machine learning models. Regarding the running time, the LR model demonstrates the shortest duration, ranging from 0.001 to 0.1 seconds for all runs. However, the prediction accuracy of this model could be higher, as mentioned earlier. In this case, the machine learning model with the longest running time is SVR, ranging from 136.01 to 346.3 seconds. This, combined with the low MAPE score, indicates that the SVR model operates inefficiently with the dataset in this study. After reviewing the results of the machine learning models in this section, it is observed that XGBoost is the most suitable machine learning model for predicting deep-seated landslides, exhibiting both high prediction accuracy and a short running time.

b. Time series deep learning models

Similar to the machine learning models, in this section, the time series deep learning models will also be trained with default hyperparameters, as found in the research of Chou and Nguyen (2023). The performance results of these models are shown in Table 7. Overall, akin to the machine learning models, the time series deep learning models also demonstrate fairly good prediction accuracy, especially the best model - R-GRU model, with MAPE ranging from 7.95 to 9.13%.

The performance of the R-GRU model surpasses that of the GRU model because the R-GRU model learns patterns from time series data in both forward and backward directions on the timeline, thereby capturing more patterns. Furthermore, the R-GRU model produces significantly better prediction results with a more complex learning mechanism than other time series deep learning models. However, due to its complex operational mechanism, the R-GRU model also requires more processing time than other time series deep learning models. From the results of Table 7, it is observed that the operating time of the R-GRU model ranges from 79.81 to 212.75 seconds.

From the conducted analyses, R-GRU has been identified as the best time series deep learning model, owing to its excellent prediction performance. Compared to the best machine learning model, XGBoost (with MAPE ranging from 8.14% to 9.58%), the R-GRU model (with MAPE ranging from 7.90 to 9.13%) demonstrates higher prediction accuracy. Therefore, the R-GRU model will be chosen as the best numerical AI model.

Table 7. Performance results of time series deep learning models for predicting deep-seated displacement

Model	**MAPE (%)**		**MAE (mm)**		**RMSE (mm)**		**Time (s)**	
	1-day-ahead	**7-day-ahead**	**1-day-ahead**	**7-day-ahead**	**1-day-ahead**	**7-day-ahead**	**1-day-ahead**	**7-day-ahead**
E-2-station								
RNN	12.72	12.92	23.61	24.75	31.18	29.62	83.24	177.53
R-RNN	12.31	12.84	22.88	21.97	30.20	34.42	91.47	114.33
LSTM	8.42	8.57	17.87	16.31	21.41	22.98	123.10	151.91
R-LSTM	8.13	8.75	16.63	17.84	22.85	24.67	148.56	161.14
GRU	8.43	10.15	16.06	19.38	22.46	26.75	141.50	164.26

Model	MAPE (%)		MAE (mm)		RMSE (mm)		Time (s)	
	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead
R-GRU	**7.90**	**8.16**	15.09	15.69	20.84	23.32	156.97	172.96
SAA-station								
RNN	11.92	13.98	17.61	12.65	25.71	23.19	36.77	60.31
R-RNN	14.60	14.73	18.77	13.85	26.19	24.97	49.26	59.06
LSTM	10.64	10.94	12.73	12.25	29.21	29.57	62.84	113.76
R-LSTM	10.14	10.35	11.77	11.60	26.10	27.48	70.94	87.48
GRU	9.32	9.28	18.05	18.11	25.26	22.41	69.56	211.77
R-GRU	**8.03**	**9.13**	18.84	17.85	21.57	21.86	79.81	212.75

4.2.2 Best AI Model Finetuned by AEIO Algorithm

This section will focus on fine-tuning the hyperparameters of the numerical model to enhance its performance in predicting deep-seated displacement. The AEIO algorithm will fine-tune the hyperparameters of the study's best numerical AI model, the R-GRU model. Details regarding the names and search ranges of the hyperparameters are outlined in Table 8. The objective function of the AEIO algorithm during the fine-tuning process is to minimize the MAPE value of the R-GRU model.

Table 9 illustrates the results of the fine-tuning process. From this table, it is observed that the AEIO algorithm has successfully identified the optimal hyperparameters of the R-GRU model, significantly improving the prediction accuracy of this model. For instance, the MAPE in predicting 1-day-ahead displacement of R-GRU before fine-tuning was 7.9%, but this number decreased to only 3.03% after fine-tuning.

Fine-tuning the R-GRU model using AEIO will maximize its potential, minimizing the prediction error to the lowest possible level. Therefore, the results obtained in this section reflect the actual quality of the dataset as well as the level of difficulty in prediction. Specifically, based on the results in Table 9, it is observed that the predictions for one-day ahead displacement (with MAPE of 3.03% and 3.94%) consistently outperform those for seven-days ahead displacement (with MAPE of 6.38% and 7.96%).

One-day-ahead predictions have a shorter time horizon, making them less affected by environmental fluctuations and making changes more accessible to predict. Conversely, in the case of seven-day-ahead displacement prediction, this timeframe is long enough for various factors, such as weather conditions and human interventions, to occur, increasing uncertainty and volatility in the predicted figures.

Additionally, Table 9 indicates that predictions from the dataset of the E-2 station consistently outperform those of the SAA station. Specifically, the displacement prediction at the E-2 station is 3.03% and 6.38%, better than the corresponding numbers for the SAA station, which are 3.94% and 7.96%, respectively. This is attributed to the dataset collected by the E-2 station being more comprehensive and gathered over a more extended period than the SAA station (as shown in Table 4).

Table 10 presents the optimal hyperparameters identified by the AEIO algorithm. Furthermore, in terms of running time, most models, after fine-tuning, exhibit longer running times compared to the original model. However, this increase is entirely acceptable since the additional running time is minimal, and the benefits of fine-tuning are significant, as mentioned above, aiding in the model's more efficient operation.

Table 8. Search ranges of the hyperparameters of the optimal hybrid numerical models (Chou and Nguyen, 2023).

Hybrid model	Hyperparameter	Search range
AEIO-R-GRU	Window size	[1-720]
	Number of hidden units	[1-400]
	Learning rate	[0.0001, 0.5]
	Dropout	[0.00, 0.99]
	Number of epochs	[10, 120]
	Batch size	[32, 64]

Table 9. Performance results of hybrid time-series deep learning model with AEIO in deep-seated landslide prediction

	Model	MAPE (%)	MAE (mm)	RMSE (mm)	Time (s)
One-day-ahead displacement prediction	**E-2-station**				
	AEIO-R-GRU	3.03	6.89	17.98	196
	SAA-station				
	AEIO-R-GRU	3.94	4.16	11.20	184
Seven-day-ahead of displacement prediction	**E-2-station**				
	AEIO-R-GRU	6.38	10.02	18.05	261
	SAA-station				
	AEIO-R-GRU	7.96	12.49	7.82	248

Table 10. Optimal hyperparameter of time series deep learning model found by AEIO algorithm

	Model	Window size	Number of hidden units	Dropout rate	Learning rate	Number of epochs	Batch size
One-day-ahead	**E-2-station**						
	AEIO-R-GRU	41	81	0.27	0.7	18	64

	Model	Window size	Number of hidden units	Dropout rate	Learning rate	Number of epochs	Batch size
displacement prediction	**SAA- station**						
	AEIO-R-GRU	54	145	0.19	0.46	32	32
Seven-day-ahead of displacement prediction	**E-2- station**						
	AEIO-R-GRU	97	164	0.24	0.61	20	32
	SAA- station						
	AEIO-R-GRU	69	147	0.28	0.31	17	32

4.2.3 CNN Models

This section presents the results of utilizing CNN models, including VGG, ResNet, Inception, Xception, DenseNet, and NASNet, to predict deep-seated landslide displacement. The CNN models in this part use the default settings (Chou and Nguyen, 2023). Table 11 displays the prediction error results of the CNN models for one-day-ahead and seven-day-ahead forecasts for both E-2 and SAA stations.

The prediction results demonstrate that most CNN models produce highly accurate predictions. Specifically, predictions made by VGG, ResNet, MobileNet, DenseNet, and Inception exhibit MAPE values below 5%. Among these, MobileNet and DenseNet201 emerge as the two models with the highest accuracy. For one-day-ahead prediction, the best model for predicting displacement at the E-2 station is MobileNet, with a MAPE of 4.11%, and the best model for predicting displacement at the SAA station is DenseNet201, with a MAPE of 6.36%. For seven-day-ahead prediction, the best model for predicting displacement at the E-2 station is DenseNet201, with a MAPE of 5.3%, and the best model for predicting displacement at the SAA station is MobileNet, with a MAPE of 6.8%. These models will be selected accordingly for fine-tuning in the subsequent section.

Regarding running time, the CNN models in this section exhibit significantly longer running times compared to the numerical models in the previous sections. For example, the running time of the best CNN model to predict one-day-ahead displacement at the E-2 station—MobileNet—is 1.21 hours. In contrast, the running time of the best single numerical model for predicting this index is 159.97 seconds.

While CNN models yield better prediction results, considering their extended running times, users need to weigh practical considerations before opting for this type of model. For instance, CNN models should be employed in cases requiring accurate predictions for research and measurement purposes. Conversely, numerical models like R-GRU are more suitable for real-time predictions and computations on low-performance devices.

Table 11. Performance results of the CNN models for deep-seated displacement prediction

Model	MAPE (%)		MAE (mm)		RMSE (mm)		Time (hour)	
	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead
E-2- station								
VGG16	4.58	7.38	12.73	13.97	26.54	35.69	3.03	3.31
VGG19	4.47	6.30	12.53	15.11	25.74	32.82	3.14	2.82
ResNet50V2	4.87	7.68	15.28	12.52	31.82	27.19	2.99	3.44
ResNet101V2	4.61	6.60	9.81	9.08	34.67	32.74	2.24	2.96
ResNet152V2	4.71	6.46	7.26	12.60	21.13	19.08	2.94	2.05
InceptionV3	4.99	7.30	11.18	11.65	32.97	34.92	2.43	3.27
InceptionRestNetV2	13.32	15.78	22.51	27.08	76.75	61.11	3.22	3.08
Xception	5.27	7.34	11.60	10.20	35.86	30.68	2.94	3.29
MobileNet	**4.11**	8.92	12.22	13.62	47.43	31.72	1.21	1.44
DenseNet121	11.15	11.13	16.30	21.49	37.68	46.51	3.32	3.99
DenseNet169	4.74	7.86	11.44	12.20	17.09	36.28	3.02	3.52
DenseNet201	4.66	**5.30**	8.11	7.44	21.82	10.39	2.09	2.29
NASNetMobile	13.82	15.91	31.00	19.52	46.07	55.65	2.53	3.13
NASNetLarge	13.20	34.23	20.46	61.81	61.52	75.39	3.89	3.93
SAA- station								
VGG16	5.76	7.90	6.07	12.76	9.48	8.95	3.14	3.36
VGG19	5.95	7.32	9.14	13.45	11.68	7.03	3.55	3.20
ResNet50V2	9.87	9.35	12.43	13.81	15.71	9.75	4.57	3.83
ResNet101V2	8.48	17.68	10.56	19.36	11.47	21.94	3.54	3.40
ResNet152V2	9.43	11.42	12.32	10.35	14.91	13.27	3.35	3.88
InceptionV3	10.96	8.11	12.73	9.13	14.48	12.71	3.80	3.18
InceptionRestNetV2	9.86	11.08	13.51	16.75	18.04	21.59	3.23	2.91
Xception	7.42	7.28	7.82	7.08	10.13	10.47	3.48	3.60
MobileNet	7.12	**6.80**	8.28	9.92	11.58	13.83	1.43	2.13
DenseNet121	8.69	11.69	8.56	14.39	12.54	15.76	3.93	3.42
DenseNet169	6.55	9.56	6.16	9.61	11.08	15.51	3.60	3.76
DenseNet201	**6.36**	10.45	7.46	11.62	9.37	14.51	2.51	3.13
NASNetMobile	10.31	22.12	13.86	62.04	18.95	43.51	3.56	2.88

Model	MAPE (%)		MAE (mm)		RMSE (mm)		Time (hour)	
	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead	1-day-ahead	7-day-ahead
NASNetLarge	10.25	13.69	11.20	14.05	15.95	19.09	3.18	3.34

4.2.4 Best CNN Models Finetuned by AEIO Algorithm

In this section, as analyzed in part 4.2.3, the AEIO algorithm will sequentially fine-tune CNN models to enhance prediction accuracy. Table 12 illustrates the search range of hyperparameters for the CNN models to be fine-tuned. Table 13 presents the performance results of the CNN models after being fine-tuned.

However, a challenge in this section is that CNN models primarily analyze and learn from image data. Therefore, numerical data must be converted into image data before training. This poses a challenge because current computer hardware may need to be fully capable of efficiently converting numerical data into images for each computation. Hence, this study utilizes the optimal window sizes previously identified for fine-tuning numerical models (Table 10) for this scenario and employs these fixed window sizes for CNN models.

The results of the fine-tuning process demonstrate that the AEIO has successfully identified the optimal hyperparameters for the CNN models, enhancing their accuracy. For instance, in the case of the MobileNet model used for one-day-ahead prediction at the E-2 station, the fine-tuning process reduced the MAPE of this model from 4.11% to 2.81%. A similar trend is also observed in the remaining prediction scenarios.

Furthermore, similar to the case of AEIO-R-GRU, the CNN models exhibit the same trend, where one-day-ahead predictions are more accurate than seven-day-ahead predictions. Similarly, forecasts at the E-2 station demonstrate higher accuracy than predictions at the SAA station. The rationale for this has been explained in section 4.2.2. Lastly, the optimal hyperparameters of each CNN model, identified by the AEIO algorithm, are presented in Table 14. CNN models with optimal hyperparameters are the most effective models in this study for predicting deep-seated displacement.

Table 12. Search ranges of the hyperparameters of the optimal hybrid numerical models (Chou and Nguyen, 2023).

Hybrid model	Hyperparameter	Search range
AEIO-CNN	Learning rate	[0.00, 0.1]
	Decay	[0.00, 0.1]
	Momentum	[0.00, 0.99]

Hybrid model	Hyperparameter	Search range
	Epsilon	[1.0e-7, 0.001]
	Dropout	[0.00, 0.99]
	Epochs	[10, 120]
	Batch size	[32, 64]

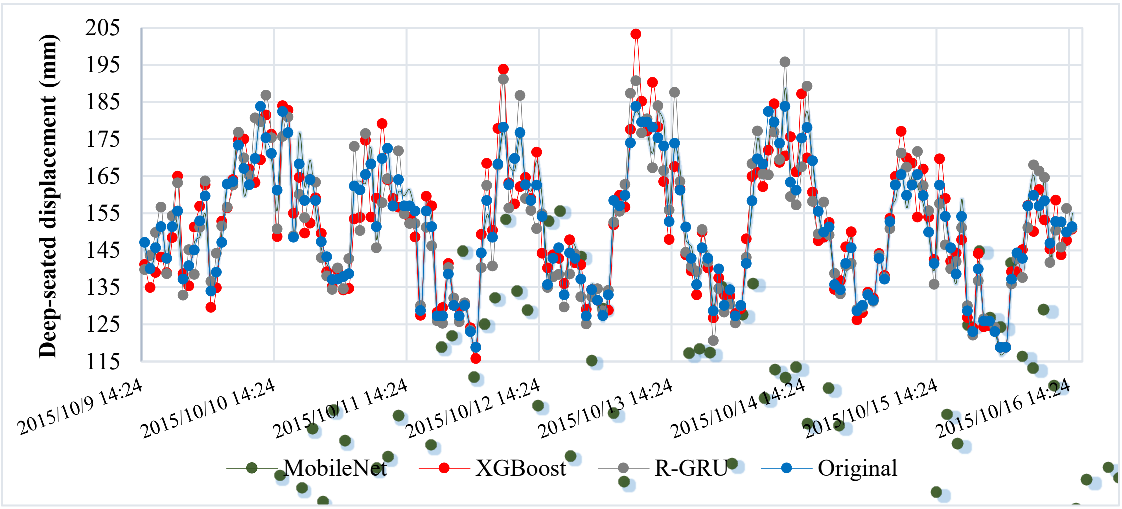
Table 13. Performance results of best CNN models with AEIO in deep-seated landslide prediction

	Model	MAPE (%)	MAE (mm)	RMSE (mm)	Time (hour)
One-day-ahead displacement prediction	**E-2-station**				
	AEIO-MobileNet	2.81	5.09	11.92	1.25
	SAA-station				
	AEIO-DenseNet201	3.30	6.32	15.65	3.48
Seven-day-ahead of displacement prediction	**E-2-station**				
	AEIO-DenseNet201	4.30	5.32	15.65	3.48
	SAA-station				
	AEIO-MobileNet	5.63	9.35	14.27	3.39

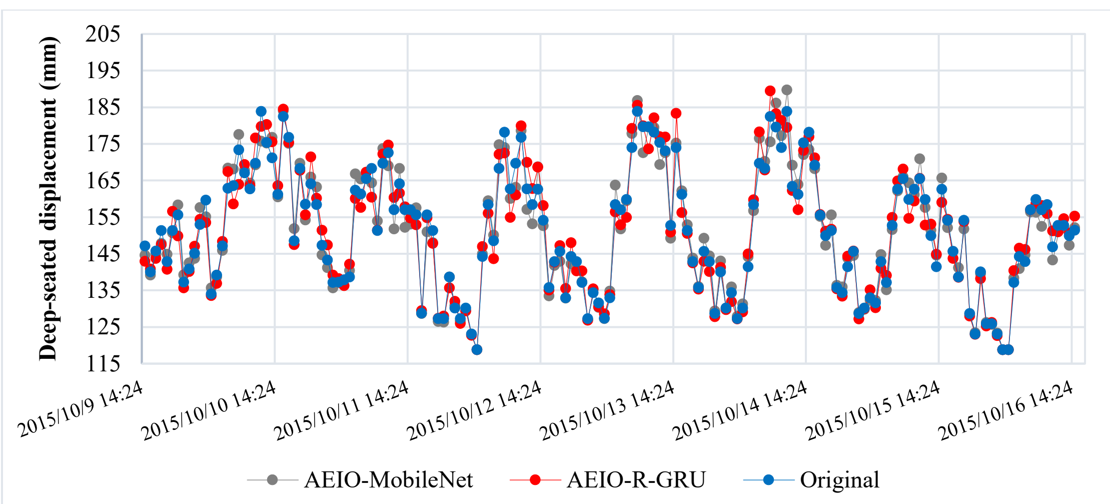
Table 14. Optimal hyperparameter of CNN models found by AEIO algorithm

	Model	Learning rate	Decay	Momentum	Epsilon	Dropout	Epochs	Batch size
One-day-ahead displacement prediction	**E-2-station**							
	AEIO-MobileNet	0.0011	0.00095	0.00001	3.0e-7	0.56	15	64
	SAA-station							
	AEIO-DenseNet201	0.00012	0.0012	0.00011	1.0e-7	0.49	16	64
Seven-day-ahead of displacement prediction	**E-2-station**							
	AEIO-DenseNet201	0.0012	0.0011	0.00022	1.0e-7	0.51	15	64
	SAA-station							
	AEIO-MobileNet	0.00014	0.00098	0.00011	2.0e-7	0.50	14	64

Figure 10 illustrates the differences between typical AI models' actual and predicted deep-seated displacement. Specifically, Figure 10a compares the performance of single models against the predicted values, while Figure 10b does the same for hybrid models. The chart shows hybrid models demonstrate superior predictive capability for deep-seated landslides compared to single models. This is evident from the displacement line of the hybrid models in Figure 10b, which closely aligns with the actual deep-seated displacement and significantly outperforms the single models depicted in Figure 10a.



a) Prediction results of deep-seated displacement by single AI models.



b) Prediction results of deep-seated displacement by AI models optimized using the AEIO algorithm.

Figure 10. Graph comparing the real and predicted deep-seated displacement.

4.3 Discussion

This study centers on landslides in Lushan Mountain, Taiwan, adopting a fundamentally different approach than previous research. While past studies primarily focused on constructing AI models for classification, calculating the probability of landslide occurrences, and generating landslide susceptibility maps (Balogun et al., 2021; Hakim et al., 2022; Jaafari et al., 2022), our study is oriented towards predicting displacement to provide warnings about potential landslide hazards.

As utilized in our calculations, computing deep-seated displacement offers several benefits. Firstly, understanding internal displacements provides accurate information for engineers to assess the resilience of structures and infrastructure in at-risk areas, facilitating the issuance of sensible warnings. Secondly, forecasting deep-seated displacement offers insights into the severity of the disaster, aiding in effective evacuation and rescue planning.

Moreover, unlike AI models in previous studies (Balogun et al., 2021; Hakim et al., 2022; Jaafari et al., 2022), our research incorporates machine learning, time series deep learning, and CNN models, utilizing metaheuristic optimization algorithms to fine-tune their hyperparameters. However, the novelty of our study lies in adopting pre-trained models, such as MobileNet, DenseNet, Inception, and VGG, rather than standard CNN models.

By employing various AI models, this study identifies the most effective model for predicting deep-seated landslides and offers a comprehensive overview of the performance of different AI models. Initially, machine learning models exhibited relatively high prediction errors, with MAPE ranging from 8.14% to 15.19%. This performance was generally lower than time-series deep learning models, which showed MAPEs ranging from 7.9% to 14.73%. The superior performance of the time series deep learning models is attributed to their ability to process sequential data and retain information from previous steps. This enables them to learn patterns from the dataset more effectively than traditional machine learning models.

However, compared to CNN models, the results of the time series deep learning models are not as strong. This disparity is attributed to CNN's superior learning mechanism. The convolutional and pooling layers in CNN enable robust feature extraction from the input data. Convolutional layers are particularly effective at identifying complex patterns and subtle features within time series data, primarily when spatial correlations exist. This capability allows CNN to uncover essential features that other models might overlook.

The models developed in this study demonstrate predictive solid capabilities for deep-seated displacement. Among them, the AEIO-MobileNet model is the most effective, achieving predictions with deficient error, indicated by a MAPE of 2.81%. However, these models' practical applicability in real-world scenarios must be improved due to the time-consuming processes involved in data collection, processing, and AI model operation, making timely predictions challenging. Meanwhile, there have been studies that successfully built real-time landslide detection systems (Wang et al., 2023; Das et al., 2020; C. et al., 2021). We acknowledge this limitation of our study. Therefore, future research endeavors will aim to address this issue.

The input data used for the AI models were selected because they significantly influence the likelihood of deep-seated landslides, as detailed in Section 3.6. However, a limitation of this study is that it does not evaluate the relative importance of each input data type on prediction accuracy. Future research should explore the impact of different combinations of input data on AI model performance. This could help identify the significance of each input type and potentially reveal the optimal combination of inputs to enhance prediction accuracy further.

5. Conclusion

This study addresses the persistent threat of landslides, a primary concern due to their severe impact on lives and property. Employing various AI models, such as machine learning, time series deep learning, CNN models, and metaheuristic optimization algorithms, the research focuses on predicting deep-seated landslides at Lushan Mountain in Ren'ai Township, Nantou County. The study aims to enhance early prediction accuracy by utilizing eight years of displacement and groundwater level data from Lushan Mountain and weather data from the POWER project. The predictions cover one-day and seven-day intervals, serving diverse purposes in landslide forecasting for timely evacuation. The research explores single and hybrid AI models to determine the most effective approach. The following conclusions are drawn from this research:

(a). CNN models optimized by the novel AEIO algorithm yield the best prediction results. In particular, AEIO-MobileNet predicts one-day-ahead displacement at the E-2 station with a MAPE score of only 2.81%, demonstrating high accuracy.

(b). While CNN models boast high prediction accuracy, their computational time is also considerable. Therefore, decisions regarding their usage should also consider real-world constraints.

(c). The AEIO-R-GRU model also yields reasonably good prediction results, although not on par with CNN models. The best result achieved by the AEIO-R-GRU model is a MAPE of 3.03% for one-day-ahead prediction at the E-2 station.

(d). The AEIO algorithm has successfully fine-tuned hyperparameters for AI models. Especially in the case of predicting one-day-ahead displacement, it has aided the MobileNet model in improving its predictive capability by 31.6%, enabling this model to provide more accurate predictions.

(e). The prediction results from the E-2 station consistently outperform those from the SAA station. This is attributed to the fact that data from the E-2 station has been collected over a longer and more comprehensive period.

(f). The study results demonstrate that AI models can accurately predict deep-seated displacement, which can be implemented in real-world scenarios.

Declare of Competing Interest

The authors declare that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

Data Availability Statement

The data and source codes supporting this study's findings are available at https://www.researchgate.net/profile/Jui-Sheng-Chou and from the corresponding author upon reasonable request.

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Author contribution

Jui-Sheng Chou: conceptualization, methodology, supervision, writing manuscript, reviewing, and editing. Hoang-Minh Nguyen: data processing, coding, and writing manuscript. Huy-Phuong Phan: Data processing, coding, and manuscript writing. Kuo-Lung Wang: data preparation, supervision, and reviewing.

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