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Article

Study on Soil–Reinforcement Interaction and Field Performance of Reinforced Soil Walls for Geotechnical Applications Using Computer Applications and Artificial Intelligence

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Abstract: In geotechnical engineering reinforced soil walls have proven to be a viable means of increasing slopes' stability and retaining structures. This study examines the soil-reinforcement interactions and field performance of soil-reinforced walls thru the use of numerical analysis, computational tools, and artificial intelligence (AI). The methodology proposed assesses horizontal displacement, settlement, and tensile force, strain of reinforcement, pullout resistance and factor of safety for various load conditions. Three AI models are created to predict the behavior of the wall, namely "Artificial Neural Network (ANN)", "Random Forest (RF)", and "Extreme Gradient Boosting (XGBoost)". The ANN model results in a high coefficient of determination (R2 = 0.98) with a value of MAE and RMSE of 1.21 mm and 1.68 mm respectively, whereas the training and validation harms were equal to 0.0021 and 0.0032 respectively. XGBoost model had the highest prediction accuracy of 98.6%, whereas ANN and RF models had prediction accuracy of 97.9% and 95.8%, respectively, while all other models had prediction accuracy less than 97.3%. The results show the ability of AI based computer applications to predict soil–reinforcement interaction with reliability and their ability to improve the design, stability analysis and field performance assessment of reinforced soil barriers.
Keywords: Reinforced Soil Walls; Soil–Reinforcement Interaction; Artificial Intelligence; Geotechnical Engineering; Field Performance Prediction

1. Introduction

With the growing need for sustainable, economical, and resilient infrastructure, reinforced soil technologies are becoming more widely used in contemporary geotechnical engineering [1]. "Reinforced soil walls", also known as "Mechanically Stabilized Earth (MSE)" walls, have proven to be one of the most successful methods for constructing highway and railroad retaining walls, bridge abutments, embankments, and slope stabilization projects [2]. The reinforced soil walls offer increased flexibility, lower construction cost, faster construction time and greater adaptability to different ground conditions than the conventional reinforced concrete and gravity retaining walls [3]. These structures offer an excellent flexibility to tolerate differential settlements without causing any damage to the structure, which makes them especially suitable for soft soils, seismic areas, and complex geological conditions. Therefore, reinforced soil walls are becoming a popular choice for transportation and infrastructure applications around the world because of their durability, reliability and cost effectiveness [4,5]. Figure 1 depicts a standard reinforced soil wall design frequently utilised in geotechnical engineering, highlighting the essential structural elements of the reinforced soil wall and their interaction with the adjacent soil.

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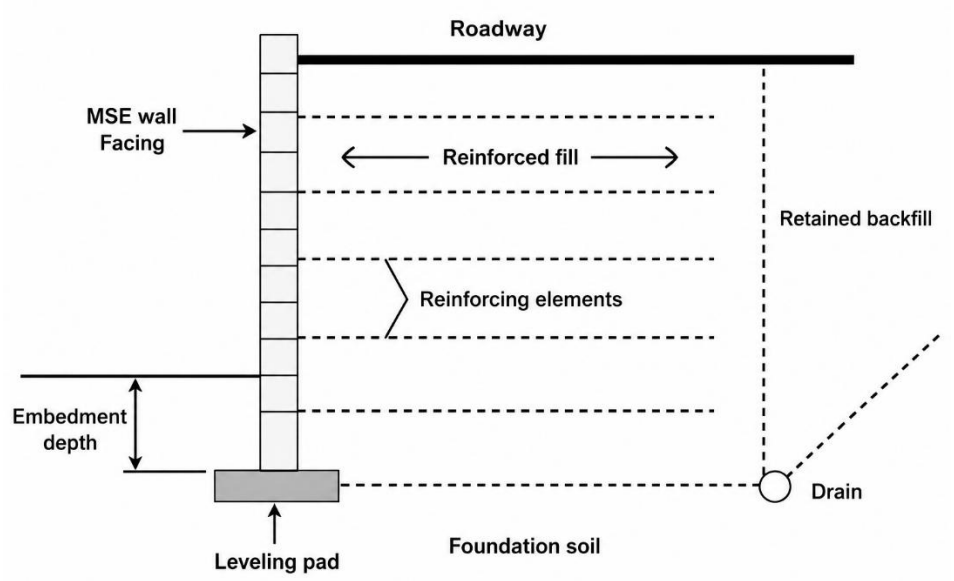


Figure 1: Schematic illustration of a reinforced soil wall system used in geotechnical applications [6]

The interactions between the backfill soil and reinforcement materials are major factors affecting the structural performance of reinforced soil walls. Geogrids, geotextiles, steel strips, and metallic meshes are examples of reinforcement elements that "can give soil tensile resistance and boost the stability of the reinforced soil mass [7, 8]". The efficiency of this interaction is dependent on the soil type, particle gradation, moisture content, reinforcement stiffness, surface characteristics, reinforcement length, spacing, and construction quality [9]. The processes of stress transmission at the soil-reinforcement interface include friction, passive resistance, and mechanical interlocking, all of which influence pullout resistance, load distribution, deformation properties, and wall stability. Thus, knowledge of these interaction mechanisms becomes essential for design of reinforced soil walls that can safely perform under various loading and environmental conditions [10].

Laboratory testing, numerical analysis, and field performance studies have been used to advance understanding of the behavior of reinforced soil. Lab testing has been helpful in determining the interface shear strength, pullout resistance of reinforcement, and deformation characteristics, and numerical modeling has allowed for detailed analysis of stress distribution and failure mechanisms in a reinforced soil system [11, 12]. Field monitoring has also shown the need to consider the reinforcement strain, wall displacement, settlement and earth pressure under actual service conditions. These methods have helped to develop an improved design methodology, by comparing the theoretical predictions to the observed performance in the field [13].

The factors affecting long-term performance of reinforced soil walls are traffic loading, surcharge loading, groundwater movement, rainfall infiltration, seismic activity, and environmental degradation [14]. Reinforced soil walls typically perform well but can suffer from excessive deformations, reinforcement pullout, or local instability due to variability in soil properties, characteristics of the reinforcement, drainage conditions, and construction methods [15]. Therefore, it is important to assess field performance in order to confirm design assumptions, improve construction methods and increase the durability and serviceability of reinforced soil structures [16].

Even tho reinforced soil technology has advanced significantly; it is still difficult to forecast how soil and reinforcement would interact under various geotechnical situations [17]. Typical analytical approaches tend to idealize the interface behaviour and possibly do not describe the interaction of loading characteristics, material variations and environmental factors on the wall performance [18]. The limitations underscore the need for more comprehensive investigations that combine soil–reinforcement interaction with field performance assessment to provide more dependable and performance-based design approaches.

The evaluation of reinforced soil wall performance and design has been greatly enhanced by the integration of AI and computer programs. Numerical simulation tools combined with machine learning algorithms enable accurate prediction of soil–reinforcement interaction, wall deformation, settlement, and stability, supporting reliable, cost-effective, and performance-based geotechnical engineering solutions.

Thus, the current work investigates how soil reinforcement affects reinforced soil barriers' field behaviour in geotechnical applications. The study assesses the result of reinforcement characteristics and soil properties on the host of stresses induced into the soil, the deformation characteristics, and the structural stability under realistic loading conditions. The initiative aims to enhance the design, construction, and enduring efficacy of reinforced soil wall systems by investigating the interaction between soil and reinforcement and its correlation to wall performance. The results are expected to benefit the design of safer, more economical and durable reinforced soil structures that have been in use in modern geotechnical presentations. The following is a list of the study objectives:

- To investigate the interaction mechanism between backfill soil and geogrid reinforcement in reinforced soil walls under geotechnical loading conditions.
- To evaluate the influence of soil properties and reinforcement characteristics on the stress distribution, deformation behavior, and structural stability of reinforced soil walls.
- To develop a finite element model of a reinforced soil wall using PLAXIS 2D for simulating soil–reinforcement interaction and predicting wall performance under practical loading conditions.
- To analyze the field performance of reinforced soil walls by assessing key parameters such as lateral displacement, settlement, reinforcement tensile force, and pullout resistance.
- To identify an effective reinforcement configuration that improves the stability, serviceability, and long-term performance of reinforced soil walls for sustainable geotechnical engineering applications.

2. Review of Literature

The soil-reinforcement interaction that dictates the mechanical performance of reinforced soil walls has been the topic of significant contemporary research, conducted using experimental, numerical, and analytical techniques. Damians et al. (2024) [19] performed laboratory pullout tests and three-dimensional numerical simulations to investigate how stiffness of the steel reinforcement, interface characteristics, and soil properties affect both pullout resistance and soil deformations. Likewise, Mengxi et al. (2024) [20] investigated the cyclic shear response of polypropylene geogrid-reinforced sandy soil and found that the shear strength, stiffness, and damping properties at the interface significantly rely “on both the normal stress and the shear displacement amplitude under repeated loading”. Razeghi et al. (2024) [21] combined the finite element analysis with artificial neural networks to analyze the load distribution of reinforcement in short and tall GRS walls, and showed that reinforcement stiffness and spacing were the most significant parameters that affect the performance of the wall. Additionally, Gul et al. (2022) [22] “found that the addition of glass fibers significantly increased the strength and ductility of fine-grained soils”, while Fareghian et al. (2023) [23] reported improved shear strength, tensile strength, and reduced swelling potential when recycled waste tyre textile fibers were added to fine-grained soils. The results of these studies to date demonstrate the critical role of reinforcement properties, interface mechanisms, and soil characteristics in enhancing the structural behavior and stability of reinforced soil systems.

Table 1: Summary of Recent Literature on Soil Reinforcement and Reinforced Soil Walls

Author	Methodology	Key Findings
Ding et al. (2026)	Multi-scale experimental analysis (SEM, EDS, FTIR, DSC, tensile tests) on 21-year-old PP geostrips	Identified depth-dependent degradation and significant tensile strength loss due to oxidation and environmental exposure.

Zhang et al. (2026)	Temperature-dependent analytical model with limit equilibrium analysis	Demonstrated that temperature significantly affects reinforcement tension and wall stability, especially for marginal backfills.
Kim et al. (2025)	Field investigation, DCP testing, and stability analysis	Water infiltration significantly reduced subgrade strength and wall stability; proposed effective remediation techniques.
Razeghi et al. (2024)	Finite Element Method (FEM) integrated with Artificial Neural Network (ANN)	Reinforcement stiffness and spacing were the dominant factors influencing load distribution and wall behavior.
Damians et al. (2024)	Laboratory pullout tests with calibrated 3D numerical modeling	Improved understanding of soil–reinforcement interface behavior and pullout resistance.
Akbar et al. (2024)	Shaking table experiments and FE simulations	Geogrid reinforcement effectively reduced wall displacement, settlement, and lateral earth pressure under seismic loading.
Javadi et al. (2024)	Numerical investigation of Post-Tensioned MSE Walls	Post-tensioning significantly reduced wall displacement and reinforcement tensile forces.
Mengxi et al. (2024)	Cyclic direct shear tests on geogrid-reinforced sandy soil	Normal stress and cyclic loading significantly influenced interface strength and damping characteristics.
Fareghian et al. (2023)	Laboratory tests on fiber-reinforced soils	Waste tire textile fibers improved shear strength, tensile strength, and reduced swelling.
Hulagabali et al. (2023)	FEM and analytical stability analysis (AASHTO, BS8006, TB10025)	Reinforcement spacing, wall inclination, and surcharge strongly influenced wall stability.
Gul et al. (2022)	Experimental investigation with ANN prediction	Glass fibers significantly improved the mechanical properties of fine-grained soils.
Elshafey et al. (2021)	ABAQUS-based finite element analysis of reinforced quay walls	Geogrid stiffness and reinforcement length greatly affected wall deformation and stability.

Additionally, a number of researchers have been interested in the field performance, durability, and longevity of reinforced soil walls under different environmental and loading conditions. Ding et al. (2026) [24] studied the 21-year degradation of polypropylene geostrips from a reinforced soil wall, and found that after 21 years, there was noticeable degradation of tensile strength resulting from combination of environmental exposure, sustained loading, and oxidation. Zhang et al. (2026) [25] created an analytical model that demonstrates the significant effect of thermal changes on reinforcement tension and stability, especially for walls formed using marginal backfill. Elshafey et al. (2021) [26] Utilising finite element simulation, it was determined that the rigidity of the geogrid, the length of reinforcement, and the spacing have a considerable impact on the lateral performance of reinforced quay walls, as noted by Javadi et al. (2024) [27] showed that adding a post-tensioning system to a mechanically stabilized earth wall can substantially decrease wall deformations and tensile forces in the reinforcement. Furthermore, Hulagabali et al. 2023 [28] conducted the static stability and seismic stability analysis, and emphasised the significance of spacing of reinforcement, inclination of walls, surcharge loading, and the type of soil for enhancing inner stability. According to Akbar et al. (2024) [29] geogrid-reinforced retaining walls significantly overcome the lateral pressure, settlement, and seismic displacement, while Kim et al. (2025) [30] pointed out the importance of having adequate drainage, continuous monitoring, and timely maintenance to prevent wall failure due to water infiltration. The results of these investigations have significantly advanced the information of the performance of a reinforced soil wall, but the majority of investigations focus on one aspect of the wall, either reinforcement configuration, environmental factors, or loading conditions. Hence, further study was needed to produce more effective, robust and performance-based design

approaches in geotechnical engineering using reinforced soil walls, incorporating soil–reinforcement interaction and observation of field performance.

3. Materials and Methods

Figure 2 illustrates the overall study methodology adopted for evaluating soil–reinforcement interaction and the field performance of reinforced soil walls. The framework includes material selection and characterization, reinforced soil wall model development, numerical modeling using PLAXIS 2D, soil–reinforcement interaction analysis, and field performance evaluation to assess structural stability and deformation behavior.

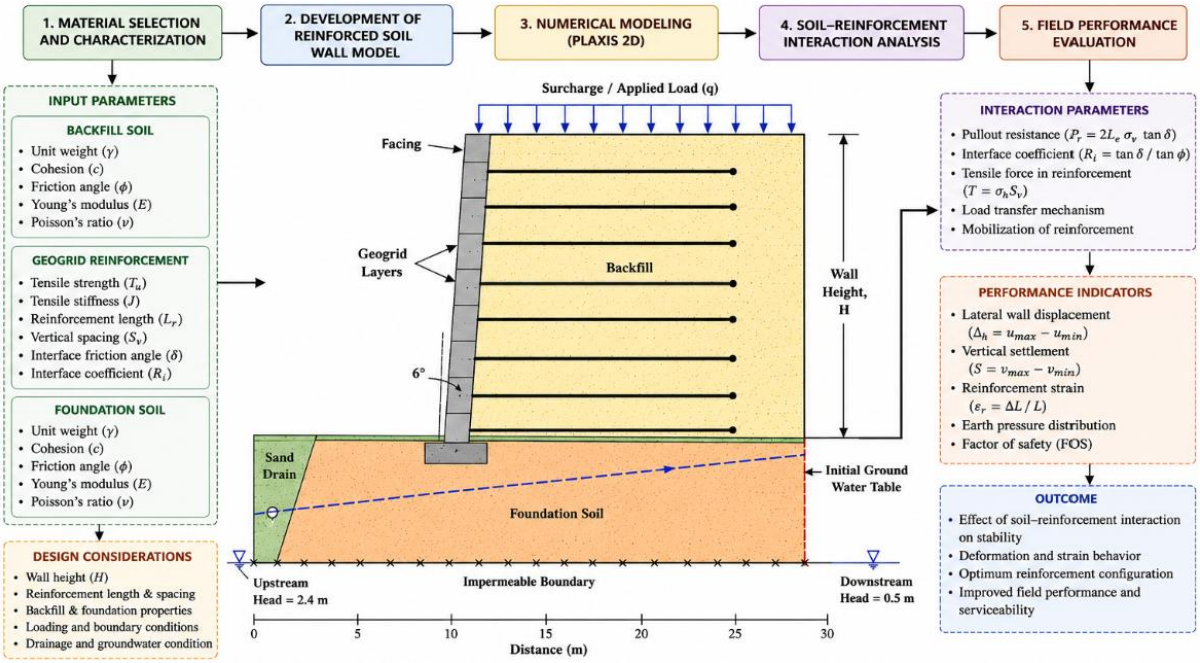


Figure 2: Proposed Methodology

3.1 Material Selection and Soil Characterization

The engineering properties of backfill soil, reinforcement material and foundation soil are the most important design considerations for a reinforced soil wall. Their proper selection is critical for stress transfer, pullout properties and long-term structural stability. The well-graded granular backfill is considered because of its excellent drainage properties, high shear strength and good soil–reinforcement interaction in the present study. The numerical model is employed to evaluate the soil-reinforcement interaction under field loads [31]. The mechanical parameters of the soil and reinforcement are selected in accordance with basic geotechnical design guidelines. The following subsections are used to discuss the characterization of the selected materials.

3.1.1 Backfill Soil Properties

A well-graded granular soil is chosen as reinforced backfill material due to its high shear strength, good drainage properties, and low compressibility. These parameters include “unit weight (γ)”, “cohesion (c)”, “internal friction angle (ϕ)”, “Young's modulus (E)” and “Poisson's ratio (ν)”, and are used to quantify the engineering behavior of the soil. These parameters directly affect the stress distribution, deformation behavior and the mobilization of reinforcement forces in the reinforced soil mass [32].

The shear strength of the backfill soil is evaluated using the Mohr–Coulomb failure criterion:

$$\tau = c + \sigma_n \tan\phi$$

where τ is shear strength (kPa), c is soil cohesion (kPa), σ_n is normal stress acting on the failure plane (kPa), ϕ is internal friction angle (°).

The effective vertical stress within the reinforced soil mass is calculated as:

$$\sigma_v = \gamma H$$

where σ_v is vertical stress (kPa), γ is unit weight of soil (kN/m³), H is depth below the ground surface (m).

The lateral earth pressure acting on the reinforced soil wall is determined using Rankine's active earth pressure theory:

$$\sigma_h = K_a \gamma H$$

$$K_a = \tan^2\left(45° - \frac{\phi}{2}\right)$$

where σ_h is horizontal earth pressure (kPa) and K_a is active earth pressure coefficient.

The lateral earth pressure calculated is then inputted in a numerical analysis to calculate the stresses on the reinforcement layers and facing of the wall.

All of these parameters are used to model the soil's stress–strain response in a realistic manner for use in numerical analysis.

3.1.2 Reinforcement Material Properties

Geogrid reinforcement is used due to its high tensile strength, corrosion resistance, flexibility and good interlocking properties with granular soils. The reinforcement layers provide the reinforced soil mass more tensile strength, stop it from deforming laterally, and boost the wall's stability. The main reinforcement parameters taken into account are: tensile strength, tensile stiffness, spacing between the reinforcements, length of the reinforcement, and its surface friction properties [33].

The tensile stress developed in the reinforcement is calculated as

$$\sigma_r = \frac{T}{A}$$

where σ_r is tensile stress in reinforcement (kPa), T is tensile force (kN), and A is cross-sectional area of reinforcement (m²).

The tensile stiffness of the reinforcement, which controls deformation under loading, is expressed as

$$J = E_r t$$

where J is tensile stiffness (kN/m), E_r is Young's modulus of reinforcement (MPa), and t is reinforcement thickness (m).

The pullout resistance (maximum resistance that can be developed along the interface between soil and reinforcement) is used to evaluate the interaction between reinforcement and surrounding soil:

$$P_r = 2 L_e \sigma_v \tan\delta$$

where P_r is pullout resistance per unit width (kN/m), L_e is effective embedded reinforcement length (m), σ_v is vertical effective stress (kPa), δ is soil–reinforcement interface friction angle (°).

The interface interaction is further represented using the interface coefficient:

$$R_i = \frac{\tan \delta}{\tan \phi}$$

where R_i is interface coefficient, δ is interface friction angle, and ϕ is soil friction angle.

A higher value of R_i indicates stronger interaction and improved stress transfer between the reinforcement and surrounding soil.

3.1.3 Foundation Soil Characteristics

The foundation soil is a factor of support for the reinforced soil wall and plays a significant role in the settlement and stability of the wall. Settlement is prevented from being too great by using a stable foundation, which guarantees appropriate bearing capacity under service loads. Unit weight, cohesion and friction angle, elastic modulus and Poisson's ratio are the engineering properties of the foundation soil [34].

The ultimate bearing capacity is estimated using Terzaghi's bearing capacity equation:

$$q_u = cN_c + \gamma D_f N_q + \frac{1}{2}\gamma B N_\gamma$$

where q_u is ultimate bearing capacity (kPa), D_f is foundation depth (m), B is foundation width (m), N_c, N_q, N_γ is bearing capacity factors.

The allowable bearing capacity is determined by

$$q_{allow} = \frac{q_u}{FOS}$$

where q_{allow} is allowable bearing capacity (kPa), FOS is factor of safety.

The immediate settlement of the foundation soil is estimated as

$$S = \frac{qB(1-\nu^2)}{E} I_s$$

where S is settlement (m), q is applied pressure (kPa), B is foundation width (m), E is Young's modulus (MPa), ν is Poisson's ratio, and I_s is influence factor

The selected foundation properties entered into the numerical model is used to make a realistic prediction of the wall deformation and stability.

Table 2: Engineering Properties of Materials Used in the Reinforced Soil Wall Model

Parameter	Symbol	Backfill Soil	Foundation Soil	Geogrid Reinforcement	Unit
Unit Weight	γ	18	19	–	kN/m³
Cohesion	c	5	15	–	kPa
Internal Friction Angle	ϕ	35	32	–	°
Young's Modulus	E	40	30	1500	MPa
Poisson's Ratio	ν	0.30	0.30	–	–
Tensile Strength	T_u	–	–	120	kN/m
Tensile Stiffness	J	–	–	600	kN/m

Reinforcement Length	L_r	–	–	0.8H	m
Vertical Reinforcement Spacing	S_v	–	–	0.60	m
Reinforcement Thickness	t	–	–	3	mm
Interface Reduction Coefficient	R_{inter}	–	–	0.85	–

3.2 Development of Reinforced Soil Wall Model

The objective of the reinforced soil wall model is to examine the response of backfill soil concerning geogrid reinforcement under actual geotechnical loads. This model is a typical mechanically stabilized earth (MSE) wall that includes a reinforced backfill, modular facing panels, geogrid reinforcement layers, foundation soils, and a drainage system. The wall geometry is determined as per the general geotechnical design guidelines, which provide for sufficient structural stability and serviceability. The reinforcement layers are placed horizontally in the backfill at regular vertical intervals, providing additional tensile strength, lateral stability and overall performance of the reinforced soil structure. The stress distribution, reinforcement behavior, deformation characteristics and stability under field loading conditions are evaluated with the developed wall model.

The geometry of the reinforced soil wall is defined by parameters such as wall "height (H)", "reinforcement length (L_r)", "reinforcement spacing (S_v)", "facing thickness (t_f)" , and "foundation depth (D_f) ". The reinforcement length is generally selected as a proportion of the wall height to provide sufficient anchorage and prevent pullout failure. It is expressed as

$$L_r = \alpha H$$

where L_r is reinforcement length (m), H is wall height (m), α is reinforcement length ratio (typically 0.7–1.0).

The vertical spacing between reinforcement layers is calculated as

$$S_v = \frac{H}{N}$$

where S_v is vertical spacing between reinforcement layers (m), H is wall height (m), N is total number of reinforcement layers.

The reinforced soil wall is loaded with self-weight and surcharge loading to simulate field conditions. The vertical stresses on the reinforced soil mass are summed to determine the total vertical stress acting on the reinforced soil mass.

$$\sigma_v = \gamma H + q$$

where σ_v is total vertical stress (kPa), γ is unit weight of backfill soil (kN/m³), H is wall height (m), q is surcharge load (kPa).

Using Rankine's active earth pressure theory, the lateral earth pressure on the wall facing is obtained as follows:

$$\sigma_h = K_a(\gamma H + q)$$

$$K_a = \tan^2\left(45° - \frac{\phi}{2}\right)$$

where σ_h is horizontal earth pressure (kPa), K_a is active earth pressure coefficient, ϕ is internal friction angle of the backfill soil (°).

The developed reinforced soil wall model is then applied to numerical simulation of displacement, reinforcement tensile force, stress distribution and performance of the whole field under various geotechnical load conditions. The geometrical parameters used to design the model of the reinforced soil wall are summarized in the Table 3.

Table 3: Geometrical Parameters of the Reinforced Soil Wall Model

Parameter	Symbol	Typical Value	Unit
Wall Height	H	6.0	m
Reinforcement Length	L_r	4.8 (0.8H)	m
Vertical Reinforcement Spacing	S_v	0.60	m
Facing Thickness	t_f	0.20	m
Foundation Depth	D_f	1.50	m
Wall Width	B	10.0	m
Surcharge Load	q	20	kPa

3.3 Numerical Modeling

To examine the relationship between the backfill soil and geogrid reinforcement under realistic loading scenarios, numerical modelling of the reinforced soil wall is conducted using the "Finite Element Method (FEM)" software PLAXIS 2D. The model is a representation of the field conditions of a "mechanically stabilized earth (MSE)" wall and includes the following elements: reinforced backfill, foundation soil, facing panels, geogrid reinforcement, and surcharge loading. The analysis is performed to study the stress distribution, wall deformations, reinforcement behavior and structural stability.

The soil behavior is simulated by the Mohr–Coulomb constitutive model in which the soil is assumed to behave elastically prior to yielding, and perfectly plastically after yielding. Shear strength of soil is determined by:

$$\tau = c + \sigma_n \tan\phi$$

where τ is shear strength (kPa), c is cohesion (kPa), σ_n is normal stress (kPa), ϕ is internal friction angle (°).

The elastic response of the soil is represented by Hooke's law:

$$\sigma = E\varepsilon$$

where σ is normal stress (kPa), E is Young's modulus (MPa), ε is strain

The reinforcement layers and wall facing are the areas of stress concentration, and a medium density finite element mesh is created to ensure that the mesh is computational efficient but also captures the stress concentrations around the reinforcement layers and wall facing.

The engagement between reinforcement and soil is modelled using interface elements, with the interaction intensity represented by the values of these elements.

$$R_{inter} = \frac{\tan\delta}{\tan\phi}$$

where R_{inter} is interface reduction factor, δ is interface friction angle (°), ϕ is soil friction angle (°).

A finite element mesh of triangular elements is created to model the stress concentration and deformation around the reinforcement layers with accuracy. Both side and base boundaries are restricted horizontally and bases are restricted vertically, and side boundaries are free to move vertically. The surcharge load is uniformly distributed at the ground surface in addition to the self-weight of the soil.

Wall displacement, stress distribution, reinforcement tensile forces, settlement and stability of the wall are all predicted by the numerical model, and all used to assess the interaction between the soil and the reinforcement as well as to evaluate field performance in the reinforced soil walls subjected to geotechnical loading.

3.4 Data collection

The Deep Excavation Risk Monitoring Dataset (DEARM) [35] is a comprehensive geotechnical dataset created for the prediction and assessment of excavation stability, structural performance and prediction of the stability of deep excavations using artificial intelligence techniques. It includes geotechnical, structural and environmental parameters such as soil parameters, excavation depth, characteristics of retaining wall, groundwater level, rainfall, pore water pressure, ground settlement, lateral wall displacement, and response of reinforcement. The database contains a variety of conditions of excavation and various types of structural behaviour, which can be used to analyse the deformation of structures, their risks and their performance to be stable. It offers a sound base to train and validate machine learning models to predict geotechnical behaviour and enhance the decision making process, in infrastructure engineering applications.

3.5 Data Preprocessing

The generated dataset was then preprocessed before data was used for the artificial intelligence models to improve data quality and optimize the performance of the models. Data was initially handled using mean imputation for missing values and duplicate records were eliminated to ensure consistency in the data. The Outliers were determined using the “Inter Quartile Range (IQR)” method, namely:

$$IQR = Q_3 - Q_1$$

$$\text{Lower Limit} = Q_1 - 1.5(\text{IQR})$$

$$\text{Upper Limit} = Q_3 + 1.5(\text{IQR})$$

Data outside these range submitted as outliers and deleted. Then, all the numeric attributes were scaled to a shared range using min-max normalization for convergence of the model.

$$X_{norms} = \frac{X - X_{min}}{X_{max} - X_{min}}$$

where (Xmin) and (Xmax) are the minimum and maximum values of the relevant feature, respectively, while (X) is the original feature value. Finally, the processed dataset was split into their training (80%) and validation (20%) sets, which were then randomly split to the testing (20%) set, to guarantee unbiased model training, validation, and prediction of the performance of the reinforced soil wall.

3.6 Artificial Intelligence Model

- **Artificial Neural Network (ANN)**

To predict the structural performance of reinforced soil walls, the Artificial Neural Network (ANN) was used to learn the complicated nonlinear relationship between the geotechnical properties and the different characteristics of the reinforcement. The model comprises of interconnected input, hidden and output layers that automatically identify key features from the data. ANN can effectively predict maximum displacement, settlement, tensile force, pull-out resistance and factor of safety, and with high prediction accuracy for geotechnical engineering applications.

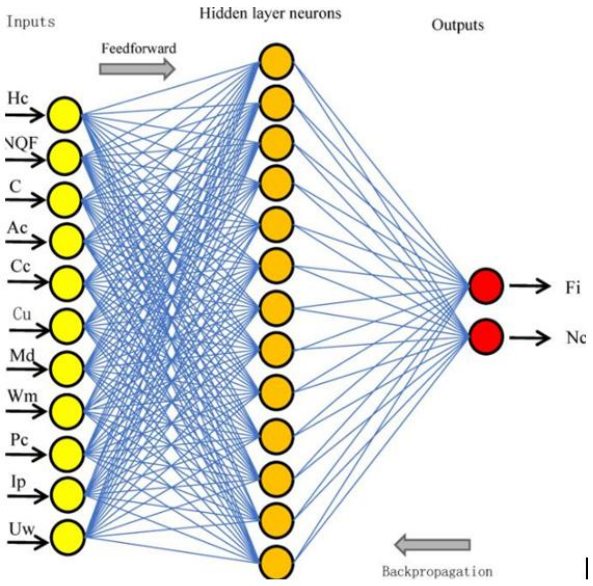


Figure 3: Architecture of the Artificial Neural Network (ANN) [36]

- **Random Forest (RF)**

The behaviour of reinforced soil wall (RSW) was estimated using Random Forest (RF) model with multiple decision trees. Several trees are used to combine their predictions and random sampling and feature selection prevent overfitting the algorithm, which increases the accuracy of the prediction. Random Forest is a good predictor of the deformation and stability behavior of the soil based on the nonlinear nature of the relationship among the soil attributes, reinforcement parameters and structural response outcomes, and is therefore suitable for modeling the nonlinear relationships.

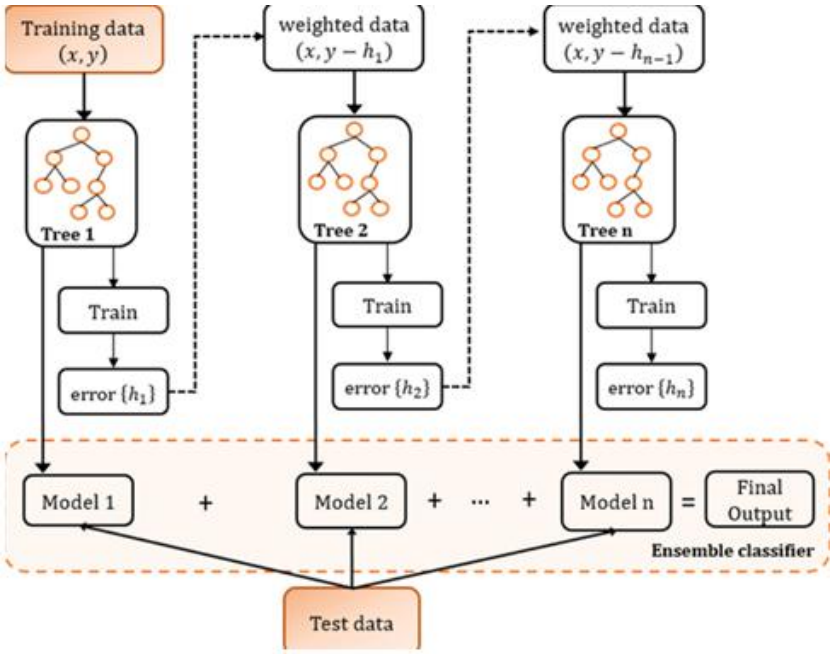


Figure 4: Random Forest (RF) framework [37]

- **XGBoost**

To construct an effective predicting model of the reinforced soil wall performance, the algorithm Extreme Gradient Boosting (XGBoost) was used. XGBoost iteratively builds decision trees as it minimizes the errors of the predictions by using a gradient optimization technique, thus delivering high accuracy and computational speed. It exhibits good ability to accurately simulate the complicated interactions between soil properties, reinforcement characteristics and loading conditions, showing good prediction performance for displacement, settlement, tensile force, pullout resistance and factor of safety.

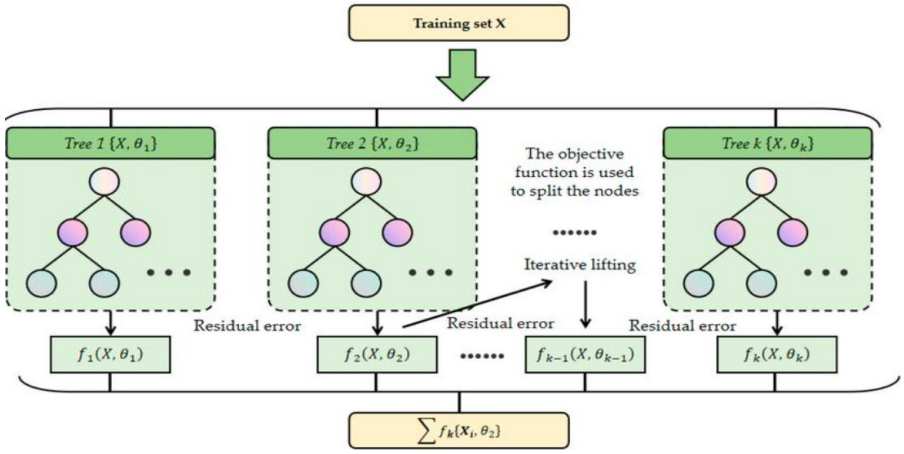


Figure 5: XGBoost prediction framework [38]

3.7 Soil–Reinforcement Interaction Analysis

The relationship between the soil and reinforcement is a critical element influencing the stability and effectiveness of reinforced soil barriers. For this study, the communication between the soil and the reinforcement is assessed based on the stress transfer, mobilization of tensile forces, behavior of the "soil–reinforcement interface" and pullout resistance between the geogrid reinforcement and the adjacent backfill soil. An efficient interaction helps to better distribute load, reduce lateral deformation and increase "the stability of the reinforced soil structure". In order to accurately represent the frictional resistance and mechanical interlocking that occurs under applied stress circumstances, the numerical analysis takes into consideration the interface elements between the soil and reinforcement.

The pullout resistance developed along the reinforcement is calculated using

$$P_r = 2L_e\sigma_v \tan\delta$$

where P_r is pullout resistance (kN/m), L_e is effective embedded reinforcement length (m), σ_v is vertical effective stress (kPa), δ is soil–reinforcement interface friction angle (°).

The mobilized tensile force in the reinforcement is also measured besides pullout resistance, and this is used to assess the load transmission mechanism among the soil and reinforcement.

The tensile force mobilized within the reinforcement is estimated as

$$T = \sigma_h S_v$$

where T is tensile force in reinforcement (kN/m), σ_h is horizontal earth pressure (kPa), S_v is vertical spacing of reinforcement layers (m).

The results that are obtained are utilized to assess reinforcement efficiency, stress Distribution, pullout resistance and deformation characteristics which give a complete evaluation of the interaction between soil and reinforcement under practical geotechnical loading conditions.

3.8 Field Performance Evaluation

The performance of the reinforced soil wall in the field is assessed by analysing its deformation patterns and the reinforcement's response to imposed loads. The assessment is based on important performance indicators like lateral wall displacement and reinforcement strain, reflecting the effectiveness of soil–reinforcement interaction and structural stability of the wall. Numerical results are examined on the deformation patterns and the serviceability of a reinforced soil system under real geotechnical conditions.

The lateral displacement of the wall is calculated as

$$\Delta_h = u_{max} - u_{min}$$

where Δ_h is the lateral wall displacement (m), u_{max} is the maximum horizontal displacement (m), and u_{min} is the minimum horizontal displacement (m).

The vertical settlement is calculated as

$$S = v_{max} - v_{min}$$

where S is vertical settlement (m), v_{max} is maximum vertical displacement (m), v_{min} is minimum vertical displacement (m).

The reinforcement strain is determined by

$$\varepsilon_r = \frac{\Delta L}{L}$$

where ε_r is the reinforcement strain, ΔL is the extension of the reinforcement (m), and L is the original reinforcement length (m). The performance indicators consist of the measures of stability, deformation, and long-term performance of a reinforced soil wall under field loading conditions.

4. Results & Discussion

This segment evaluates the efficacy of the suggested artificial intelligence-driven methodology for examining soil-reinforcement interactions and the operational performance of reinforced soil barriers in practical applications. Various numerical simulations and artificial intelligence models are provided to evaluate the main geotechnical aspects under study and are related to the model training, accuracy of predictions, horizontal displacement, settlement, tensile force, pullout resistance, factor of safety, earth pressure and reinforcement strain. The outcomes are examined to evaluate the models' prediction power and demonstrate their suitability for stability evaluation and the best design of reinforced soil barriers in dependable geotechnical engineering applications.

Figure 6 shows the "Artificial Neural Network (ANN)" model's training and validation loss curves over 100 epochs, demonstrating the model's convergence throughout training. “The training loss goes from 0.90 to 0.0021, and the validation loss goes from 0.95 to 0.0032”, which means that the error for predictions is reduced by over 99%. The small loss gap (0.0011) between the training loss and the validation loss implies very good generalization of the model with very little overfitting. This strong convergence enables accurate predictions of soil-reinforcement interactions and the effectiveness of the reinforced soil wall, hence aiding reliable geotechnical assessments thru computational methods and artificial intelligence strategies.

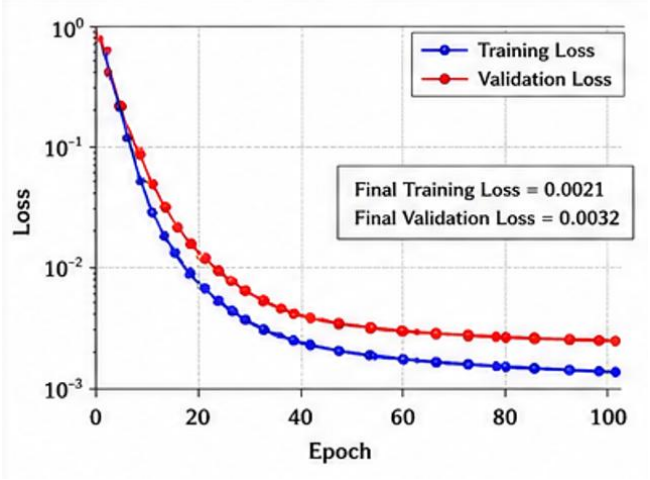


Figure 6: ANN training and validation loss[39,40]

The comparative illustration of the actual displacement values and those predicted by the ANN for the reinforced soil walls is presented in figure 7, demonstrating a remarkably precise prediction. As shown by the close agreement with the ideal fit line close to 1:1 over the range of predicted displacements of about 3–56 mm, the predicted values are in good agreement with the measured responses. The developed ANN model has a high R2 value of 0.98 which shows that the variation in displacement is captured at a high level of accuracy. In addition, the model shows low "Mean Absolute Error (MAE)" value of 1.21 mm and "Root Mean Square Error (RMSE)" value of 1.68 mm, which indicate that there is a low level of uncertainty in the prediction. The results confirm the accuracy of artificial intelligence and computer applications in modelling soil–reinforcement interaction and predicting the field performance of soil reinforced walls for geotechnical engineering applications.

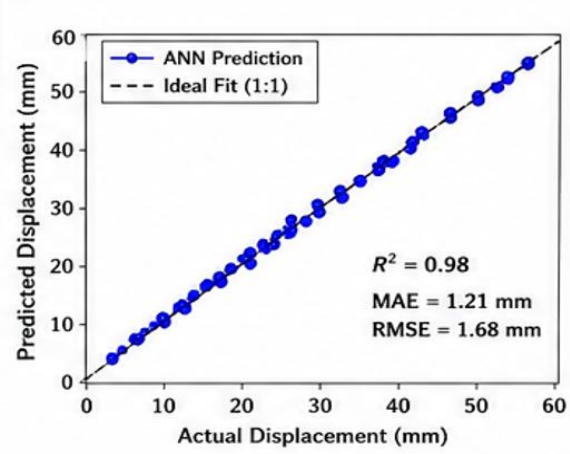


Figure 7: ANN prediction accuracy for wall displacement

This is a comparison of the prediction accuracy of three artificial intelligence models for assessing soil–reinforcement interaction and reinforced soil wall performance as shown in figure 8. In comparison to the models, XGBoost has the highest prediction accuracy of 98.6%, followed by ANN which recorded 97.9%, while RF recorded 95.8%. The performance gap between XGBoost and ANN is only 0.7% while that of XGBoost is 2.8% better than Random Forest, which shows XGBoost to be more effective than Random Forest in predicting the target variable. Results of high accuracy >95% for all three models suggest that all have captured the complex geotechnical behavior extremely well. The results indicate the capability of computer applications and utilization of artificial intelligence techniques for the reliable prediction, performance evaluation and optimal design decision making in reinforced soil wall design and geotechnical applications.

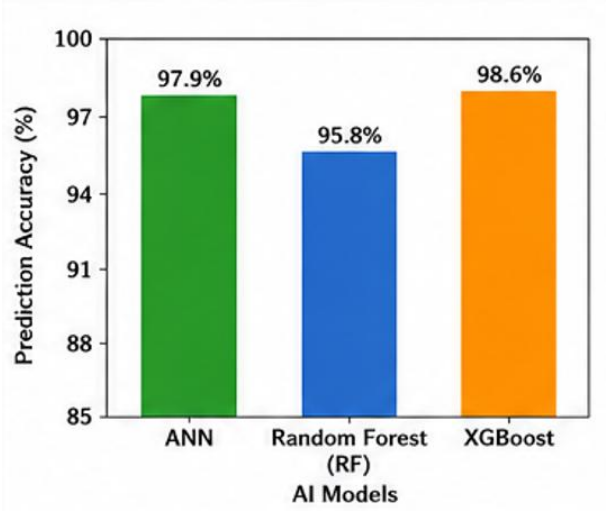


Figure 8: Comparative prediction accuracy of AI models

Horizontal displacement appears to rise moderately with the elevation of the reinforced earth barrier, as illustrated in Figure 9, which correlates with the wall's height. The displacement increases from 0 mm at the wall base (0 m) to about 56 mm at the peak wall height (5.8 m), suggesting that the wall underwent increasing lateral deformation during loading. The intermediate observations reveal that the displacements at 2.8 m and 4.1 m are almost 20 mm and 35 mm, respectively, and are consistent throughout the wall, exhibiting a uniform deformation pattern.

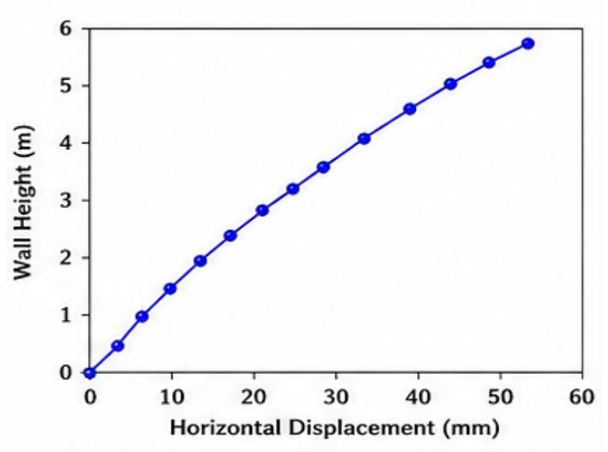


Figure 9: Wall height versus horizontal displacement

This profile helps to gain insight into the soil-reinforcement interaction and structural behavior. Computer applications based on the application of artificial intelligence can well predict such deformation patterns which can help to enhance the stability assessment, design optimization of the reinforcement, and reliable “estimation of the field performance of reinforced soil walls in geotechnical submissions”.

Figure 10 displays the profile used for the site's settlement analysis for the reinforced soil wall's field performance at different distances from the wall face. The range of the monitoring distance is 0–10 m and the settlements differ from “approximately −18 mm at the near of the wall face to about −2 mm at 10 m”.

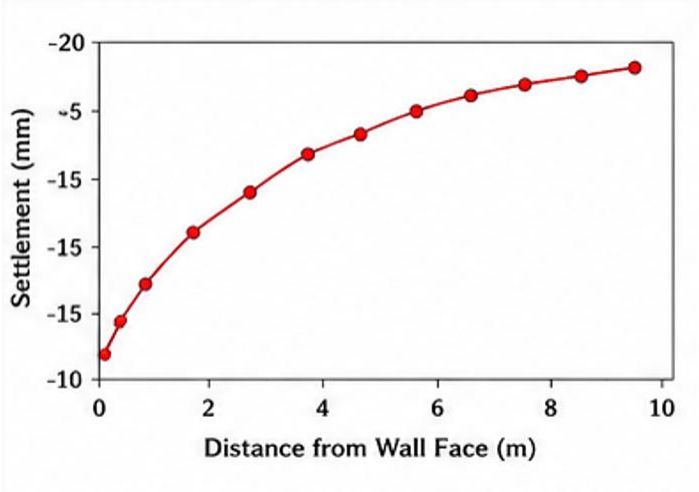


Figure 10: Settlement variation from wall face

A distribution of tensile forces in the reinforcement is adopted as shown in Figure 11 to assess the soil–reinforcement interaction under different reinforcement spacing (Sr) conditions of (0.40 m, 0.60 m, 0.80 m). This analysis includes 10 reinforcement layers, with the tensile force going up from bottom layers to top layers where it reaches its maximum in the neighborhood of the Layer 5.

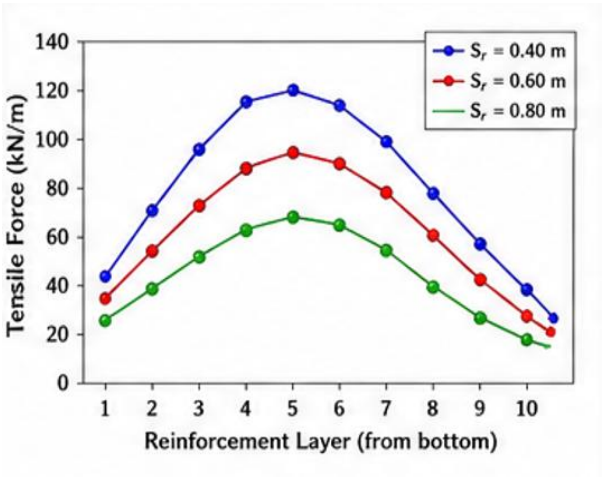


Figure 11: Reinforcement tensile force distribution

The peak tensile forces are approximately 120 kN/m for Sr is 0.40 m, 95 kN/m for Sr is 0.60 m, and 68 kN/m for Sr is 0.80 m. The tensile force distribution is then integrated into the numerical model and artificial intelligence framework for evaluating the distribution of tensile force, reinforcement efficiency, interaction between soil and reinforcement and the performance of the reinforced soil wall under geotechnical loading conditions.

The pullout resistance profiles illustrated in Figure 12 were utilised to assess the interaction between soil and reinforcement for varying lengths of reinforcement. Reinforcement length (L_r) varies between 1 m and 7 m and corresponding pullout resistance increases from around 12 kN/m to around 215 kN/m.

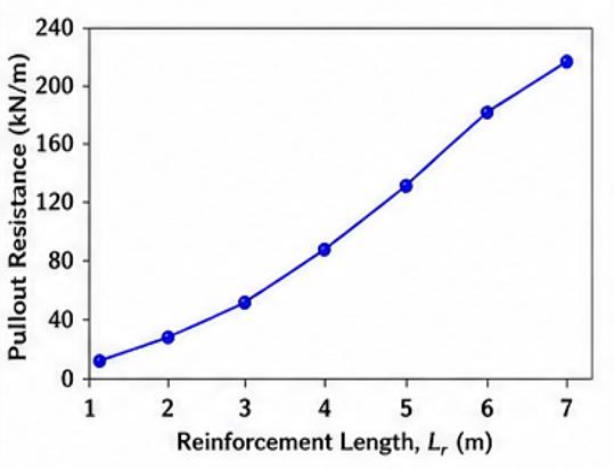


Figure 12: Pullout resistance versus reinforcement length

The pull out resistance gradually increases up to 4 m, at which point it is almost 85 kN/m, then increases sharply to about “130 kN/m at 5 m and 180 kN/m at 6 m”. To accurately assess the stability of reinforced soil walls and their performance in the field under geotechnical loading conditions, the relationship is integrated into numerical models and an AI framework that measures anchorage efficiency, interface behaviour, and stress transfer from soil to reinforcement.

Figure 13 shows the correlation between the “factor of safety (FOS)” applied “to the stability of the reinforced soil wall, and the surcharge weight”. The load on the surcharge varies between 0 and 60 kPa and the factor of safety decreases from about 3 to 1, thus showing a progressive loss of structural integrity as the external load increases. Intermediate values have a factor of safety of approximately 2.2 @ 15 kPa, 1.6 @ 30 kPa and 1.2 @ 45 kPa. This stability profile is implemented in the numerical modelling and artificial intelligence framework to evaluate the effect of surcharge loading on soil-reinforcement interaction, soil deformative behaviour and the overall performance of the field reinforced soil wall in geotechnical submissions.

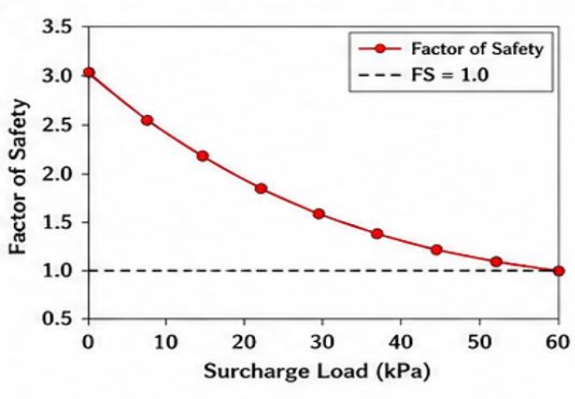


Figure 13: Factor of safety under surcharge loading

A horizontal earth pressure profile is depicted in Figure 14, which was utilised to evaluate the interaction between soil and reinforcement in the reinforced soil wall model. The depth of the wall is from 0 to 6.7 m and the horizontal earth pressure (σ_h) is linearly distributed from 0 kPa on the ground surface to about 100 kPa at the greatest depth. The pressure distribution is calculated using the active earth pressure relationship σ_h is K_aγz, “where K_a is an active earth pressure coefficient of 0.27 and ϕ is internal friction angle of 35°”.

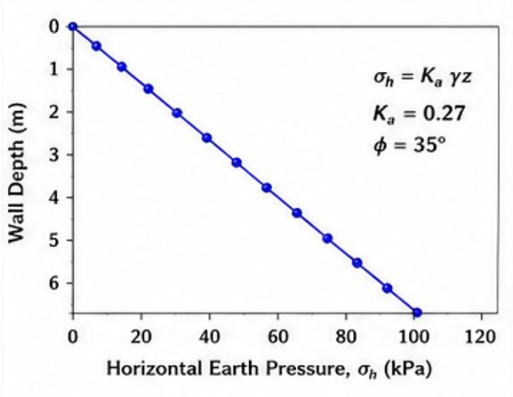


Figure 14: Earth pressure variation along wall depth

This loading scenario is included into the numerical model and the artificial intelligence framework to replicate actual loading conditions, facilitating the evaluation of stress transfer and the analysis of the constancy and deformation characteristics of "reinforced soil walls" under geotechnical loading conditions.

The reinforcement strain distribution used in the model of reinforced soil wall for the evaluation of soil–reinf interaction is revealed in figure 15. "The analysis includes 10 reinforcement layers": the strain is approximately 0.05% at Layer 1 and gradually increases up to Layer 5, where the maximum strain is approximately 0.21%, and then it is reduced all the way down to Layer 10, which has a strain of nearly 0.05%. The section of the reinforced soil mass with the greatest mobilization of tensile forces and load transfer is identified as the maximum extension which occurred in the middle reinforcement layers. The strain profile is used in conjunction with numerical modelling and artificial intelligence to evaluate the reinforced soil wall's performance, interface interaction, deformation behaviour, and reinforcement behaviour under field geotechnical loading circumstances.

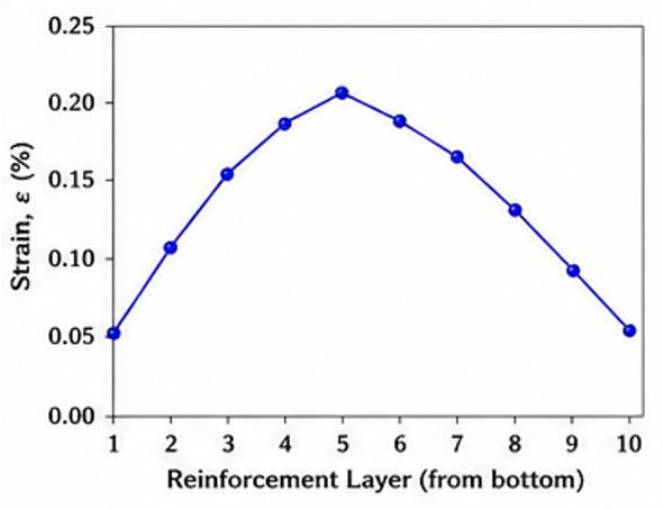


Figure 15: Reinforcement strain distribution across layers

5. Conclusion

The present study provides a thorough investigation of soil–reinforcement interaction and the behavior of soil-reinforcing walls in the field using the numerical simulation together with artificial intelligence techniques. The methodology developed successfully required the evaluation of the important geotechnical parameters, such as horizontal displacement, settlement, reinforcement tensile force, reinforcement strain, pullout resistance, earth pressure distribution, and Factor of Safety. The greatest horizontal displacement of the reinforcement wall was under

56 mm, while the pullout resistance escalated from about 12 kN/m to 215 kN/m as the reinforcement length grew, indicating improved anchorage efficacy. The influence of external loading on wall stability is shown as the factor of safety decreased from 3.0 to 1.0 as the surcharge loading increased from 0 to 60 kPa. In terms of predictive accuracy, XGBoost demonstrated the best performance with a score of 98.6%, followed by ANN (97.9%) and to the least RF (95.8%). “Moreover, the ANN model showed very good prediction capability with an R^2 of 0.98”, “an MAE of 1.21 mm, an RMSE of 1.68 mm” and the final training and validation losses of 0.0021 and 0.0032 respectively. The results highlight that the combination of computer application and AI offers accurate, efficient, and reliable observational tools to expect the behavior of secure soil walls, aiming to optimize their design, assess their stability and make more informed decisions in contemporary geotechnical engineering applications.

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