

CHAPTER 5

NUMERICAL SIMULATION AND LANDSLIDE HAZARD CHARTS

5.1 Introduction

The residual soil plays a significant role in governing the stability of slopes. The geotechnical properties of the bedrock and the residual soil are not uniform. Instead, they follow a stochastic pattern, although the selected lithologies are the same in the study area (Table 4.4 to Table 4.15). This can be attributed to the varying hydrological regime and weathering process owing to intense anthropogenic activities accompanied by changing local climatic conditions. In order to model these stochastic variations, probabilistic analysis has been utilised to give a reliable result for the selected lithologies in the Lesser Himalayan region. In order to carry out probabilistic analysis, statistical analysis of the data obtained through in-situ testing, laboratory testing and literature review was performed initially. During statistical analysis, the statistical distributions and their respective distribution parameters are identified for each selected random variable. After that, sampling was performed using the Monte Carlo Simulation method based on the statistical analysis results. The results obtained through probabilistic numerical analysis was finally utilised to formulate landslide hazard charts that will be useful in identifying the landslide potential for the slopes under study by considering a few physical and geotechnical parameters of the slope.

5.2 Probabilistic Slope Stability Analysis

Probabilistic analysis requires at least one random variable as an input parameter from all the geotechnical properties. Statistical properties of the selected random variables used for probabilistic analysis are determined by statistical analysis of available geotechnical and geological data (Vanmarcke 1980). The type of statistical distribution (generally normal/lognormal/triangular/exponential for geotechnical parameters), together with the

distribution parameters (mean, standard deviation, relative minimum and relative maximum values), define a Probability Density Function (PDF) for a random variable. The statistical distribution for a particular random variable is generally obtained using curve fitting of the geotechnical data obtained through laboratory tests, field investigations and literature review. A PDF describes the distribution of possible values that a random variable may assume for a hypothetical, infinite set of observations of the variable (Wang et al. 2015).

After selecting the random variable and identifying its PDF and statistical properties, the probabilistic analysis can be performed using various sampling methods like Monte Carlo, Latin Hypercube, or the Point Estimate method. The Monte Carlo Sampling Method (MCSM) has been used in the present study since the number of samples can be defined directly, and there is flexibility in choosing from a wide variety of statistical distributions for each variable. The sampling procedure has been already explained in Section 2.4.2

5.2.1 Statistical Analysis of Random Geotechnical Variables

Owing to difficulty in conducting detail bedrock geotechnical characterization due to limited resources, complex topography and harsh climatic conditions, the bedrock properties of the selected lithologies was taken from several case studies performed across the selected area (Falae et al. 2021; Kainthola et al. 2015; Kanungo et al. 2013; Mahanta et al. 2016; Mishra et al. 2018; Pain et al. 2014; Pandit et al. 2016; Solanki et al. 2019). The statistical distribution of the several random variables (geotechnical properties) of the residual soil, the weathered rock mass and the bed rock layer was obtained from curve fitting of the data obtained from field observations (Table 4.2), laboratory testing (Table 4.4 to Table 4.15) and detailed literature review (Table 4.17 and Table 4.18). The curve fitting of a statistical model describes how well it fits a set of observations into standard statistical distribution. Curve filling typically summarises the

discrepancy between observed values and the values expected under the model in development. Statistical analysis has been performed using Statistica Software (StatSoft 2011). Kolmogorov–Smirnov test, Anderson-Darling test and Chi-Square test are important tests for identifying the most appropriate PDF and its distribution parameters for the selected random geotechnical variable. Kolmogorov–Smirnov test has been used in the present study for the selection of a particular PDF to select a random geotechnical variable.

The Kolmogorov–Smirnov test (K–S test or KS test) is a nonparametric test of the equality of continuous, one-dimensional probability distributions that can be used to compare a sample with a reference probability distribution (one-sample K–S test) or to compare two samples (two-sample K–S test) (Chakravarti et al. 1967). The Kolmogorov–Smirnov statistic quantifies a distance between the empirical distribution function of the sample and the Cumulative Distribution Function (CDF) of the reference distribution (Fig 5.1).

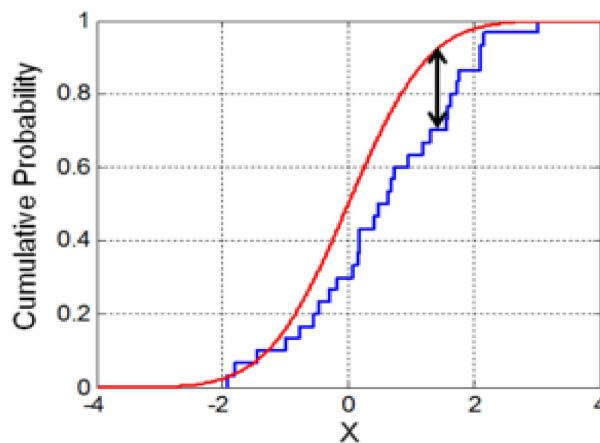


Fig. 5.1. Illustration of the Kolmogorov–Smirnov statistic. The red line is a model CDF, the blue line is an empirical CDF, and the black arrow is the K–S statistic (Selezneva et al. 2003)

The Kolmogorov-Smirnov test is defined by (Ruppert 2004):

Null Hypothesis (H_0): The data follow a specified distribution

Alternate Hypothesis (H_a): The data do not follow the specified distribution

Test Statistic or D statistics: The Kolmogorov-Smirnov test statistic is defined as

$$D = \sup_x |F_0(x) - F_{data}(x)| \quad (5.1)$$

where $F_0(x)$ is the CDF of the hypothesised distribution and $F_{data}(x)$ is the empirical distribution function of your observed data. The hypothesis regarding the distributional form is rejected if the test statistic, D , is greater than the critical value obtained from the K-S Test P-Value table.

An attractive feature of this test is that the distribution of the K-S test statistic itself does not depend on the underlying cumulative distribution function being tested, i.e., the test is distribution-free. There is no restriction on sample size in the K-S test (e.g., the chi-square goodness-of-fit test depends on adequate sample size for the approximations to be valid). Also, the D statistics used for the test is easy to calculate.

The geotechnical parameters that affect the slope stability analysis generally follow a continuous PDF (Normal, Uniform, Triangular, Beta, Exponential, Lognormal and Gamma distribution) (Wang et al. 2015). Thus, during curve fitting using the K-S test, efforts have been made to select the best fit continuous distribution for each random variable. The results of the curve fitting are shown in Table 5.1 to Table 5.5. It was observed that the random geotechnical parameters mostly follow the lognormal distribution followed by the normal distribution. A very few geotechnical parameters follow the triangular distribution. Most soil strength measurements reflect the influence of moderate to large volumes of soils within which the effects of individual elements add to those of other elements to produce the macroscopic property. Thus, from a random process model view, soil strength is in averaging process, and the obtained results tend towards lognormal and normal distributions.

The distribution parameters obtained from the selected statistical distribution of the various geotechnical properties representing the residual soil (natural disturbed and remoulded), weathered

rock mass and the bed rock layer is shown in Table 5.1 to Table 5.5. The identification of distribution parameters includes Mean, Standard Deviation (StD), Relative Minimum and Relative Maximum. The mean denotes the weighted average of the values that the random variable can take, representing the measure of the central location of a random variable. The standard deviation of a random variable measures the variance or scatter of the variable about the mean value. It must be noted that the standard deviation is applicable for Normal, Lognormal, Beta, and Gamma distributions, whereas it is not applicable for Uniform, Triangular, or Exponential distributions. A Uniform and Triangular distribution is specified by its minimum, maximum and mean values only. The Minimum and Maximum values define the allowable limits of a random variable. For the purposes of data input, the Minimum/Maximum values are specified as Relative quantities (i.e., as distances from the Mean) rather than as absolute values. This simplifies the data input and is much less prone to error. During the analysis, the Relative Minimum and Maximum values are converted to the actual Minimum and Maximum values when the statistical sampling is carried out for each random variable, i.e.

$$\text{Minimum} = \text{Mean} - \text{Relative Minimum} \quad (5.2)$$

$$\text{Maximum} = \text{Mean} + \text{Relative Maximum} \quad (5.3)$$

Table 5.1: Statistical distribution and distribution parameters of residual soil (natural disturbed sample)

Properties	PDF	Mean	StD	Relative Min.	Relative Max.
Cohesion (kPa)	Log Normal	29.233	17.512	11.134	14.542
Friction Angle ($^{\circ}$)	Log Normal	34.867	4.754	3.247	5.543
Unit Weight (kN/m³)	Triangular	0.026	NA	0.001	0.001
Young's Modulus (MPa)	Log Normal	72.167	32.748	28.377	34.632
Soil Rock Interface Cohesion (kPa)	Normal	1.258	0.751	0.314	0.314
Soil Rock Interface Friction Angle ($^{\circ}$)	Normal	31.409	3.357	6.528	6.528

Table 5.2: Statistical distribution and distribution parameters of residual soil (remoulded sample)

Cohesion (kPa)								
Water content (%)	0	0	0	0	10	10	10	10
Fine content (%)	0	10	20	30	0	10	20	30
PDF	NA	Normal	Log Normal	Log Normal	NA	Normal	Log Normal	Normal
Mean	NA	2.43	6.34	16.81	NA	12.67	44.54	56.85
StD	NA	1.42	2.22	2.48	NA	4.36	15.96	19.04
Relative Min.	NA	1.1	1.9	2.1	NA	4.05	12.95	16.94
Relative Max.	NA	1.1	2.1	2.3	NA	4.05	14.01	16.94
Water content (%)	20	20	20	20	30	30	30	30
Fine content (%)	0	10	20	30	0	10	20	30
PDF	NA	Normal	Normal	Normal	NA	Normal	Log Normal	Normal
Mean	NA	6.35	25.49	45.94	NA	2.88	22.95	34.34
StD	NA	2.24	9.13	15.41	NA	1.34	17.12	11.6
Relative Min.	NA	2.1	8.3	11.2	NA	1.1	12.15	9.8
Relative Max.	NA	2.1	8.3	11.2	NA	1.1	12.19	9.8
Angle of Friction (°)								
Water content (%)	0	0	0	0	10	10	10	10
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Normal	Triangular	Log Normal	Log Normal	Log Normal	Log Normal	Log Normal	Normal
Mean	41.82	41.46	39.21	35.69	39.58	36.42	30.96	28
StD	1.64	NA	1.95	1.84	1.51	1.44	1.39	1.2
Relative Min.	4.92	4.206	5.85	5.52	4.53	4.32	4.17	3.6
Relative Max.	4.92	4.206	5.89	5.56	4.57	4.36	4.21	3.6
Water content (%)	20	20	20	20	30	30	30	30
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Normal	Log Normal	Log Normal	Normal	Normal	Log Normal	Triangular	Log Normal
Mean	35.62	32.78	30.21	25.66	32.01	26.33	24.09	20.38
StD	2.16	1.98	1.16	1.55	1.5	1.36	NA	1.33
Relative Min.	6.48	5.94	3.48	4.65	4.5	4.08	4.83	3.99
Relative Max.	6.48	5.99	3.51	4.65	4.5	4.14	4.83	4.06
Young's Modulus (MPa)								
Water content (%)	0	0	0	0	10	10	10	10
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Mean	96.69	96.32	89.35	81.26	90.03	82.24	70.13	64.92
StD	17.6	17.73	16.88	15.32	16.79	15.72	14.8	12.14
Relative Min.	52.8	53.19	50.64	45.96	50.37	47.16	44.4	36.42
Relative Max.	52.8	53.19	50.64	45.96	50.37	47.16	44.4	36.42
Water content (%)	20	20	20	20	30	30	30	30
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal

Mean	81	72.85	64.78	53.48	68.89	48.25	44.5	41.29
StD	15.11	13.57	12.11	9.88	12.95	8.95	8.63	7.56
Relative Min.	45.33	40.71	36.33	29.64	38.85	26.85	25.89	22.68
Relative Max.	45.33	40.71	36.33	29.64	38.85	26.85	25.89	22.68
Unit Weight (kN/m³)								
Fine content (%)	0	10	20	30				
PDF	Triangular	Normal	Normal	Normal				
Mean	0.026	0.026	0.027	0.027				
StD	NA	0.0006	0.0006	0.0006				
Relative Min.	0.0022	0.0018	0.0017	0.0019				
Relative Max.	0.0022	0.0019	0.0017	0.0019				

Table 5.3: Statistical distribution and distribution parameters of remoulded residual soil-weathered rock interface strength parameter

Soil Rock Interface Cohesion (kPa)								
Water content (%)	0	0	0	0	10	10	10	10
Fine content (%)	0	10	20	30	0	10	20	30
PDF	NA	NA	NA	Normal	NA	NA	Normal	Normal
Mean	NA	NA	NA	0.508	NA	NA	1.512	2.510
StD	NA	NA	NA	0.062	NA	NA	0.844	1.400
Relative Min.	NA	NA	NA	0.125	NA	NA	1.012	1.680
Relative Max.	NA	NA	NA	0.125	NA	NA	1.012	1.680
Water content (%)	20	20	20	20	30	30	30	30
Fine content (%)	0	10	20	30	0	10	20	30
PDF	NA	NA	Normal	Normal	NA	NA	Normal	Normal
Mean	NA	NA	1.260	2.092	NA	NA	0.804	1.210
StD	NA	NA	0.703	1.167	NA	NA	0.281	0.675
Relative Min.	NA	NA	0.844	1.400	NA	NA	0.337	0.810
Relative Max.	NA	NA	0.844	1.400	NA	NA	0.337	0.810
Soil Rock Interface Friction Angle (°)								
Water content (%)	0	0	0	0	10	10	10	10
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Log Normal	Normal	Log Normal	Normal	Log Normal	Normal	Log Normal	Log Normal
Mean	37.120	35.022	33.408	31.170	31.738	29.612	29.099	28.197
StD	3.281	2.866	2.953	2.551	2.805	2.423	2.598	2.510
Relative Min.	6.562	5.732	5.906	5.102	5.610	4.847	5.197	5.020
Relative Max.	6.844	5.732	6.495	5.102	5.880	4.847	5.833	5.624
Water content (%)	20	20	20	20	30	30	30	30
Fine content (%)	0	10	20	30	0	10	20	30
PDF	Log Normal	Normal	Log Normal	Log Normal	Log Normal	Log Normal	Log Normal	Log Normal
Mean	28.864	27.431	25.857	24.989	25.708	24.989	23.280	22.490
StD	2.525	2.302	2.259	2.209	2.272	2.209	2.146	1.988
Relative Min.	5.049	4.604	4.518	4.417	4.544	4.417	4.292	3.976
Relative Max.	5.366	4.604	4.749	4.736	4.935	4.948	4.562	4.295

Table 5.4: Statistical distribution and distribution parameters of weathered rock mass

Properties	PDF	Mean	StD	Relative Min.	Relative Max.
Cohesion (MPa)	Normal	10.37	5.19	5.19	5.19
Friction Angle (°)	Log Normal	28.11	8.27	8.27	10.12
Unit Weight (kN/m³)	Log Normal	0.0272	0.0007	0.0007	0.0009
Young's Modulus (GPa)	Log Normal	33.07	15.3	15.3	18.5
Tensile Strength (MPa)	Normal	9.4	4.55	4.55	4.55
Poisson's Ratio	Normal	0.225	0.045	0.075	0.075

Table 5.5: Statistical distribution and distribution parameters of bedrock

Properties	PDF	Mean	StD	Relative Min.	Relative Max.
Cohesion (MPa)	Log Normal	18.991	1.7320	1.732	1.918
Friction Angle (°)	Log Normal	33.479	2.9903	2.99	3.472
Unit Weight (kN/m³)	Triangular	0.0265	NA	0.0021	0.0021
Young's Modulus (GPa)	Log Normal	61.08	3.5	7	11
Tensile Strength (MPa)	Log Normal	13.885	1.7621	1.7621	2.061
Poisson's Ratio	Normal	0.251	0.02	0.06	0.06

5.3 Numerical Simulation

Numerical simulations have been performed using Rocscience RS2 V9.0 (<https://www.rocscience.com/software/rs2>), a finite element package for analysing stability and deformation based on the Shear Strength Reduction (SSR) technique. The application of SSR, in combination with the Finite Element Method (FEM), has been used by many researchers to evaluate the FOS and other deformation parameters for soil as well as rock slope (Dawson et al. 1999; Griffiths and Lane 1999; Pain et al. 2014; Singh et al. 2013). Apart from the presence of SSR based FEM technique, RS2 V9.0 also has an inbuilt probabilistic analysis method, which performs probabilistic analysis using various sampling methods like MCSM, Point Estimation method and Latin Hypercube method.

The step involved in numerical simulation includes identifying and gathering different geo-mechanical properties of the slope that affects its stability. These include the material properties of the geomaterial and the physical features like the thickness of the three layers (residual soil, weathered rock and bedrock), slope height, slope profile and slope angle. The following physio-

mechanical parameters that affect the overall stability of a residual soil slope were used for simulation:

- i. **Geo-Mechanical Properties:** It includes the geotechnical properties of residual soil, weathered rock layer, bedrock, and soil rock joint interface properties. The selected statistical distributions and the distribution parameters (Table 5.1 to Table 5.5) for different geo-mechanical parameters have been used for probabilistic numerical analysis.
- ii. **Physical properties:** It includes the topographical data of the physical features of the slopes like slope height, slope angle, slope profile and thickness of different layers constituting the slope.

The stability analysis in the present study has been divided into two parts. The first one includes a quick and reasonable identification of landslide hazards based on field investigations and laboratory testing of the natural (disturbed) soil samples. This will include utilising fifteen independent input variables representing the geotechnical parameters of the residual soil (disturbed), weathered rock mass layer and the topological variations of the slope. The quick identification of landslide hazards is based on the in-situ conditions of the slope. The second analysis includes a detailed investigation incorporating the variation in water content and percentage fines in the residual soil. This will include the utilisation of seventeen independent input variables representing the geotechnical parameters of the remoulded residual soil, weathered rock mass layer and the topological variations of the slope. The detailed landslide hazard identification will be helpful during stability assessment of the slope under varying water and percentage of fines content or in the case where the behaviour of the slope is needed to be assessed over a period of time.

5.3.1 Quick Identification of Landslide Hazard

Numerical models have been prepared by varying the slope height, the slope angle, and the thickness of the residual soil layer. The geotechnical parameters and their statistical properties listed in Table 5.1, Table 5.4 and Table 5.5 have been used to develop the numerical models. The slope height was varied from 50m to 500m with an interval of 50m. The selected range for height is based on field observations and literature studies. The overall slope angle was varied from 15° to 60° , with an interval of 15° . The presence of residual soil is mainly associated with gentle to moderate ($<60^{\circ}$) slope inclinations. A slope steeper than 60° was not considered since steep slopes ($>60^{\circ}$) are generally devoid of the residual soil layer and are composed of only the weathered and bed rock layer. In some cases, a very thin layer of the residual soil layer may be present; however, it is affected mainly by the slope erosion process rather than slope failure. The thickness of the residual soil layer was varied from 0.5m to 15m (0.5m, 1m, 2m, 3m, 4m, 5m, 7m, 9m, 12m, and 15m). This range is also based on field observations and literature studies. Four hundred numerical models have been simulated based on different permutation combinations of the slope height, the thickness of residual soil and the slope angle variations. Convex slope profile has been observed during field investigation (Table 4.2) and by several authors (Anbalagan et al. 2008; Chaudhary et al. 2010; Hasegawa et al. 2009; Kumar et al. 2017; Sah et al. 2018; Singh et al. 2013) in Lesser Himalayan Region. Thus a convex slope profile has been simulated by making the gentle slope at the higher level (crown portion) and steeper slope at lower levels (toe portion). The entire slope is modelled into three layers. The top layer is the residual soil layer, followed by a weathered layer that overrides the bottom bedrock. The middle-weathered layer is subdivided into two equal parts, i.e., highly weathered and moderately weathered, to incorporate the effect of weathering with depth (Little 1969; Rahardjo et al. 2004).

The thickness of the overall weathered layer has been kept two times that of the residual soil due to harsh climate and hydrological profile in the study area accompanied with increased anthropogenic activities resulting in extensive and deep weathering process in the Lesser Himalayan Region. The thickness of the residual soil layer was increased by 1.2 times as it reached the toe of the slope to incorporate the accumulation of thick debris and natural creep movement (Anbalagan et al. 2008; Chaudhary et al. 2010; Kanungo et al. 2013; Kumar et al. 2017; Kumar et al. 2018; Pandit et al. 2016; Singh et al. 2013). In all the slope models, a 25m bench width is maintained at the toe and crest of the slope. Fixed boundary conditions (zero displacements) have been used at the base of the model, and roller boundary along the lateral sides. However, the slope face and the rock-soil interface were kept free for showing strain and displacement. Two-dimensional 6-noded triangular plain strain elements have been used to discretise across the selected slope profile. A uniform meshing option has been used for the soil and weathered rock layer and graded meshing for the bedrock layer. The average element size of around 0.1m, 0.5m and 5m are kept for the residual soil, the weathered rock, and the bedrock layer, respectively.

The weathered layer of the Lesser Himalayan Region generally has 2-3 parallel crisscross joint sets as observed during field observations (Table 4.2, Fig. 4.6 and Fig. 4.7) along with extensive literature studies (Gupta et al. 2016a; Kumar et al. 2018; Pain et al. 2014; Sah et al. 2018; Sarkar et al. 1995; Sharma et al. 2015). Two crisscross joint sets with a mean dip angle of 35° and 70° having standard deviations of 5° (for both the joint sets) have been taken for the entire weathered rock layer. The Joint density for the top weathered layer is taken 0.01 cm/cm^2 , while for the bottom weathered layer is taken 0.001 cm/cm^2 in order to simulate the natural weathering process of the study area. For the bedrock, the Veneziano model for joint distribution has been considered, which resembles the best in situ condition for bedrock for the Himalayan Region

(Dershowitz and Einstein 1988). The basic slope model used for numerical simulation is shown in Fig. 5.2.

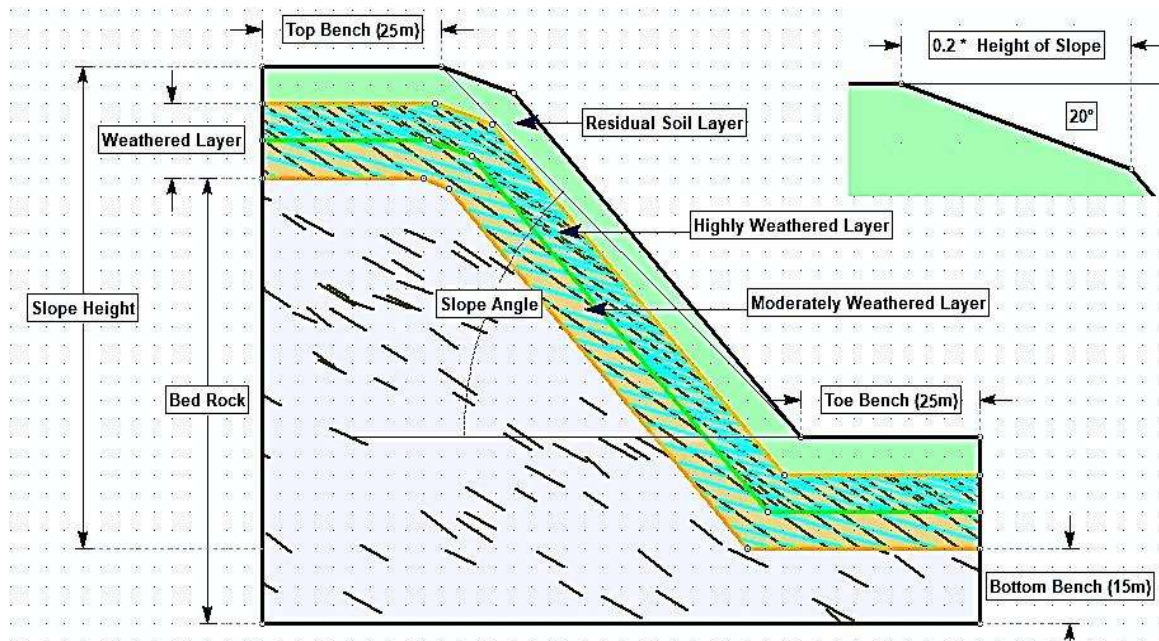


Fig. 5.2. Basic slope model used for numerical simulation

A study by Gerrard (1994) inferred that the properties of the residual soil would influence the overall stability of the residual soil slope. However, this behaviour is limited by the depth of soil cover. If the soil cover is less, the effect of discontinuities (spacing and orientation) will undoubtedly be going to affect the location and shape of the slip surface. Thus, the heterogeneity in terms of some joints or cracks in the bedrock layer was kept to simulate the natural slope profile. Numerical analysis was performed by using FEM based software so that the prior assumptions on the shape and location of failure surfaces can be eliminated (Griffiths and Lane 1999). This will help in observing (if any) the effect of joint heterogeneity (spacing and orientation) on the behaviour of residual soil slope.

Four hundred slope models were analysed, and the value of probabilistic FOS of every model has been calculated. The graphs between the FOS and thickness of residual soil for varying

slope height and different slope angle is shown in Fig 5.3. The lowest FOS value obtained from the analysis was 0.192 for the slope with 60° slope angle, 500m slope height, and 15m thickness of the residual soil. While, the highest value of FOS obtained through the analysis was 12.012 for the slope with 15° slope angle, 450m slope height, and 0.5m thickness of the residual soil.

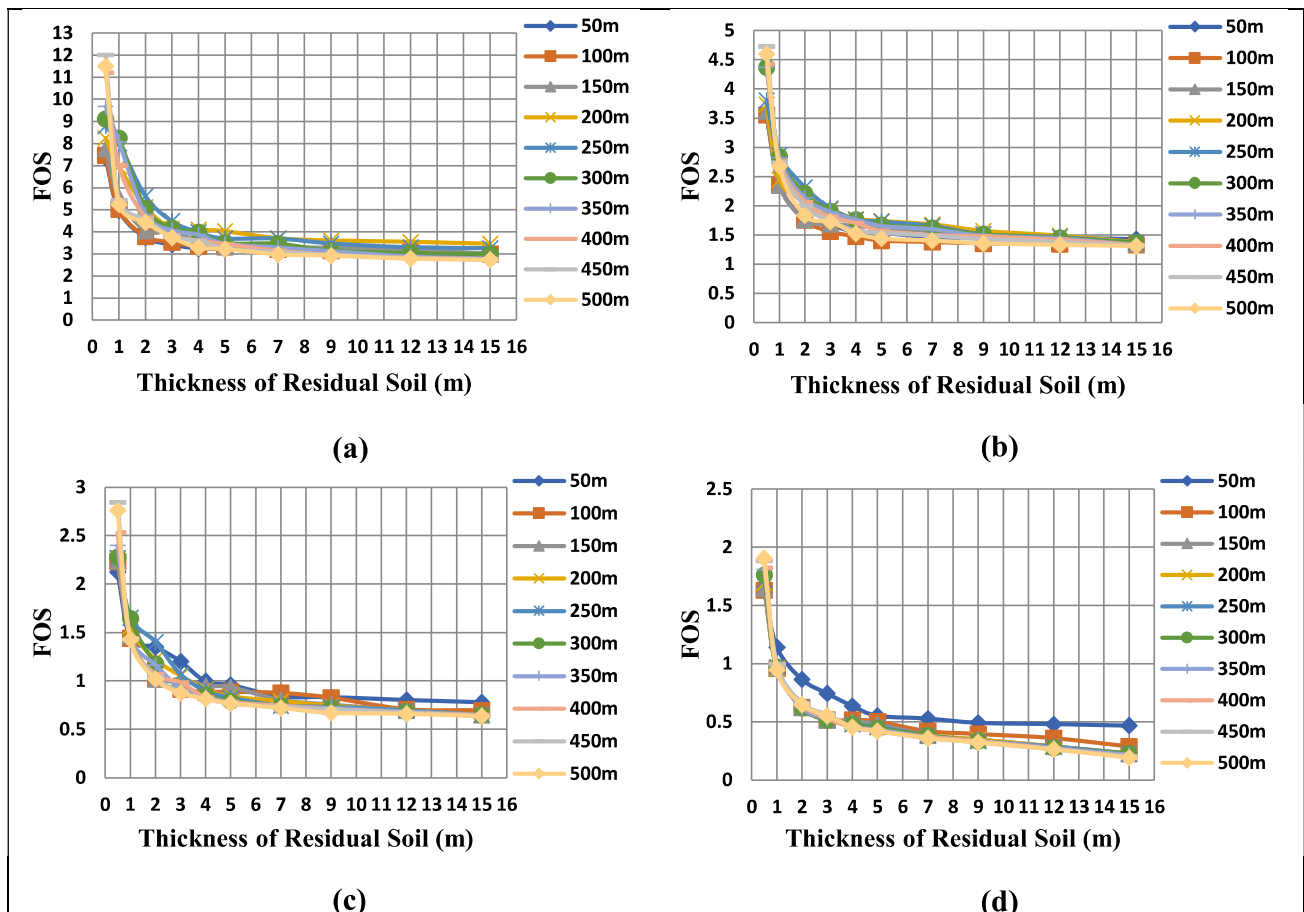


Fig. 5.3. Variation of FOS with the thickness of residual soil for varying slope heights and constant slope angle of (a) 15° (b) 30° (c) 45°, and (d) 60°

Analysis of the results indicates that the top layer that is the residual soil layer starts becoming unstable for the slope of 45° or more, which resulted in FOS less than 1 for these slopes. The cases when FOS is less than one does not mean the entire slope has failed; instead, in many cases, localised failure was observed. This observation is according to field observations (Fig. 2.2 and Fig. 4.3), where many localised failures were observed in the entire study area. It was also

observed that as the depth of the residual soil layer increase beyond 0.5m, there is a drastic drop in FOS as the soil cover increases for all slope angles. This reduction in FOS was observed up to 4-5m soil cover; after that, an increase in thickness of the soil layer does not affect FOS. This is because almost all of the slope failure in residual soil slope are concentrated in the 4-5m soil layer from top. Hence, it is the region which decides the stability of the residual slopes. Increasing the depth of the soil layer beyond 5m does not affect much on the location of the slip surface.

The FOS of higher slopes is more than smaller slopes till 0.5m residual soil layer. Because of thinner soil cover on the higher slope, the failure is governed by the strength of bedrock and the weathered rock instead of the soil layer. The thin soil cover is generally affected by continuous erosion processes or localised slips rather than a massive dislocation. As the residual soil cover increases more than 0.5m, the FOS of the higher slope become lesser than the smaller slope for the same depth of residual soil. Numerical simulations indicate that when the depth of soil cover is less (up to 4-5m soil cover for $\leq 30^\circ$ slope inclination and up to 3-4m soil cover for $\geq 45^\circ$ slope inclination), the failure surface can pass through the soil-rock interface resulting in complete failure of the residual soil layer along with some weathered rock blocks due to scrapping action by the soil during its downward movement. Thus, the debris produced has some boulders along with the soil (Fig. 5.4). When the depth of soil cover becomes more than 4-5m and 3-4m for $\leq 30^\circ$ slope inclination and $\geq 45^\circ$ slope inclination, respectively, the failure surface does not reach the entire soil layer depth, instead of producing shallow soil slips.

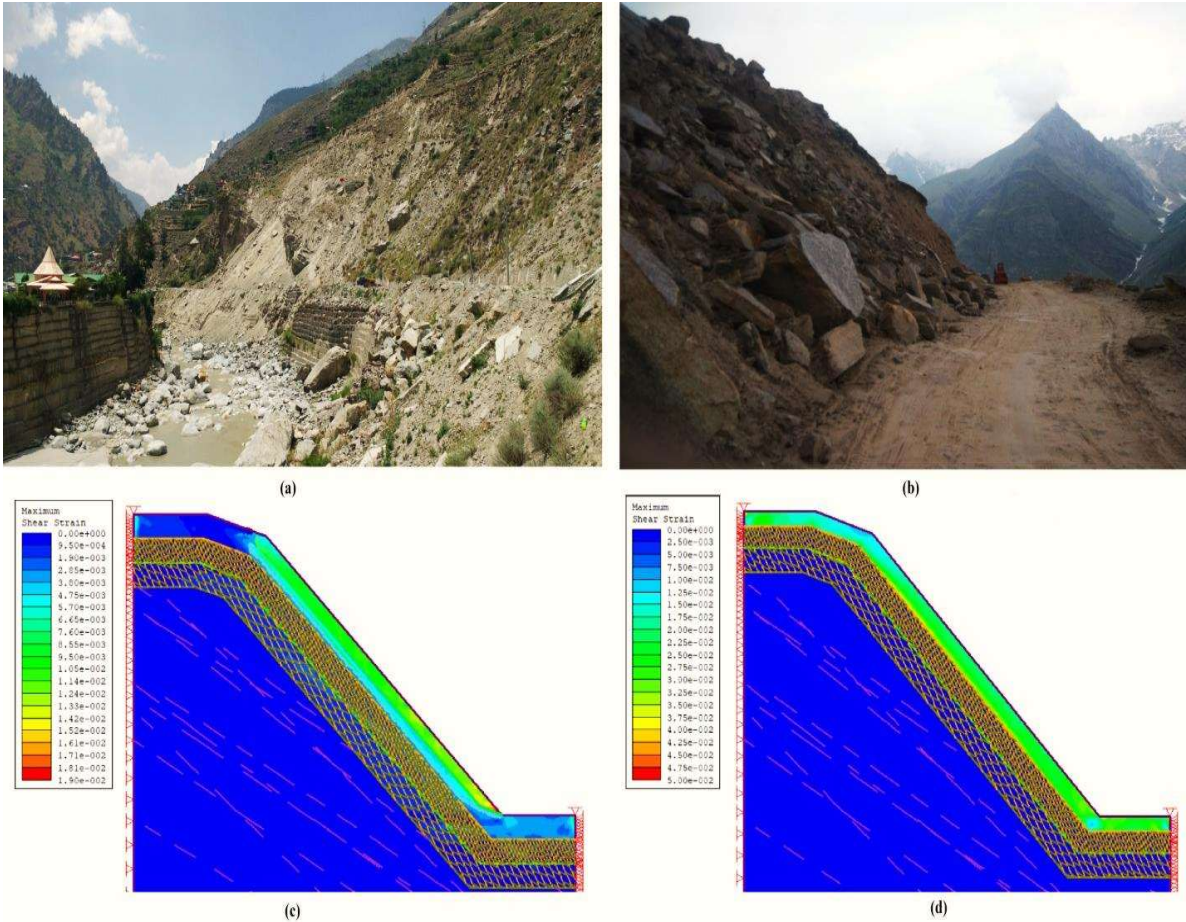


Fig. 5.4. Presence of weathered rock in the form of scrapped boulders in slid mass (a and b) in case of shallow soil cover (c) Failure surface for 10m residual soil layer, 100m high, and 45° slope (d) Failure surface for 5m residual soil layer, 100m high, and 45° slope

In the case of 15° and 30° slope inclination, the FOS decreased with an increase in the thickness of residual soil, although they had never gone below 2.724 and 1.312, respectively, which show that the slopes were stable although some fluctuations took place. When the slope angle was kept constant as 45° , it has also demonstrated the same declining trend as the smaller slope angle, but the values of FOS have fallen below 1.0 for all slopes having a residual soil layer of 3m or more. Also, for the 60° slope angle, the values of FOS has gone below 1.0 for all the slopes having more than 1m soil cover, which displays that all the steep residual soil slopes are highly unstable. This can be ascertained from the field investigations like steep slopes have highly

fractured rock on the surface with an almost null soil cover (Fig. 4.7). In those cases, the top residual soil layer is affected mainly by the erosional problem while only the rest two-layer remains intact i.e., the weathered middle layer and the parent bedrock.

Table 5.6 represents the percentage difference of FOS between two extreme slope heights (50m and 500m) for two extreme depths of soil cover (0.5m and 15m) for various slope angles. It is observed that for gentle slope (15° and 30°) and thin soil cover (0.5m), the variation in FOS is more between 50m and 500m high slope. As the soil cover increases (15m), this difference in FOS reduces. Thus, it can be concluded that for gentler slopes, the variation in FOS with height will be more for shallow soil cover rather than thick soil cover. For steeper slope (60°), the percentage variation in FOS for 50m and 500m is less for slope having thin soil cover and this difference increases as the soil depth increases. Thus, for steeper slopes, the percentage variation in FOS with height is less for slopes having thin soil cover than slopes having thick soil cover. The percentage difference in FOS for various heights is visible as the depth of soil cover increases. The thin soil cover on steeper slopes is mainly affected by continuous erosional processes rather than landslides.

Table 5.6: Percentage difference in FOS between 50m and 500m high slope

Slope Inclination	0.5m Soil Cover			15m Soil Cover		
	FOS		Percentage Difference in FOS	FOS		Percentage Difference in FOS
	50m	500m		50m	500m	
15° Slope	7.04	11.50	48.11%	2.95	2.72	8.11%
30° Slope	3.54	4.59	25.83%	1.49	1.31	12.85%
45° Slope	2.12	2.59	19.96%	0.89	0.74	18.40%
60° Slope	1.63	1.90	15.30%	0.27	0.19	34.78%

5.3.1.1 Hazard Chart for Quick Identification of Landslide Risk

Numerical simulation results indicate that the FOS depends on the combination of many geotechnical and physical factors of the slopes. In order to obtain the significance of the various

geotechnical and topological parameters used during numerical simulation on the stability of the slope, correlation analysis has been performed. The correlation coefficients obtained for the selected input parameters are shown in Table 5.7.

Table 5.7: Correlation coefficients obtained from correlation analysis of the slope stability parameters under natural (disturbed) residual soil conditions

Number	Parameters	Correlation Coefficient for FOS
1	Slope angle	-0.73
2	Slope height	-0.32
3	Soil cover	-0.43
4	Soil friction angle	0.18
5	Soil cohesion	0.12
6	Soil unit weight	0.16
7	Soil young's modulus	0.19
8	Weathered rock friction angle	-0.04
9	Weathered rock cohesion	-0.03
10	Weathered rock unit weight	-0.03
11	Weathered rock young's modulus	-0.06
12	Weathered rock Poisson's ratio	-0.05
13	Weathered rock tensile strength	-0.03
14	Soil rock interface cohesion	0.04
15	Soil rock interface friction angle	0.13

The correlation analysis indicates a strong and moderate negative correlation between the slope physical parameters (slope angle, slope height and soil cover) and FOS. This implies an increase in value of any of the slope physical parameters, the FOS decreases significantly. A weak positive correlation exists between residual soil geotechnical parameters (soil cohesion, soil unit weight, soil friction angle, soil young's modulus, and soil rock interface friction angle) and FOS. This implies that with an increase in value of any of the soil geotechnical parameters, the shear strength of the soil layer increases to a limited extent, which in turn leads to an marginal increase in FOS. While a very weak negative correlation exists between the weathered layer geotechnical parameters (rock mass cohesion, rock mass unit weight, rock mass friction angle, rock mass young's modulus, rock mass tensile strength, rock mass Poisson's ratio and soil rock interface

cohesion) with the FOS. The very weak correlation between the geotechnical parameters of the weathered layer with the FOS may be attributed to the fact that the effect of the weathered layer is more subtle in the case of slope having residual soil cover. In the case of residual soil slope, the stability is governed by the physical parameters and geotechnical properties of residual soil. This phenomenon is observed during field observations (Fig. 3.6 and Fig 4.5) and results of numerical simulations (Fig 5.4), along with documented results from the Literature Review. Also, the presence of a negative correlation of weathered layer geotechnical parameters with FOS is because an increase in the strength parameters makes the weathered layer stronger compared to the top residual soil layer, leaving the residual soil layer more susceptible to failure.

A Landslide Hazard chart has been formulated based on the three most important slope topographical parameters (slope height, slope angle and thickness of residual soil) obtained from the correlation analysis (correlation coefficient > 0.2). The proposed hazard chart has slope height, slope angle, and thickness of residual soil as three axes (scales). Selecting one value from each side will form a combination which is a triangle in this case. The in-centre of the triangle is represented as the FOS for that particular slope parameter combination (Fig. 5.5).

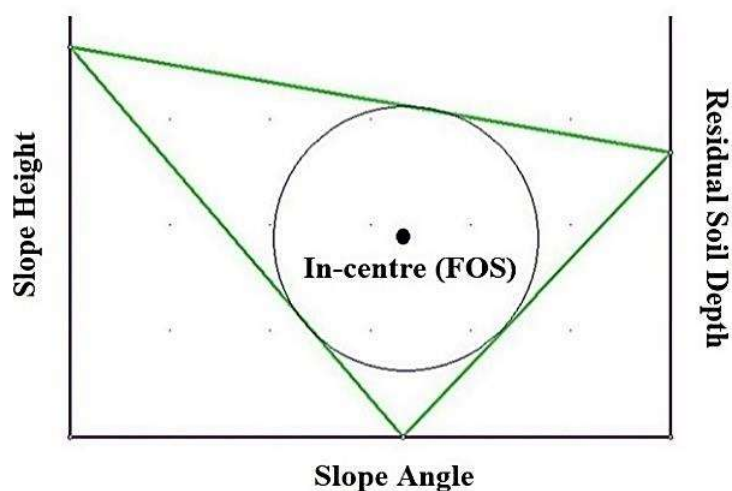


Fig. 5.5. The in-centre for a particular combination of the physical slope parameters

In the same manner, the in-centre of all the 400 slope models have been plotted on the chart, and these points have represented the location of the FOS for the slope formed by the respective combination of the three slope physical parameters Fig. 5.6. It shows the in-centre for various combinations of slope height, slope angle, and residual soil depth forms clusters around some regions in the hazard chart. Three distinct zones have been created to show the trend of variation of FOS for all the models. The zones are categorized as failed zone ($FOS < 1$), vulnerable zone ($1 \leq FOS \leq 1.5$), safe zone ($FOS > 1.5$) (Fig. 5.7). The vulnerable zone overlaps some areas of the transition from safe and fail zones. All those combinations of slope whose in-centre falls on the fail zone of the risk chat are usually unsafe, and those combinations in which the in-centre falls on the safe zone of the chart are safer. The in-centre in the middle portion of the hazard chart shows vulnerable slopes.

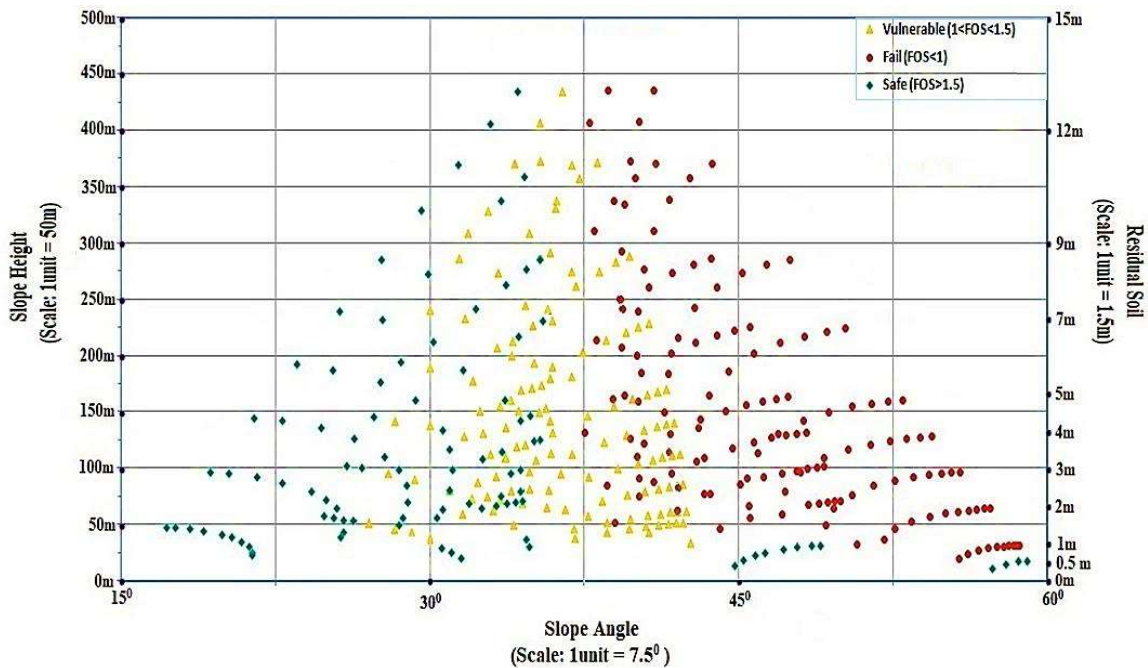


Fig. 5.6. Location of the in-centre (FOS) of the triangles formed from various combinations of slope physical parameters

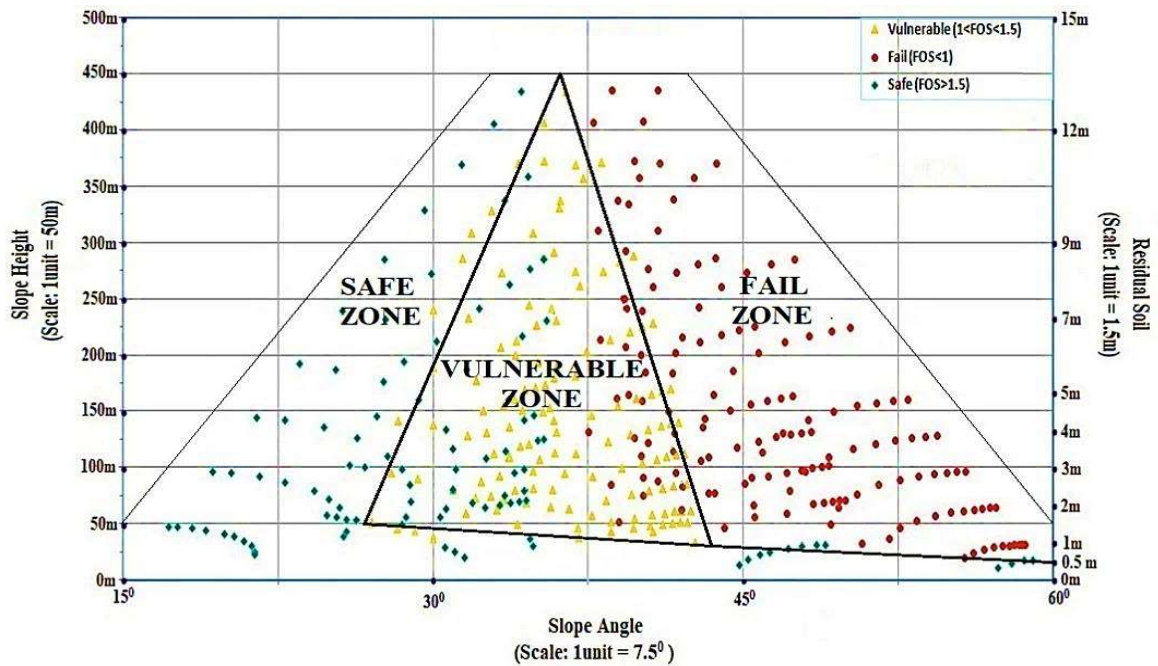


Fig. 5.7. Landslide vulnerability zones in the proposed Hazard Chart for quick identification of landslide vulnerability

5.3.1.2 Validation of the Proposed Quick Identification Landslide Hazard Chart

Results from published case studies on the selected lithologies (limestone, dolostone and dolomitic limestone) have been taken for validating the proposed quick identification landslide hazard chart (Table 5.8 and Fig 5.8). The slope geotechnical parameters of all the six case studies were used to locate the position of in-centre (FOS) in the proposed hazard chart, and all the obtained locations of the in-centres for each case studies are in accordance with the FOS ranges obtained from numerical analysis of the respective case studies. Thus validating the utility of the proposed quick identification Landslide Hazard Chart.

Table 5.8: Data taken from various case studies for validating the proposed quick landslide hazard chart

Reference	Slope Height (m)	Slope Angle (deg)	Soil Cover (m)	FOS from case study	Location of FOS in the proposed hazard chart
Kumar et al. (2017)	300 – 400	60	5 – 10	0.012 – 0.4	Fail

Kainthola et al. (2013)	500	35	<0.5	1.4 – 1.5	Vulnerable
Pandit et al. (2016)	100	30 - 40	3 - 5	1.03 – 1.18	Vulnerable
Sah et al. (2018)	100 – 300	30 – 45	1 – 5	0.4 – 1.1	Fail- Vulnerable
Gupta et al. (2016a)	500	70	5	Fail	Fail
Siddque and Pradhan (2018)	20 – 45	58	10	0.98 – 0.99	Vulnerable

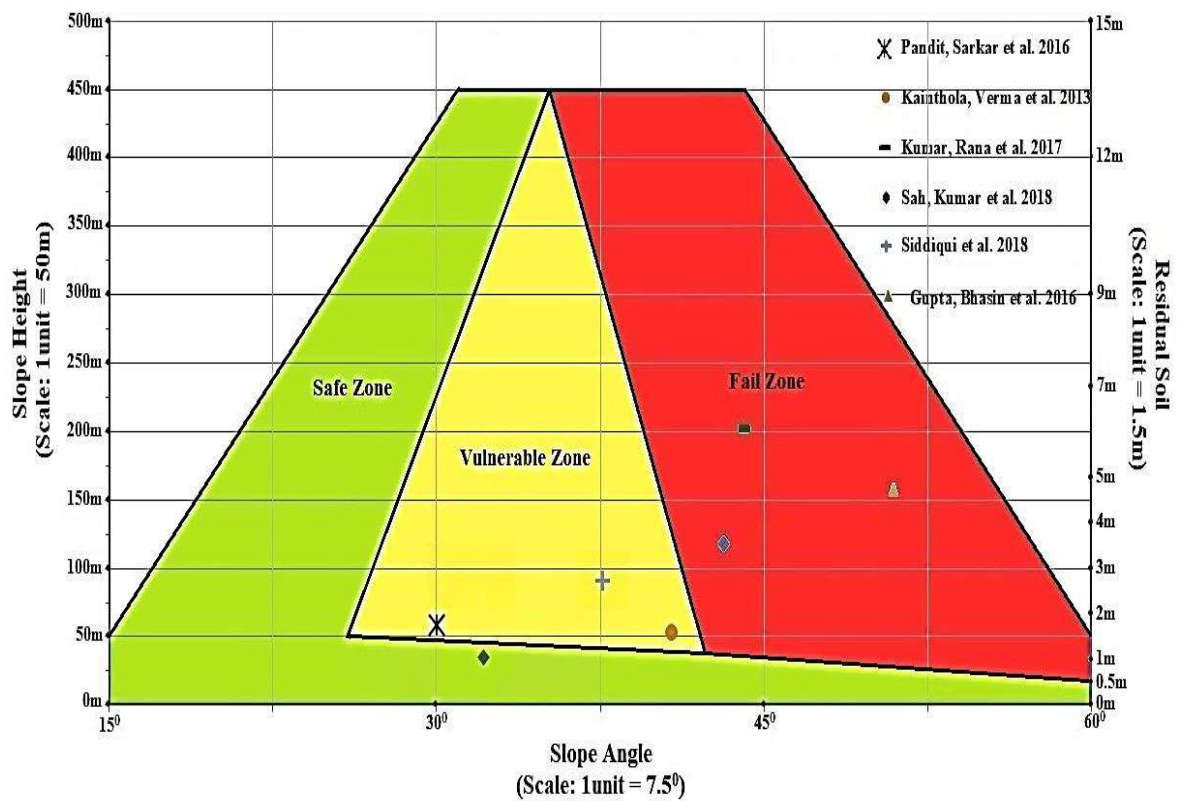


Fig. 5.8. Validation of proposed Hazard Chart for quick identification of landslide vulnerability

The proposed hazard chart for quick identification of landslide vulnerability of the residual soil slope of Lesser Himalaya is based on the combination of slope height, slope angle, and soil cover. This can be used for the initial and quick identification of instability with an acceptable level of confidence by using three easily obtainable slope physical parameters. The primary purpose of formulating a chart is to assist investigators and policymakers during the preliminary

investigation of the study area, thereby helping them focus more on the vulnerable slopes. Also, this work can act as a guide for the formulation of hazard charts for other regions affected by slope stability problems.

5.3.2. Detail Identification of Landslide Hazard

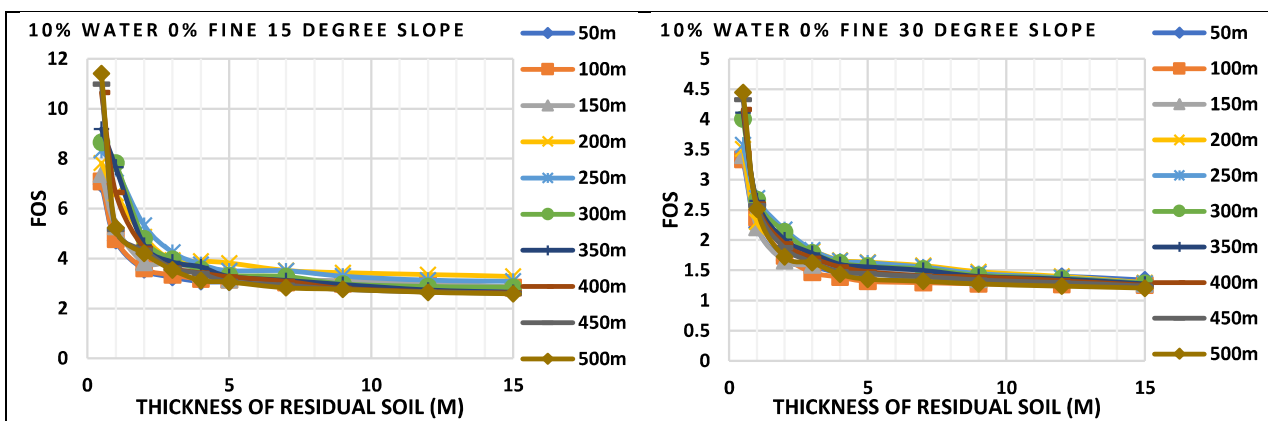
Water content and grain size distribution are two factors that vary with time and location. The variation in water content and the presence of finer particles significantly affect the overall stability of the residual soil slope. Thus, their effect needs to be thoroughly studied and implemented into the numerical analysis. In order to incorporate the effect of water and percentage of fine grain particles in the residual soil, numerical models were prepared by varying the height of the slope, the angle of the slope, the thickness of the residual soil layer, and the percentage of finer particle present in the residual soil under different water content.

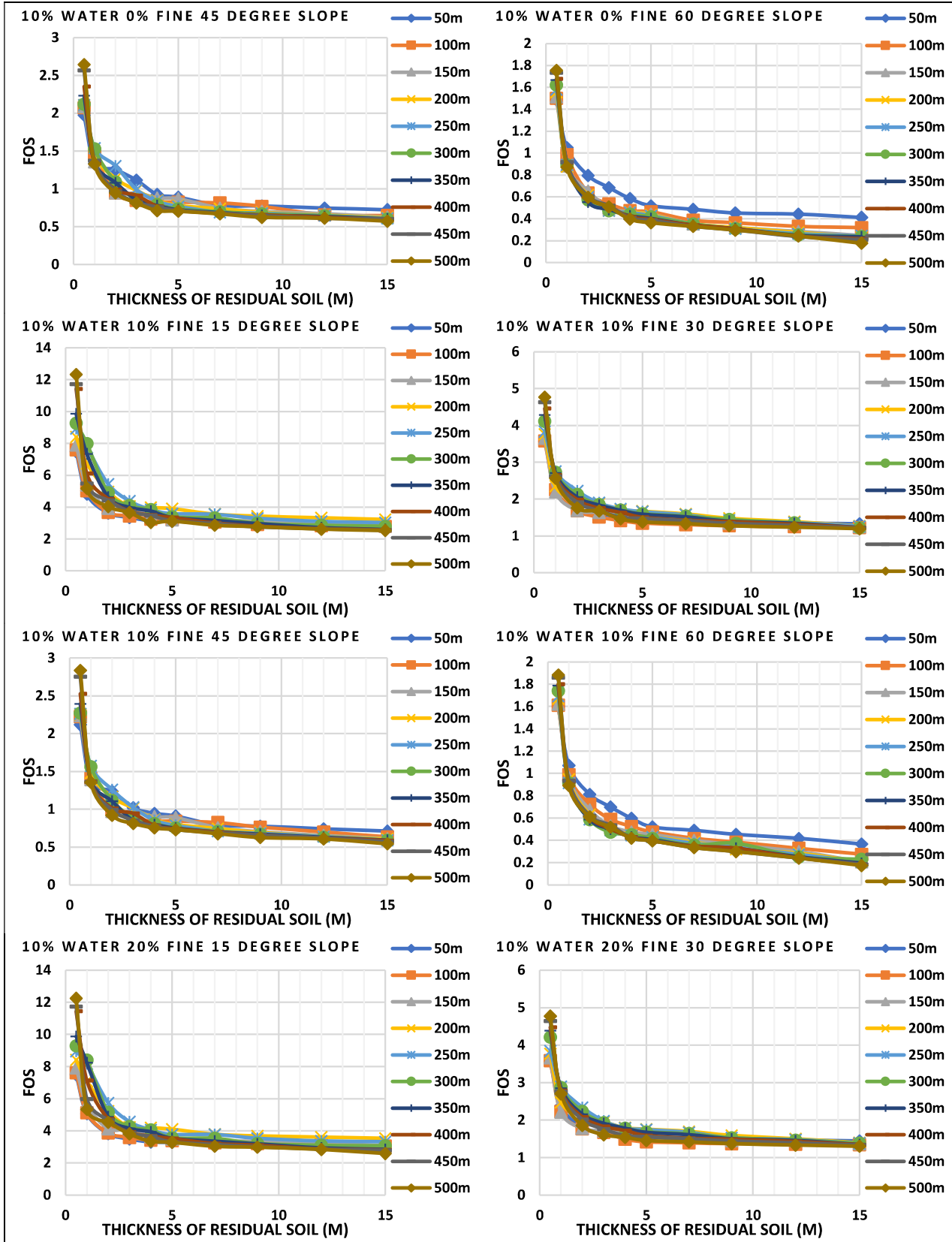
The same variation in slope height, slope angle and residual soil depth as analysed previously in quick identification of landslide hazard has been used. Laboratory tests indicate that natural water content mostly varied from 12-17%, with an average of 14% (Fig 4.12). For assessment, maximum water content was taken around 2 times, i.e., 30%, corresponding to 100% saturation level as given in Table 4.10. Thus, models were analyzed for dry condition (0% water content), 10%, 20% and 30% water content, which corresponds to around 0%, 38-50%, 75-85% and 100% soil saturation respectively. The percentage of fines (silt and clay) varied from 13 to 20%, with an average of 16% (Fig 4.10). For assessment, fine content was taken around 2 times, i.e., 30% which corresponds to 0%, 10%, 20% and 30% fine content in the analysis.

One thousand six hundred numerical models have been simulated based on different permutation combinations of the slope height, the thickness of residual soil, the slope angle and percentage fine variations. These 1600 numerical models were analysed for four different water

content (or saturation) levels. Thus, 6400 models were prepared for complete numerical analysis of residual soil slope. Similar slope topology and boundary conditions as used in quick identification of vulnerability have been considered in simulations. The statistical distributions and distribution parameters under different remoulded conditions were taken from Table 5.2 to Table 5.5.

Six thousand and four hundred slope models were analysed, and the value of probabilistic FOS of every model has been calculated. The graphs between FOS and thickness of residual soil for varying slope height, slope angle and percentage fines under 10% water content is shown in Fig. 5.9. While the FOS graphs for 0%, 20% and 30% water content are shown in Appendix I. The lowest FOS value obtained from the analysis was 0.15 for the slope with 60° slope angle, 500m slope height, 15m thickness of the residual soil possessing 30% fine particles and 30% water content (100% saturation). The highest FOS value through the analysis was 14.35 obtained by the slope with 15° slope angle, 500m slope height, 0.5m thickness of the residual soil possessing 10% fine particles and 0% water content (dry condition).





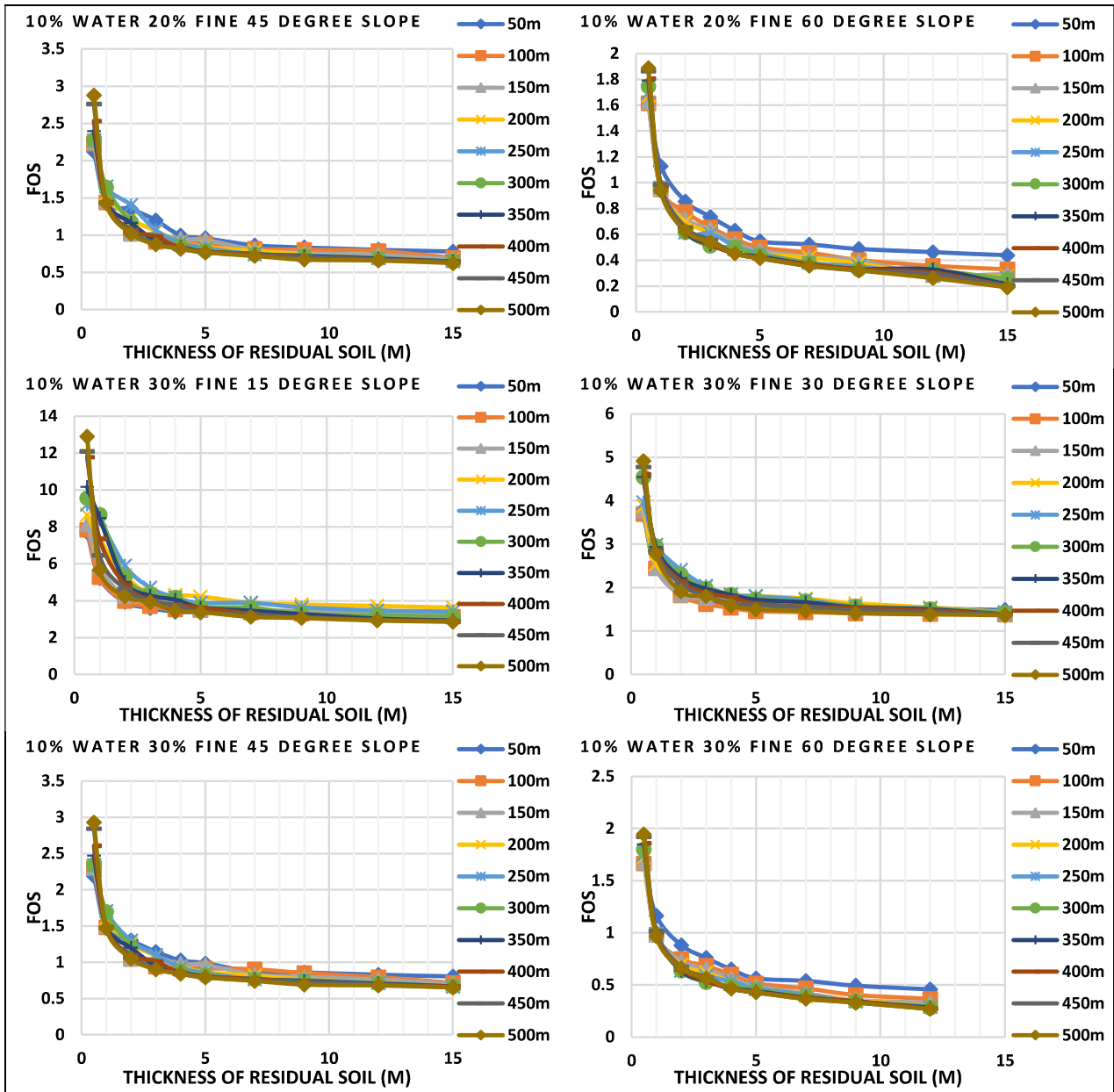


Fig. 5.9. FOS Vs. The thickness of residual soil for various combinations of slope angle and percentage of fines in residual soil under 10% soil water content

When the slope angle was kept constant at 15° and 30° , the FOS values decreased with an increase in the thickness of residual soil, although they had never gone below 2.23 and 1.06, respectively (both cases are for 30% fine and 30% water content), which show that the slopes were in the range of vulnerable to stable although some fluctuations took place. Results also indicate

that the top layer that is the residual soil layer starts becoming unstable ($FOS < 1$) for 45° slope inclinations possessing 4m or more soil cover, and for the slope of 60° its 2m or more soil cover for different percentages of finer particles in case of dry slope (0% water content). In case of 10% water content (or 38-50% saturation), the top residual soil layer starts becoming unstable ($FOS < 1$) for 45° slope inclinations possessing 3m or more soil cover and for the slope of 60° its 2m or more soil cover for different percentage of finer particles. In case of 20% water content (or 75-85% saturation), the top residual soil layer starts becoming unstable ($FOS < 1$) for 45° slope inclinations possessing 3m or more soil cover and for the slope of 60° its 1m or more soil cover for different percentage of finer particles. In case of 30% water content (or 100% saturation), the top residual soil layer starts becoming unstable ($FOS < 1$) for 45° slope inclinations possessing 2m or more soil cover and for the slope of 60° its 1m or more soil cover for different percentage of finer particles.

It was also observed that as the depth of the residual soil layer increase beyond 0.5m, there is a drastic drop in FOS as the soil cover increases for all slope angles. This reduction in FOS was observed up to 4-5m soil cover. After that, an increase in the thickness of the soil layer does not affect FOS. The relationship between water content, % fine and FOS is very complex. In the case of 0% water content (dry slope), FOS increases up to 10-15% fine content and then decreases. In the case of 10% and 20% water content, the FOS increases continuously up to 20-25% fine content and then starts decreasing. For 30% water content (fully saturated condition), FOS reduces continuously with an increase in % fine. When the water content is more ($\geq 20\%$), and the depth of soil cover is less (up to 3-4m for $\leq 30^\circ$ slope angle and up to 1.5-2m for $\geq 45^\circ$ slope angle), the failure surface passes through the soil-rock interface resulted in complete failure of the residual soil layer along with some weathered rock due to scrapping action by the soil during its downward movement. Thus, the debris produced has some boulders along with moist soil. When the depth of

soil cover becomes more than 5m and 2m for $\leq 30^\circ$ slope angle and $\geq 45^\circ$ slope angle respectively and the water content is more ($\geq 20\%$), the failure surface does not reach the entire depth of the soil layer, instead produces shallow soil slips.

Results also indicate that keeping all the variables constant, the FOS decreases with increased water content from the dry state (0% water content) to a fully saturated state (30% water content). Also, it was noted that with the increase in water content and slope inclination, the thickness of the residual soil layer that the slope could sustain without failure reduces, keeping the rest variables constant. In the case of gentle slopes (15° and 30° slope inclination), the FOS decreases from highly stable (>5.0) to just stable (1.0) with an increase in soil depth (from 0.5m to 15m) and water content from dry to 30% for all slope parameters. For moderate slope (45° slope inclination), the maximum depth of stable residual soil cover reduces from 4m to 1m with increased water content from dry to 30%. In the case of a steep slope (60° slope inclination), the maximum depth of stable residual soil cover reduces from 1m to 0.5m with increased water content from dry to 30%.

The analysis also shows that the FOS of higher slopes is more than smaller slopes till 0.5m residual soil cover, which can be ascertained because, for thinner soil cover on the higher slope, the failure is governed by the bedrock and the weathered region. The thin soil cover is generally affected by a continuous erosion process rather than massive dislocation giving it more FOS than smaller slopes. As the soil depth increases beyond 0.5m, the FOS of the smaller slope becomes more than, the higher slopes.

5.3.2.1 Hazard Chart for Detail Identification of Landslide Risk

Numerical simulation results indicate that the overall stability of a residual soil slope depends on a combination of many factors. In order to obtain the significance of the various

geotechnical, hydrological and topological parameters used during numerical simulation on the stability of the slope, correlation analysis has been performed. The correlation coefficients obtained for the selected input parameters are shown in Table 5.9.

Table 5.9: Correlation coefficients obtained from correlation analysis of the slope stability parameters under remoulded residual soil conditions

Number	Parameters	Correlation Coefficient for FOS
1	Slope angle	-0.63
2	Slope height	-0.29
3	Soil cover	-0.33
4	Percentage of fine particle in soil	0.22
5	Soil water content	-0.51
6	Soil friction angle	0.18
7	Soil cohesion	0.14
8	Soil unit weight	0.13
9	Soil young's modulus	0.16
10	Weathered rock friction angle	-0.01
11	Weathered rock cohesion	-0.02
12	Weathered rock unit weight	-0.01
13	Weathered rock young's modulus	-0.01
14	Weathered rock Poisson's ratio	-0.02
15	Weathered rock tensile strength	-0.01
16	Soil rock interface cohesion	0.02
17	Soil rock interface friction angle	0.08

The correlation coefficients depicted in Table 5.9 indicates a strong and moderate correlation between the slope physical parameters (slope angle, slope height and soil cover), water content and % fines of residual soil with FOS. A strong and negative correlation between slope physical parameters and soil water content with FOS is evident owing to the marked influence of various slope topological parameters and soil water content on rendering the slopes vulnerable to failure. A weak correlation exists between residual soil geotechnical parameters (soil cohesion, soil unit weight, soil friction angle and soil young's modulus) and FOS. The weak and positive correlation between soil geotechnical parameters with FOS indicates that with an increase in these parameters, the shear strength of the soil layer increases partially, which in turn leads to an increase

in FOS marginally. While a very weak correlation exists between the weathered layer geotechnical parameters (rock mass cohesion, rock mass unit weight, rock mass friction angle, rock mass young's modulus, rock mass tensile strength, rock mass Poisson's ratio and soil rock interface cohesion and friction angle) with the FOS. The very weak correlation between the weathered layer geotechnical parameters with the FOS may be attributed to the fact that the effect of the weathered layer is more subtle in the case of slope having residual soil cover. In this case, the residual soil layer governs the slope failure susceptibility. This phenomenon is observed during field observations (Fig. 3.6 and Fig. 4.5) and numerical simulations (Fig 5.4) along with documented results from Literature Review where the top residual soil layer is primarily affected by stability issues while the weathered and bed rock layer remains mostly idle. Also, the presence of a negative correlation of weathered layer geotechnical parameters with FOS is because an increase in the strength parameters makes the weathered layer stronger compared to the top residual soil layer, leaving the residual soil layer more susceptible to failure. The residual soil-weathered rock interface strength parameters showed a least positive correlation with FOS indicating an increase in interface joint strength parameter will make the slope less vulnerable to failure.

Four Landslide Hazard charts have been formulated based on the five most important slope topographical and geotechnical parameters (slope height, slope angle, the thickness of residual soil, soil water content and % fines in soil) obtained from the correlation analysis (correlation coefficient > 0.2). The proposed hazard charts have slope height, slope angle, the thickness of residual soil and percentage of fines as four axes (scales) for a particular soil water content value. Selecting one value from each side of the slope height, slope angle, and residual soil depth will form a triangular combination. Similarly, another triangular combination is formed by selecting the corresponding percentage of fines with the slope height and residual soil depth. The in-centre

of the two triangles formed from the quadrilateral (four parameters) is joined with a straight line. The mid-point of the straight line joining the in-centre of both triangles represent the FOS for that particular slope parameter combination, as shown in Fig. 5.10.

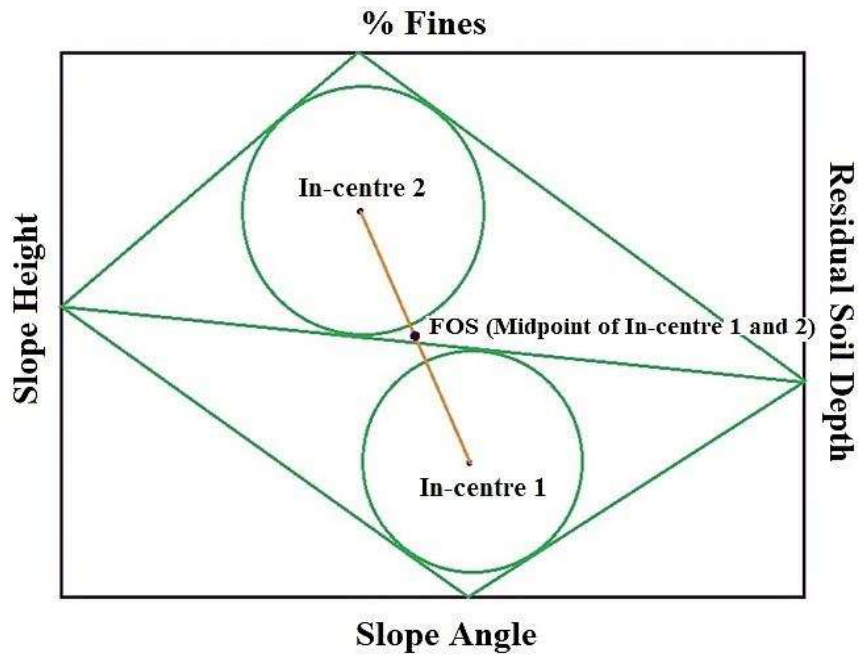


Fig. 5.10. Determination of FOS for a particular combination of the physical and geotechnical slope parameters

Similarly, the midpoint of the two developed in-centre of all the 6400 models (in a set of 1600 each for different soil water content) have been plotted in the charts. The midpoints represented the location of FOS in the chart for the slope formed by the respective combination of the five slope parameters (Fig. 5.11 to Fig. 5.14).

0% WC in Residual Soil

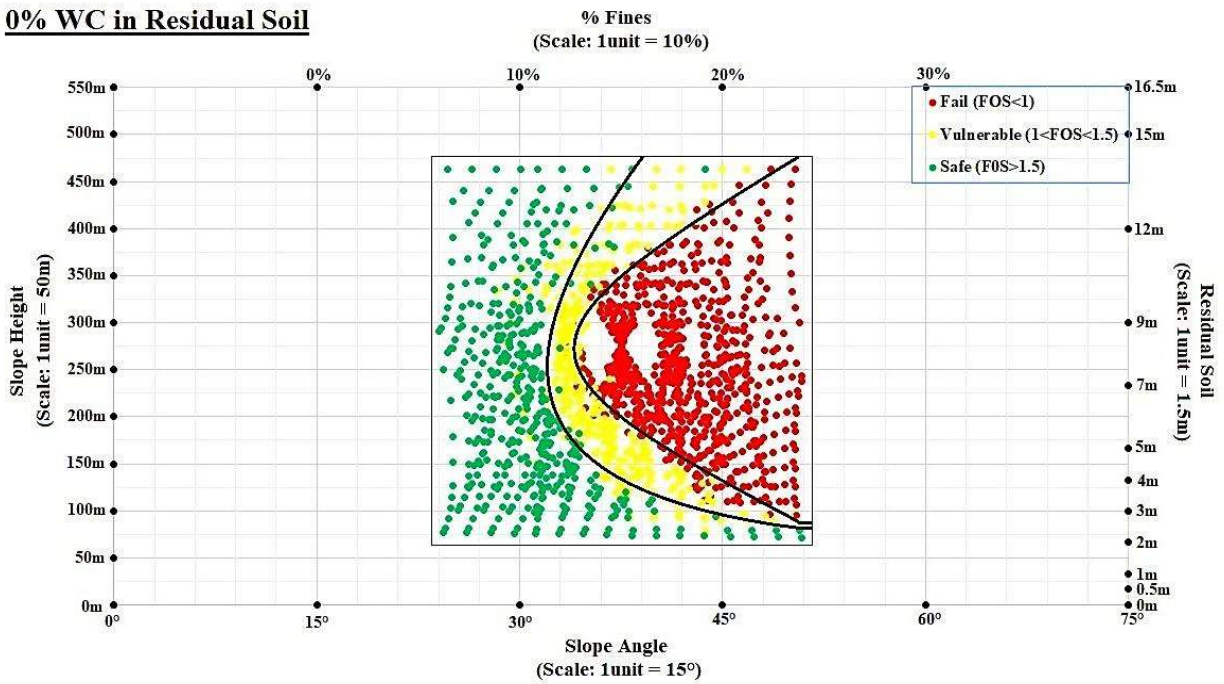


Fig. 5.11. Proposed Hazard Chart for detailed identification of landslide vulnerability in case of 0% WC of residual soil

10% WC in Residual Soil

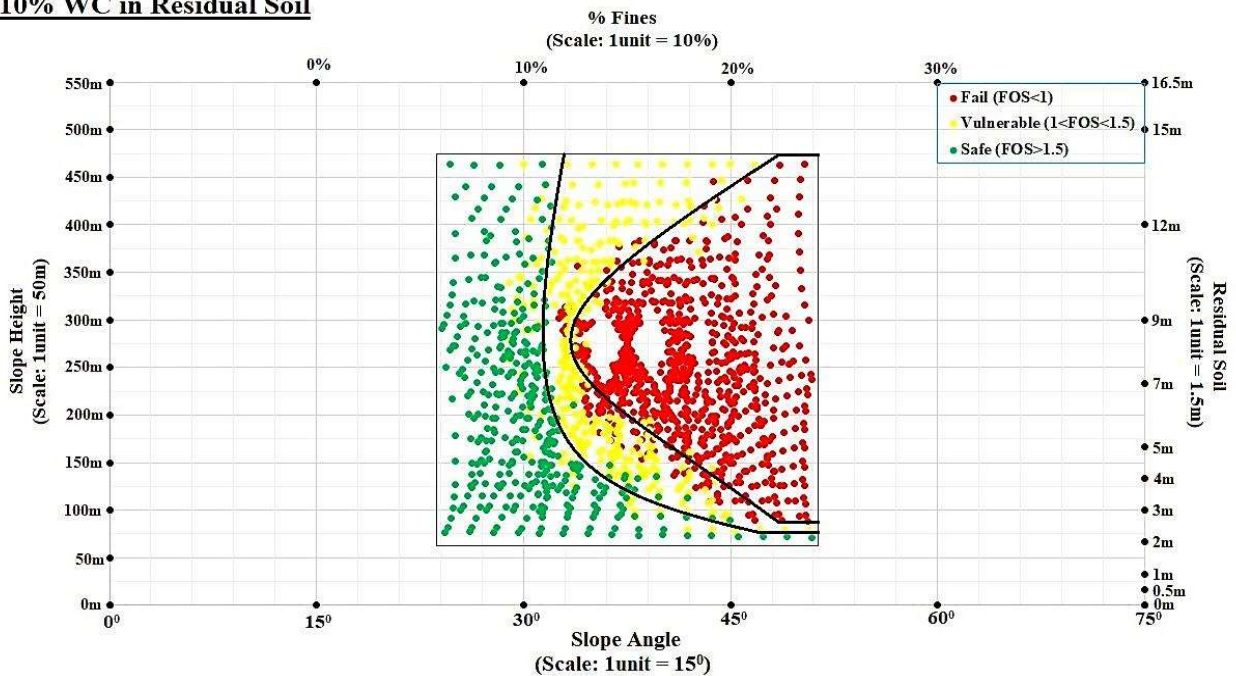


Fig. 5.12. Proposed Hazard Chart for detailed identification of landslide vulnerability in case of 10% WC of residual soil

20% WC in Residual Soil

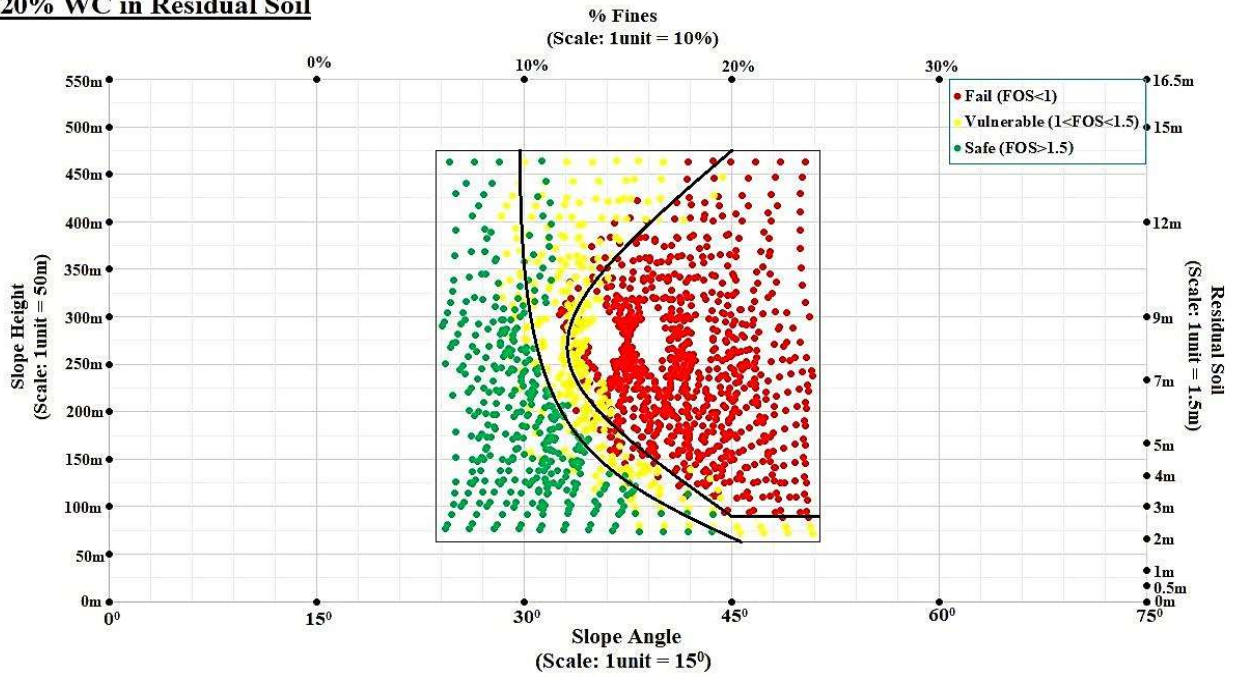


Fig. 5.13. Proposed Hazard Chart for detailed identification of landslide vulnerability in case of 20% WC of residual soil

30% WC in Residual Soil

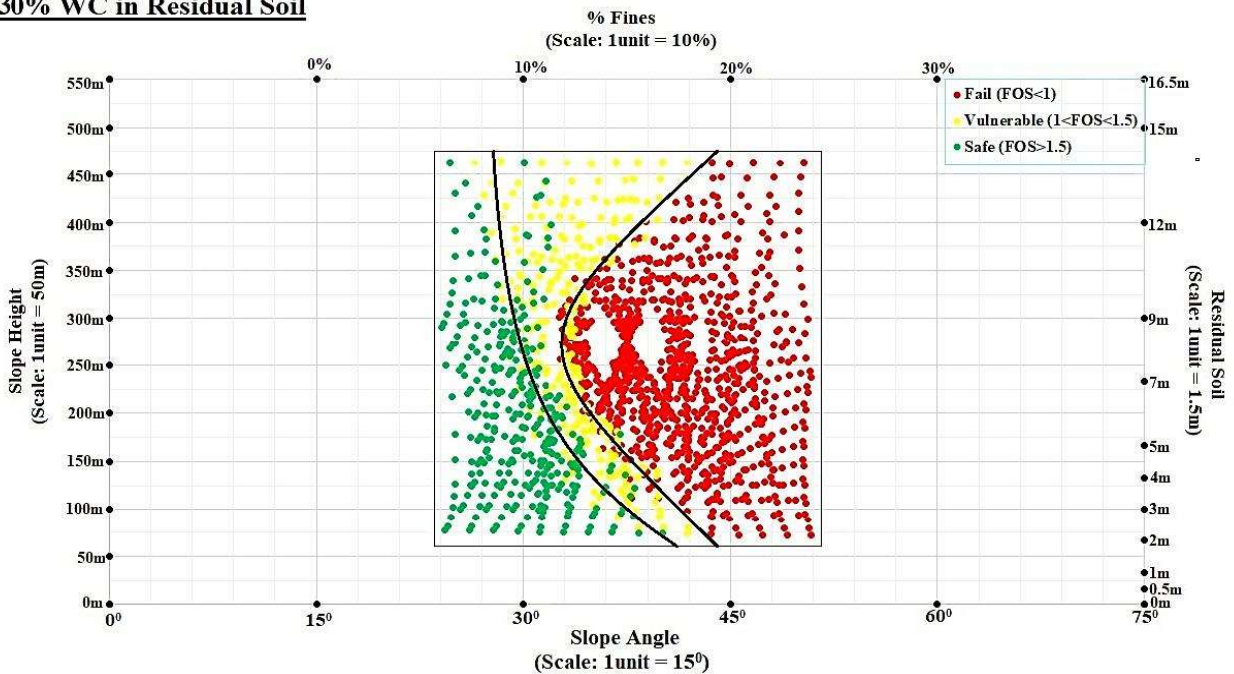


Fig. 5.14. Proposed Hazard Chart for detailed identification of landslide vulnerability in case of 30% WC of residual soil

The proposed detailed identification of landslide hazard charts will help assess the long-term stability of the residual soil slopes. A detailed study of the proposed hazard charts shows that the midpoints of the line joining the in-centres (FOS location) for various combinations of slope height, slope angle, residual soil depth and % fines form clusters around some regions in the respective hazard charts. Three distinct zones (or vulnerability zones) have been created to show the trend of variation of FOS for all the models. The zones are categorised as failed zone ($FOS < 1$) marked as red, vulnerable zone ($1 \leq FOS \leq 1.5$) marked as yellow, and safe zone ($FOS > 1.5$) marked as green in the hazard chart. The failed zone is completely separated from the safe zone. The vulnerable zone overlaps some areas of the transition from safe and fail zones. It was observed that with the increase in the water content, there is also a gradual increase in the area of the Vulnerable and Fail Zone in the hazard chart. The individual percentage of the potential hazard conditions (fail, safe and vulnerable) from the total numerical simulations for different water content is given in Table 5.10. With the increase in water content from 0 to 30% (from dry to fully saturated condition), there have been an increase of 6.37% of fail slope models and 8.94% of vulnerable slope models, whereas a decrease of 15.31% of safe slope models.

Table 5.10: Percentage of individual potential hazard combinations out of total 6400 slope physical and geotechnical combinations

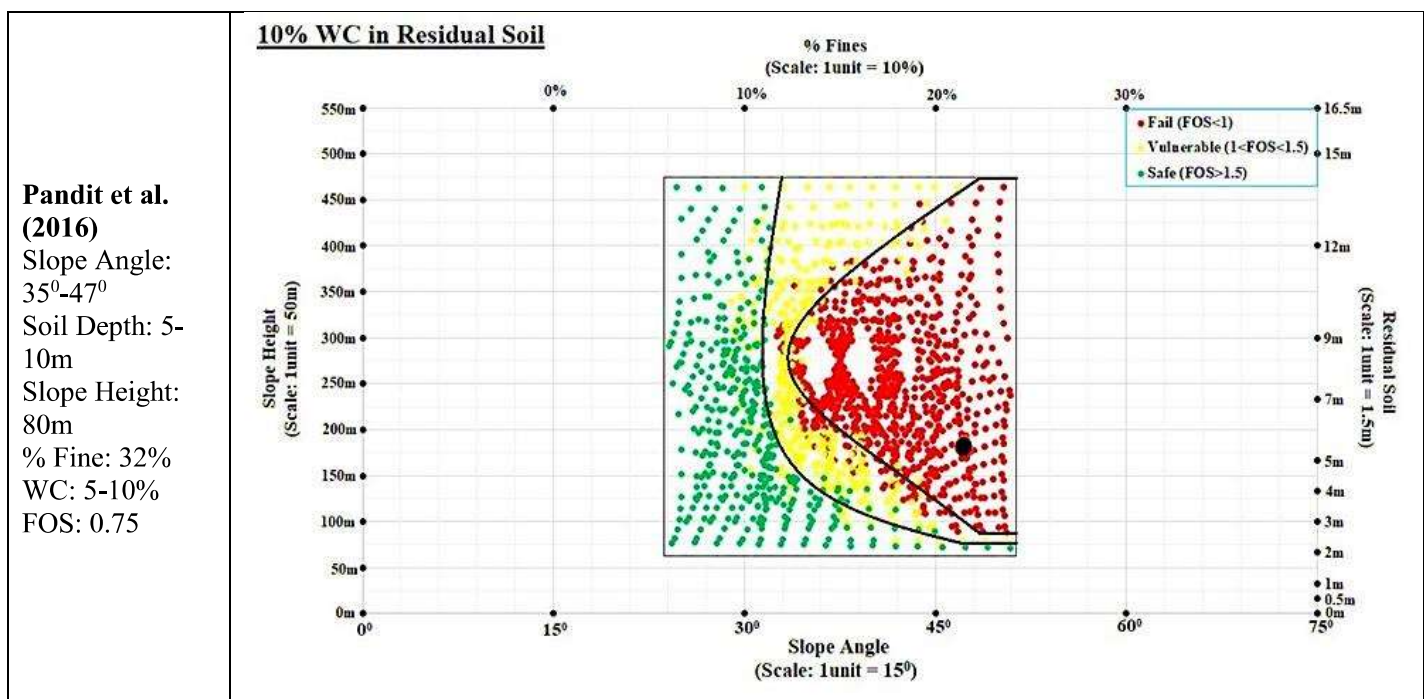
Water Content	Fail Zone	Vulnerable Zone	Safe Zone
0%	38.06%	11.12%	50.81%
10%	41.25%	14.12%	44.62%
20%	42.31%	15.62%	42.06%
30%	45.43%	19.06%	35.51%

5.3.2.2 Validation of the Proposed Detail Identification Landslide Hazard Chart

Results from published case studies (literature) on the selected lithologies (limestone, dolostone and dolomitic limestone) have been taken for validating the authentication of the proposed detail identification landslide hazard charts (Table 5.11). The slope geotechnical and

mechanical parameters from five case studies were used to locate the position of the midpoint of the incentres of the two triangles (representing FOS) in the proposed hazard chart. All the obtained locations of the midpoints for each case study are in accordance with the FOS ranges obtained from numerical analysis of the respective case studies by different researchers. Thus validating the utility of the proposed detail identification Hazard Chart.

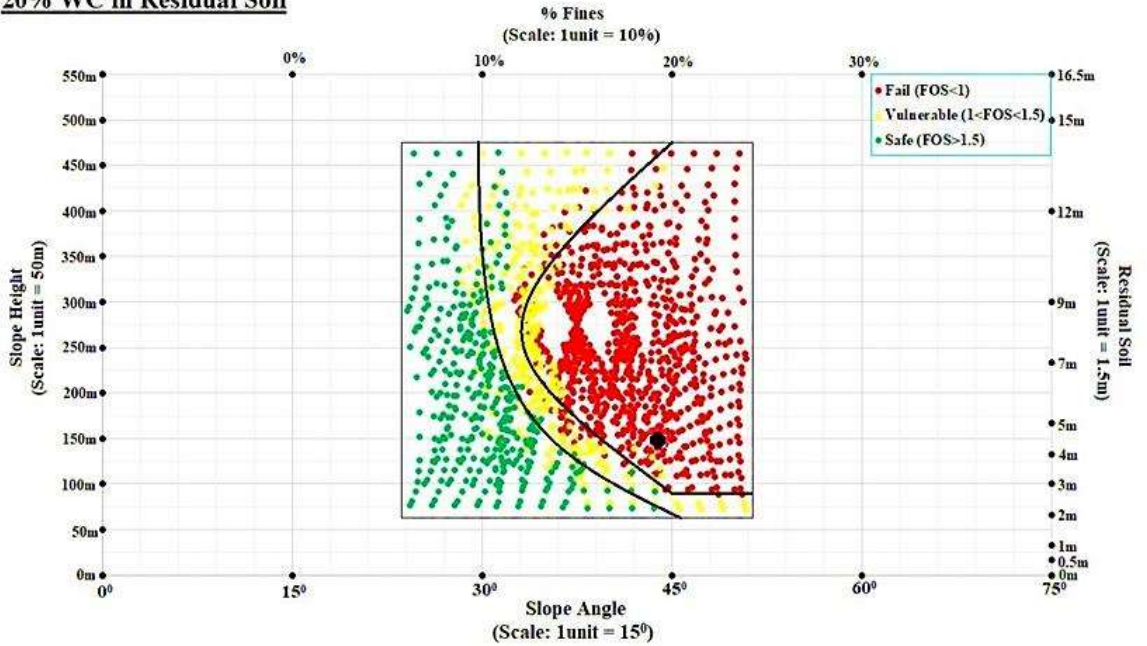
Table 5.11: Validation of proposed Hazard Chart for detailed identification of landslide vulnerability



Kanungo et al. (2013)

Slope Angle: 45°-55°
 Soil Depth: 4.9m
 Slope Height: 75-90m
 % Fine: 30%-40%
 WC: 24%
 FOS: 0.45

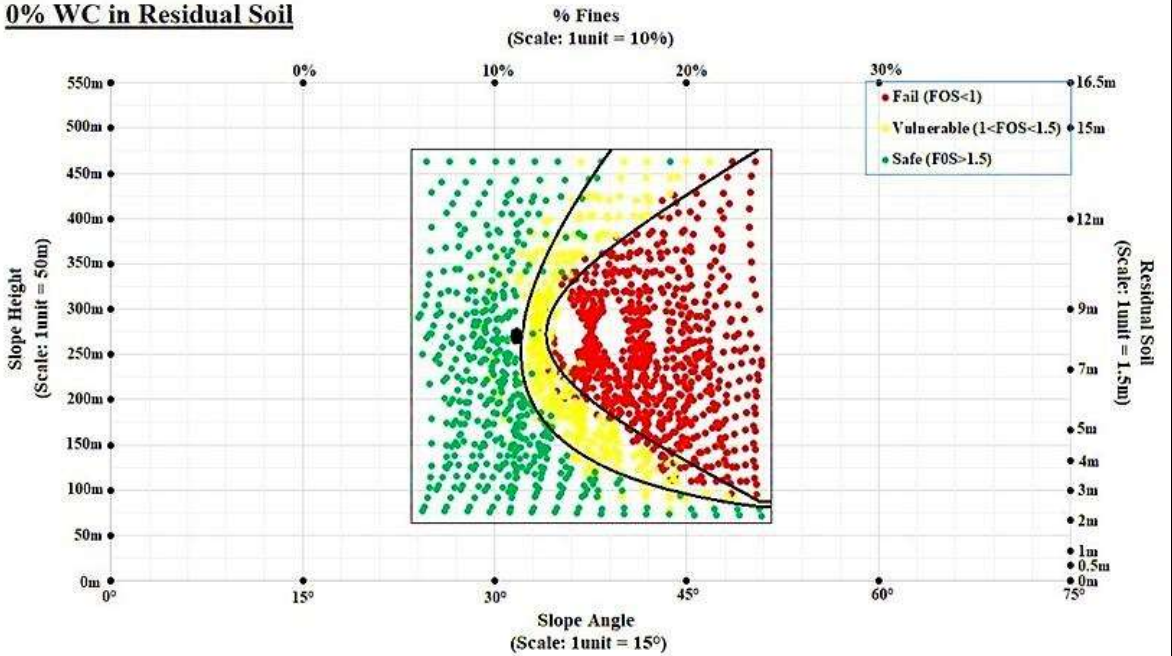
20% WC in Residual Soil



Kainthola et al. (2013)

Slope Angle: 32°-38°
 Soil Depth: 0.1-0.5m
 Slope Height: 500m
 % Fine: 5-10%
 WC: 0%
 FOS: 1.4-1.6

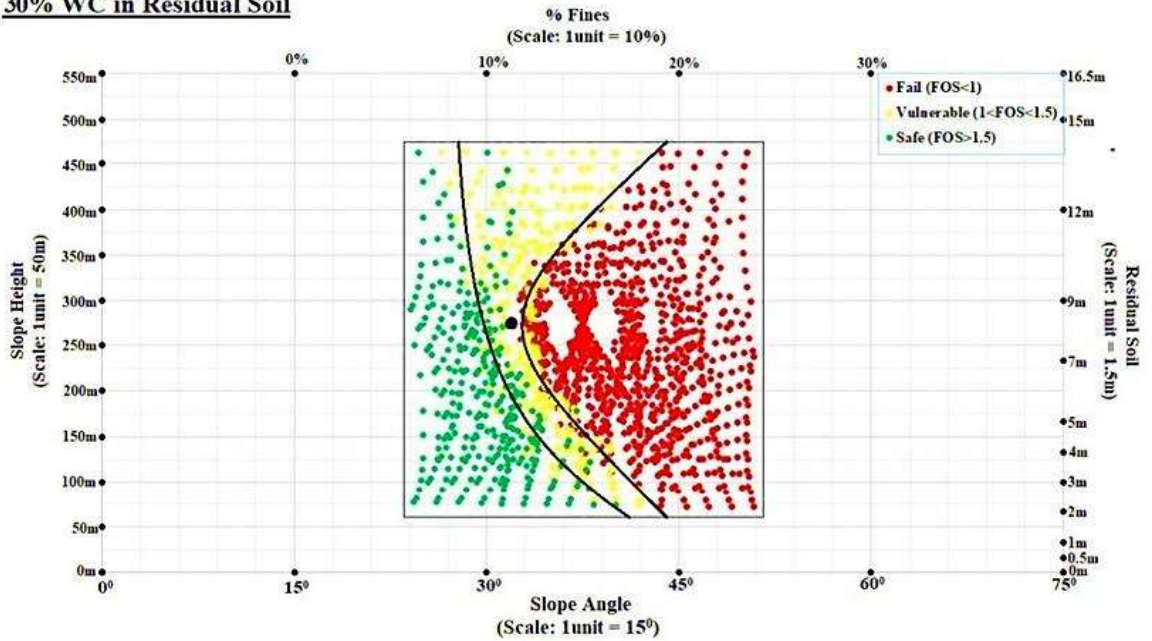
0% WC in Residual Soil



Kainthola et al. (2013)

Slope Angle: 32°-38°
 Soil Depth: 0.1-0.5m
 Slope Height: 500m
 % Fine: 5-10%
 WC: 30%
 FOS: 1.2-1.4

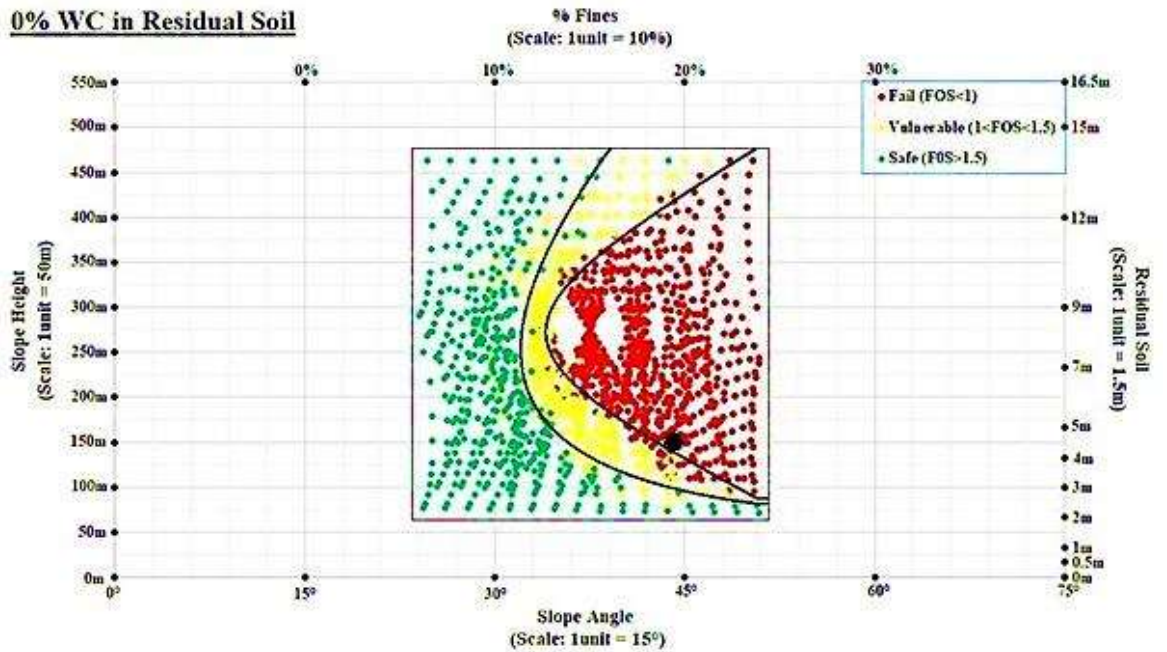
30% WC in Residual Soil

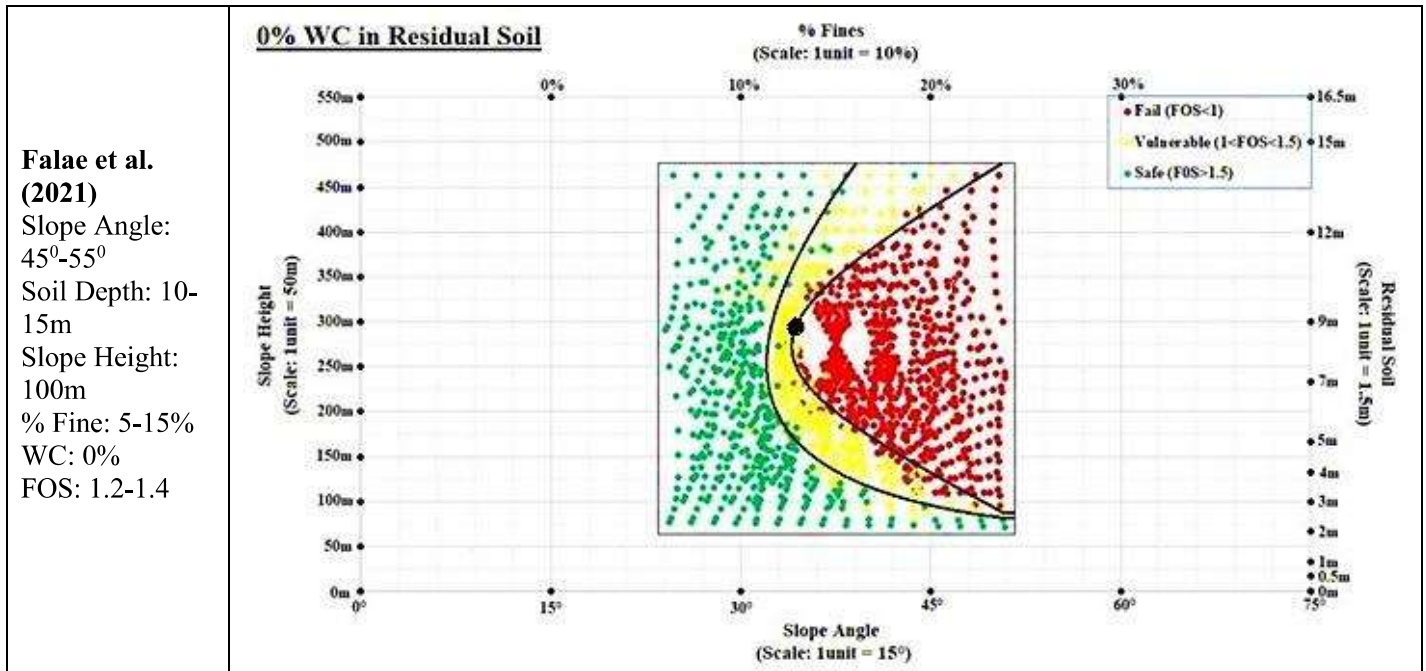


Solanki et al. (2019)

Slope Angle: 50°-70°
 Soil Depth: 2-10m
 Slope Height: 180m
 % Fine: 9.6%
 WC: 0%
 FOS: 0.83

0% WC in Residual Soil





5.4 Discussion

Statistical analysis of the geotechnical data indicates high variability in the obtained test results, which justifies the use of probabilistic numerical analysis for the study. The geotechnical parameters mostly follow the lognormal probability density function followed by the normal probability density function. While very few parameters followed a triangular probability density function. The obtained probability density function indicates that the values of particular geotechnical parameters are spread around a central/mean value. The cohesion, friction angle and young's modulus of both soil and rock have shown maximum variability, which is expressed in terms of a higher value of the standard deviation of the obtained data.

Finite element-based numerical simulations have been performed using field investigation results, laboratory experiments and detailed literature survey. The results indicate the significance of considering the residual soil layer while performing stability analysis. The FOS decreased to a certain level with an increase in thickness of residual soil, keeping the rest factor constant. After that, there was not much visible change in FOS with increased soil thickness. There is a limited

possibility of the presence of a thick layer of residual soil on slopes greater than 45° . The variation in FOS with height will be more for shallow soil cover than thick soil cover in gentler slopes. As the slope becomes steeper, the variation in FOS with height decreases for shallow soil cover and increases for deeper soil cover. The relationship between water content, percentage fine and FOS is very complex. In the case of the dry slope, FOS increases up to 10-15% fine content and then starts decreasing. In the case of 10% and 20% water content, the FOS increases continuously up to 20-25% fine content and then starts decreasing. For 30% water content, FOS reduces continuously with an increase in % fine. As the water content increases (from dry to fully saturate), the thickness of the residual soil that a particular slope can sustain without failure reduces significantly from 4-5m to less than 1m for moderate slopes (40° - 60°). In the case of steep slopes ($>60^\circ$), it reduces from 1m to less than 0.5m.

Increase in the water and fine content in the residual soil, the difference in FOS between the 0.5m and 15m soil cover for a particular slope angle and height gets reduced. Thus, it can be concluded that increasing the water and fine content brings more homogeneity in the FOS, having a different depth of soil cover for any particular slope inclination and height. With the increase in water content from 0 to 30%, there has been an increase of 6.37% of fail slope geometrical combination and 8.94% of vulnerable slope geometrical combination out of 6400 numerical models analysed, whereas a decrease of 15.31% of safe slope geometrical combination was observed.

The failure in residual soil slope is due to the critical combination of slope physical parameters, water content and % fines in the soil and not from maximum values of any one parameter alone. This has been observed through correlation analysis, where a strong correlation exists between the slope physical parameters, water content and % fines in the residual soil with

FOS. Thus, for reliable identification of landslide hazards, Landslide Hazard Charts have been proposed. These charts have three regions, namely fail ($FOS < 1$), vulnerable ($1 < FOS < 1.5$) and safe ($FOS > 1$), based on the obtained numerical simulation results. The stability state of a given slope will fall in either of the three regions based on the combination of slope height, slope, angle, soil cover, % fine and water content. Several case studies were used to validate the utility of the proposed Landslide Hazard Charts. The primary purpose of formulating this kind of chart is to assist investigators and policymakers during the preliminary investigation of the study area, thereby helping them in focusing more on the vulnerable slopes. Also, incorporating percentage fines and water content in the proposed Landslide Hazard Charts will help in analysing the long-term stability of the residual soil slopes.

The present chapter discusses numerical simulation results in developing Landslide Hazard Charts. The same datasets can also be used to develop advanced machine learning models like the Artificial Neural Network for stability prediction, as discussed in the next chapter. The key benefit of developing the Artificial Neural Network model is that it can update the database easily; thus, more detailed information can be included in the stability predicting model without developing the model again from the beginning.