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# Stability of Slopes and Underground Excavations

## Proceedings of Indian Geotechnical Conference 2020 Volume 3

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Editors

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# Contents

# About the Editors

**Dr. C. N. V. Satyanarayana Reddy** is a Professor of Civil Engineering at College of Engineering, Andhra University, Visakhapatnam, India, and has 28 years of teaching, research, and consultancy experience. His expertise and research interests are in the areas of reinforced soils, ground improvement, landfills, soil retention in excavations, deep foundations, and forensic geotechnical engineering. He obtained B.Tech. in Civil Engineering from Nagarjuna University, M.Tech. in Geotechnical Engineering from Indian Institute of Technology (IIT) Madras, M.E. (Structures) from Andhra University, and Ph.D. from National Institute of Technology (NIT) Warangal, India. He has guided 8 Ph.D. scholars and 92 M.Tech. dissertations. He has more than 110 publications in various national and international journals and seminars/conference proceedings. He has organized more than 30 seminars, workshops, and training programs. He is fellow of Indian Geotechnical Society, The Institution of Engineers (India) and Life member of Indian Roads Congress, Indian Concrete Institute, Indian Society for Technical Education, Indian Society for Rock Mechanics and tunneling Technology. He handled several research projects funded by DST, UGC and AICTE. He received the Engineer of the Year 2006 Award from Govt. of Andhra Pradesh and The Institution of Engineers (India) A.P. State Centre, Best Academician Award for the year 2014 from Andhra University and Andhra Pradesh Scientist Award 2020 in Civil Engineering Discipline from A.P. State Council of Science and Technology, Govt. of A.P. He served as National Executive Committee member of Indian Geotechnical Society during the period 2013-2020. He served as a member in H-4 Committee on Embankment, Ground Improvement and Drainage Committee of Indian Roads Congress (IRC) for the term 2018-2020. He is serving as member of TC 213 on "Scour and Erosion" of International Society for Soil mechanics and Geotechnical Engineering (ISSMGE).

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**Mr. Ravikiran Vaidya** is Principal Engineer and Founder of Geo Dynamics, a company involved in deep foundation testing. He has been instrumental in popularizing and pioneering various methods for deep foundation testing in India. It is to his credit that methods like high strain dynamic testing, integrity testing, sonic logging, etc., are now routinely used all over India to verify pile foundations and also form a part of all specifications of all major projects. He has recently worked on thermal integrity profiling for bored piles and indigenized the bidirectional load testing technology. He has written several technical papers on the subject, and his work has been cited by several authors in various articles and dissertations. He is also Guest Lecturer at academic and industry forums.

# Prediction of Stability of an Infinite Slope Using Geospatial Techniques

**Srirama Dinesh, Chirasmayee Savitha, and Arif Ali Baig Moghal**

## 1 Introduction

Geospatial techniques comprise Remote Sensing, Photogrammetric, Geographical Information Systems (GIS), and Global Positioning Systems (GPS). They deal with acquisition, processing, storing, manipulating, storing, and disseminating spatial data. Remote sensing of the earth is a science and art of obtaining information about natural and artificial features. GIS refers to the analysis, capturing manipulating spatially related data. Photogrammetry refers to the acquisition processing of data using photographs. GPS refers to satellites positioned in space, which provides accurate and precise location information of the earth's features. Information collected from conventional and geospatial techniques can perform various spatial and temporal analyses of various land resources. Soil, one of the natural materials, has different properties and varies both spatially and temporally. Soil properties, index, and engineering properties help predict the soil's suitability as foundation and construction material. Engineering property, shear strength, is used to determine the slope's stability, bearing capacity, and the earth's pressure on one of the significant parameters, soil moisture.

Slope stability assumes a significant job in structural building, particularly in the design of expressways, railways, channels, surface mining, decline removal earth banks, and dams, just like numerous other human exercises, including construction

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and unearthing. Changes in external loads and pore water may cause slope failure and mass movement of the well-stabilized slopes [1]. Highway alignments, established along the hilly or mountainous terrain, taking or without considering hazard maps, are subjected to slope failures. The mass movement of soil succeeded by slope failure poses a high risk of damage to both lives and infrastructure. Quantitative and qualitative assessment of such mass movement of soil, its exact configuration, and spatial location is complicated to predict. However, depending on the in situ data and a few analytical postulates, quantitative assessments can be made. This quantitative examination decides the safety characteristics considering taking into account the causes that constitute the condition of strength and potential outcomes of the slopes to fail, regularly turned in a lead indicator called Factor of Safety (FOS). However, these assessments have a few limitations due to the difficulties in obtaining, checking, and processing large spatial and temporal data sets and varying soil moisture. With limited site investigation data and a lack of temporally varied data, useful slope failure analysis in mountainous areas, especially in mountainous urban areas, has become a paramount concern. With its potential and versatility for processing spatial data and temporal data, geospatial technologies have attracted significant attention to assessing soil and its properties. By establishing a statistical relationship between the slope stability and the factors influencing it and utilizing geospatial technologies in both acquisitions of spatial and temporal data and utilizing GIS, the FOS data can be created, assessed, and a map can be disseminated. The maps thus prepared help ease the planning of infrastructure before construction and indicate the possible failure zones or the risk-prone areas near the existing infrastructure.

In India, 15% of the area is prone to landslides [2]. Numerous landslides triggered by unusually high rainfall in India's Western Ghats regions caused widespread damage to property and life and resulted in 14.9% of landslides in the moderate slopes area in Karnataka state [3]. Considering the necessities and possibilities of geospatial techniques, the stability of an infinite slope was carried out near the Ballari area, which covers a part of National Highway 150A (NH 150A); a motorway in Karnataka state that connects Jewargi and Chamarajanagar employing the limit equilibrium method for the stability of an infinite slope is predicted. The infinite slope model used to calculate an FOS based on limit equilibrium analysis determines the balance between shear stress and shear strength. The necessary input parameters in developing the infinite slope model are (i) Cohesion, (ii) Angle of Shearing Resistance, (iii) Unit Weight of Soil, and (iv) Soil moisture. Soil water content is assessed from field observations; the estimations of these variables ($c$, $\varphi$, $\gamma$) are evaluated through the correlations. Digital Elevation Model (DEM) obtained from Cartosat-1 from Bhuvan is utilized in this study (Fig. 1).

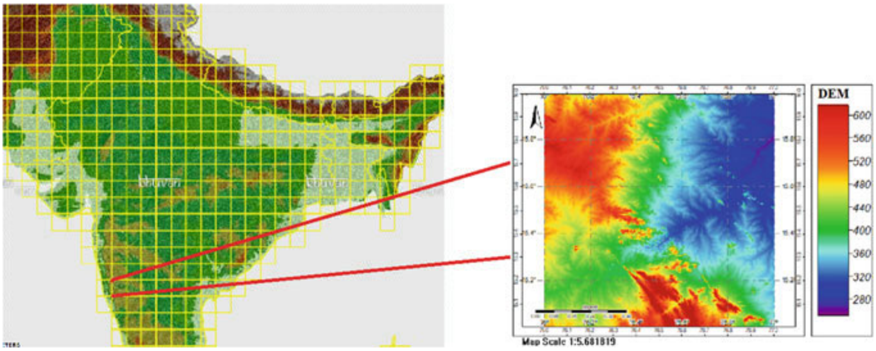


**Fig.1** Cartosat Dem data from Bhuvan website

## 2 Objectives

The primary advance in this paper is by utilizing geospatial technologies to assess the sensitivity of the infinite slope over a spatial extent. To make the study achieve effectively, the explicit goals of this exploration are as follows:

1. Soil moisture maps to be prepared.
2. To determine the slope angle from Cartosat-1 DEM data.
3. Slope stability modeling using (i) Cohesion, (ii) Angle of Shearing Resistance, and (iii) Unit Weight of Soil.
4. To predict the Factor of Safety (FOS) of infinite slope from SAGA GIS.

## 3 Materials and Methods

### *3.1 Materials*

Primary Data collected during field investigation, including satellite data and ancillary data, is used in this research. For satellite data, Cartosat-1 DEM was used. The Cartosat-1 Digital Elevation Model (CartoDEM) is a National DEM developed by the Indian Space Research Organization (ISRO), having a resolution of 2.5 m. The data extent was from 76–77°E and 15–16°N. However, the data was clipped further specific to the study area extent, i.e., 76.60–77°E and 15–15.32°N. The extent of NH150A obtained from urban land use and land cover map acquired from the Bhuvan website used in preparing a road network map for the study area is shown in Fig. 2. The extent of the NH150A, along with its terrain characteristics, is shown in Fig. 3.

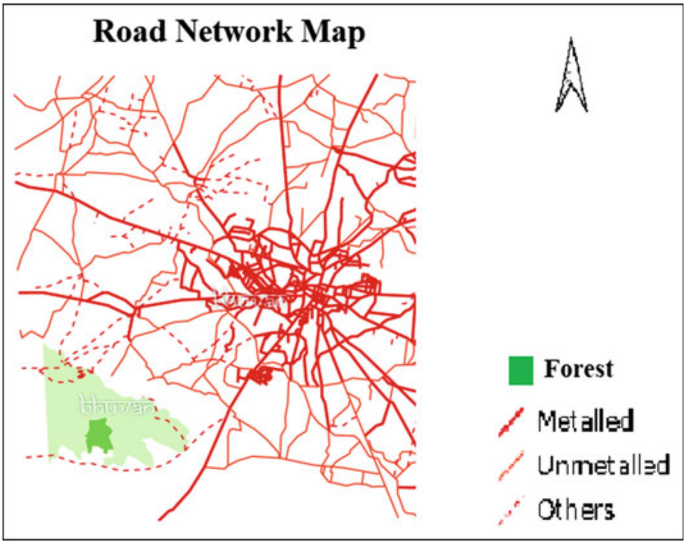


**Fig.2** Overlaid map of the study area

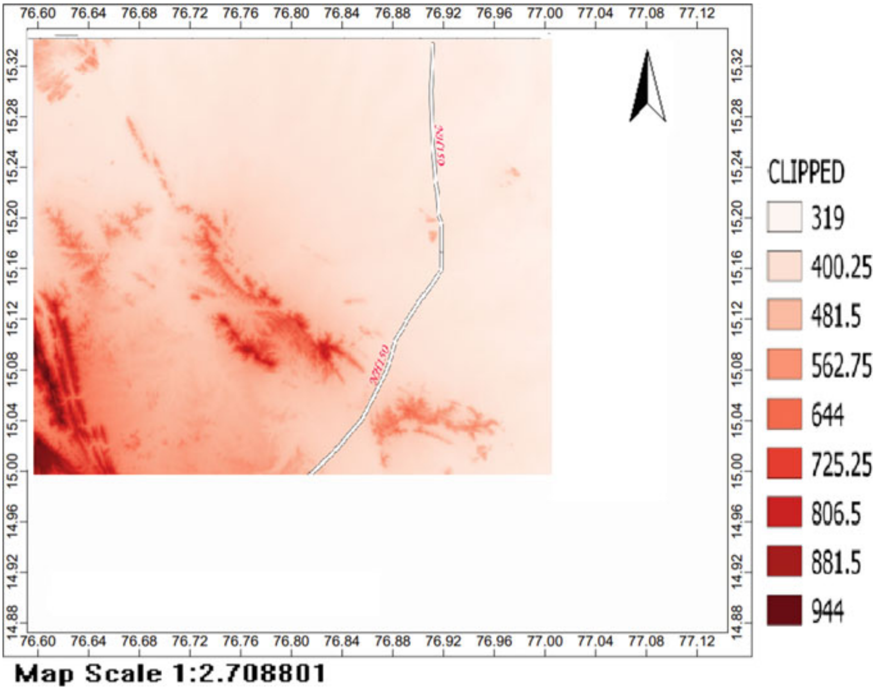


**Fig.3** Topographic feature of the study area

## *3.2 Methods*

### 3.2.1 Field Observation

Variables such as soil water content and soil samples of 20 selected points from the study region were obtained during the field investigation that was performed on Wednesday, January 2, 2019. Open-source software such as QGIS is used for mapping. SAGA GIS software is used for image processing.

### 3.2.2 Infinite Slope Stability Modeling

The slope's stability is a function of various parameters and depends on the soil geotechnical properties, land use land cover, and geological features. Frictional resistance of the soil is affected by the presence of water and pore water pressure. As the quantity of interstitial fluid rises, the soil weight increases, further destabilizing the slope. Evaluating the slope's stability using the infinite slope model provides simple equations for determining the Factor of Safety (FOS) with a surface of plane failure parallel to the slope surface. By adapting Factor of Safety (FOS) [4] for the hydrostatic condition used in this research for the infinite model, we get

$$\begin{aligned}\mathrm{FS} = {} & (\tan\phi/\tan\alpha) + (\mathrm{c}/(\gamma(\mathrm{D}-\mathrm{y}))\,(1/(\sin\alpha\cos\alpha)) \\ & + (\mathrm{y}/(\mathrm{D}-\mathrm{y}))(\gamma\omega/\gamma)\,(\tan\phi/\tan\alpha)\end{aligned} \tag{1}$$

where D assumed as 10 m is the height of soil from the water table, and y estimated to be a constant 2.5 m is the thickness of the slab, reflecting the average debris-flow thickness in the region of the study area [4] and recommended for a shallow landslide [5].

Considering the influence of geotechnical parameters alone on the stability of an infinite slope using limit state equilibrium condition and modeling in the QGIS software, an FOS map can be developed. The necessary input parameters in developing the infinite slope model are (i) Cohesion, (ii) Angle of Shearing Resistance, (iii) Unit Weight of Soil, and (iv) Slope Angle. Utilizing the relationship between the soil moisture (ω) and geotechnical parameters, adapted in [6, 7], the cohesion of the soil (c), angle of shearing resistance (ø), and unit weight of the soil (γ) for an infinite slope are determined from the QGIS model maker from the equations below.

(i) The cohesion of the soil (c in kPa):

$$c = -1.2009\omega^2 + 56.412\omega - 587.87 \tag{2}$$

(ii) Angle of shearing resistance:

$$\phi = 11212\omega^{-1.1929} \tag{3}$$

(iii) The unit weight of the soil ($\gamma$ in kN/m$^3$):

$$Y = -0.1337\omega + 17.457 \tag{4}$$

The values thus obtained served as input parameters for determining the Factor of Safety.

## 4 Results

As shown in Fig. 4, the soil moisture map prepared from soil moisture measurements made at 11 points in the field serves as an essential input parameter to determine the (i) Cohesion, (ii) Angle of Shearing Resistance, and (iii) Unit Weight of Soil. Measurement of slope angle is made from Carosat-1 DEM data. Figure 5 presents the Factor of Safety Map for the entire study area. Each pixel in the image represents the value of FOS. It provides a quantitative sign of slope stability. A value of FOS = 1.0 indicates that the slope is at the verge of failure; under the current condition value of FOS, less than 1.0 points out that the slope is unstable, and a value of FOS greater than 1.0 points toward a stable slope [8]. Figure 5 explains the dependence of conditionally stable elements on the soil moisture within the elevation. The least

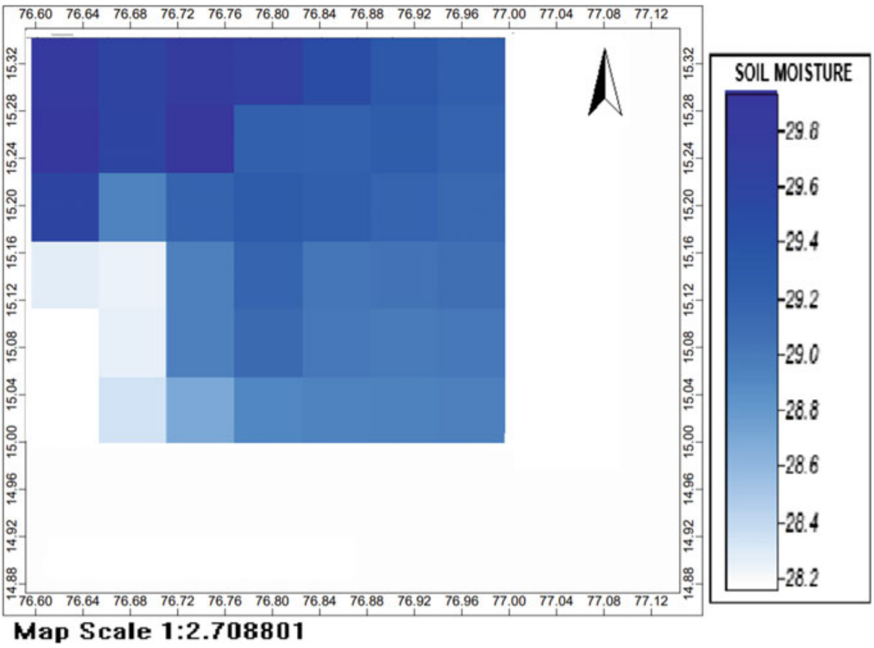


**Fig. 4** Soil moisture mapped interpolated from field observations

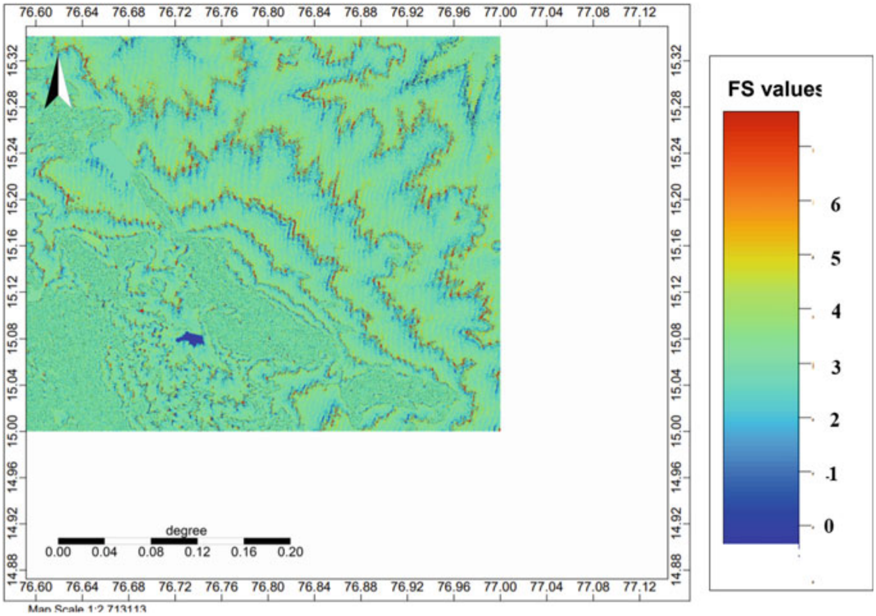


**Fig. 5** Slope stability map depicting location of unstable slopes

factor of safety in the southwest part of the study area is attributed to forest cover having more soil moisture. Frictional resistance dependant on the soil moisture is least in the southwest region with high elevations. Further, the factor of safety values more significant than the one with the least slope failure is concentrated in regions with low soil moisture.

For validating the model, laboratory experiments were carried out. Table 1 shows the comparative analysis of soil parameters of 11 observation samples.

## 5 Conclusions

This paper presents the prediction of the infinite slope stability of NH150A across the Ballari region using geospatial techniques. The model created in QGIS estimates where a failure phenomenon could occur by simulating most geotechnical parameters and assessing its stability based on the infinite slope model. The application of geospatial techniques in predicting the stability of an infinite slope demonstrates the model's ability to perform according to input parameters and terrain topography; moreover, it highlights the strengths of the model that can be disseminated at the spatial extent. Soil moisture, one of the critical parameters, varies both spatially and temporally. Further enhancement of the model in predicting the stability of an infinite

**Table 1** Comparative analysis of soil parameters

| Borehole | Geospatial | | | | Experimental | | |
|---|---|---|---|---|---|---|---|
| | Soil moisture (%) | Cohesion (kPa) | Friction angle (°) | Unit weight (kN/m$^3$) | Cohesion (kPa) | Friction angle (°) | Unit weight (kN/m$^3$) |
| 1 | 30 | 23.7 | 19.39 | 13.45 | 15.31 | 16.34 | 19.42 |
| 2 | 25 | 71.9 | 24.10 | 14.11 | 65.4 | 22.19 | 20.06 |
| 3 | 24.98 | 71.9 | 24.12 | 14.12 | 68.09 | 24.27 | 18.33 |
| 4 | 28 | 50.2 | 21.05 | 13.71 | 41.11 | 17.02 | 19.25 |
| 5 | 28.1 | 49.1 | 20.96 | 13.70 | 40.21 | 17.12 | 19.41 |
| 6 | 25.1 | 71.5 | 23.98 | 14.10 | 67.85 | 24.25 | 19.87 |
| 7 | 26.1 | 66.4 | 22.89 | 13.97 | 61.28 | 22.61 | 19.92 |
| 8 | 28.3 | 46.8 | 20.79 | 13.67 | 39.66 | 17.37 | 18.45 |
| 9 | 30.1 | 22.1 | 19.31 | 13.43 | 15.45 | 18.43 | 18.03 |
| 10 | 28.01 | 50.1 | 21.04 | 13.71 | 41.06 | 21.55 | 19.63 |
| 11 | 27.3 | 57.2 | 21.70 | 13.81 | 53.55 | 23.61 | 20.71 |

slope at the temporal scale from satellite-derived soil moisture data is possible using geospatial techniques. However, the accuracy and reliability of the model should be validated with the ground truth measurements. Natural soil moisture varies seasonally, and which in turn influences the stability of slopes, which need to be considered. The $R^2$ values of 0.991, 0.657, and 0.523 for c, φ, and γ, respectively, are found to be statistically significant. The proposed model has the ability to represent a visual and virtual geotechnical laboratory as correlations are arrived at using soil moisture with slope and geotechnical parameters.

## References

1. Park, S., Kim, W., Lee, J., Baek, Y.: Case study on slope stability changes caused by earthquakes—focusing on Gyeongju 5.8 $M_L$ EQ. Sustain. **10**, 3441 (2018)
2. Walde, S., Kale, K., Kundu, S., Nagaraj, P., Shelar, T., Shukla, VK.: GIS-based landslide susceptibility assessment of Malin area: a case study in the watershed India. In: 17th Esri India User Conference 2017, New Delhi (2017)
3. Martha, T.R., Roy, P., Khanna, K., Mrinalni, K., Vinod Kumar, K.: Landslides mapped using satellite data in the Western Ghats of India after excess rainfall during August 2018. Curr. Sci. **117**(5):804–812. (2019) https://doi.org/10.18520/cs/v117/i5/804-812
4. Rahardjo, H., Lim, T.T., Chang, M.F., Fredlund, D.G.: Shear-strength characteristics of a residual soil. Can. Geotech. J. **32**, 60–77 (1995)
5. Terlien, M.: The determination of statistical and deterministic hydrological landslide-triggering thresholds. Environ. Geol. **35**, 124–130 (1998)
6. Cocka, E., Erol, O., Armangil, F.: Effects of compaction moisture content on the shear strength of an unsaturated clay. Geotech. Geol. Eng. **22**, 285–297 (2004)

7. Omar, H., Ibrahim, A.L., Hashim, M.: Slope stability analysis using remote sensing data in department of remote sensing, faculty of geoinformation science and engineering. Universiti Teknologi Malaysia. Vol, Proceeding of AARS-ACR (2007)
8. Duncan, J.M., Wright, S.G.: Soil Strength and Slope Stability. Wiley, Hoboken, New Jersey (2005)
9. Dickson. Qin, Z., Karnieli, A., Berliner, P.: A mono-window algorithm for retrieving land surface temperature from landsat TM data and its application to the Israel–Egypt border region. Int. J. Remote. Sens. **22**(18), 3719–3746 (2001)
10. Raj, J.K.: Characterization of the weathering profile developed over porphyritic biotite granite in Peninsular Malaysia. Bull. Int. Assoc. Eng. Geol. Paris. **32**, 121–127 (1985)

# Application of Bi-directional Extreme Learning Machine in Predicting Stability of Slope of Railway Embankment in Seismic Condition

**Abidhan Bardhan, B. Dhilipkumar, Lakshmi Mulagala, and Pijush Samui**

## 1 Introduction

Railway tracks are normally built on the natural ground surface or the elevated formation and the tracks are laid on a prepared bed called Permanent way, prepared either in cutting, filling of earthwork, or combination of both. Necessary longitudinal gradients and cross slopes are provided during the construction of the formation bed. The rails are attached to the sleeper with help of fasteners and the sleepers rest on a ballast cushion. All these elements together are called 'rail track system' and act as a single unit. In general, railway projects are carried out with large earthwork which leads to high initial expenditure during the course of the construction of permanent way. Therefore, for the safety of the entire system, a detailed analysis should be done before the track system comes into actual use.

Evaluation of slope stability is a challenging task for geotechnical engineers which is the most encountered problem in the transport network. The heterogeneous property of soil makes it difficult for engineers to assess reliability accurately. Nowadays, several methods are available to determine the slope stability of the embankment. These methods are of two types, i.e. deterministic or probabilistic [1–4]. Methods like the Strength reduction method (SRM), Limit equilibrium method (LEM), and Limit analysis method comes under deterministic type. The deterministic analysis is

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based on the evaluation of the factor of safety which will determine the stability of the embankment. Among the various slip surfaces, the one which gives a minimum factor of safety is termed as a critical slip surface and the corresponding factor of safety is termed as a critical factor of safety. For the determination of the critical factor of safety, a trial and error approach is normally being used.

On the other hand, undesirable constituents such as pebbles, wastes, organic matter, etc. develop spatial variability within the soil and uncertainties in soil parameters, i.e. cohesion, internal friction, and unit weight. Because of these uncertainties involved, the deterministic methods have limitations in their application. Using the LEM, satisfactory results can only be obtained when the soil parameters are correctly accessed. Therefore, due to the complex and multi-factorial interactions between factors that affect slope stability, the task of assessment of slope stability remains a significant challenge for geotechnical engineers [5]. Considering these phenomena, this study implements a soft computing approach, i.e. Bi-Directional extreme learning machine (Bi-ELM) for the assessment of slope stability. The remainder of this paper is structured as follows including the Instruction section. In the next section, the methodological details of LEM techniques along with the employed soft computing techniques, i.e. ELM and Bi-ELM are furnished. This is followed by, discussion of the analysis of slope stability and results and discussion. At the end, a summary and conclusion is furnished.

# 2 Methodology

## 2.1 Conventional Analysis of Slopes

In the LEM technique, the factor of safety of slopes can be defined as the ratio between resistance and disturbance along a probable slope surface. Many available methods that are based on the method of slices [6] can be used to determine the factor of safety. For a typical slope given in Fig. 1, the factor of safety can be determined using the Bishop‘s simplified method given by

$$FOS = \frac{\sum_{i=1}^{n} [C_i \Delta x_i + (W_i - u_i \Delta x_i) \tan(\phi_i)] \frac{sec\alpha_i}{1+\tan(\phi_i)\tan(\alpha_i)/FOS}}{\sum_{i=1}^{n} (W_i \ \tan \alpha_i)} \tag{1}$$

where $W_i$ are $\Delta x_i$ are the weight and width of the ith slice, respectively, $\phi_i$ and $C_i$ represent the angle of internal friction and cohesion, respectively, at the base of ith slice, $u_i$ is the pore water pressure and $\alpha_i$ is the tangential angle, respectively, at the base of ith slice and $n$ denotes the total number of the slice. To calculate the critical factor of safety, a trial and error method is used.

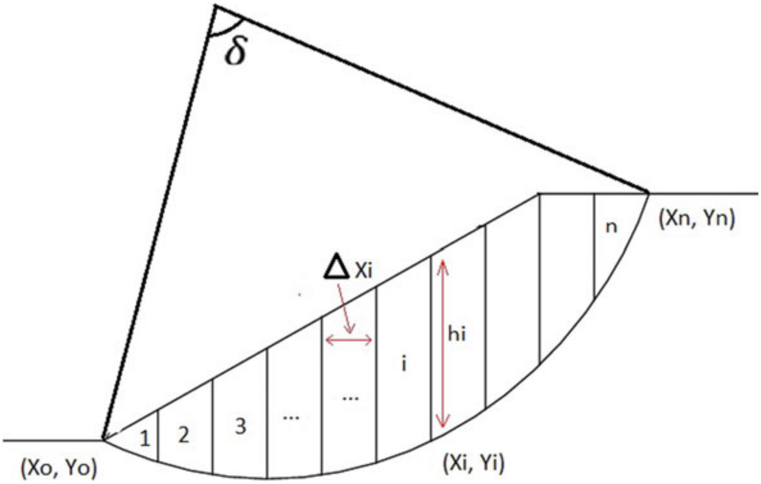


**Fig. 1** Sectional details of a typical soil slope

## *2.2 Extreme Learning Machine*

ELM, proposed by Huang et al. [5] is a type of single layer feed-forward network used in the classification and regression problem. During training, weights and biases are assigned at random and then the output weights are calculated with a defined number of the hidden layer neurons and activation function. Network structure of ELM is shown in Fig. 2 with a single hidden layer having 2 neurons.

Now, for example, a set with input $X_i = [X_{i1}, X_{i2}, X_{i3} \ldots.., X_{in}]^T \in \mathbb{R}^n$ and output $Y_i = [Y_{i1}, Y_{i2}, Y_{i3} \ldots.., Y_{im}]^T \in \mathbb{R}^m$ where $i = 1, 2, 3, \ldots..p$, then the structure of the ELM can be mathematically expressed as

$$t_j = \sum_{k=1}^{p} \beta_k g\left(\mathrm{w}_k, b_k, z_j\right) \tag{2}$$

where $w_k$ and $b_k$ represent the input weight and biases of the $kth$ hidden node, $z_j = \left[z_{ij}, z_{2j}, z_{3j} \ldots.., z_{nj}\right]^T$ is the output weight, $g(w_k, b_k, z_j)$ represents the output of the $kth$ hidden node to the input of $z_j$, $t_j$ represents the predicted output of the corresponding input $z_j$ and j is the number of training samples. Right after the generation of input weight and biases randomly, ELM estimates $\beta$ using the following expression:

$$\beta_{min} = ||H \times \beta - T|| \tag{3}$$

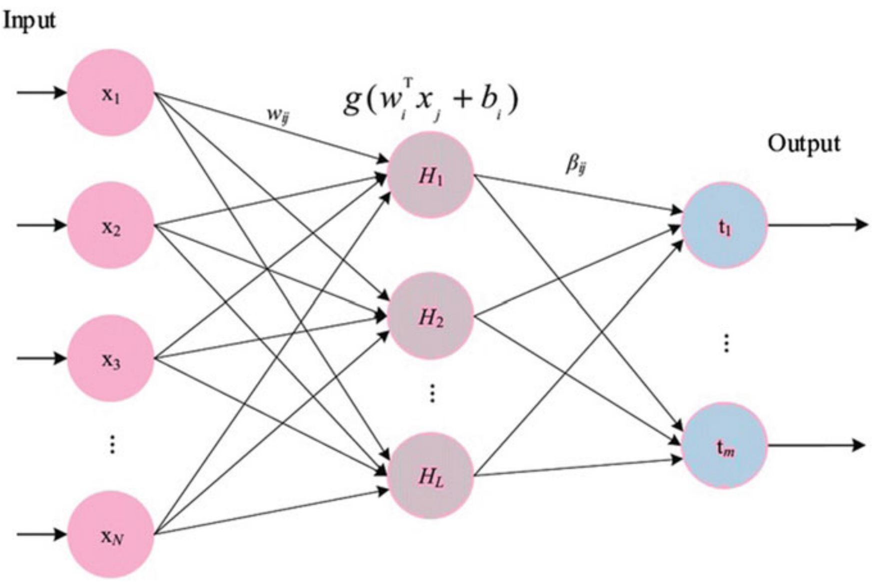


**Fig. 2** A basic structure of ELMs

And, in the next step, the output weights are calculated using the linear equation given by

$$\beta_{min} = H * pin\mathrm{v}(Y) \tag{4}$$

where H represents the output vector coming from the hidden layer and $pinv(Y)$ represents the Moore–Penrose pseudoinverse training data. The output vector can be written as

$$H = \begin{bmatrix} g(\mathrm{w}_1, b_1, x_1) & \cdots & g(\mathrm{w}_p, b_p, x_1) \\ \vdots & \ddots & \vdots \\ g(\mathrm{w}_1, b_1, x_q) & \ldots & g(\mathrm{w}_p, b_p, x_q) \end{bmatrix} \tag{5}$$

Lastly, the output weight from the hidden layer is used to get the desired output for a new set of data, i.e. testing data as follows:

$$Y_{i-new} = X_{i-new} * z_j \tag{6}$$

### 2.3 Bi-directional ELM

Although the structure of ELM seems simple and has much faster training speed than traditional tuning-based learning methods, but the selection of an optimum number of neurons in the hidden layer still remains an intractable challenge. Generally, the number of hidden neurons is predefined by the users and the trial and error approach has been followed to obtain the optimal no. of hidden neurons. Thus, this process can't always obtain the best network structure which likely causes under-fitting or over-fitting.

To avoid this problem, Yang et al. [7] proposed Bi-ELM, in which Yang divides the training operation into two parts. When the number of hidden nodes $L \in \{2n+1, n \in Z\}$, the hidden node parameter $(\omega_i, b_i)$ is generated randomly. When the number of hidden nodes $L \in \{2n, n \in Z$, the hidden node parameter $\omega_i$, $b_i$ is obtained as per the following expressions:

$$\widehat{\omega}2n = g^{-1}(u(H_{2n})) \cdot x^{-1} \tag{7}$$

$$\widehat{b}2n = \sqrt{mse\left(g^{-1}(u(H_{2n})) - \omega 2n \cdot x\right)} \tag{8}$$

$$\widehat{H}2n = u^{-1}\left(g^{-1}\omega 2n \cdot x + b2n\right) \tag{9}$$

where $u^{-1}$ and $g^{-1}$ indicate the inverse functions of $u$ and $g$, respectively.

Several applications of Extreme Learning Machine are available in the literature [8–11] and researchers are using this technique in predicting the desired output in every field of engineering.

## 3 Slope Stability Analysis

As mention in the previous section, the limit equilibrium approach is used in this study in estimating the stability of slopes. To perform the analysis, 50 data sets are generated randomly considering the lower limit and upper limit of the soil parameter (Table 1) and then the slope stability analysis has been performed in SLOPE-W software separately for static as well as seismic conditions. A 12.293 m high embankment with 2H:1 V side slopes is considered in the analysis. The shear strength properties for different layers are presented in Fig. 3. The typical section of the proposed formation comprises of sleeper and ballast cushion (350 mm depth) at the top followed by a 600 mm thick blanket layer and which is underlaid by a 1000 mm thick prepared subgrade. The prepared subgrade is an integral part of the embankment fill of varying height.

**Table 1** Statistical details of soil parameters for different layers

| Parameters | Min | Max | Mean | Median | Std. error | Std. dev | Variance | Kurtosis | Skewness |
|---|---|---|---|---|---|---|---|---|---|
| $\gamma_1$ | 17.00 | 18.43 | 17.76 | 17.78 | 0.05 | 0.46 | 0.21 | −1.47 | −0.02 |
| $C_1$ | 2.00 | 10.00 | 5.70 | 5.68 | 0.22 | 2.23 | 4.97 | −1.09 | 0.08 |
| $\phi_1$ | 26.00 | 33.70 | 29.67 | 29.75 | 0.23 | 2.34 | 5.50 | −1.26 | 0.07 |
| $\gamma_2$ | 15.50 | 18.60 | 16.96 | 17.11 | 0.08 | 0.80 | 0.64 | −0.83 | −0.07 |
| $C_2$ | 0.00 | 155.00 | 83.88 | 91.00 | 4.41 | 44.06 | 1941.52 | −0.90 | −0.37 |
| $\phi_2$ | 9.80 | 34.00 | 21.70 | 21.05 | 0.74 | 7.40 | 54.83 | −1.18 | 0.12 |
| $\gamma_3$ | 16.00 | 17.70 | 16.88 | 16.89 | 0.05 | 0.47 | 0.22 | −1.10 | −0.09 |
| $C_3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | – | – |
| $\phi_3$ | 27.00 | 31.00 | 28.99 | 28.96 | 0.10 | 1.03 | 1.05 | −0.76 | −0.03 |

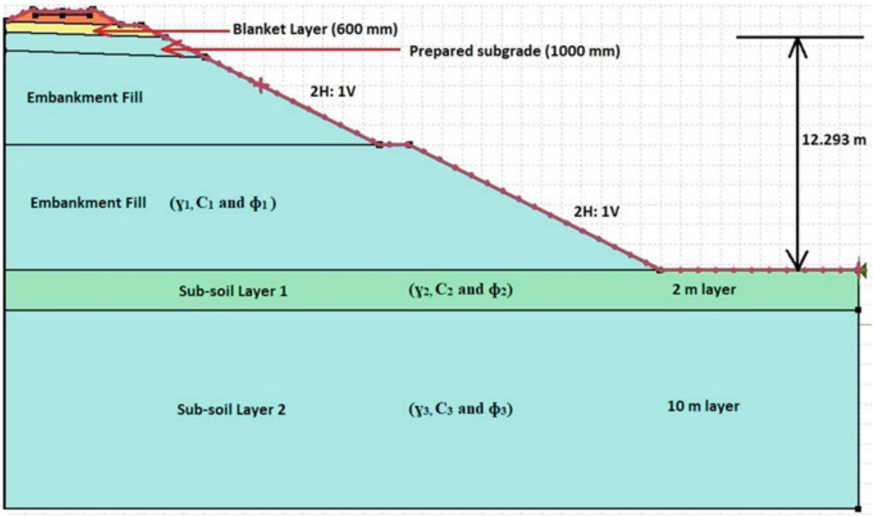


**Fig. 3** Cross-sectional details of 12.293 m high embankment

For the embankment fill, the values of shear parameters considered as $\gamma_1$, $C_1$ and $\phi_1$, for the sub-soil layer-1, it is $\gamma_2$, $C_2$ and $\phi_2$ and for sub-soil layer-2, it is $\gamma_3$, $C_3$ and $\phi_3$. The statistical details of the shear parameters of different layers considered in the analysis are given in Table 1.

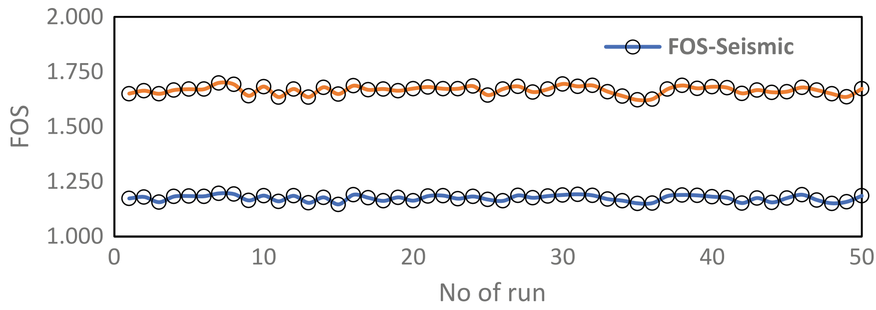


**Fig. 4** Variation in FOS in static and seismic condition in different cases

# 4 Results and Discussion

## *4.1 Evaluation of FOS in Static and Seismic Conditions*

The values of the factor of safety have been calculated in SLOPE-W software in static conditions as well as seismic conditions. To determine the factor of safety in seismic conditions, the values of co-efficient of ground acceleration $k_h$ and $k_v$ are considered as 0.16 and 0.08$g$, respectively, for Zone III. The values of Z, I and S are taken as 0.16, 1.5 and 2.0. Figure 4 represents the variation of factor of safety for different values of cohesion, angle of internal friction and unit weight of soils. The values of the critical factor of safety in static and seismic conditions are obtained as 1.622 and 1.146, respectively. Figures 5 and 6 the critical failure surface, respectively, for static analysis and seismic-based analysis.

## *4.2 Assessment of Bi-directional ELM Model*

Now, prior to the development of the model, the total dataset has been normalized between 0 and 1, and then divided into two portions, i.e. training and testing. In the training portion, 75% of the entire dataset has been selected randomly and the balance 25% of data is considered as a testing dataset. The training dataset is used to develop the Bi-ELM model, while the testing dataset is used to validate the developed model. Once the model is developed, the capability of the developed model is then assessed using five performance parameters, namely, Adjusted R$^2$ ($Adj.R^2$), mean absolute error ($MAE$), determination co-efficient ($R^2$), root mean square error ($RMSE$) and weighted mean absolute percentage error ($WMAPE$), which can be mathematically expressed as [12–15]:

$$Adj.R^2 = 1 - \frac{(n-1)}{(n-p-1)}(1-R^2) \tag{10}$$

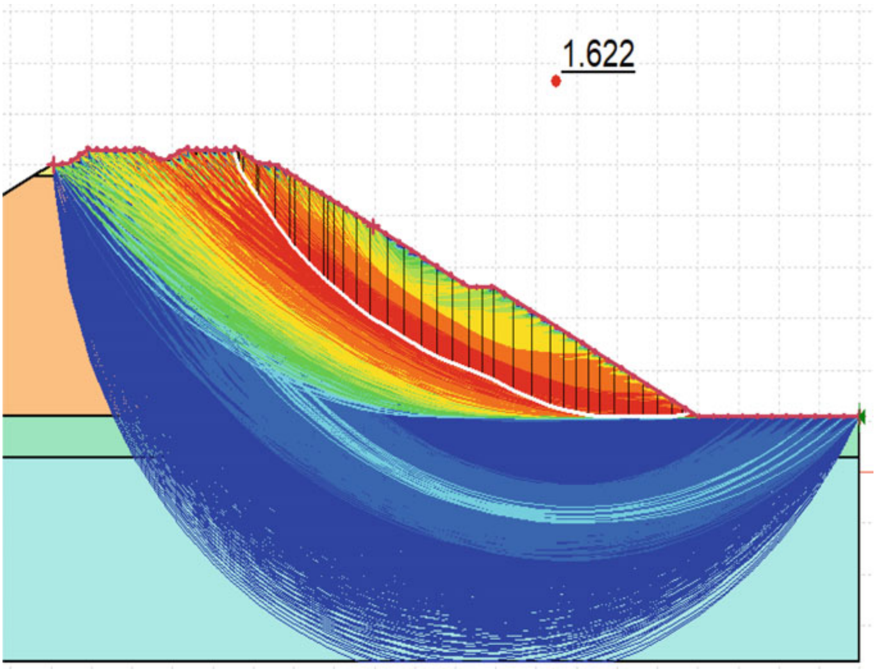


**Fig. 5** Analysis of factor of safety in static condition showing all failure surface

$$MAE = \frac{1}{n}\sum\nolimits_{i=1}^{n}\left|\left(\hat{y}_i - a_i\right)\right| \tag{11}$$

$$R^2 = \frac{\sum_{i=1}^{n}(a_i - a_{mean})^2 - \sum_{i=1}^{n}(a_i - p_i)^2}{\sum_{i=1}^{n}(a_i - a_{mean})^2} \tag{12}$$

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(a_i - p_i)^2} \tag{13}$$

$$WMAPE = \frac{\sum_{i=1}^{n}\left|\frac{a_i - p_i}{y_i}\right| \times a_i}{\sum_{i=1}^{n} a_i} \tag{14}$$

where $a_i$ and $p_i$ are the observed and predicted $ith$ value, $n$ is the number of samples in a dataset, $a_{mean}$ is the mean of the observed values. For a perfect model, the value of these statistical parameters should be equal to their ideal value as $Adj.R^2 = 1$, $MAE = 0$, $R^2 = 1$, $RMSE = 0$ and $WMAPE = 0$.

Table 2 represents the details of performance parameters determined for the developed model in the training and testing phase. As can be seen, the values of all the performance parameters are quite close to their ideal value. The Bi-ELM model achieved 100% accuracy in terms of $R^2$ value ($R^2 = 0.9983$ i.e., 99.83%) in the

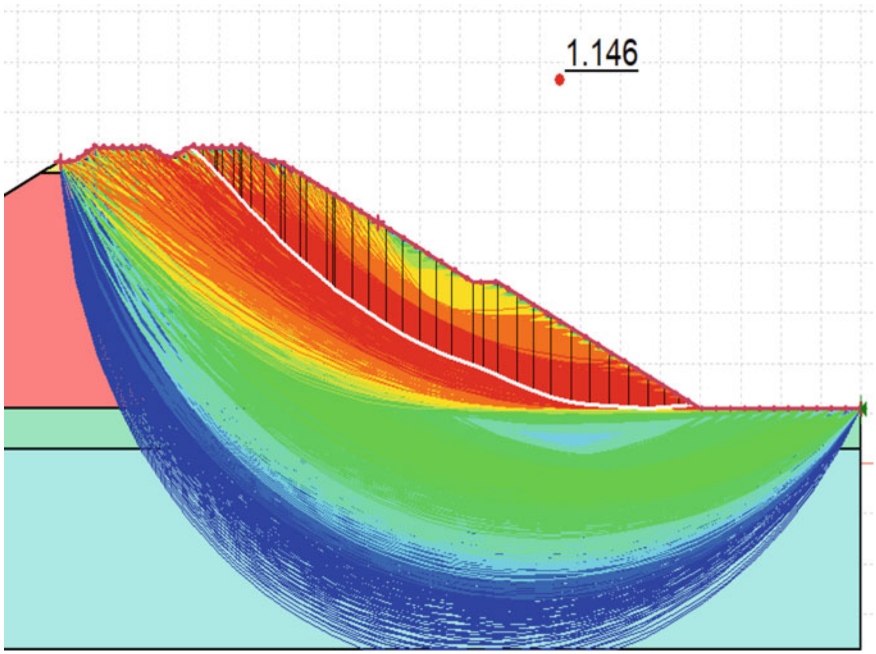


**Fig. 6** Analysis of factor of safety in seismic condition showing all failure surface

**Table 2** Performance parameters of the developed model in training and testing phase

| Parameters | Bi-ELM (Training) | Bi-ELM (Testing) |
|---|---|---|
| Adj.$R^2$ | 0.9980 | 0.9971 |
| MAE | 0.0149 | 0.0150 |
| $R^2$ | 0.9983 | 0.9983 |
| RMSE | 0.0184 | 0.0181 |
| WMAPE | 0.0312 | 0.0259 |

training phase as well as in the testing phase. Also, the values of MAE (0.0149 in training and 0.0150 in testing phase) and RMSE (0.0184 in the training and 0.0181 in the testing phase) show that the model has very good generalization capability in both the phase. It is also understood from the other performance parameters that the capability in predicting the factor of safety in the static as well as seismic conditions of the developed model is quite satisfactory (Fig. 7).

Also, the match between the actual and predicted values of the factor of safety is shown in Fig. 8 in the form of a scatter plot. As can be seen, all the values predicted by Bi-ELM lie on the line of the ideal model, and hence the developed Bi-ELM model can be considered as a perfect model to predict the factor of safety of any railway embankment provided that the wide range of data is available.


**Fig. 7** Graphical representation of the performance of the Bi-ELM model Fig. **a** showing MAE, RMSE and WMAPE, and Fig. **b** showing Adj. $R^2$ and $R^2$

## 5 Summary and Conclusion

In this study, the authors developed a soft computing model, i.e. Bi-Directional Extreme Learning Machine to predict the slope stability of railway embankment. For this, the values of shear strength parameters of soils are generated randomly and considered in the analysis. A 12.293 m high embankment is considered with embankment fill, sub-soil layer-1 and sub-soil layer-2. Different values of cohesion, angle of internal friction and unit weight are considered for all three layers. A set of 50 data was generated randomly and assigned in each run to obtained the factor of safety in the static case as well as in the seismic case separately.

In the next stage, the values of $\gamma_1, C_1$, $\phi_1$, $\gamma_2, C_2$, $\phi_2 \gamma_3, C_3$, $\phi_3$, $k_h$ and *fos* is used to develop the soft computing model. However, prior to the development of the model, the entire dataset has been normalized between 0 and 1 and then divided into training and testing datasets. Right after the data partitioning, the training dataset is used to develop the Bi-ELM model. Later, the developed model is assessed in terms of performance parameters ($Adj.R^2$, MAE, $R^2$, $RMSE$ and WMAPE). It is

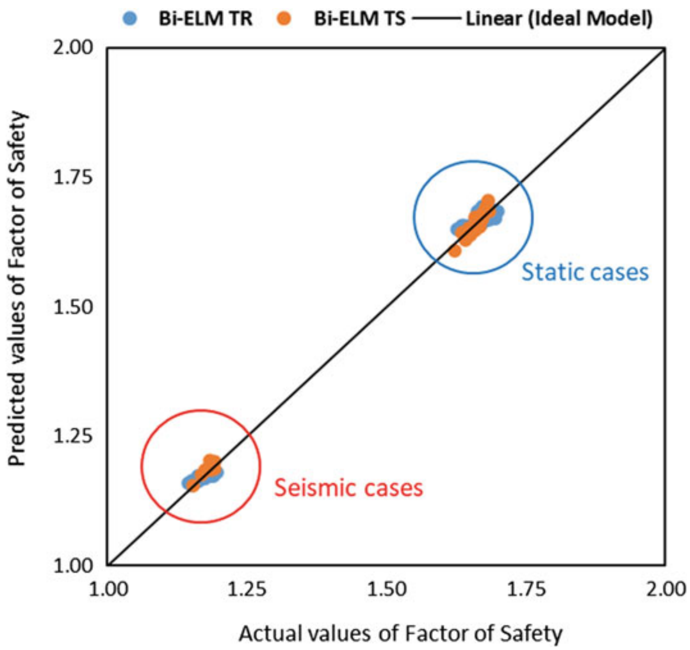


**Fig.8** Scatter plot showing the match between actual and predicted values of factor safety

understood from the results of the performance parameters that the developed model is capable enough of predicting the factor of safety. Overall, the Bi-ELM model is highly recommended as an intelligent tool to assist the decision-making process for the assessment of slope stability.