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Discussions

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

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Abstract

Deep-seated landslides, becoming increasingly frequent due to changing climate patterns, pose significant risks to human life and infrastructure. This research contributes to developing predictive early warning systems for deep-seated slope displacements, 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 stands out for its precision in predicting 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

The 378 landslides recorded worldwide between 1997 and 2017 resulted in the deaths of 18,414 people and left 4.8 million others injured, with associated costs estimated at around USD 8 billion (Ageenko et al., 2022). 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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
Discussions

al., 2022; Hungr et al., 2014). These issues are further exacerbated in countries with complex geological and climatic conditions.

Deep-seated landslides, or gravitational deformations, involve slow movement of soil or rock at depths greater than 10m, impacting large areas and leading to significant debris flows (Dou et al., 2015). 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). Consequently, in this study, groundwater levels will serve as inputs for models designed to predict landslides.

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). In contemporary times, an increasing array of novel data-driven solutions is being developed to overcome the constraints of traditional machine-learning approaches. 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 landslides on the northern slope of Lushan Mountain in Ren'ai Township, Nantou County. The geological characteristics of this area

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Natural Hazards and Earth System Sciences
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EGU
Discussions

have undergone extensive research. 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 could assist in minimizing property loss, guiding schedule adjustments, improving work safety, and ensuring smooth traffic flow during critical periods.

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 (see Figure 1). 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. on water-induced landslides in the Three Gorges Reservoir project area highlights the significant impact of hydrological conditions on the likelihood of such disasters (Keqiang et al., 2015).

Similarly, Preisig developed a groundwater prediction model for analyzing the stability of a compound slide in the Jura Mountains (Preisig, 2020). Additionally, Srivastava et al. explored machine learning algorithms to forecast rainfall and established thresholds for landslide probabilities (Srivastava et al., 2020). 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. conducted in-depth studies on the mechanisms of landslide occurrence based on the geological conditions of the area (Lin et al., 2020). While successfully providing valuable insights into the evolution of deep-seated gravitational deformations, their research somewhat overlooked the importance of hydrological conditions and groundwater levels in landslide formation.

To address the limitations of previous landslide research in the Lushan Mountain area, this study will explore using hydrological conditions and groundwater levels as inputs for AI models to predict deep-seated displacement, thus aiding in landslide forecasting in this region.

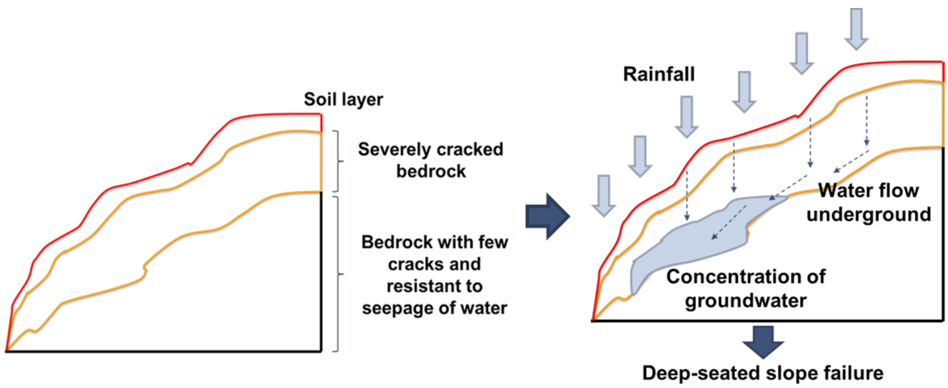

Figure 1. Schematic illustration showing the effects of groundwater on deep-seated slope failure

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 et al. 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 (Crosta and Agliardi, 2003). 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 (Xu et al., 2018).

Moreover, physical-based numerical modeling methods, which simulate phenomena at a laboratory scale, 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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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). In another study, Wu et al. employed the numerical discontinuous deformation analysis method to simulate a blocky assembly's post-failure behavior, incorporating earthquake seismic data (Wu, 2010). Meanwhile, Jiang et al. utilized fluid-solid coupling theory to simulate displacement, capturing the interaction between fluid and solid materials (Jiang et al., 2011).

Stability analysis is another commonly used method related to physics, which evaluates the forces acting on ~~a~~ slope behavior. W. Fu & Liao 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 (Fu and Liao, 2010). Subsequently, the micro-units 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). Hence, conventional methods have shown limited success in handling big data, especially in identifying highly intricate samples that require analysis of time series relationships or complex nonlinear associations.

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. employed a logistic regression model to predict landslides based on discrete data in four regions of Romania (Margarint et al., 2013). 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. utilized 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 (Pham et al., 2016). 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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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 is computationally intensive and labor-intensive, limiting its applicability when rapid forecasting is required.

Given that slope profiles and soil parameters are one-dimensional variables, 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, can be employed to uncover the relationship between slope stability and input parameters with minimal computational overhead (Fu et al., 2022). Additionally, CNN models have been used in studies of this disaster. While CNN was initially designed for image processing, its input and internal architecture are tailored for two-dimensional matrices, including the convolution kernel and feature map. To address the one-dimensional nature of slope profiles and soil physical and mechanical parameters, Pei, Meng, & Zhu developed a 1D-CNN model with dynamic inputs to account for time-varying trigger factors (Pei et al., 2021). Their approach demonstrated superior performance to conventional machine learning models regarding accuracy and robustness. However, it's worth noting that this approach has yet to gain widespread adoption.

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 landslide prediction. 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.'s study 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 (Dahal et al., 2024). 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. studied landslide susceptibility mapping in Western Serbia (Balogun et al., 2021). 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. 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 (Hakim et al., 2022). This research demonstrates that GWO and ICA effectively fine-tuned the CNN model, resulting in a highly accurate landslide susceptibility map.

Jaafari et al. 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 (Jaafari et al., 2022). 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 architecture of a typical CNN, as illustrated in Figure 2, comprises an input layer (to receive image data), followed by hidden layers (including convolutional, pooling, and fully connected layers), and concludes with the output layers. As depicted in Figure 2, the complexity of CNN progressively increases from the convolutional layer to the fully connected (FC) layer. This design enables CNN to recognize relatively simple patterns (lines, curves, etc.) before progressing to capture more intricate features (faces, objects, etc.), with the ultimate aim of extracting relevant information for accurate pattern identification.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
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Discussions

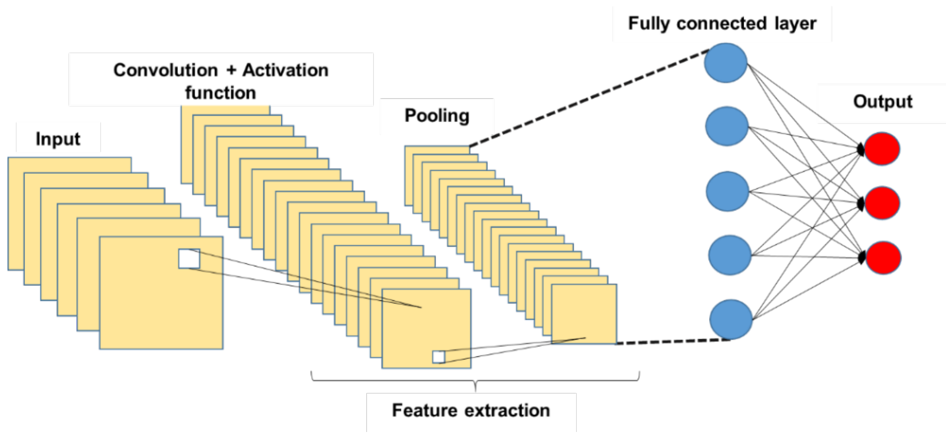

Figure 2. Structure of basic CNN.

As illustrated in Figure 3, the convolutional layer is responsible for most computations in the network. This involves extracting local features from an image using a set of learnable filters known as kernels. The behavior of the filter in the convolutional layer is influenced by two main factors: stride and padding. Stride refers to the pixel shift of the filter across the image, while padding aims to preserve information at the corners. In each iteration, a portion of the image is convolved with a filter to generate a dot product of pixels within its receptive field. This process is replicated across the entire image to produce a feature map. The convolution operation is defined as follows:

$$C_i = b_i + \sum_{j=1}^{d_i} I_j * F_{ij}\,,\ \ i = 1 \dots d_c \tag{1}$$

where C_i is the output of the convolutional layer or feature map, b_i is the bias, d_i is the depth of input, I_j is the input image, F_{ij} is the filter, and d_c is the depth of the convolutional layer.

The multiplicative operations are usually followed by an activation function (the final element in the convolutional layer), which introduces nonlinearity and creates intricate mappings between network inputs and outputs. The activation function can be defined as follows:

$$Y_i = f(C_i) \tag{2}$$

where, Y_i is the output of the convolutional layer after the activation function, and f is the activation function.

A rectified linear unit ReLU is a nonlinear CNN function with output $f(x) = max(0, x)$. A ReLU converts all negative values to zero or returns the original input values if the input exceeds zero. ReLU is only one of many activation functions; however, it has proven to be the most effective overall.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
Discussions

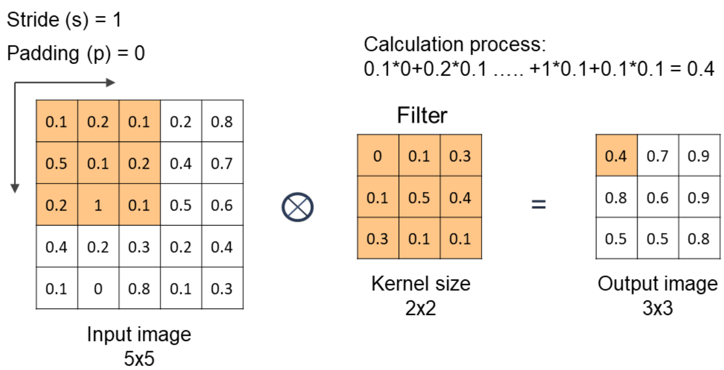

Figure 3. Processing flow in convolution layer.

Pooling layers after the convolution layer can down-sample feature maps by summarizing features within the coverage area of a 2-D filter to reduce sensitivity to feature location, thereby improving resilience to changes in the position of features. Pooling layers also decrease the dimensions of the feature map, reducing the number of parameters to be dealt with, thereby decreasing computational overhead. Output dimensions from the pooling layer are computed as follows:

$$\frac{c_w - f_w + 1}{s} * \frac{c_h - f_h + 1}{s} * c_n \quad (3)$$

where c_n is the number of channels in the feature map and $f_w * f_h$ indicate the width and height of the filter.

Max pooling and average pooling are commonly used in CNN. Max pooling accentuates salient features by selecting the maximum value within the filter's coverage area. In contrast, average pooling calculates the mean value within the exact location, providing a representative feature value. Illustrations of max pooling and average pooling are presented in Figure 4.

The final stage of a CNN comprises a series of fully connected (FC) layers. After the convolution and pooling operations, the feature map is flattened into a one-dimensional vector that connects to the FC layers, resembling an ANN. FC layers identify specific features, each represented by a neuron. In regression tasks, each neuron in the FC layer corresponds to a feature contributing to the final numerical output. The value transmitted by each neuron indicates its significance toward the regression result. FC layers are designed to predict the best continuous value for the target variable by combining and processing these neuron outputs. Figure 5 illustrates the structure of an FC layer.

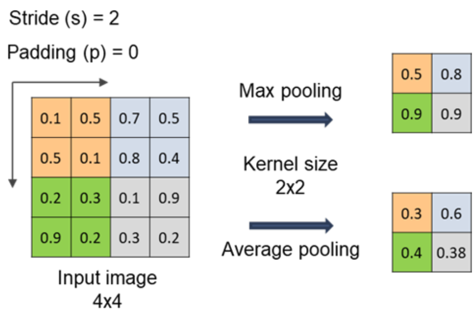

Figure 4. Max Pooling and Average Pooling.

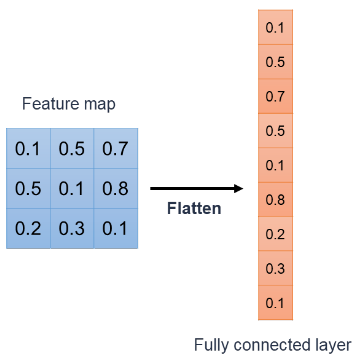

Figure 5. Structure of fully connected layer.

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., 2016), Xception (Chollet, 2016), MobileNet (Kalenichenko et al., 2017), DenseNet (Huang et al., 2017), and NASNet (Zoph et al., 2018).

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 includes an input layer, a hidden layer with a variable number of RNN cells, and an output layer designed for label identification based on future displacement values. Figure 6 illustrates the structure of simple RNNs.

Each cell in an RNN acts as a memory cell, which is interconnected to enable the sequential transfer of time-dependent input information within a sliding window. This makes it possible to consider temporal correlations between events that may be widely separated in the time dimension. The following formula presents the hidden unit of standard RNNs at time t:

$$h_t = tanh(W_x * x_t + W_h * h_{t-1} + b) \tag{4}$$

where x_t is the input vector at time t; h_t is the output vectors of hidden units for time t; W_x and W_h respectively indicate the input and interconnected weight matrices for the output of the

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

hidden layer; *b* is the bias term; and *tanh()* represents the hyperbolic tangent activation function, i.e., $tanh(x) = \frac{1-e^{2x}}{1+e^{2x}}$. RNNs are well-suited to learning time series involving short-term dependencies.

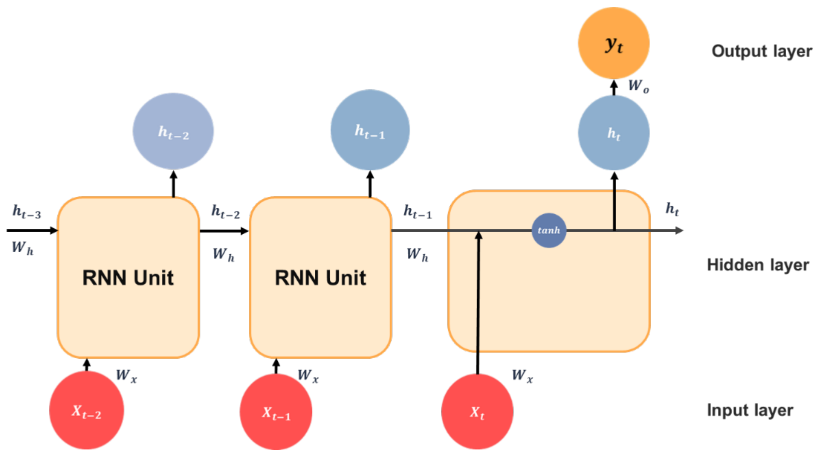

Figure 6. Structure of basic RNNs.

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 7). 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.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

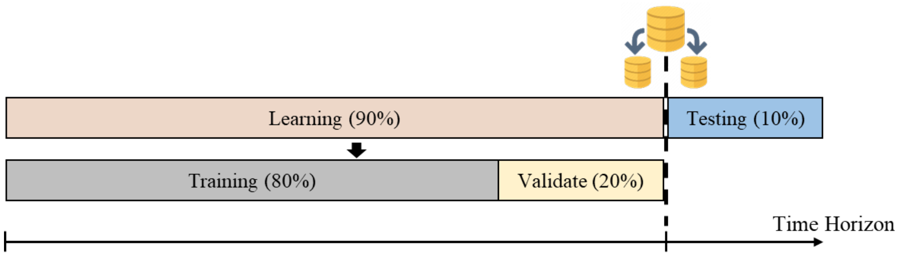

Figure 7. Data are splitting under the proposed Holdout scheme.

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).

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. Figure 8 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.

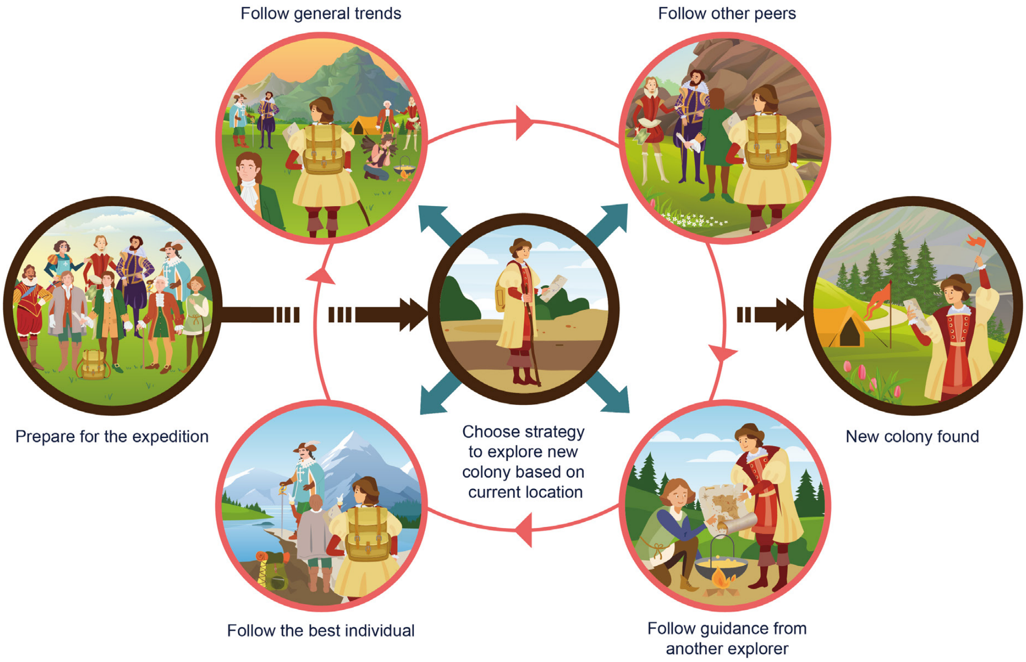

Figure 8. Illustration of Age of Exploration-Inspired Optimizer

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.

- **Explorers follow general trends**

The explorer choosing this movement type will calculate the distance from their location to the center of all other explorers, 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:

$$x_{i,d}(t+1) = x_{i,d}(t) + \alpha * \left(Meanvl_d(t) - x_{i,d}(t)\right) \times rand(0,1) \times R \tag{5}$$

$$Meanvl_d(t) = \frac{x_{1,d}(t)+x_{2,d}(t)+\cdots+x_{n_{Pop},d}(t)}{n_{Pop}} \tag{6}$$

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. $R = round(1 + rand(0,1) \times 1)$

- **Explorers follow three other peers**

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
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Discussions

Explorers employing this movement method will calculate the average position of three randomly selected other explorers and then move toward this newly calculated average position. The explorer's new position is computed using the following formula:

$$x_{i,d}(t+1) = x_{i,d}(t) + \left(\frac{x_{1,d}(t)+x_{2,d}(t)+x_{3,d}(t)}{3} - x_{i,d}(t)\right) \times rand(0,1) \times R \tag{7}$$

where: $x_{1,d}(t)$, $x_{2,d}(t)$ and $x_{3,d}(t)$ are three random explorers in dimension *d* at iteration *t*.

- **Explorers follow the best one**

According to this strategy, the explorer will move closer to the position of another explorer currently holding the best position, as determined by the following formula:

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

where: $Best_d(t)$ represents the position of the particle with the best fitness in dimension d at iteration t.

- **Explorers follow guidance from another one**

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

$$x_{i,d}(t+1) = x_{i,d}(t) + \left(Best_d(t) - x_{1,d}(t)\right) \times rand(0,1) \times R \tag{9}$$

- **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:

$$\varepsilon_d = \left(0.1 + \frac{t}{MaxIt}\right) \times (Meanvl_d(t) - Best_d(t)) \tag{10}$$

$$MinPts = round\left(1 + \frac{t}{MaxIt} \times 10\right) \tag{11}$$

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 9 presents a flowchart illustrating the process by which the AEIO algorithm aids in fine-tuning hyperparameters for AI models.

3.6 Experiment Setup

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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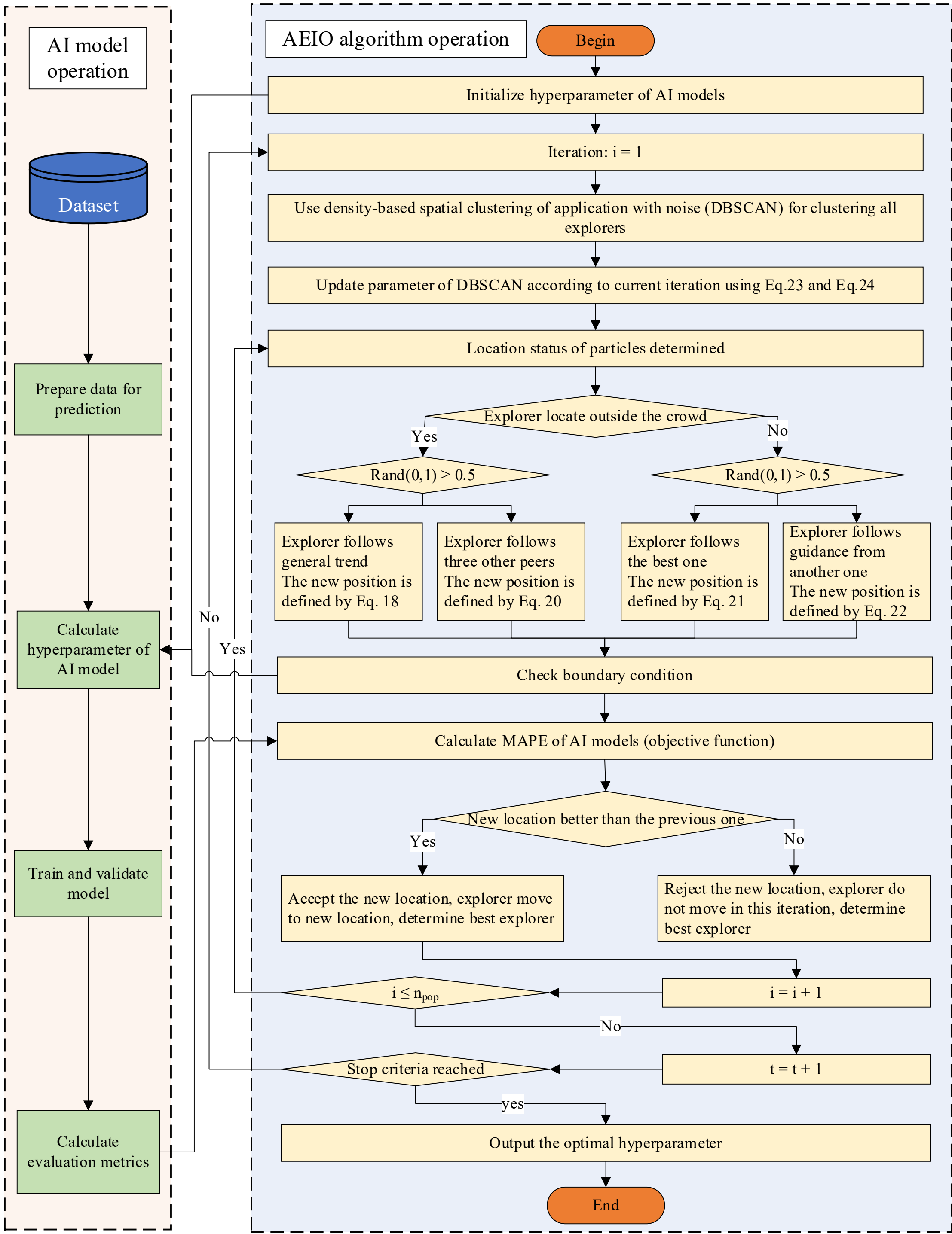

384

385 Figure 9. Flowchart of the fine-tuning process of AI models by the AEIO algorithm

386 **3.6.1 Research Area**

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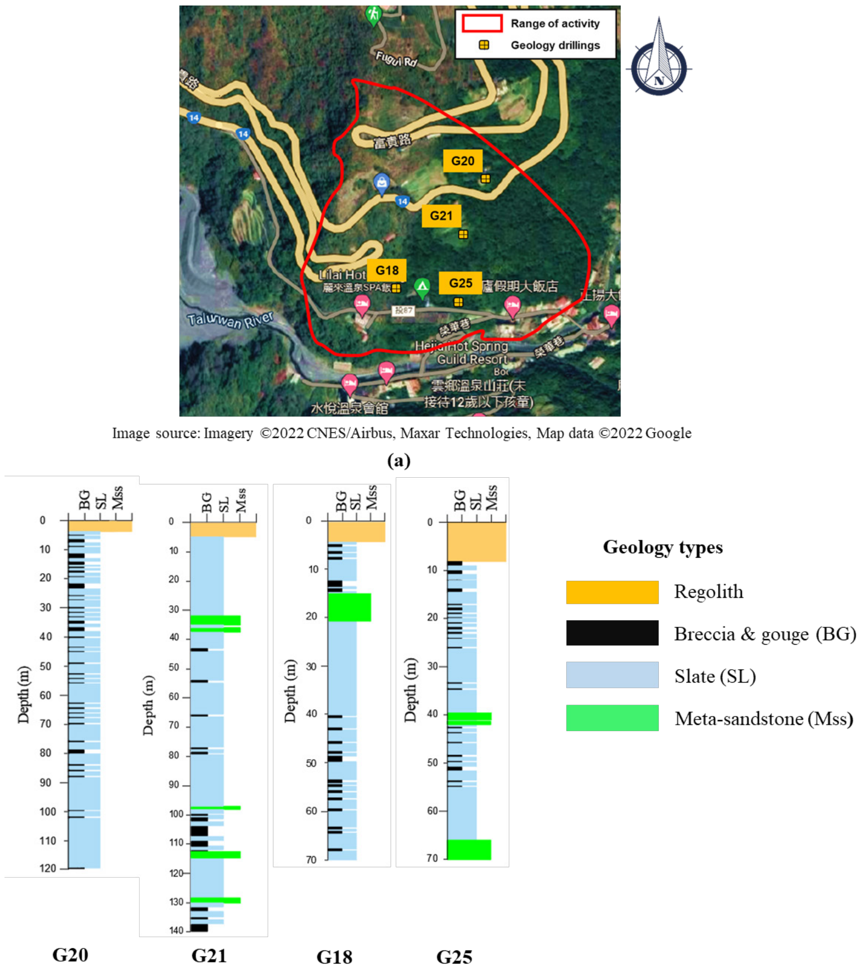
Preprint. Discussion started: 10 June 2024



(b)

Figure 10. Illustration of (a) research location and (b) geological drilling survey

The current study focuses on the northern slope of Lushan hot spring in Ren'ai Township, Nantou County (Figure 10a), 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. (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 10b 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.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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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 cleavages that have recently undergone flexural folding along the eastern boundary. Notably, horizontal cleavages near the toe region also exhibit inter-cleavage gouges. 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 11.

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. in 2023 (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.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

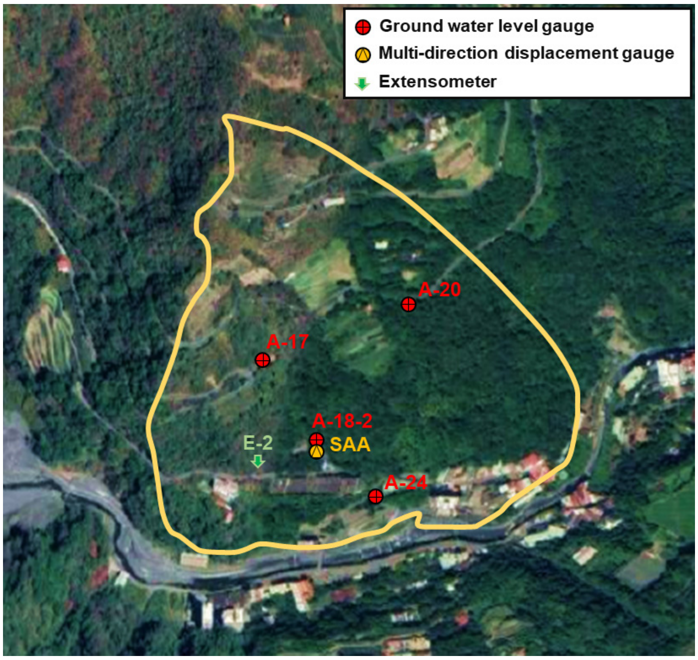

Image source: Imagery ©2022 CNES/Airbus, Maxar Technologies, Map data ©2022 Google

Figure 11. Locations of measurement devices

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 (year/month/day/hour: minute)**	**Rain end time (year/month/day/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

No.	Rain onset (year/month/day/hour: minute)	Rain end time (year/month/day/hour: minute)	Accumulating rainfall (mm)	Drop rain hour (hr)	Event
3	9/282008 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 variations in displacement (Figure 12 and Figure 13) and groundwater levels (Figure 14) over time have been plotted.

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Preprint. Discussion started: 10 June 2024

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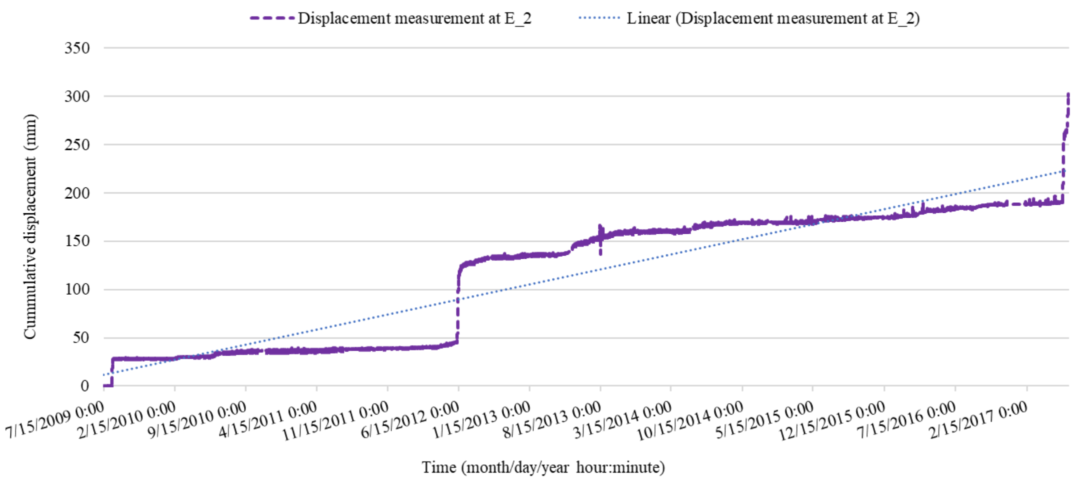

Figure 12. Time series data indicating measured displacements from extensometer E_2

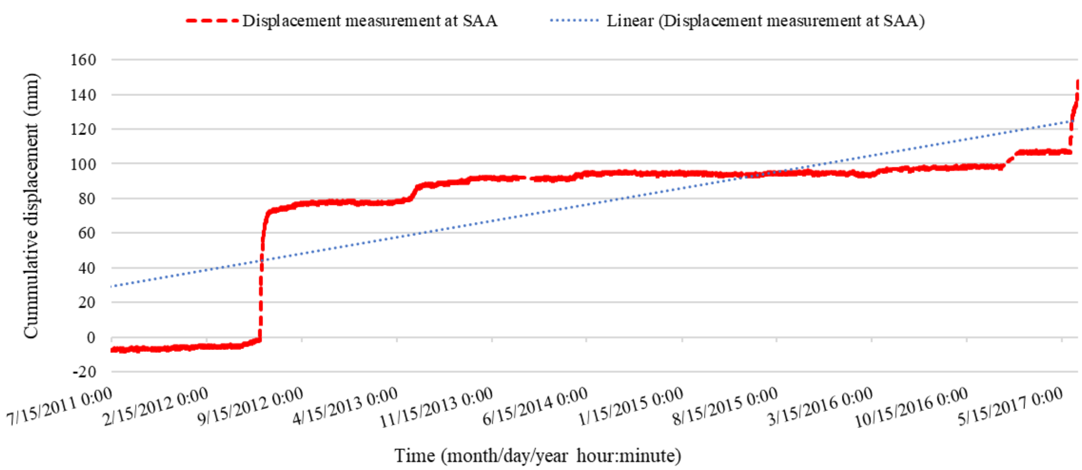

Figure 13. Time series data indicating measured displacements from extensometer SAA

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Preprint. Discussion started: 10 June 2024

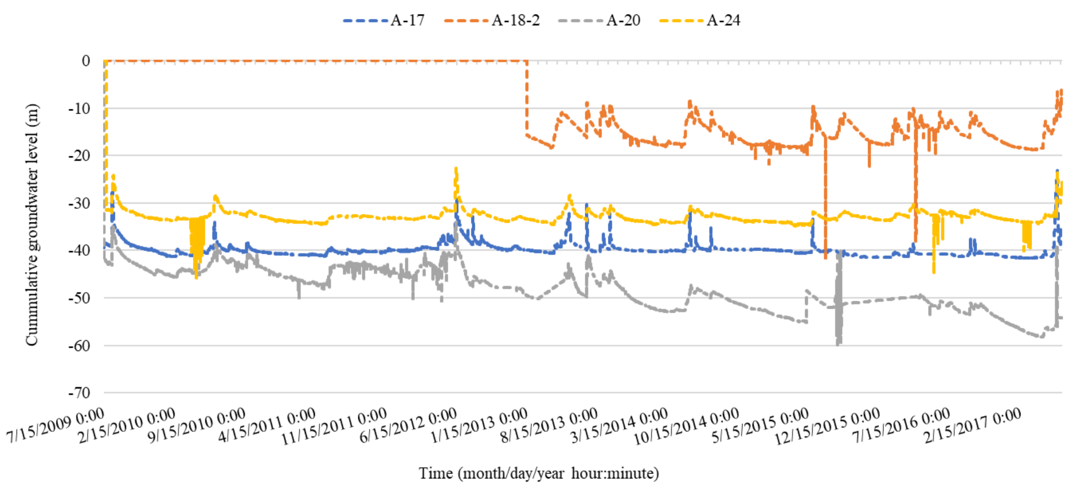

Figure 14. Groundwater levels at stations A-17, A-18-2, A-20, and A-24

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 August 6, 2012, to August 17, 2012, totaling 1029 mm over 219 hours (as indicated in Table 2). 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 12 and Figure 13.

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. These factors significantly impact the soil structure and can trigger substantial displacement or landslides. 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.

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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 (ºC)	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).

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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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 15. 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.

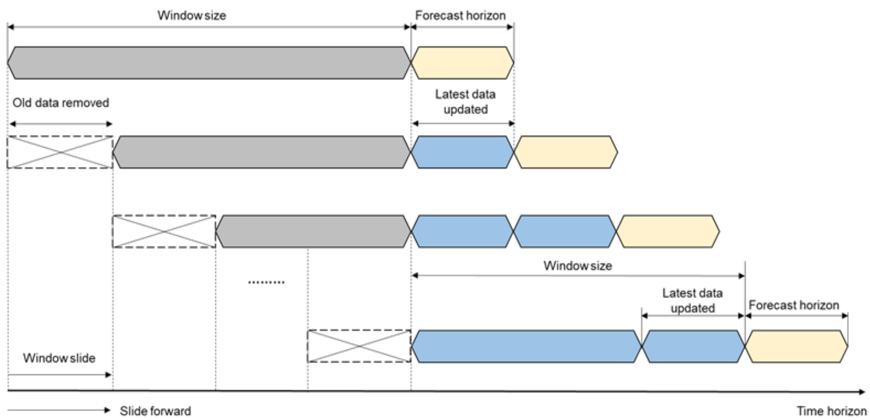

Figure 15. Sliding window technique

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.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Classification of the displacement value	Attention value	Warning value	Action value
Corresponding displacement value	2 mm/month	0.5 mm/day	10 mm/day
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 landslides 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 16. 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.

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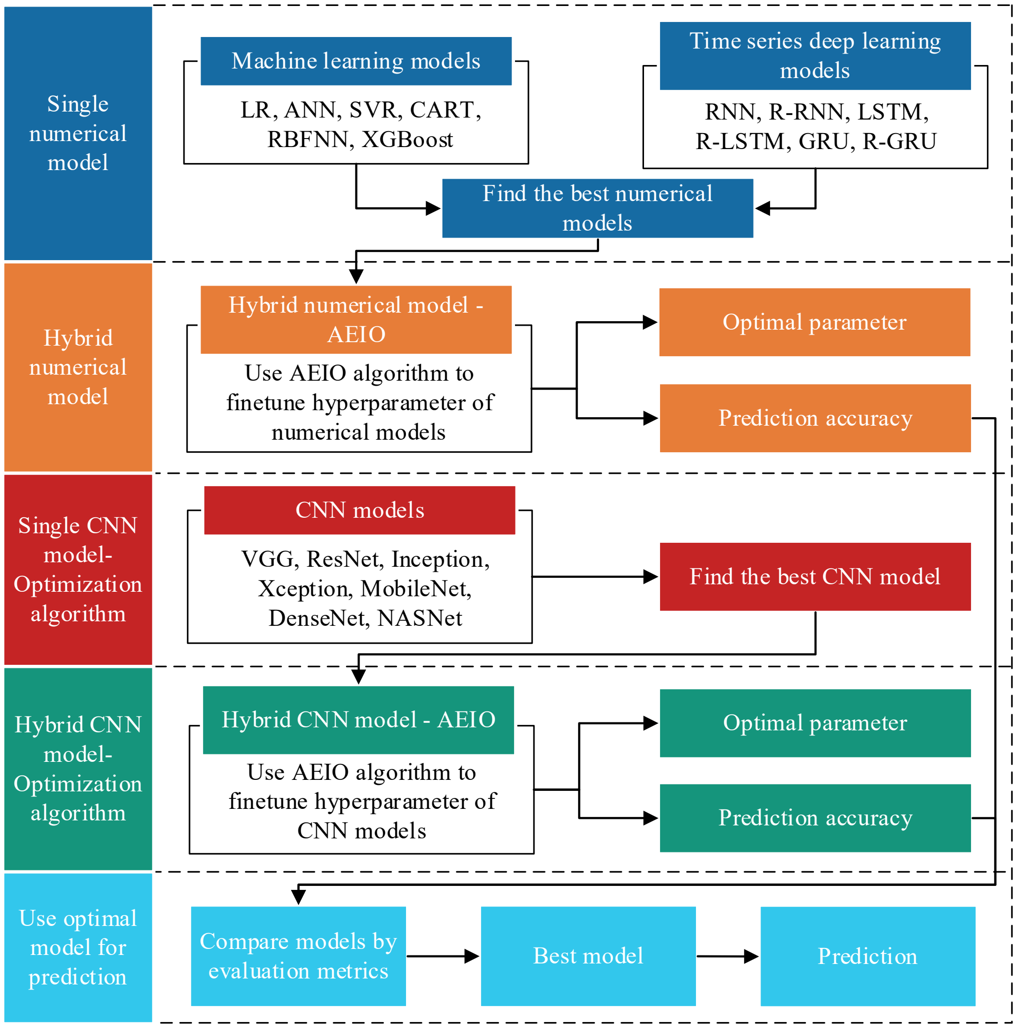

Figure 16. Diagram depicting the steps of choosing the optimal AI model to predict deep-seated landslide

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

This section will present the experimental results of the steps outlined in Figure 16, 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 Chou and Nguyen's research in 2023 (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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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. The following section will compare this model with the best time series deep learning model to select the optimal numerical model for fine-tuning.

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 Chou and Nguyen's research in 2023 (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. R-GRU will undergo fine-tuning in the following section using the AEIO algorithm, further enhancing this model's accuracy.

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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-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
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 landslides. 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. All other predictions similarly show a decreasing trend.

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.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

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

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
Open Access
EGU
Discussions

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
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
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. Compared to models in previous sections, CNN models with optimal hyperparameters obtained in this section exhibit the most minor errors, indicating that these are the most effective models in this study for predicting landslide occurrences.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences Discussions

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]
	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
	E-2-station							

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

	Model	Learning rate	Decay	Momentum	Epsilon	Dropout	Epochs	Batch size
Seven-day-ahead of displacement prediction	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

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 conventional CNN models. The practicality of employing these pre-trained models has demonstrated effectiveness in predicting displacement in this research.

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.

5. Conclusion and Recommendations

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences Discussions

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.

References

Ageenko, A., Hansen, L. C., Lyng, K. L., Bodum, L., and Arsanjani, J. J.: Landslide Susceptibility Mapping Using Machine Learning: A Danish Case Study, Isprs Int J Geo-Inf, 11, https://doi.org/10.3390/ijgi11060324, 2022.

Aggarwal, A., Alshehri, M., Kumar, M., Alfarraj, O., Sharma, P., and Pardasani, K. R.: Landslide data analysis using various time-series forecasting models, Comput Electr Eng, 88, https://doi.org/10.1016/j.compeleceng.2020.106858, 2020.

Alzubaidi, L., Zhang, J., Humaidi, A. J., Al-Dujaili, A., Duan, Y., Al-Shamma, O., Santamaría, J., Fadhel, M. A., Al-Amidie, M., and Farhan, L.: Review of deep learning: concepts, CNN architectures, challenges, applications, future directions, Journal of Big Data, 8, 53, https://doi.org/10.1186/s40537-021-00444-8, 2021.

Balogun, A. L., Rezaie, F., Pham, Q. B., Gigovic, L., Drobnjak, S., Aina, Y. A., Panahi, M., Yekeen, S. T., and Lee, S.: Spatial prediction of landslide susceptibility in western Serbia using hybrid support vector regression (SVR) with GWO, BAT and COA algorithms, Geosci Front, 12, https://doi.org/10.1016/j.gsf.2020.10.009, 2021.

Breiman, L.: Classification and Regression Trees, Taylor & Francis Group, New York, https://doi.org/10.1201/9781315139470, 1984.

C., P., R., A., Kanwar, V. S., and B., N.: Design and Development of Real-time landslide early warning system through low cost soil and rainfall sensors, Materials Today: Proceedings, 45, 5649-5654, https://doi.org/10.1016/j.matpr.2021.02.456, 2021.

Caleca, F., Scaini, C., Frodella, W., and Tofani, V.: Regional-scale landslide risk assessment in Central Asia, Nat Hazard Earth Sys, 24, 13-27, https://doi.org/10.5194/nhess-24-13-2024, 2024.

Chae, B.-G., Park, H. J., Catani, F., Simoni, A., and Berti, M.: Landslide prediction, monitoring and early warning: a concise review of state-of-the-art, Geosciences Journal, 21, 1033-1070, https://doi.org/10.1007/s12303-017-0034-4, 2017.

Chen;, T. and Guestrin, C.: XGBoost: A Scalable Tree Boosting System, In Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining, New York, NY, USA, 785–794, https://doi.org/10.1145/2939672.2939785, 2016.

Chollet, F.: Xception: Deep Learning with Depthwise Separable Convolutions, 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Honolulu, HI, USA, July 21 2017, https://doi.org/10.48550/arXiv.1610.02357, 2017.

Chou, J. S. and Ngo, N. T.: Time series analytics using sliding window metaheuristic optimization-based machine learning system for identifying building energy consumption patterns, Appl Energ, 177, 751-770, https://doi.org/10.1016/j.apenergy.2016.05.074, 2016.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences
Open Access
Discussions

Chou, J. S. and Nguyen, N. Q.: Forecasting Regional Energy Consumption via Jellyfish Search-Optimized Convolutional-Based Deep Learning, Int J Energ Res, Volume 2023, https://doi.org/10.1155/2023/3056688, 2023.

Corominas, J., van Westen, C., Frattini, P., Cascini, L., Malet, J. P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F., Pitilakis, K., Winter, M. G., Pastor, M., Ferlisi, S., Tofani, V., Hervás, J., and Smith, J. T.: Recommendations for the quantitative analysis of landslide risk, Bulletin of Engineering Geology and the Environment, 73, 209-263, https://doi.org/10.1007/s10064-013-0538-8, 2014.

Cotecchia, F., Santaloia, F., and Tagarelli, V.: Towards A Geo-Hydro-Mechanical Characterization of Landslide Classes: Preliminary Results, Applied Sciences, 10, https://doi.org/10.3390/app10227960, 2020.

Crosta, G. B. and Agliardi, F.: Failure forecast for large rock slides by surface displacement measurements, Canadian Geotechnical Journal, 40, 176-191, https://doi.org/10.1139/t02-085, 2003.

Dahal, A., Tanyas, H., Westen, C. v., Meijde, M. v. d., Mai, P. M., Huser, R., and Lombardo, L.: Space–time landslide hazard modeling via Ensemble Neural Networks, Nat Hazard Earth Sys, 24, 823-845, https://doi.org/10.5194/nhess-24-823-2024, 2024.

Das, K., Majumdar, S., Moulik, S., and Fujita, M.: Real-Time Threshold-based Landslide Prediction System for Hilly Region using Wireless Sensor Networks, 2020 IEEE International Conference on Consumer Electronics - Taiwan (ICCE-Taiwan), Taoyuan, Taiwan, https://doi.org/10.1109/ICCE-Taiwan49838.2020.9258181, 2020.

Das, S., Sarkar, S., and Kanungo, D. P.: Rainfall-induced landslide (RFIL) disaster in Dima Hasao, Assam, Northeast India, Landslides, 19, 2801-2808, https://doi.org/10.1007/s10346-022-01962-z, 2022.

Di Nunno, F., de Marinis, G., and Granata, F.: Short-term forecasts of streamflow in the UK based on a novel hybrid artificial intelligence algorithm, Scientific Reports, 13, 7036, https://doi.org/10.1038/s41598-023-34316-3, 2023.

Dou, J., Paudel, U., Oguchi, T., Uchiyama, S., and Hayakawa, Y. S.: Shallow and Deep-Seated Landslide Differentiation Using Support Vector Machines: A Case Study of the Chuetsu Area, Japan, Terr Atmos Ocean Sci, 26, 227-239, https://doi.org/10.3319/Tao.2014.12.02.07(Eosi), 2015.

Drucker, H., Burges, C. J. C., Kaufman, L., Smola, A., and Vapnik, V.: Support vector regression machines, NIPS'96: Proceedings of the 9th International Conference on Neural Information Processing Systems, 155-161, 1996.

Elman, J. L.: Finding Structure in Time, Cognitive Sci, 14, 179-211, https://doi.org/10.1016/0364-0213(90)90002-E, 1990.

Fu, W. X. and Liao, Y.: Non-linear shear strength reduction technique in slope stability calculation, Comput Geotech, 37, 288-298, https://doi.org/10.1016/j.compgeo.2009.11.002, 2010.

Fu, Y., Lin, M., Zhang, Y., Chen, G., and Liu, Y.: Slope stability analysis based on big data and convolutional neural network, Frontiers of Structural and Civil Engineering, 16, 882-895, https://doi.org/10.1007/s11709-022-0859-4, 2022.

Hakim, W. L., Rezaie, F., Nur, A. S., Panahi, M., Khosravi, K., Lee, C. W., and Lee, S.: Convolutional neural network (CNN) with metaheuristic optimization algorithms for landslide susceptibility mapping in Icheon, South Korea, J Environ Manage, 305, https://doi.org/10.1016/j.jenvman.2021.114367, 2022.

Han, H. G., Chen, Q. L., and Qiao, J. F.: Research on an online self-organizing radial basis function neural network, Neural Comput Appl, 19, 667-676, https://doi.org/10.1007/s00521-009-0323-6, 2010.

https://doi.org/10.5194/nhess-2024-86
Preprint. Discussion started: 10 June 2024

Natural Hazards and Earth System Sciences Discussions

Han, J., Kamber, M., and Pei, J.: Data Mining: Concepts and Techniques, Southeast Asia Edition, Morgan Kaufmann Publishers Inc., San Francisco, CA, United States, 696 pp., https://doi.org/10.1016/C2009-0-61819-5, 2006.

He, K., Zhang, X., Ren, S., and Sun, J.: Deep Residual Learning for Image Recognition, 2016 IEEE Conference on Computer Vision and Pattern Recognition, https://doi.org/10.48550/arXiv.1512.03385, 2016.

Hu, B., Su, G., Jiang, J., Sheng, J., and Li, J.: Uncertain Prediction for Slope Displacement Time-Series Using Gaussian Process Machine Learning, Ieee Access, PP, 1-1, https://doi.org/10.1109/ACCESS.2019.2894807, 2019.

Hu, X. L., Wu, S. S., Zhang, G. C., Zheng, W. B., Liu, C., He, C. C., Liu, Z. X., Guo, X. Y., and Zhang, H.: Landslide displacement prediction using kinematics-based random forests method: A case study in Jinping Reservoir Area, China, Eng Geol, 283, https://doi.org/10.1016/j.enggeo.2020.105975, 2021.

Huang, G., Liu, Z., Maaten, L. v. d., and Weinberger, K. Q.: Densely Connected Convolutional Networks, 2017 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), https://doi.org/10.1109/CVPR.2017.243, 2017.

Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11, 167-194, https://doi.org/10.1007/s10346-013-0436-y, 2014.

Jaafari, A., Jaafari, A., Panahi, M., Panahi, M., Mafi-Gholami, D., Mafi-Gholami, D., Rahmati, O., Rahmati, O., Shahabi, H., Shahabi, H., Shirzadi, A., Shirzadi, A., Lee, S., Lee, S., Bui, D. T., Bui, D. T., Pradhan, B., and Pradhan, B.: Swarm intelligence optimization of the group method of data handling using the cuckoo search and whale optimization algorithms to model and predict landslides, Appl Soft Comput, 116, https://doi.org/10.1016/j.asoc.2021.108254, 2022.

Jiang, J., Ehret, D., Xiang, W., Rohn, J., Huang, L., Yan, S., and Bi, R.: Numerical simulation of Qiaotou Landslide deformation caused by drawdown of the Three Gorges Reservoir, China, Environmental Earth Sciences, 62, 411-419, https://doi.org/10.1007/s12665-010-0536-0, 2011.

Jones, J. N., Bennett, G. L., Abanco, C., Matera, M. A. M., and Tan, F. J.: Multi-event assessment of typhoon-triggered landslide susceptibility in the Philippines, Nat Hazard Earth Sys, 23, 1095-1115, https://doi.org/10.5194/nhess-23-1095-2023, 2023.

Kalenichenko, A. G. H. M. Z. B. C. D., Wang, W., Weyand, T., Andreetto, M., and Adam, H.: MobileNets: Efficient Convolutional Neural Networks for Mobile Vision Applications, CoRR, abs/1704.04861, https://doi.org/10.48550/arXiv.1704.04861, 2017.

Keqiang, H., Zhiliang, W., Xiaoyun, M., and Zengtao, L.: Research on the displacement response ratio of groundwater dynamic augment and its application in evaluation of the slope stability, Environmental Earth Sciences, 74, 5773-5791, https://doi.org/10.1007/s12665-015-4595-0, 2015.

Lau, Y. M., Wang, K. L., Wang, Y. H., Yiu, W. H., Ooi, G. H., Tan, P. S., Wu, J., Leung, M. L., Lui, H. L., and Chen, C. W.: Monitoring of rainfall-induced landslides at Songmao and Lushan, Taiwan, using IoT and big data-based monitoring system, Landslides, 20, 271-296, https://doi.org/10.1007/s10346-022-01964-x, 2023.

Lee, Y. F. and Chi, Y. Y.: Rainfall-induced landslide risk at Lushan, Taiwan, Eng Geol, 123, 113-121, https://doi.org/10.1016/j.enggeo.2011.03.006, 2011.

Li, H., Xu, Q., He, Y., and Deng, J.: Prediction of landslide displacement with an ensemble-based extreme learning machine and copula models, Landslides, 15, 2047-2059, https://doi.org/10.1007/s10346-018-1020-2, 2018.

Lin, H. H., Lin, M. L., Lu, J. H., Chi, C. C., and Fei, L. Y.: Deep-seated gravitational slope deformation in Lushan, Taiwan: Transformation from cleavage-controlled to weakened rockmass-controlled deformation, Eng Geol, 264, https://doi.org/10.1016/j.enggeo.2019.105387, 2020.

Liu, C. Y., Jiang, Z. S., Han, X. S., and Zhou, W. X.: Slope displacement prediction using sequential intelligent computing algorithms, Measurement, 134, 634-648, https://doi.org/10.1016/j.measurement.2018.10.094, 2019.

Margarint, M. C., Grozavu, A., and Patriche, C. V.: Assessing the spatial variability of coefficients of landslide predictors in different regions of Romania using logistic regression, Nat Hazard Earth Sys, 13, 3339-3355, https://doi.org/10.5194/nhess-13-3339-2013, 2013.

McCulloch, W. and Pitts, A.: A Logical Calculus of the Ideas Immanent in Nervous Activity (1943), Ideas That Created the Future, 79-88, https://doi.org/10.1007/BF02478259, 2021.

Miao, H. B. and Wang, G. H.: Prediction of landslide velocity and displacement from groundwater level changes considering the shear rate-dependent friction of sliding zone soil, Eng Geol, 327, https://doi.org/10.1016/j.enggeo.2023.107361, 2023.

Millán-Arancibia, C. and Lavado-Casimiro, W.: Rainfall thresholds estimation for shallow landslides in Peru from gridded daily data, Nat Hazard Earth Sys, 23, 1191-1206, https://doi.org/10.5194/nhess-23-1191-2023, 2023.

Mufundirwa, A., Fujii, Y., and Kodama, J.: A new practical method for prediction of geomechanical failure-time, Int J Rock Mech Min, 47, 1079-1090, https://doi.org/10.1016/j.ijrmms.2010.07.001, 2010.

Pei, H., Meng, F., and Zhu, H.: Landslide displacement prediction based on a novel hybrid model and convolutional neural network considering time-varying factors, Bulletin of Engineering Geology and the Environment, 80, 7403-7422, https://doi.org/10.1007/s10064-021-02424-x, 2021.

Perkins, J. P., Oakley, N. S., Collins, B. D., Corbett, S. C., and Burgess, W. P.: Characterizing the scale of regional landslide triggering from storm hydrometeorology, Nat Hazard Earth Sys, https://doi.org/10.5194/egusphere-2024-873, 2024.

Peternel, T., Janža, M., Šegina, E., Bezak, N., and Maček, M.: Recognition of Landslide Triggering Mechanisms and Dynamics Using GNSS, UAV Photogrammetry and In Situ Monitoring Data, Remote Sensing, 14, https://doi.org/10.3390/rs14143277, 2022.

Petley, D. N., Mantovani, F., Bulmer, M. H., and Zannoni, A.: The use of surface monitoring data for the interpretation of landslide movement patterns, Geomorphology, 66, 133-147, https://doi.org/10.1016/j.geomorph.2004.09.011, 2005.

Pham, B. T., Pradhan, B., Bui, D. T., Prakash, I., and Dholakia, M. B.: A comparative study of different machine learning methods for landslide susceptibility assessment: A case study of Uttarakhand area (India), Environ Modell Softw, 84, 240-250, https://doi.org/10.1016/j.envsoft.2016.07.005, 2016.

Preisig, G.: Forecasting the long-term activity of deep-seated landslides via groundwater flow and slope stability modelling, Landslides, 17, 1693-1702, https://doi.org/10.1007/s10346-020-01427-1, 2020.

Ruitang, L., Zhaowei, C., Zexiong, W., Zhenghan, Z., Jiahao, L., Zhencheng, G., and Yuchong, C.: Mountain Slope Monitoring Guidelines (TGS-SLOPEM106), 2017.

Simonyan, K. and Zisserman, A.: Very Deep Convolutional Networks for Large-Scale Image Recognition, ICLR2015, https://doi.org/10.48550/arXiv.1409.1556, 2015.

Srivastava, S., Anand, N., Sharma, S., Dhar, S., and Sinha, L. K.: Monthly Rainfall Prediction Using Various Machine Learning Algorithms for Early Warning of Landslide Occurrence, 2020 International Conference for Emerging Technology (INCET), Belgaum, India, 5-7 June 2020, 1-7, https://doi.org/10.1109/INCET49848.2020.9154184, 2020.

https://doi.org/10.5194/nhess-2024-86
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Stanton, J. M.: Galton, Pearson, and the Peas: A Brief History of Linear Regression for Statistics Instructors, Journal of Statistics Education, 9, https://doi.org/10.1080/10691898.2001.11910537, 2001.

Szegedy, C., Vanhoucke, V., Ioffe, S., Shlens, J., and Wojna, Z.: Rethinking the Inception Architecture for Computer Vision, 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 27-30 June 2016, 2818-2826, https://doi.org/10.1109/CVPR.2016.308, 2016.

Thai Pham, B., Shirzadi, A., Shahabi, H., Omidvar, E., Singh, S. K., Sahana, M., Talebpour Asl, D., Bin Ahmad, B., Kim Quoc, N., and Lee, S.: Landslide Susceptibility Assessment by Novel Hybrid Machine Learning Algorithms, Sustainability-Basel, 11, https://doi.org/10.3390/su11164386, 2019.

van Natijne, A. L., Bogaard, T. A., Zieher, T., Pfeiffer, J., and Lindenbergh, R. C.: Machine-learning-based nowcasting of the Vögelsberg deep-seated landslide: why predicting slow deformation is not so easy, Nat Hazard Earth Sys, 23, 3723-3745, https://doi.org/10.5194/nhess-23-3723-2023, 2023.

Wang, Y., Dong, J., Zhang, L., Deng, S. H., Zhang, G. K., Liao, M. S., and Gong, J. Y.: Automatic detection and update of landslide inventory before and after impoundments at the Lianghekou reservoir using Sentinel-1 InSAR, Int J Appl Earth Obs, 118, https://doi.org/10.1016/j.jag.2023.103224, 2023.

Wu, J. H.: Seismic landslide simulations in discontinuous deformation analysis, Comput Geotech, 37, 594-601, https://doi.org/10.1016/j.compgeo.2010.03.007, 2010.

Xu, J., Jiang, Y., and Yang, C.: Landslide Displacement Prediction during the Sliding Process Using XGBoost, SVR and RNNs, Applied Sciences, 12, https://doi.org/10.3390/app12126056, 2022.

Xu, J., Li, H., Du, K., Yan, C., Zhao, X., Li, W., and Xu, X.: Field investigation of force and displacement within a strata slope using a real-time remote monitoring system, Environmental Earth Sciences, 77, 552, https://doi.org/10.1007/s12665-018-7729-3, 2018.

Yang, B., Yin, K., Lacasse, S., and Liu, Z.: Time series analysis and long short-term memory neural network to predict landslide displacement, Landslides, 16, https://doi.org/10.1007/s10346-018-01127-x, 2019.

Yang, S., Jin, A., Nie, W., Liu, C., and Li, Y.: Research on SSA-LSTM-Based Slope Monitoring and Early Warning Model, Sustainability-Basel, 14, https://doi.org/10.3390/su141610246, 2022.

Zhang, L., Shi, B., Zhu, H., Yu, X. B., Han, H., and Fan, X.: PSO-SVM-based deep displacement prediction of Majiagou landslide considering the deformation hysteresis effect, Landslides, 18, 179-193, https://doi.org/10.1007/s10346-020-01426-2, 2021.

Zhang, W., Li, H., Tang, L., Gu, X., Wang, L., and Wang, L.: Displacement prediction of Jiuxianping landslide using gated recurrent unit (GRU) networks, Acta Geotechnica, 17, 1367-1382, https://doi.org/10.1007/s11440-022-01495-8, 2022.

Zhang, W. G., Zhang, R. H., Wu, C. Z., Goh, A. T. C., Lacasse, S., Liu, Z. Q., and Liu, H. L.: State-of-the-art review of soft computing applications in underground excavations, Geosci Front, 11, 1095-1106, https://doi.org/10.1016/j.gsf.2019.12.003, 2020.

Zhou, C., Yin, K., Cao, Y., Ahmed, B., and Fu, X.: A novel method for landslide displacement prediction by integrating advanced computational intelligence algorithms, Scientific Reports, 8, 7287, https://doi.org/10.1038/s41598-018-25567-6, 2018.

Zoph, B., Vasudevan, V., Shlens, J., and Le, Q. V.: Learning Transferable Architectures for Scalable Image Recognition, 2018 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), https://doi.org/10.1109/CVPR.2018.00907, 2018.