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Rain-induced failures on residual soil slopes

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ABSTRACT

The hilly region of Western Ghats, India, is a site of frequent landslides, which have caused a severe loss of lives and property. The region is characterised by the presence of residual soils, rugged topography, high relief, and medium to steep slopes. During the heavy rainfall, the pore water pressure is built quickly in the residual soils.

This study deals with a probabilistic stability analysis of rain-induced failures on residual soil slopes. A mass movement analysis is also attempted using the momentum transfer law for the Parmachi Landslide. Attention is given to the associated risk of sliding, incorporating important factors, which influence the failure of natural slopes. A landslide hazard prediction procedure is presented and its application to debris flows at Parmachi is shown as an example. The probability of failure is evaluated in conjunction with the consequences of failure. Decision analysis is also tried with the probabilistic slope stability analysis of the Parmachi Landslide. The evaluated risk and decision theory are used to suggest a decision-making process for landslide hazard mitigation.

INTRODUCTION

Landslides are quite frequent in the hilly regions of Western Ghats, India. Most of the slides are caused by heavy rainfall, though other causes may also contribute occasionally. Anthropogenic activities such as toe cutting for roadways and settlements, quarrying, and unplanned land use add to their frequency of occurrence and hence to the fragile nature of the slopes. The region is characterised by the presence of residual soils. The soil cover may vary in depth from 0.5 to 10 m. The general topography is rugged with high relief and medium to steep slope of 70°–80°. The slopes in this highly vegetated region are in a state of marginal stability. An intense rainfall easily triggers off a sudden failure. Therefore, it is necessary to adopt mitigation or remedial measures at potential landslide-prone areas. The measures to be adopted depend on the likely risk of damage due to landslide. In the present work, a new approach is suggested for evaluating the risk associated with the occurrence of a landslide, with specific reference to Parmachi, located about 300 km south of Bombay.

The traditional approach to landslide studies involves a qualitative technique based on consideration of the probable contributory factors and their spatial variation. On the other hand, the engineering quantitative approach uses the deterministic technique, which involves analysis of slope instability and calculation of post-failure mass movement parameters using principles of mechanics. This paper attempts to combine both the methodologies through the use of a Digital Terrain Model (DTM) and the concept of overlaying of parameters. Also, a probabilistic analysis is employed in place of the traditional deterministic analysis. A subsequent spatial analysis of mass movements would enable demarcating areas and activities likely to be affected.

THE STUDY AREA

A large landslide occurred at Parmachi (Latitude 18° 8' N and Longitude 73° 36' E) in the Western Ghats on 28 June 1994 resulting in the death of 15 persons and destruction of a few houses. Prior to the occurrence of the landslide, there was a heavy downpour in the area for three days, and it had a maximum intensity of 240 mm/day during the last twenty-four hours. The landslide involved movement of about 30,000 m^3 of soil and rock over approximately 300 m. The elevations and slope angles at the location vary from 240 m to 500 m and from 50° to 60°, respectively.

METHODOLOGY

About 500 m x 400 m of the area was divided into grids of 16 m x 16 m. The infinite slope method was used for the stability analysis. This method was preferred as it allowed the consideration of local variations in slope conditions and, more importantly, the superposition of thematic information subsequently for risk evaluation. A factor of safety value was obtained for each grid. Within a grid, the slope and thickness of the surface layer was assumed to be constant. The analysis was carried out for different intensities and durations of rainfall. The fluctuation of groundwater table was incorporated into the analysis by considering a saturated flow within the soil layer.

The analysis proceeds in the following sequence of steps:

1. Development of digital terrain model;
2. A grid-by-grid infinite slope stability analysis incorporating effect of groundwater table rise due to rainwater infiltration and also effect of vegetation;

3. Calculation of probability of failure using Point Estimate Method (PEM) for each grid for a given intensity and duration of rainfall;
4. Computation of mass movement; and
5. Computation of risk and damage.

INFINITE SLOPE STABILITY ANALYSIS

Since a grid-by-grid analysis can be carried out based on the data available for each grid, a value for the factor of safety for each grid is obtained readily. This can easily be integrated with the DTM and other terrain-related information within the framework of a GIS. The infinite slope method allows the comparison of the stability of a grid with that of the neighbouring ones (i.e., it gives a picture of the relative stability of the individual grids).

For the typical infinite slope section the factor of safety (FS) is written as:

$$\mathrm{FS}=\frac{c_d+\left[(\gamma_{sat}-\gamma_w)(h-z)+\gamma_1(H-h)\right]\cos^2\beta\tan\phi_d}{\left[\gamma_{sat}(h-z)+\gamma_1(H-h)\right]\cos\beta\sin\beta} \qquad (1)$$

where c_d = drained soil cohesion (kN/m^2)

γ_{sat} = saturated unit weight of the soil (kN/m^3)

γ_1 = unit weight of the soil (kN/m^3)

H = thickness of soil cover (m)

h = groundwater table height (m)

z = depth of the failure surface from the top (m)

ϕ_d = angle of shearing resistance (degrees)

β = angle of inclination of slope (degrees)

The effect of vegetation is incorporated in the form of root cohesion c_r and surcharge (i.e., load of the tree) T (Shasko and Keller 1991).

Calculation of time to failure of each grid

The time to failure (t) is calculated on the basis of the groundwater table rise required for the FS to become unity as follows:

$$\mathrm{t}=\frac{\eta}{\varepsilon\sin\beta\cos\beta}\left[-1+\left(\sqrt{1+\frac{2h}{r}\varepsilon\, k\sin\beta\cos\beta}\right)\right] \qquad (2)$$

where

η = effective porosity,

ε = slope parameter representing curvature of the terrain,

k = saturated hydraulic conductivity, and

r = rainfall intensity

PROBABILITY OF FAILURE

Failure of a slope is defined as the event whereby FS receives a value smaller than or equal to unity. Thus, if F denotes failure, we have:

$$\mathrm{F}=[\mathrm{FS}\le 1] \qquad (3)$$

If f (FS) represents the probability density function of the factor of safety FS_i along a potential failure surface S_i, then the probability of failure of a slope along S is

$$\mathrm{P}[\mathrm{F}|\mathrm{S}_i]=\int_{-\infty}^{1}\mathrm{f}(\mathrm{FS}_i)\,\mathrm{d}(\mathrm{FS}_i)=\mathrm{F}_i\,(1) \qquad (4)$$

in which $P[F \mid S_i]$ denotes the conditional probability of failure given that the latter occurs along S_i and F_i (1) is the cumulative distribution of FS_i evaluated at $FS_i = 1$. If there are N possible failure surfaces, each with probability of occurrence $P[S_i]$, i = 1, 2, ..., N, then, from the total probability theorem, the probability of failure p_f of the slope is equal to

$$\mathrm{p_f}=\mathrm{P}[\mathrm{F}]=\sum_{i=1}^{N}\mathrm{P}[\mathrm{F}|\mathrm{S}_i]\;\;\mathrm{P}[\mathrm{S}_i] \qquad (5)$$

with $\sum_{i=1}^{N}P[S_i]=1$. Among the possible failure surfaces, the critical one is the surface that corresponds to the minimum value of the conventional factor of safety. If the latter is denoted by S_c (i.e., S_c is the critical surface for which FS = min.) and the probability of its occurrence by $P[S_c]$, then Equation (5) may be written as

$$\mathrm{p_f}=\mathrm{P}[\mathrm{F}|\mathrm{S_c}]\,\mathrm{P}[\mathrm{S_c}]+\sum_{i=1}^{N-1}\mathrm{P}[\mathrm{F}|\mathrm{S}_i]\,\mathrm{P}[\mathrm{S}_i] \qquad (6)$$

It is assumed that the critical surface S_c has a much higher probability of occurrence (A-Grivas, 1981) than any other potential surface S_i, then Equation (6) becomes

$$\mathrm{p_f}=\mathrm{P}[\mathrm{F}]\approx\mathrm{P}[\mathrm{F}\mid\mathrm{S_c}] \qquad (7)$$

Combining Equations (4) and (7), it is found that

$$\mathrm{p_f}=\int_{-\infty}^{1}\mathrm{f}(\mathrm{FS_c})\,\mathrm{d}(\mathrm{FS_c})=\mathrm{F_c}\,(1) \qquad (8)$$

in which F_c (1) is the cumulative distribution of the factor of safety along the critical surface evaluated. For large values of p_f, variations in the form of the probability density function is not important, whereas it is important for small values.

Point estimate method

In the present study, the Rosenblueth's Point Estimate Method (PEM) has been used to calculate the probability of failure (Rosenblueth 1975). This method approximates the original Probability Density Function (PDF) by assuming that the entire probability mass of variable X is concentrated at two points: x_- and x_+. The four unknowns: the locations of x_- and x_+ and the corresponding probability masses p_- and p_+ (called weighting factors) are determined in such a manner that the first three moments of the original random variable X are preserved. The solutions for x_-, x_+, p_- and p_+ are

$$x_- = \mu - z_-\sigma;\ x_+ = \mu + z_+\sigma;\ p_+ = \frac{z_-}{z_+ + z_-},\text{ and } p_- = 1 - p_+ \qquad (9)$$

where $z_+ = \frac{\gamma}{2} + \sqrt{1 + \left(\frac{\gamma}{2}\right)^2}$ and $z_- = z_+ - \gamma$ with γ being the skewness coefficient of the random variable X.

For problems involving N random variables, the two points for each variable are computed according to above equations and permutated producing a total of 2^N possible points of evaluation in the parameter space. The *r*th moment of $Y = g(X) = g(X_1, X_2, \ldots, X_N)$ about the origin can be approximated as

$$E(Y^r) = \sum p_{(\delta 1, \delta 2, \ldots, \delta N)}\, y^r_{(\delta 1, \delta 2, \ldots, \delta N)} \qquad (10)$$

in which the subscript δ_i is a sign indicator that can only be + or - for representing the random variable X_i having the value of $x_{i+} = \mu_i + z_{i+}\sigma_i$ or $x_{i-} = \mu_i - z_{i-}\sigma_i$, respectively; $p(\delta_1, \delta_2, \ldots, \delta_N)$ is determined by

$$p_{(\delta 1, \delta 2, \ldots, \delta N)} = \prod_{i=1}^{N} p_{i,\delta i} + \sum_{i=1}^{N-1}\left(\sum_{j=i+1}^{N} \delta_i\, \delta_j\, a_{ij}\right) \qquad (11)$$

$$\text{in which } a_{ij} = \frac{\rho_{ij} / 2^N}{\sqrt{\prod_{i=1}^{N}\left[1 + \left(\frac{\gamma_i}{2}\right)^2\right]}}$$

where ρ_{ij} is the correlation coefficient between random variables X_i and X_j. The number of terms in the summation of Equation (10) is 2^N which corresponds to the total number of possible combinations of + and - for all N random variables. For each term of the summation in Equation (10), the model has to be evaluated once at the corresponding point in the parameter space.

Risk evaluation

A common definition of risk is: Risk = Probability of occurrence of the catastrophic event x Probability of failure of slope x Consequences of failure.

In the present case, instability due to excessive rainfall is considered. Probabilistic method is used for computing the factor of safety so as to account for the variability in the soil parameters involved in the formulation and the uncertainties associated with the methods of analysis.

ANALYSIS AND RESULTS

Stability and mass movement

The stability of the slope in the study area is analysed by the above method for different rainfall intensities and duration. The effect of vegetation has been considered. The resulting mass movement is calculated.

It is observed that there are only a few local regions of failure when rainfall intensity of 240 mm/day (0.01 m/hr) occurs for 24 hours. There is a much larger region of contiguous failed grids when rainfall intensity increases to 300 mm/day (0.0125 m/hr) and occurs for 24 hours. If we consider the latter to be an extensive failure of the slope, then the comparison of the two cases shows that rainfall intensity plays a very significant role in inducing failure.

The results obtained for constant rainfall intensities and varying duration have demonstrated how gradually the slope reaches to the state of failure when duration of rainfall increases. However, it was seen that increase in duration is less critical than increase in intensity of rainfall. Further, if we consider the effects of root cohesion and surcharge, we find that nominal root cohesion of 3.5 kN/m² and surcharge of 10 kN/m add to the stability of slope.

For the critical slope section, mass movement analysis using a momentum transfer law (DST 1997) shows a run out distance of 300 m and duration of 18 sec. The computed thickness of deposit was 0.89 m. When superimposed over the DTM, this indicates that the human settlement in the area lies within the run out distance.

Effect of rainfall and probability of failure

It has been seen (DST 1997) that a minimum seasonal cumulative antecedent rainfall R_a of 800 cm is required before a high intensity monsoon rainstorm can trigger debris flows at Parmachi. Iida's groundwater movement model (Okimura and Kawatani 1986) has been used to study the relationship between average rainfall intensity and groundwater response for a slope with data as given in Table 1.

A value of FS = 1.0 represents failure. The mean values of the soil properties given in Table 1 were used in Equation (1) to evaluate h_{wf}, which is the value of the height of water table with respect to failure plane at FS = 1.0. The result is h_{wf} = 1.435 m. Slope failure would occur when the water level h_w equals or exceeds h_{wf}. The cumulated rainfall R_f that would

Table 1: Slope and soil data used for Parmachi Landslide

Slope and soil parameters	Mean	Range	COV
z (m)	1.5	0.50–3.00	0.60
α (degrees)	40	40–60	0.20
k (m/hr)	0.001	3.8×10^{-4}–0.035	0.50
ϕ' (degrees)	30	26–34	0.10
c' (kN/m²)	10	7–18	0.40
γ (kN/m³)	21.70	20.3–22.74	0.03
η (%)	0.423	0.334–0.512	0.20

produce $h_w = h_{wf}$ was calculated from average rainfall intensity and duration. The calculated R_f falls in the range 25–45 cm, depending on the rainfall intensity. Two rainstorms which had triggered the debris flows in the study area are considered in the present study: a storm of August 20, 1992, which caused some property damage at Parmachi due to debris flow, and the other, a storm of June 28, 1994, which caused more extensive damage (Nair et al. 1996).

Two cases are considered:

- c, ϕ and γ as random variables and correlation coefficients considered between the variables are: $\rho(c,\phi) = 0.25$, $\rho(\phi,\gamma) = 0.30$ and $\rho(\gamma,c) = 0.20$, and results are given in Table 2 and
- c, ϕ and z as random variables with $\rho(c,\phi) = 0.25$, $\rho(\phi,z) = 0.40$ and $\rho(z,c) = 0.20$, and results are given in Table 3

Our calculations showed that for the given soil data (Table 1), bursts of rainfall with intensities greater than 180 mm/day for about 3 days and 240 mm/day for about one day are needed to produce $h_w \geq h_{wf}$. From this study, it is possible to develop a rainfall threshold for debris flows knowing the number of slides in the area. The higher the probability of failure for a given condition, the more likely the occurrence of debris flows. Different thresholds can be constructed for different probabilities of failure.

DECISION ANALYSIS

The application of the above analysis lies in decision-making for arriving at a suitable mitigation measures. The decision analysis as applied to the Parmachi Landslide is described below considering the pre-failure conditions. The decision tree showing the succession of events is first constructed. Given that rainfall is the main causative factor, two possibilities, which exist at the first chance node, are: critical rainfall occurs or rainfall is less than critical. If critical rainfall does occur, then the second chance node has the possibilities: a landslide takes place or there is no landslide. Lastly, given that a landslide occurs, the possible damages are:

(a) damage to structures/infrastructure such as road,
(b) loss of lives, and
(c) other consequences. The decision tree is constructed logically following this sequence.

Table 2: Effect of rainfall intensity and duration on probability of failure (c, ϕ and γ as random variables) $\rho(c,\phi) = 0.25$, $\rho(\phi,\gamma) = 0.30$, and $\rho(\gamma, c) = 0.20$

S. No.	Intensity of rainfall (mm/day)	Duration	Water table height (m) ($h_w \leq z$)	Central factor of safety (CFS)	COV (FS) (%)	p_f
1	180	At 24 hr	0.1094	1.2871	21.440	0.14753
		At 48 hr	0.8713	1.1192	23.555	0.32336
		At 60 hr	1.5000	0.9865	25.728	0.51884
2	240	At 12 hr	0.1694	1.2736	21.590	0.15866
		At 24 hr	1.3434	1.0191	25.142	0.46744

Table 3: Effect of rainfall intensity and duration on probability of failure (c, ϕ, and z as random variables) $\rho(c,\phi) = 0.25$, $\rho(\phi,z) = 0.40$, and $\rho(z,c) = 0.20$

S. No.	Intensity of rainfall (mm/day)	Duration	Water table height (m) ($h_w \leq z$)	Central factor of safety (CFS)	COV (FS) (%)	p_f
1	180	At 24 hrs	0.1094	1.2871	40.674	0.18398
		At 48 hrs	0.8713	1.1192	41.017	0.25024
		At 60 hrs	1.5000	0.9865	45.558	0.29526
2	240	At 12 hrs	0.1694	1.2736	40.524	0.18917
		At 24 hrs	1.3434	1.0191	43.545	0.27641

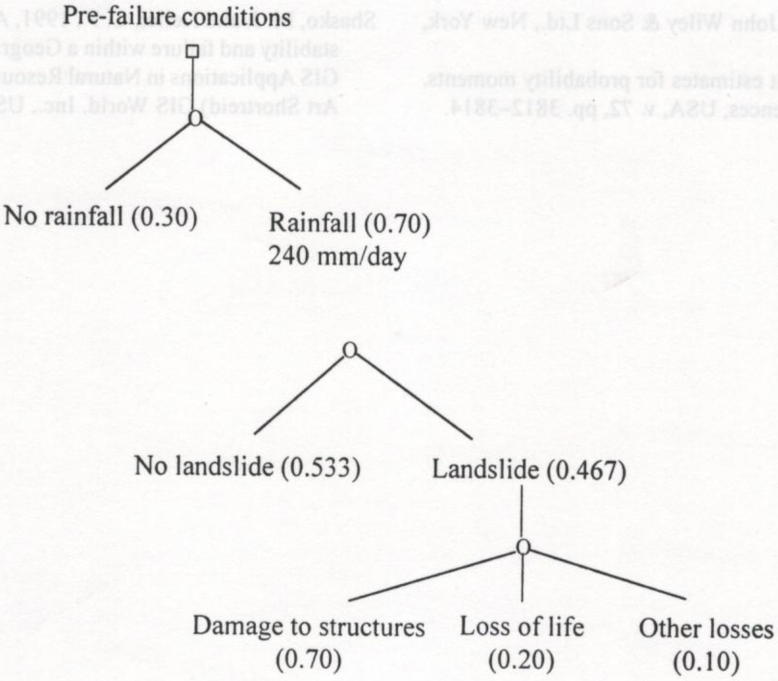

Fig. 1: Decision analysis for Parmachi Landslide

Based on the infinite slope analysis described earlier, the critical rainfall is taken as 240 mm/day (0.01 m/hr) for 24 hours. The probability of occurrence of landslide is 0.467 from Table 2. The decision tree and the subsequent calculations are shown in Fig. 1. Assigning probability values to the probable damage is based entirely on engineering judgement and type of structures in the area. Product of the probabilities along any path in the tree gives the overall probability of occurrence of a certain type of damage. The overall probability in this case is seen to be about 0.229 for loss of property and 0.065 for loss of life, while for other losses it is 0.033.

CONCLUSIONS

Rainfall-induced landslides in residual soils may be better understood by using the above approach, which combines the data from the fields of terrain modelling and probabilistic analysis.

The intensity of critical rainfall of 240 mm/day, computed by the present approach, agrees well with the reported rainfall intensity in the study area at the time of landslide occurrence. The run out distance and the thickness of deposit also agree with the observed values at the site. The duration of run out, however, could not be verified due to the lack of reliable eyewitness accounts.

The probability-based decision analysis is a simple and convenient tool, which gives a fair idea of the overall risk that is faced by an area exposed to landslide proneness. Mitigation measures can be planned on the basis of the magnitudes of the overall probabilities. However, it must be noted that the same value of probability may have different degrees of significance for different sites.

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