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SLOPE PROFILE MORPHOMETRY AS AN INDICATOR FOR SLOPE MOVEMENT

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Abstract

Two dimensional slope profile morphometric investigation in a part of the land failure prone Garhwal region of the Lesser Himalaya, Tehri district, U. P., India, indicates that the landslip morphology is closely related to the dominant movement processes active in this terrain. Technique developed for the morphometric analysis of landslips involves the use of five morphometric indices. Each index has been formulated to give an indication of the processes responsible for producing variation on landslip form. The measurements indicated the degree of dilation, flowage, displacement and tenuity. The depth/length ratio is used as a numerical parameter to classify landslips into process groups. Multivariate discriminant function criteria have been worked out to differentiate between various slope movement processes. The result indicated that among all two dimensional slope profile morphometric indices, Classification, Dilation and Tenuity indices contribute significantly in discriminating various slope movement processes. Based on these indices, bivariate and univariate plots have been prepared as discriminant tools to predict various types of slope movements.

Introduction

The study of mass-movement in general, and landslips in particular, has often centered around morphology. The reason for this, is not that the morphology is of interest in itself but that landslip form can be interpreted to give an indication of the process that is periodically or continuously sculpturing the face of the earth. This paper presents and shows the use of morphometric technique. It is shown that significant morphometric indices can be obtained from a landslip, and that they will give some indication of the processes involved in its initial formation in reference to its immediate environment.

Keywords: Morphometry; Slope profile; Morphometric index; Slope movement

Morphometric analysis of mass-movement is a well suited research method for the quantitative approach, allowing statements to be made with some degree of confidence concerning their objectivity and significance.

The techniques outlined are applied to sixty transverse slope profiles in twelve randomly selected drainage basins with known slope stability conditions.

The Terrain

The present investigation covers an area in the Garhwal region of the Lesser Himalayan mountains in

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the Tehri district Garhwal U. P., India (Fig. 1). The river Ganga girdles the study area in the east, south and west. The northern boundary is demarcated by a prominent topographic ridge. The terrain is characterized by small concavo-convex steep slopes, high relief, rugged topography, and poor soil or regolith cover. The area is also transversed by a number of ridges (R_2,----R_6, Fig. 1). The elevation ranges from 500 m to more than 2200 m from mean sea level. The hillslope with an angle of more than 25° constitutes about 86% of the area. Approximately 63% of hillslope is occupied by forest cover. Agricultural land constitutes about 11% of the area. About 3% of the hill face is barren and the rest is characterized by sparse vegetation. Vegetation cover decreases relatively at high altitude specially along the upper part of ridges. Approximately 80% of the area is made up of quartzite. Limestone, dolomite, dark gray laminated shale, variegated purple green shale, calcareous shale, slate, phyllite and siltstone constitute about 20% of the total study area.

The Slope Morphometry Indices and the Slope Movement Processes

Crozier [2], Cooke and Doornkamp [1] and Mehrotra *et al.* [7] have demonstrated that slope morphometric indices can be used for deciphering various classes of slope movement processes. With this premise, following the descriptive criteria of Varnes [11], five morphometric indices similar to those given by Crozier [1], were defined and measured on two dimensional transverse slope profiles, for the four types of slope movement processes, commonly observed in the study area (Table 1). These slope profiles were drawn on the basis of enlarged topographic contour map in the scale of 1:3250, with 20 m contour intervals. A scheme for measurement of various landslip morphometric indices from a profile and the formulae used are shown in Figure 2. A brief description of these indices are given below:

Classification Index

The classification index is defined as the ratio of maximum depth (D) of the displaced mass with respect to original parent slope, prior to its displacement (true depth), to the overall length or maximum length (L) measured up the slope, expressed as percentage (Fig. 2). This parameter has been used as a measure of surfaciality by a number of researchers namely Skempton [9], Seleby [8], Mclean and Davidson [6], Crozier [2], Cooke and Doornkamp [1] and East [4].

In the present study, the D/L ratio is worked out for sixty individual slips derived from slope profiles drawn from topographic contour map of 1:3250. The dominant processes were confirmed through field checks at various locations. The mean values of classification index (D/L) was found to be 4.68, 7.22, 4.39 and 1.88 for rotational slide, planar slide, slide flow and fluid flow along with standard deviations 2.61, 3.76, 0.91 and 0.46 respectively (Table 2).

Dilation Index

Crozier [2] defined and calculated the dilation index as the ratio of Wx/Wc, where Wx represents the width of convex part and Wc the width of concave part in longitudinal slope section. However, in the present study dealing with the two dimensional transverse slope section, it has been defined (Tabatabaei, [10]) as the ratio of maximum height of convex part (Dx) to the maximum depth of concave part (Dc) with respect to original parent slope that existed before its disruption (Fig. 2).

Table 1. Process groups used in morphometric analysis

Process Group	Class of Movement
Fluid-Flow (FF)	Debris flow, debris avalanches
Slide-Flow (SF)	Slump/flow
Planar Slide (PS)	Debris Slide, rock slide
Rotational Slide (RS)	Earth and rock slumps

Table 2. Statistical Summary of Morphometric Indices of Each Process in the Area of Study (Modified after Crozier [2])

Morphometric Index		Process Group			
		RS	PS	SF	FF
Classification Index	M	7.68	7.22	4.39	1.88
	S	2.61	3.76	0.91	0.46
	M+s	10.29	10.98	5.30	2.34
	M - s	5.07	3.46	3.84	1.42
Dilation Index	M	0.35	0.36	0.70	1.78
	S	0.13	0.23	0.23	0.85
	M+s	0.48	0.59	0.93	2.63
	M - s	0.22	0.13	0.47	0.93
Flowage Index	M	75.92	44.00	73.94	215.95
	S	15.82	17.32	39.82	195.11
	M+s	91.47	61.32	113.76	411.06
	M - s	60.1	26.68	34.12	20.84
Displacement Index	M	48.04	73.31	54.25	53.22
	S	14.12	16.80	16.43	14.70
	M+s	62.16	90.11	70.68	67.92
	M - s	33.92	56.51	37.82	38.52
Tenuity Index	M	1.20	0.62	1.62	2.37
	S	0.11	0.24	0.44	1.20
	M+s	1.31	0.86	2.06	3.57
	M - s	1.09	0.38	1.18	1.17

M: Mean, S: One standard deviation, RS: Rotational slide, PS: Planar slide, SF: Slide-Flow, FF: Fluid-Flow.

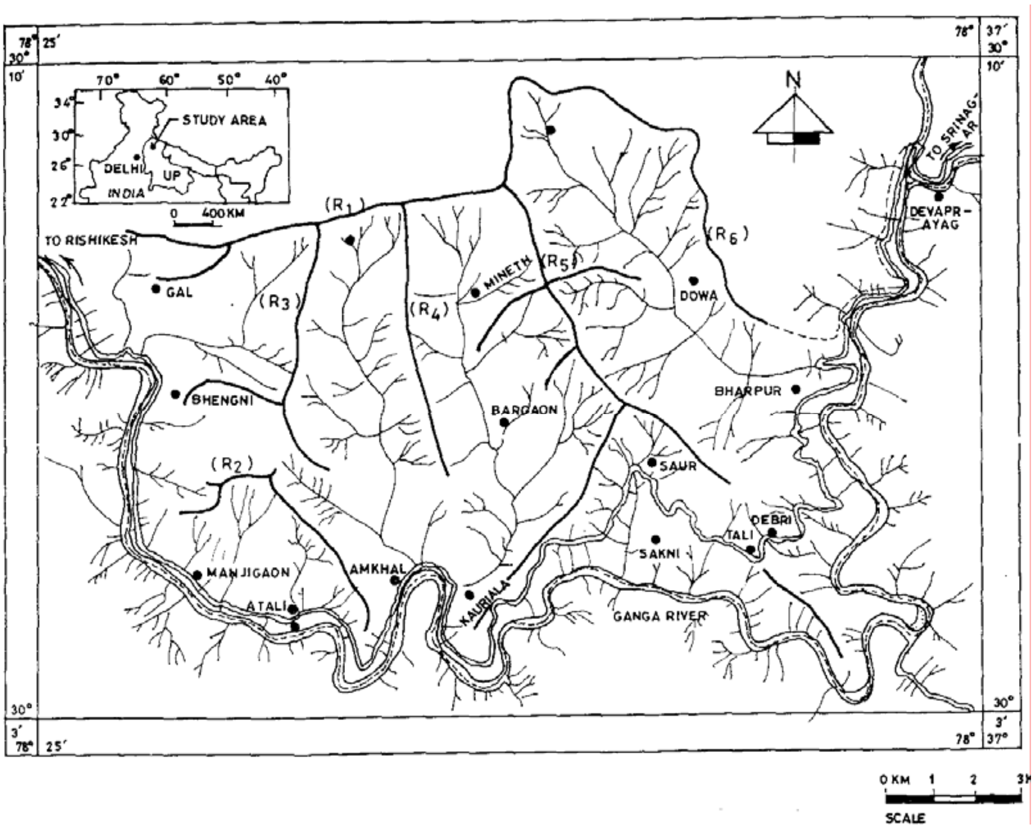

Figure 1. Location map of the study area.

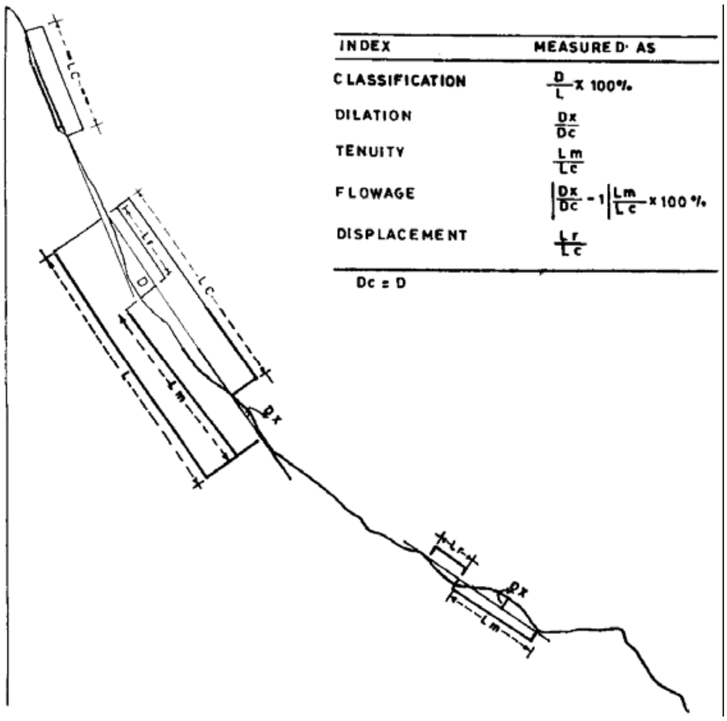

Figure 2. Landslip terminology and measurement used in the morphometric indices.

The Dx/Dc ratio is designated primarily to help in flow studies. It is a measure for shape. In other words, it measures the degree of lateral spread. The Dx/Dc ratios have the mean values 0.35, 0.36, 0.70, and 1.78. Standard deviations 0.13, 0.23, 0.23 and 0.85 are characteristic values for rotational slide, planar slide, slide flow and fluid flow, respectively (Table 2).

Tenuity Index

The tenuity index represents the Lm/Lc ratio, where Lm represents the length of displaced material or convex part and Lc length of concave part (Fig. 2).

This index reflects tenuity of displaced mass in relative to its original size (determined by Lc). It has the potential of indicating the effect of slope inclination and the microrelief features to channeling flow downslope. The mean tenuity index for each process group was computed (Table 2). It is observed that mean Lm/Lc ratios 1.20, 0.62, 1.62, 2.37 with standard deviations 0.11, 0.24, 0.44 and 1.2 are characteristically associated with rotational slide, planar slide, slide flow and fluid flow processes, respectively.

Flowage Index

The Flowage Index is defined as product of |Dx/Dc-1|×Lm/Lc×100%, where Lm is the length of displaced material or convex part and Lc the length of concave part (Fig. 2). In case Dx/Dc=1.0, the increase over 1.0 of Lm/Lc alone, may be taken as flowage index (Crozier [2]). It measures the flowage of a landslip as indicated by lateral deformation in reference to its tenuity (measured by Lm/Lc) or in other words, it is a measure of biaxial spread. This value increases with the slope angle and therefore does not offer a measure of fluidity, but rather the amount of flowage which in turn indicates relative velocity. The flowage index, when applied to rotational and planar slides may indicate mutual displacement of individual components within the displaced material.

Mean values of twenty seven landslips involving flows were computed (Table 2). The flowage index of 73.94 and 216.95 with standard deviation of 39.82 and 195.11 are characteristically found to be associated with the slide flow and fluid flow, respectively.

Displacement Index

The Displacement Index is defined as ratio between surface length of rupture (Lr), exposed in the concave part, and Lc, length of concave part (Fig. 2). This index measures the degree to which the displacement material has evacuated the surface of rupture. In a sense, it indicates the development stage of the slope movement and provides a rough guide to the residual stability of the slope. Partially excavated surfaces or concave parts with low displacement values are generally unstable and likely to be reactivated. This may be due to pounding of water up slope of the concave part, which saturates pores, increases pore water pressure and decreases strength of the mass. The steepness of the slope near crown at the contact with surface of rupture, further adds to the instability. A value of 100% for this ratio, therefore, indicates the most stable situation, where material has been entirely removed from the concave part. The lower values of displacement index with respect to the mean value of each group indicate unstable condition due to partial removal of material from concave part.

Mean values 48.04, 73.31, 54.25 and 53.22 with standard deviations 14.12, 16.80, 16.43 and 14.70 for rotational slide, planar slide, slide flow and fluid flow, respectively were found to indicate the limits below which any displacement value may indicate unstable slope (Table 2).

Discussion and Analysis

The morphometric indices thus worked out on the basis of contour map with 20 m intervals in the scale of 1:3250 for sixty slope profiles located in the areas experiencing various types of failures, are presented in Table 2 as mean and standard deviation. A perusal of this table indicates that the Classification index and Dilation index for rotational and planar slides, Tenuity index for rotational slide and slide flow, and the Displacement index for rotational slide, slide flow and fluid flow are not significantly different. The mean values of various indices in general, when considered along with their standard deviations, overlap, implying thereby that these indices on univariate basis may not always lead to a focussed decision regarding prediction and nature of slope movement process. Hence multivariate analysis of these indices was resorted to discriminate between various types of slope movement processes.

Discriminant Analysis for Slope Process Groups

The discriminant function analysis was applied to formulate a multivariate criterion to differentiate between similar slope movement processes, based on all five morphometric indices. This technique which takes into account all the five indices simultaneously, helps maximize the multivariate distance (D^2) between the two slope movement processes and minimize the spread in the values of various indices within each slope movement process. For details readers are referred to Kendall [5] and Davis [3].

The discriminant constants developed to differentiate between pairs of slope process groups are given in Table 3, and discriminant criteria to allocate an unknown slope profile to one of the various slope movement process groups are summarized in Table 4 and depicted pictorially in Figures 3-8.

Table 3. Discriminant function and criteria to differentiate various pairs of slope movement process group

Process Group	Discriminant Function	Discriminant Criteria
FF		
Vs	5.5931c - 4.2442d+0.0100f+0.0342S - 0.0669t	P>15.4874 for SF
SF		P<15.4874 for FF
FF		
Vs	1.0537c - 7.6783d+0.0346f+0.0432S - 4.8809t	P>-3.1302 for PS
PS		P<-3.1302 for FF
FF		
Vs	3.0603c - 11.3112d+0.0579f+0.1196s - 5.2498t	P>-5.0055 for RS
RS		P<-5.0055 for FF
SF		
Vs	1.1906c - 2.1812d - 0.0592f+0.0412s - 9.8985t	P>-3.8432 for PS
PS		P<-3.8432 for SF
SF		
Vs	1.4086c - 9.9840d - 0.0084f+0.0086s - 2.3680t	P>-1.6535 for RS
RS		P<-1.6535 for SF
PS		
Vs	-0.5306c - 13.5728d - 0.0171f+0.0033s - 22.346t	P>10.5630 for RS
RS		P<10.5630 for PS

SF: Fluid Flow, PS: Planar Slide, SF: Slide Flow, RS: Rotational Slide, P: Discriminant Score of a new slope profile. c, d, f, s, and t are the variables indicating classification, dilation, flowage, displacement and tenuity indices.

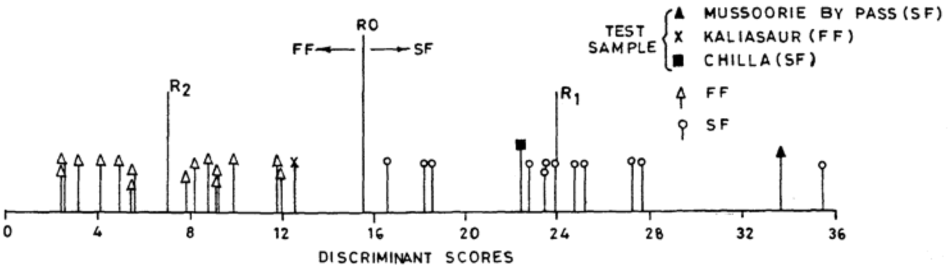

Figure 3. Location of sample on discriminant function line for differentiation between planar slide (PS) and fluid flow (FF).

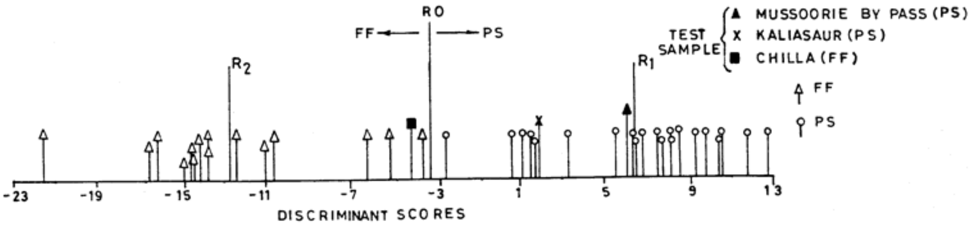

Figure 4. Location of sample on discriminant function line for differentiation between planar slide (PS) and fluid flow (FF).

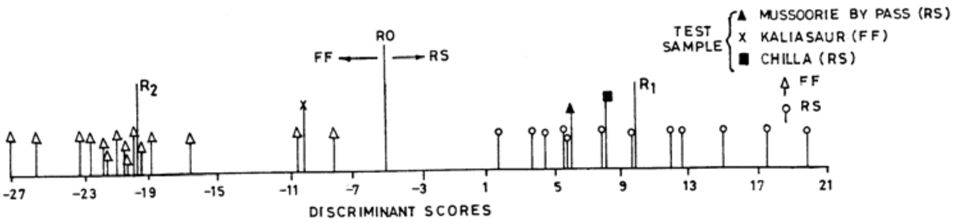

Figure 5. Location of sample on discriminate function line for differentiation between rotational slide (RS) and fluid flow (FF).

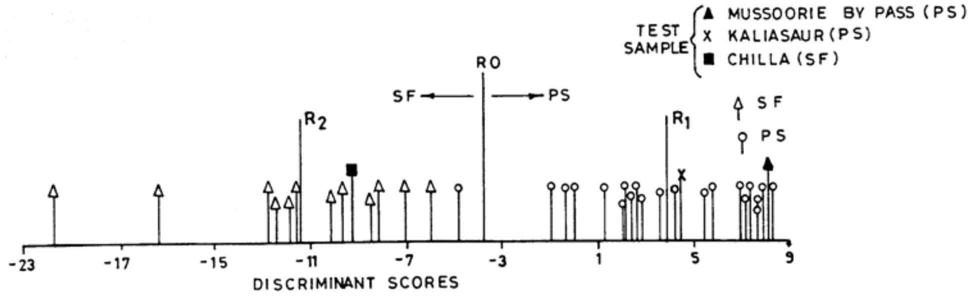

Figure 6. Location of sample on discriminant function line for differentiation between planar slide (PS) and slide flow (SF).

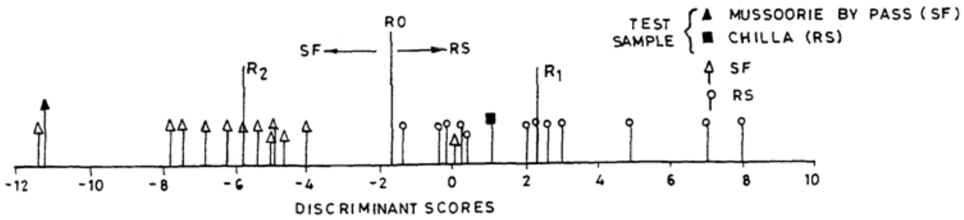

Figure 7. Location of sample on discriminant function line for differentiation between rotational slide (RS) and slide flow (SF).

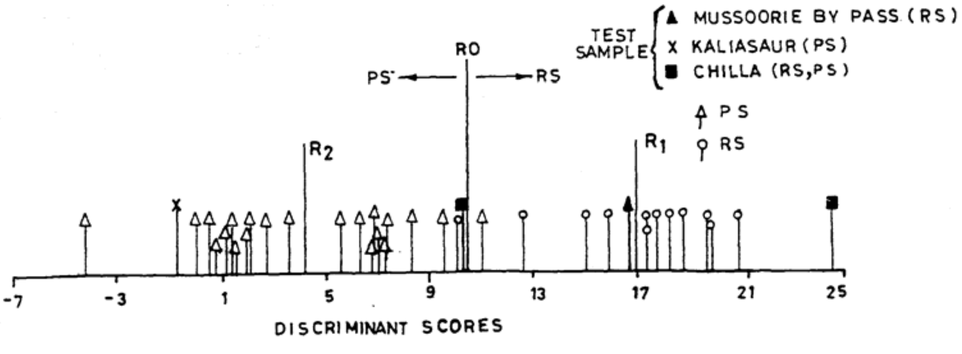

Figure 8. Location of sample on discriminant function line for differentiation between rotational slide (RS) and planar slide (PS).

Table 4. Discriminant score means and distance measure D^2

Discriminant Score Parameter	**Pairs of Slope Movement Process Group**											
	Group		Group		Group		Group		Group		Group	
	1	2	1	2	1	2	1	2	1	2	1	2
	SF	FF	PS	FF	RS	FF	PS	SF	RS	SF	RS	PS
R_1	23.9809 (SF)		6.3437 (PS)		9.7212 (RS)		3.7887 (PS)		2.4181 (RS)		16.9234 (RS)	
R_2	6.9939 (FF)		-12.6042 (FF)		-19.4752 (FF)		-11.4752 (SF)		-5.7251 (SF)		4.2027 (PS)	
R_0	15.4874		-3.1302		-5.0055		-3.8432		-1.6535		10.5630	
D^2	16.99		18.95		29.45		15.26		8.14		12.72	
F Statistic	19.02		29.25		32.99		20.30		7.99		16.92	

R_1 and R_0: Means of Discriminant Score of Groups 1 & 2, respectively; $R_0=(R_1+R_2)/2$; D^2=Mahalanobis Distance between two groups; F-statistic-significant at 1% level.

Let P be the discriminant score of a new profile. If $P>R_0$, the sample belongs to the pair under consideration whose discriminant score is greater than R_0.

If $P<R_0$, the sample belongs to the pair under consideration whose discriminant score is less than R_0.

Efficacy of the Approach

In order with a view to evaluate the usefulness of discriminant function criteria in predicting the probable slope movement process, many slope profiles were analyzed in three test areas of similar topographic nature. Of these profiles, the representative failed sections are mentioned below.

Mussorie By Pass Area

Location: 122 km NNW of the study area.

Lithology: Consists of hard, compact, highly weathered dolomite and limestone of late Precambrian age with colluvium and debris.

Structure: Beds dip northwesterly having dip angle varying from 20° to 45°. plunge overturn and recumbent folds are present along with two fault zones in NNW and SSE direction.

Base map: Contour map of 1:1200 scale with 5 m contour interval.

Analysis: slopes were analyzed with the help of morphometric indices. The Classification, Dilation, Flowage, Displacement and Tenuity indices were found to be 5.9, 0.35, 40, 35.9 and 1.14, respectively. Thus the type of movement could either be rotational slide, slide flow or planar slide. The discriminant scores were computed to be 16.79 for RS Vs PS; 1.47 for SF Vs RS and 1.48 for SF Vs PS. The analysis indicated the possibility of slope movement to be by rotational slide and planar slide. It was concluded that in the case of RS Vs PS the type of movement is rotational slide. The movement reactivates due to its low value of displacement index of 35.9.

Field observation: Toposheet based prediction (Fig. 8) regarding slope movement by rotational slide was confirmed on field checks.

Kaliasaur Slide Area

Location: 80 km NNE of the study area.

Lithology: Consist of purple white and light green quartzite, interbedded with maroon shale covered partially by debris.

Structure: Dip and dip direction is variable and changes from S to SE direction having dip angle ranging from 25° to 60°. A fault with a roughly E-W trend passes through the crest zone.

Base map: Contour map of 1:1200 scale with 5 m contour interval.

Analysis: Slopes were analyzed with the help of morphometric indices. The Classification, Dilation. Flowage, Displacement and Tenuity indices were found to be 8.04, 0.85, 28.4, 38 and 0.71, respectively. The type of movement could either be rotational slide or planar slide. The discriminant score was computed to be -0.55 which clearly indicated the type of movement is planar slide. The slope movement reactivates due to its low value of displacement index of 38.

Field observation: The toposheet based prediction (Fig. 8) regarding slope movement by planar slide was confirmed on field checks.

Table 5. Relative Contribution of Each Indices to Discriminate Between Various Slope Movement Process

Morphometric Index	**Pairs of Various Slope Movement Processes**					
	FF And SF	FF And PS	FF And RS	SF And PS	SF And RS	PS And RS
Classification Index	82.6221*	29.4801*	53.0184	21.7768*	44.8594*	0.8283
Dilation Index	27.2088*	57.7435*	55.1029	-4.8009*	42.3015*	1.0543
Flowage Index	-9.7878	-36.3133	-3.2241	12.7577	-0.2037	-4.6843
Displacement Index	-0.3381	3.9491	3.2338	5.1536	0.6566	0.6539
Tenuity Index	0.2949	45.1407*	20.8689	65.1127*	12.2836	102.1479*

FF=Fluid Flow, SF=Slide Flow, PS=Planar Slide, RS=Rotation Slide.

Chilla Slide Area

Location: 57 km SSW of the study area.

Lithology: Consist predominantly of sandstone and shale of Eocene age.

Structure: Beds dip towards hill with E-W strike and dip angle ranging from 20°-30° towards south. The presence of sheared and pulverized material indicated possibility of shear zone. However, due to lack of continuous rock exposure on slip region and thick vegetation at some locations the extent and nature could not be traced.

Base map: Contour map of 1:1200 scale with 5 m contour interval.

Analysis: Slopes were analyzed with the help of morphometric indices. The Classification, Dilation, Flowage, Displacement and Tenuity indices were found to be 6.44, 4.3, 4.12, 2.4, and 0.49, 0.47, 0.48 1.7, and 96.65, 49.47, 64.32 469, and 24.19, 45.50, 28.30 35, and 1.67, 0.88, 1.27 and 3.3 for rotational slide, planar slide, slide flow and fluid flow, respectively. Thus the slope movement is complex and reactivates by all four possible types of slope movement due to low values of displacement indices of 24.19, 45.50, 28.30 and 35.

Field observation: Toposheet based prediction (Figs. 3-6) regarding slope movement by rotational slide, planar slide, slide flow and fluid flow was confirmed on field checks.

Discriminant Function as Search Technique

All the morphometric indices included in discriminant function may not significantly contribute in distinguishing one type of slope movement from the other. Therefore, an attempt has been made to extract those indices which contribute the most in differentiating one slope process from the other. In this regard discriminant analysis approach can also help in searching meaningful variables. This technique measures only the direct contribution of each variable. It does not consider interaction between variables. If two or more of the variables in the discriminant function are not independent, their interaction may contribute to multivariate distance measure, D^2, to a greater extent. The percent contribution of each index in discriminating two slope movement processes, worked out after Davis [3], are presented in Table 5. A critical observation of this table indicates that the most important indices to discriminate between various pairs of slope movement processes are only a few in number (asterisked in Table 5).

The bivariate (Figs. 9-15) and univariate (Fig. 16) plots between the most important indices for all slope movement processes clearly bring out two distinct fields. Test samples from three areas namely Mussorie by pass, Kaliasaur and Chilla, when plotted, stand out correctly in terms of type of process groups to which actually belonged, as observed in the field. Hence, these plots can be used towards the allocation of any unknown sample into its movement class.

Conclusions

1. Morphometric indices can be used for deciphering the nature of slope movement process. The critical values of various indices suggested, may hold true in the similar terrain conditions. Since, landslip form is closely related to its immediate environmental conditions.

2. Transverse slope profiles drawn on the basis of enlarged toposheet contours may help in prediction of various processes causing various types of slope movements.

3. Discriminant function analysis may help in predicting the likely movement by various processes. For quick, easy, simple to use technique, bivariate and univariate plots have been prepared to predict various types of hazards associated with different types of slope movement processes in this type of terrain.

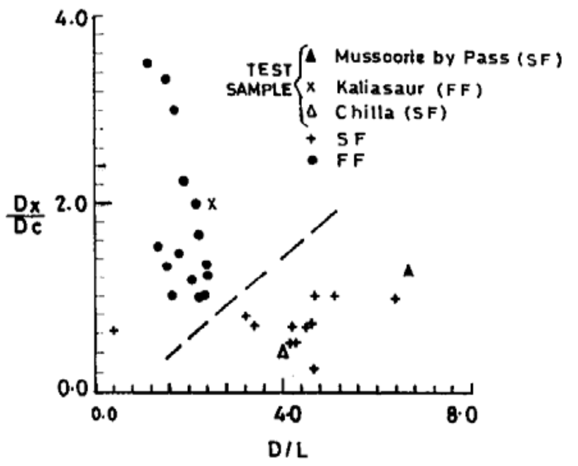

Figure 9. Location of test samples on the bivariate plot between classification (D/L) and dilation (DX/DC) indices showing distinct fields for slide flow (SF) and fluid flow (FF).

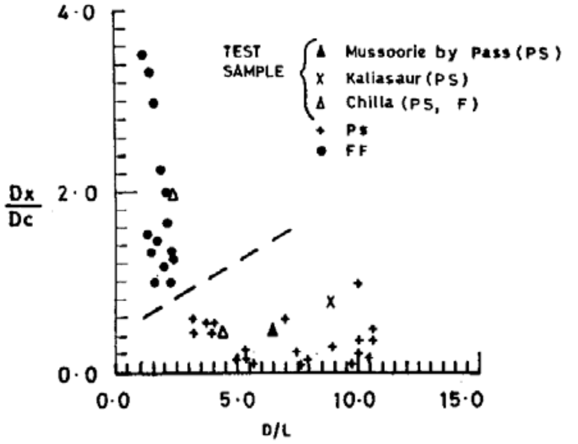

Figure 11. Location of test samples on the bivariate plot between classification (D/L) and dilation (DX/DC) indices showing distinct fields for planar slide (PS) and fluid flow (FF)

4. The geomorphological approach would be ideal for GIS mapping of landslide prone areas as only contour map is needed. However, actual values of morphological indices have to be obtained for a region, since landslip forms are closely related to their environmental conditions.

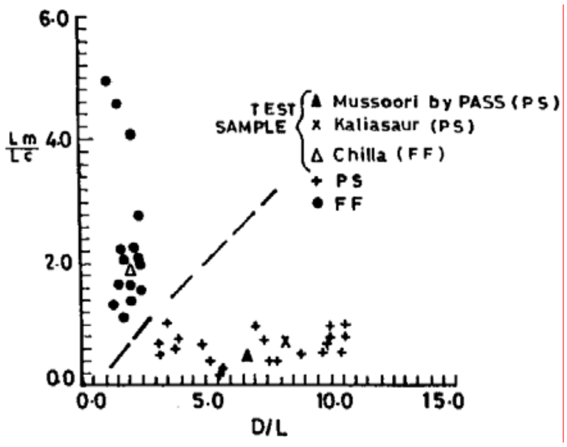

Figure 10. Location of test samples on the bivariate plot between classification (D/L) and dilation (Lm/Lc) indices showing distinct fields for planar slide (PS) and fluid flow (FF).

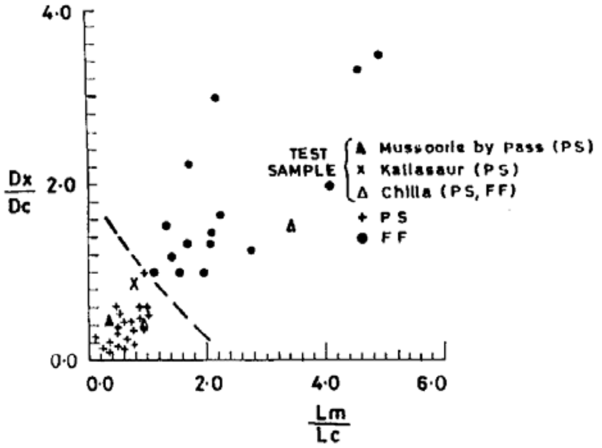

Figure 12. Location of test samples on the bivariate plot between classification (D/L) and dilation (DX/DC) indices showing distinct fields for planar slide (PS) and fluid flow (FF).

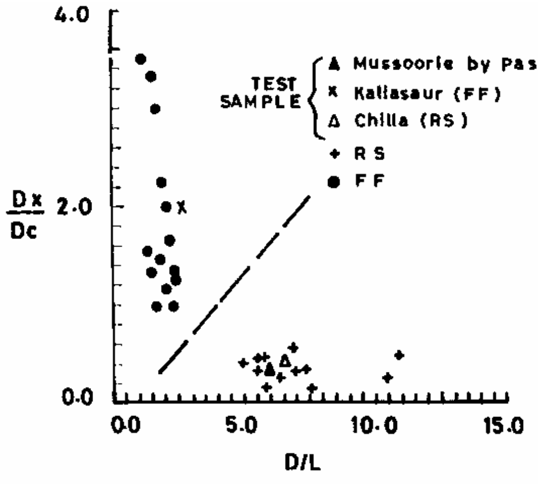

Figure 13. Location of test samples on the bivariate plot between classification (D/L) and dilation (DX/DC) indices showing distinct fields for rotational slide (RS) and fluid flow (FF).

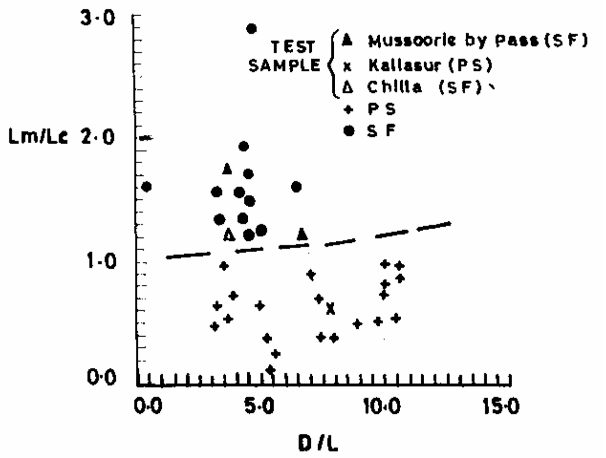

Figure 14. Location of test samples on the bivariate plot between classification (D/L) and dilation (Lm/Lc) indices showing distinct fields for planar slide (PS) and slide flow (FF).

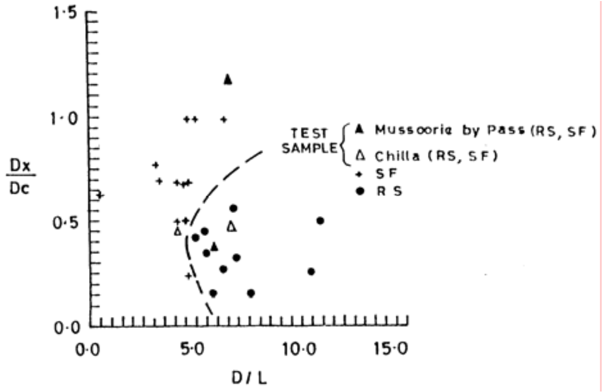

Figure 15. Location of test samples on the bivariate plot between classification (D/L) and dilation (DX/DC) indices showing distinct fields for rotational slide (RS) and slide flow (SF).

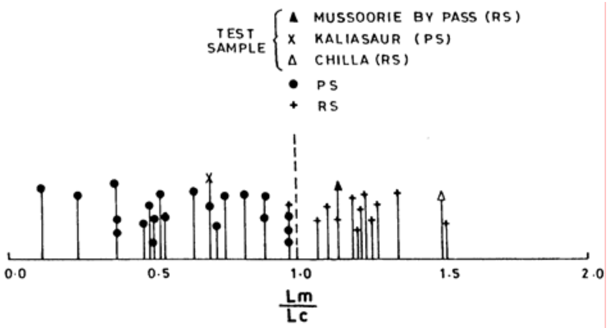

Figure 16. Location of test samples on the univariate plot of the tenuity (Lm/Lc) showing distinct fields for rotational slide (RS) and planar slide (PS).

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