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Governing factors influence on rock slope stability – Statistical analysis for plane mode of failure

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ABSTRACT

The present study was carried out to understand the relative influence of governing factors on slopes having potential plane mode of failure. For the present study secondary data for seventeen slope sections having potential plane mode of failure was procured from varied geological and geographical environment. The governing factors that were considered for statistical analysis are; slope-angle (α_f), upper-slope angle (α_s), dip of potential failure plane (α_p), dip of tension-crack (α_t), slope-height (h), cohesion (C), angle of friction (φ) and height of the water in tension-crack (Z_w). Initially, factor of safety (FoS) was determined for all possible anticipated adverse conditions to which slopes may be subjected. Later, sensitivity analysis was undertaken to know the relative importance of the governing factors on FoS. Further, one-way Analysis-of-Variance (ANOVA) was applied to examine the statistical significance of these governing factors on FoS under static and dynamic conditions. The results clearly showed that all the slope sections are unstable when saturated under static and dynamic conditions. Further, statistical analysis results showed that all considered governing factors are statistically significant for slope stability assessment however; their relative importance varies from one slope type to another. In terms of order of importance, factors 'α_p', 'Z_w', 'α_f' and 'h' revealed as the most significant factors while factors 'α_t', 'φ', 'α_s' and 'C', though significant but are relatively lower in the order of importance. The relative order of importance deduced from sensitivity analysis may be helpful in decision making to workout optimum stabilization measure for a particular slope.

1. Introduction

Rock slopes fail by different modes of failures, these are plane, wedge, toppling and rock fall (Hoek and Bray, 1981; Hocking, 1976). The most common type of failure in rock slopes is plane mode of failure (Raghuvanshi, 2019). The stability of the slope, having potential plane mode of failure, depends on governing factors namely; slope inclination (α_f), upper slope surface inclination (α_s), slope height (h), dip of potential failure plane (α_p), tension crack (α_t), shear strength parameters (Cohesion (C) and angle of friction (φ)) of potential failure surface, height of water in tension crack (Z_w) and horizontal earthquake acceleration (α) (Fig. 1) (Raghuvanshi et al., 2015; Raghuvanshi et al., 2014; Turrini and Visintainer, 1998; Anbalagan, 1992; Hoek and Bray, 1981). In case of plane mode of failure, the rock mass that rests on the potential failure plane is subjected to gravitational pull. Besides, the water forces acting along the potential failure plane tend to destabilize the slope. Also, dynamic loading and surcharge forces may also contribute to the driving forces (Raghuvanshi, 2019; Wang and Niu, 2009; Anbalagan, 1992). The main resisting forces are due to the shear strength along the potential failure plane and the component of weight of the sliding mass which acts across the potential failure plane. The ratio between the resisting forces to the driving forces defines the FoS. If this FoS is greater than '1' the slope represents stable conditions otherwise it is unstable (Raghuvanshi, 2019; Price, 2009; Sharma et al., 1995; Hoek and Bray, 1981). In the present research an attempt is made to understand the influence of governing factors on the stability condition of the slope having plane mode of failure.

Abbreviations: ANOVA, analysis of variance; φ, angle of friction; C, cohesion; α_t, dip of tension crack; α_p, dip of potential failure plane; FoS, factor of safety; Z_w, height of water in tension-crack; RMR, rock mass rating; h, slope height; α_f, slope inclination; α_s, upper slope angle.

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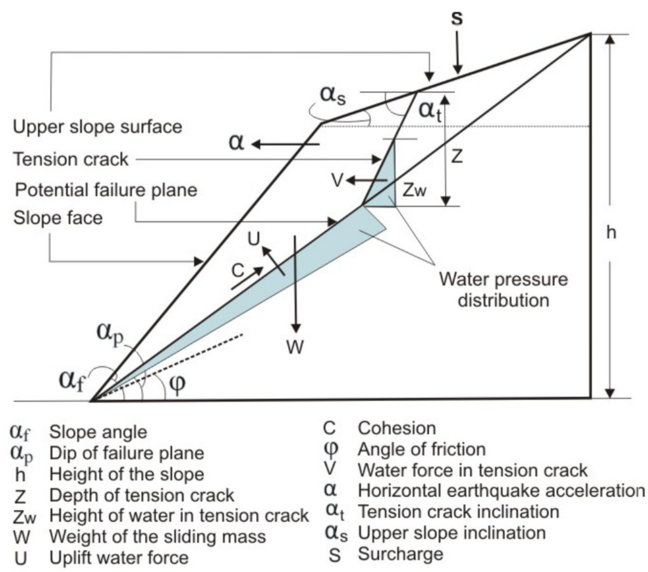

Fig. 1. Slope geometry and governing factors responsible for stability of slope having potential plane mode of failure.

2. Material and methods

For the present study, secondary data for 17 slope sections, having plane mode of failure, was procured. Each of these slopes was critically reviewed for various governing factors and FoS was computed for both static and dynamic conditions under varied water saturations. Later, sensitivity analysis for these governing factors was carried out to understand relative order of importance of these governing factors on stability condition. For sensitivity analysis initially each slope was analyzed separately and later data was further analyzed for all 17 slopes to understand the general trend and influence of each governing factors on FoS. For sensitivity analysis each of the governing factors for individual slopes were varied within its permissible limits while keeping other governing factors constant and accordingly FoS was computed for both static and dynamic conditions. The results thus obtained were further analyzed. Besides, significance of each governing factors on FoS was worked out by applying One-way Analysis-Of-Variance (ANOVA).

2.1. Description of the slope sections

In order to carry out present research study, secondary data for 17 slope sections having plane mode of failure has been obtained and analyzed. Out of these, 9 slope sections fall within Tons valley, Himalaya, India (Group 1) (Raghuvanshi and Solomon, 2005; Raghuvanshi, 1999), 1 slope section is located in Yamuna valley, Himalaya, India (Group 1) (Sharma et al., 1999) and 7 slope sections were taken from Omo Gibe basin, Ethiopia (Group 2) (Mulatu et al., 2010). The location details for these slope sections are presented in Fig. 2 and Table 1. The selection of these slope sections were made to represent all kinds of variability in geometry, geology and geographical conditions, so that the effect of governing factors on slope stability is well represented in the statistical analysis.

The slope sections falling within Group 1 forms a part in Tons valley, Himalaya, India. The Group 1 slope sections fall within "Lesser Himalayan Zone of Main Himalayan Belt". The topography of the area is highly rugged. The climate of the area is tropical monsoon with long humid summers and cold dry winters. The average annual rainfall of the area is 1650 mm and the average temperature varies between 20 and 30 °C (Raghuvanshi, 1999). Slope sections *TS1, TS2, TS4, TS6* and *TS9* are present on the right bank whereas slope sections *TS3, TS5, TS7* and *TS8* are present along the left bank of the Tons River. The slope sections height in general varies from 68 to 252 m and the slope inclination varies from 48 to 70°. The rocks exposed on these slope sections are mainly quartzites, quartzitic slates, slates, and Limestones belonging to Shimla Group, Deoban Group and Dharwad Group, respectively. All these slope sections are kinematically unstable and show potential instability for the plane mode of failure (Raghuvanshi, 1999; Raghuvanshi and Solomon, 2005). Further, the slope section (YS1) that is also covered in Group 1, falls within Yamuna valley, Himalaya, India. The slope is a part of right abutment of proposed Lakhawar dam and is 160 m high. The slope in general is inclined towards northeast (N50°) and dips at a moderate angle (58°). The rock exposed throughout the slope section is doleratie (Sharma et al., 1999).

The Group 2 comprises 7 slope sections that fall mainly along the road that runs from Fofa town to Gilgel Gibe – II powerhouse in Omo Gibe Basin, south western Ethiopia. The regional geology of the Omo-Gibe River basin in which Group 2 slope sections fall, comprises of Precambrian crystalline basement, Eocene to Miocene volcanic rocks, Quaternary lacustrine deposits, alluvial sediments and volcanic flows (Davidson and Rex, 1983). The eastern side of Group 2 slopes is bounded by major escarpment along the Gibe River that is oriented almost towards the Ethiopian rift system to the east. The climate of the area is semi-arid with one distinct rainy season (from June to August) and it receives annual average precipitation of 1320 mm (Mulatu et al., 2010). The Group 2 slope sections height in general varies from 11 to 50 m. The rock exposed along these slope sections is Rhyolite. These slope sections are moderate to steeply dipping and slope angle falls within a range of 57–78° (Mulatu et al., 2010).

2.1.1. Governing factors

The instability in slopes primarily depends on the relationship between driving and resisting forces (Hoek and Bray, 1981). These driving and resisting forces are resulted from various governing factors. The main driving force is due to gravitational pull which entirely depends on the geometry of the slope (Raghuvanshi, 2019; Hamza and Raghuvanshi, 2017; Bell, 2007). The geometry of the slope having plane mode of failure includes; slope inclination (α_f), height of the slope (h), upper slope surface inclination (α_s), dip of potential failure plane (α_p), dip direction of potential failure plane, (Ψ_p) and inclination of the tension crack or release joint (α_t) (Raghuvanshi, 2019; Sharma et al., 1995; Hoek and Bray, 1981). The geometrical parameters for various slope sections considered in the present study are presented in Table 2.

Slope inclination (α_f) is the most important governing factor for the plane mode of failure. Steeper the slope section more prone it will be for instability (Raghuvanshi, 2019; Hamza and Raghuvanshi, 2017). In slopes having plane mode of failure the potential sliding rock mass is confined in between the sliding surface and the slope face (Fig. 1). Thus, in steeper slope sections more rock mass will be available for sliding and the driving force due to gravity will increase making the slope susceptible for instability (Raghuvanshi, 2019). The slope angle for various slope sections considered in the present study, in general, varies from 48 to 78° (Table 2).

Slope height (h) – In general, as the slope height increases the slope will be more susceptible for instability. As the height of the slope increases the shear stress increases which induce instability in the slope (Raghuvanshi, 2019; Hack, 2002; Anbalagan, 1992; Hoek and Bray, 1981). The slope height for various slope sections in the present study varies from 11 to 252 m (Table 2).

Upper slope surface inclination (α_s) – In case of plane mode of failure the upper slope inclination adds to the shearing stress as

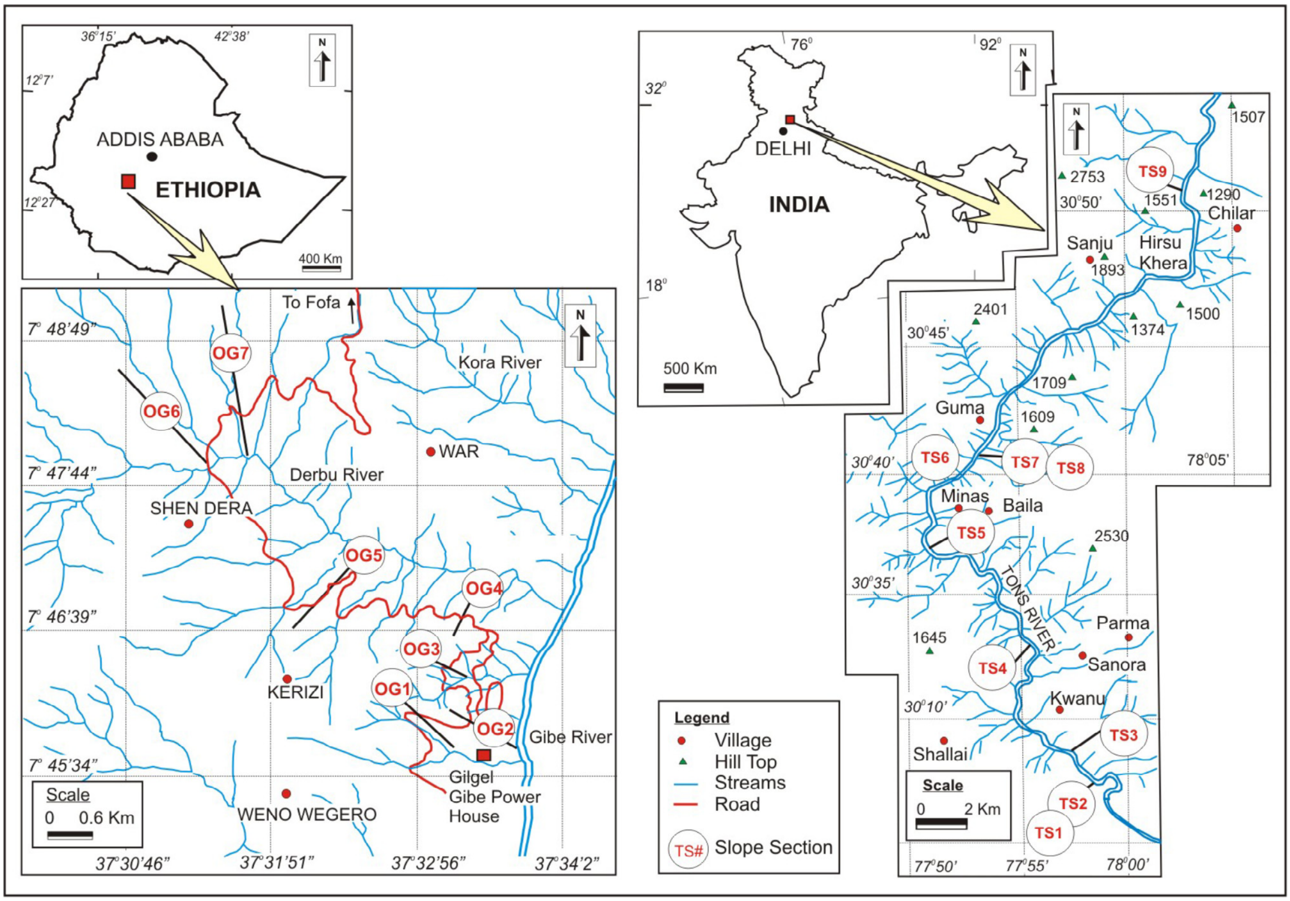

Fig. 2. Location of slope sections considered for the present study.

Table 1
Slopes considered for the present study.

Group	Slope-No.	Location Lat.;Long. (deg.;dec.)	Altitude (m)	Slope height (m)	Slope Direction/angle (deg.)	Exposed Rock Type	Valley
Group-1	TS1	30.66;77.78	840	150	N 34/50	Quartzite	Tons-valley, India
	TS2	30.66;77.78	680	68	N 34/52	Quartzitic slates	
	TS3	30.67;77.77	695	105	N 205/70	Quartzite with Slates	
	TS4	30.71;77.75	860	177	N 29/48	Slates	
	TS5	30.74;77.71	875	104	N 223/60	Quartzitic slates	
	TS6	30.77;77.71	835	192	N 146/50	Limestone	
	TS7	30.78;77.72	785	237	N 292/59	Limestone	
	TS8	30.78;77.72	905	140	N 292/55	Limestone	
	TS9	30.90;77.87	920	252	N 128/50	Quartzite	
	YS1	30.52;77.94	668	160	N 50/58	Dolerite	Yamuna-valley, India
Group-2	OG1	7.77;37.55	1420	50	N 170/75	Rhyolite	Omo-Gibe Basin, Ethiopia
	OG2	7.77;37.56	1375	50	N 210/74	Rhyolite	
	OG3	7.78;37.55	1330	30	N 335/76	Rhyolite	
	OG4	7.78;37.56	1440	50	N 185/78	Rhyolite	
	OG5	7.79;37.54	1460	18	N 315/60	Rhyolite	
	OG6	7.79;37.52	1555	19	N 080/57	Rhyolite, Basalt	
	OG7	7.80;37.52	1470	11	N 270/72	Rhyolite	

the weight of the sliding mass increases with the inclination of the upper slope surface. Thus, the potential instability in the slope increases (Sharma et al., 1995). Also, upper slope surface is the potential source of the ground water recharge. Surface flow and water logging on upper slope surface may lead to the water inflow through tension crack which ultimately reaches the potential failure plane (Raghuvanshi, 2019). Thus, uplift water forces may develop along the potential failure plane and effective shear strength along the failure surface will reduce (Raghuvanshi et al., 2014; Price, 2009). The upper slope inclination for various slope sections in the present study varies from 0 to 30° (Table 2).

Potential failure plane (α_p) – The orientation of the potential failure surface and its relation to the slope inclination defines the kinematic conditions. The strike of the slope (Ψ_f) and the potential failure surface (Ψ_p) must be nearly parallel (±20°) (Hoek and Bray, 1981). Also, dip of potential failure plane (α_p) must be smaller to the slope inclination (α_f). Besides, dip of the potential failure plane (α_p) must be greater than the angle of friction (φ) of the potential

Table 2
Input parameters for the slopes used for FoS analysis.

	Slope-Sections	Slope-height (h) (m)	Slope-angle (βf/αf)[a] (°)	Potential failure plane (βp/αp)[b] (°)	Upper slope-angle (βs/αs)[c] (°)	Tension crack-angle (αt) (°)	Rock- Density (γ) (T m^{-3})	Angle of friction (φ) (°)	Cohesion (C) (T m^{-2})	Horizontal earthquake acceleration (α)
Group-1	TS1	150	N34/50	N50/42	N34/10	78	2.75	40.0	16.0	0.15
	TS2	68	N34/52	N50/42	N34/13	78	2.72	30.0	16.0	0.15
	TS3	105	N205/70	N209/63	0/0	90	2.72	17.44	5.61	0.15
	TS4	177	N29/48	N22/38	N29/10	72	2.5	16.88	7.65	0.15
	TS5	104	N223/60	N220/50	N223/30	72	2.5	19.91	9.69	0.15
	TS6	192	N146/50	N132/42	N146/10	80	2.6	16.48	14.07	0.15
	TS7	237	N292/59	N312/46	N292/10	72	2.6	31.32	19.12	0.15
	TS8	140	N292/55	N312/46	N292/5	72	2.6	34.14	19.12	0.15
	TS9	252	N128/50	N140/40	N128/20	54	2.8	26.25	13.26	0.15
	YS1	160	N50/58	N50/53	0/0	46	2.75	40.0	10.0	0.15
Group-2	OG1	50	N170/75	N145/41	N 170/17	63	2.45	39.70	10.71	0.08
	OG2	50	N210/74	N216/59	N210/20	90	2.45	45.70	11.47	0.08
	OG3	30	N335/76	N213/21	N 335/15	90	2.45	20.5	11.47	0.08
	OG4	50	N185/78	N169/39	N185/26	90	2.45	13.5	7.65	0.08
	OG5	18	N315/60	N316/40	N315/24	77	2.45	39.96	7.65	0.08
	OG6	19	N080/57	N80/46	N080/20	83	2.89	37.80	7.34	0.08
	OG7	11	N270/72	N270/54	N270/27	85	2.45	43.89	6.12	0.08

[a] βf–slope face inclination direction; αf -slope face angle.
[b] βp–potential failure plane dip direction; αp – dip of potential failure plane.
[c] βs–upper slope face inclination direction; αs – upper slope face angle.

failure plane. If these conditions are satisfied the slope will be susceptible for plane mode of failure (Raghuvanshi, 2019; Sharma et al., 1995; Kovari and Fritz, 1984; Hoek and Bray, 1981). The dip of potential failure planes for various slope sections considered in the present study, in general, varies from 21 to 63° (Table 2).

Inclination of the tension crack or release joint (α_t) – In case of plane mode of failure tension develops in the upper portion of the slope whenever shear stresses exceeds the shear strength along the potential failure plane. This results into development of a tension crack. The rock mass detach along the tension crack and slides along the potential failure surface (Raghuvanshi, 2019). In rock slopes tension crack generally develops along the pre existing discontinuities dipping into the excavation or towards the valley (Sharma et al., 1995) or it may be dipping into the hill at any inclination (Sharma et al., 1999). However, Hoek and Bray (1981) assumed tension crack to be vertical. For the present study the tension crack inclination for various slope sections varies from 46 to 90° (Table 2).

Shear strength along potential failure plane - The main resistance against driving forces results from shear strength along the potential failure plane. The main shear strength parameters responsible in this regard are cohesion (C) and the angle of friction (φ). The initial value of shear stress required to cause sliding when normal stress acting on potential failure plane is considered zero, corresponds to cohesive strength (C) (Johnson and Degraff, 1991; Hoek and Bray, 1981). The normal (σ) and shear (τ) stress acting on potential failure plane are related by equation; $\tau = C + \sigma \cdot tan\phi$ (Johnson and Degraff, 1991).

For the present study the angle of friction (ϕ) for potential failure surfaces, considered for the slopes falling within Group 1 and 2 were estimated by empirical methods; Rock mass rating system (RMR) (Bieniawski, 1989) and Law of friction (Barton, 1973) (Mulatu et al., 2010; Raghuvanshi and Solomon, 2005; Raghuvanshi, 1999; Sharma et al., 1999). It is worth mentioning that the estimations made for 'ϕ' by empirical method RMR are for rock mass. However, for plane failure analysis the 'ϕ' value needs to be estimated for potential failure plane. Thus, based on the potential failure plane characteristics the value of 'ϕ' was logically adopted for the analysis (Table 2). Further, the slope sections for which 'ϕ' values were estimated by Law of friction (Barton, 1973) were directly utilized for the present analysis, as these values corresponds to the potential failure plane. However, for slope sections OG3 and OG4 (Group 2) the 'ϕ' values obtained from RMR were adopted as the values obtained by Law of friction were high and do not corresponds to the actual characteristics of the potential failure planes (Table 2). Further, the cohesion (C) for potential failure plane for various slope sections considered in the present study were initially estimated by the RMR however the values of 'C' obtained by RMR corresponds to the rock mass (Bieniawski, 1989). For plane failure analysis 'C' value is required for the potential failure plane. Therefore, the values of 'C' obtained from RMR were logically reduced based on the characteristics of the potential failure plane (Mulatu et al., 2010; Raghuvanshi and Solomon, 2005; Raghuvanshi, 1999; Sharma et al., 1999) and the same values of 'C' were used in the analysis carried out during the present study (Table 2).

Water forces within the slope - In case of plane mode of failure water contributes to the driving forces and thus it destabilizes the slope (Raghuvanshi, 2019; Raghuvanshi et al., 2015; Raghuvanshi et al., 2014; Hoek and Bray, 1981). The water on upper slope surface enters the tension crack and seeps along the potential failure plane to escape where the failure plane daylight on the slope face. This water within the tension crack will develop water force 'V' and also an uplift water force 'U' along the potential failure plane, which ultimately contributes to the driving forces, thus instability in the slope is induced (Raghuvanshi, 2019; Hossain, 2011; Ahmadi and Eslami, 2011; Hoek and Bray, 1981) (Fig. 1). Further, the uplift water force along the potential failure surface will reduce the effective normal stress and also shear strength along the failure surface will be reduced due to the saturation. Thus, resisting forces reduces and driving forces increase (Raghuvanshi, 2019; Raghuvanshi et al., 2015; Hack, 2002). For the present study the effect of water forces on stability condition was considered by taking variable depths of water in the tension crack. This was done to simulate the anticipated adverse conditions to which the slopes may be subjected.

3. Analysis and results

3.1. Stability analysis

For the present study, slope stability analysis for all 17 slope sections was carried out by using Modified plane failure analytical technique proposed by Sharma et al. (1995). The governing factors that were considered are; inclination of the slope (α_f), upper slope surface inclination (α_s), slope height (h), dip of potential failure plane (α_p), tension crack or upper release joint (α_t), cohesion (C) and angle of friction (φ) of the potential failure plane, height of the water in the tension crack (Z_w) and horizontal earthquake acceleration (α). The stability analysis was carried out for both static and dynamic cases. In order to carry out stability analysis, computational spread sheet was developed in MS Excel and stability analysis was computed for all possible anticipated conditions by considering variable water saturation situations under both static and dynamic conditions. The input parameters used for the slope stability analysis are presented in Table 2. The results thus obtained are presented in Table 3 and Fig. 3. A perusal of results clearly indicates that all the slope sections are unstable under varied water saturation situations for both static and dynamic conditions, as the factor of safety (FoS) for all these cases is below 1. A FoS value <1 indicates unstable condition (Raghuvanshi, 2019; Price, 2009; Sharma et al., 1995; Hoek and Bray, 1981). However, about 9 slope sections are stable under dry conditions while remaining slopes are unstable even in dry conditions. Further, it can be noted that values of FoS reduces significantly as water saturation increases. Similarly, under dynamic conditions FoS reduces as compared to static case Table 3 and Fig. 3.

3.2. Sensitivity analysis

In order to understand the effect of individual factor on FoS a sensitivity analysis (one-factor-at-a-time approach) (Saltelli et al., 2000) was applied. In the present study 8 governing factors (α_f, α_s α_p, α_t, h, C, φ and Z_w) were considered for the sensitivity analysis. The basis on which these governing factors were selected is a fact that all these governing factors are the inherent factors on which stability of the slope having plane mode of failure will depend. Each of these governing factors contributes to the resisting or to the driving forces which will define the slope stability condition. For this reason all these governing factors were used in the sensitivity analysis.

For analysis each of these governing factors were varied within its permissible limits around nominal values while keeping all other factors constant (Table 4) (Raghuvanshi and Solomon, 2005; Saltelli et al., 2000; Sharma et al., 1999). The permissible limits for factors 'α_f', 'α_p' and 'φ' were defined with respect to the kinematic condition; $\alpha_f > \alpha_p > \varphi$. It implies that for plane failure 'α_f' must be greater than 'α_p' while in turn it should be greater than 'φ' (Raghuvanshi, 2019; Ali et al., 2015; Hoek and Bray, 1981; Markland, 1972; Hocking, 1976). Thus, the value for 'α_p' for each slope section under study was varied in between 'α_f' and 'φ' values. Similarly, value of 'α_f' was varied in between corresponding value of 'α_p' and a maximum of 89°. The value of 'α_s' was varied from 0° (horizontal) upto a value less than 'α_p'. These values of 'α_s' was varied based on the general condition $\alpha_s < \alpha_p$, as defined in the Modified plane failure analytical technique proposed by Sharma et al. (1995). The value of 'α_t' was varied from 90° (vertical) to a value equal to the dip of any existing discontinuity plane oriented towards the valley. For this it was assumed that in rock slope, tension crack will develop along some pre existing discontinuity and the rock mass will detach through this tension crack or release surface and it will slide on the potential failure plane (Raghuvanshi, 2019; Sharma et al., 1995; Hoek and Bray, 1981). Further, values for 'Z_w' was varied from a minimum $Z_w = 0$ (dry) to a maximum of about 75% of the depth of the tension crack ($Z_w = ¾ Z_L$, where; Z_L is the depth of the tension crack). Here, it was assumed that practically fully saturated anticipated conditions may exist when the tension crack is 3/4th fill with water. The height (h) of the slope was varied from full height of the slope (h) to a minimum of about 10% of the total height of the slope. The value of cohesion (C) and angle of friction (φ) were varied arbitrarily above and below the nominal value. Thus, corresponding variation in FoS values were observed for each individual case and thus order of importance of each governing factors was worked out.

The sensitivity analysis results (Table 5 and Fig. 4) clearly indicates that in about 35.2% of slope sections 'α_f' is 1st or 2nd order important factor which influence FoS under both static and dynamic conditions. Similarly, in 47% of the slope sections, 'α_p' is 1st or 2nd order important factor. Further, in 41% slope sections Z_w is 1st or 2nd order important factor in static case while under dynamic condition in 35% of the slope sections Z_w is 1st or 2nd order important factor. Similarly, factor 'h' also contributes significantly, as in 29% slope sections it is 1st or 2nd order important factor in static conditions while in dynamic condition in 35% slope sections it is 1st or 2nd order important factor. The remaining factors are not that much important in 1st or 2nd order of importance.

3.3. Analysis of variance (ANOVA)

For the present study, attempt was made to test differences among the values of FoS for each individual governing factor by

Table 3
Stability analysis results of the slopes used for the analysis.

	Slope-sections	Factor of safety (FoS)					
		Static-condition			Dynamic-condition		
		Dry	Moderately-saturated	Fully-saturated	Dry	Moderately-saturated	Fully-saturated
Group-1	TS1	1.37	0.83	0.24	1.07	0.62	0.12
	TS2	1.35	0.95	0.46	1.08	0.75	0.35
	TS3	0.47	0.30	0.20	0.39	0.20	0.10
	TS4	0.54	0.35	0.14	0.41	0.26	0.09
	TS5	0.45	0.16	0.20	0.35	0.10	0.06
	TS6	0.65	0.44	0.20	0.52	0.34	0.14
	TS7	0.79	0.23	0.17	0.61	0.13	0.08
	TS8	1.26	0.60	0.42	1.01	0.45	0.22
	TS9	0.67	0.37	0.04	0.50	0.27	0.01
	YS1	1.12	0.25	0.10	0.88	0.15	0.08
Group-2	OG1	0.95	0.30	0.18	0.81	0.25	0.06
	OG2	1.07	0.89	0.50	0.94	0.66	0.30
	OG3	1.01	0.97	0.88	0.81	0.78	0.72
	OG4	0.32	0.25	0.13	0.27	0.21	0.11
	OG5	1.29	0.94	0.45	1.12	0.81	0.37
	OG6	1.54	0.99	0.33	1.37	0.87	0.27
	OG7	1.30	0.04	0.02	1.16	0.02	0.01

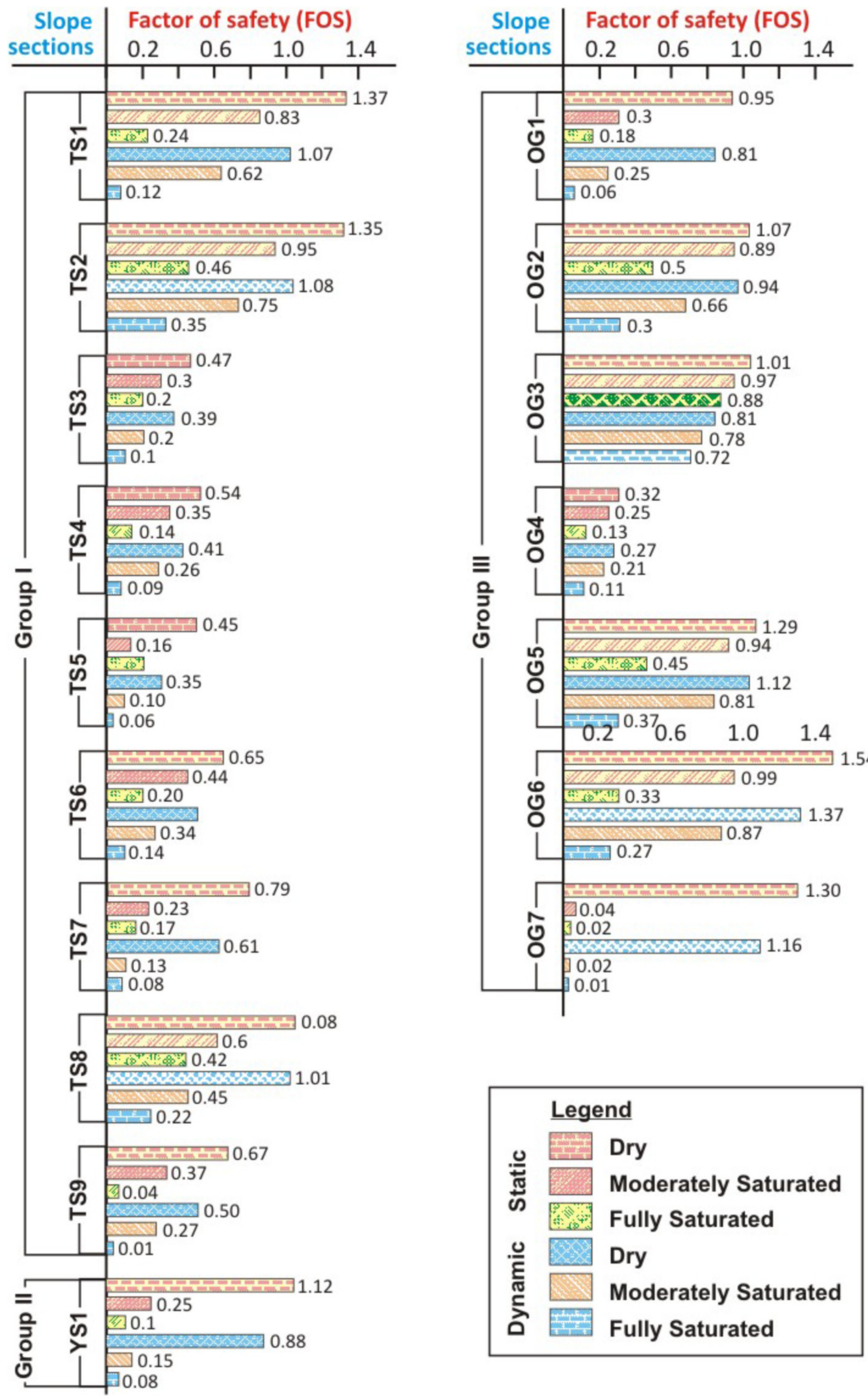

Fig. 3. Factor of safety (FoS) of slope sections under anticipated conditions.

examining the amount of variation within the samples and relative amount of variation between the samples. Thus, the One-way ANOVA was applied to test whether there is a significant difference in the individual/treatment effects under study data/variables or such variation in values of FoS is just by chance (Kothari, 2009; Tull and Hawkins, 2008). In this technique single factor is considered at a time and its significance is studied by observing its variation within the samples and the variation between the samples (Saravanavel, 2007; Yamane, 1964). In order to carry out ANOVA, FoS was computed for static and dynamic conditions by varying each of the governing factors (α_f, α_s α_p, α_t, h, C, φ and Z_w) within its permissible limits around nominal values while keeping all other factors constant. The same was done for all 17 slope sections. Later, 'F' values were computed for each governing factor. 'F' is the ratio among 'variance between the samples' to 'variance within the samples'. The 'F' value indicates whether the difference among several FoS mean values is statistically significant or not. For this the computed 'F' values were compared with the standard (F-Table) values, for known degree of freedom at different level of significance. If the computed 'F' value was greater than the standard 'F'

Table 4
Governing factors value variation for sensitivity analysis.

	Slope-section	Governing factors value-variation							
		αf (deg.)	αs (deg.)	αp (deg.)	αt (deg.)	h (m)	C (KN/m^2)	∅ (deg.)	Zw (m)
Group-1	TS1	45–77	0.0–40	42.0–48.3	42.0–85.8	15–150	78.40–203.84	24.0–52	0.00–72
	TS2	45–77	0.0–40	33.6–50.4	33.6–85.8	10–68	78.40–203.84	18.0–39.0	0.00–42
	TS3	65–89	0.0–55	37.8–69.3	37.8–90.0	10–105	27.48–71.46	10.5–22.7	0.00–79
	TS4	52–88	6.0–45	30.0–57.5	30.0–86.4	10–104	47.48–123.44	11.9–25.9	0.00–96
	TS5	47.2–76.7	3.6–40	32.2–55.2	32.2–86.4	20–237	93.68–243.58	18.8–40.7	0.00–78
	TS6	50–89	2.7–40	36.8–52.9	36.8–86.4	10–140	93.68–243.58	20.5–44.4	0.00–91
	TS7	45–89	0.0–40	22.8–45.6	22.8–86.4	10–177	37.48–97.46	10.1–21.9	0.00–233
	TS8	45–85	0.0–40	25.2–48.3	25.2–88.0	20–192	68.94–179.24	9.9–21.4	0.00–91
	TS9	40–75	0.0–35	28.0–48.0	28.0–64.8	20–252	64.97–168.92	15.8–34.1	0.00–189
	YS1	55–78	0.0–45	42.4–53.0	42.4–78.0	15–160	49.00–127.4	24.0–52.0	0.00–120
Group-2	OG1	45–75	0.0–35	41.0–57.4	41.0–75.6	5–50	52.47–136.44	23.8–51.6	0.00–38
	OG2	62–89	0.0–55	47.2–70.8	47.2–90.0	10–50	56.20–146.12	27.4–59.4	0.00–38
	OG3	25–75	2.0–20	21.0–29.4	21.0–90.0	10–30	56.20–146.12	12.3–26.7	0.00–23
	OG4	45–89	0.0–35	23.4–54.6	23.4–90.0	10–50	37.49–97.46	8.1–17.6	0.00–38
	OG5	44–84	0.0–35	40.0–56.0	40.0–84.7	10–18	37.49–97.46	24.0–51.9	0.00–14
	OG6	50–88	0.0–40	41.4–55.2	41.4–83.0	9–19	35.96–93.50	22.7–49.1	0.00–14
	OG7	57–88	0.0–40	48.6–70.2	48.6–85.0	6–9	29.99–77.96	26.3–57.1	0.00–9

Table 5
Sensitivity of factor of safety (FoS) for various governing factors.

Group	Slope section	FoS variation/Order of importance (OI)	Governing factors															
			αf	αs	αp	αt	h	C	∅	Zw	αf	αs	αp	αt	h	C	∅	Zw
			Factor of safety (FoS) Static condition								Factor of safety (FoS) Dynamic condition							
Group 1	TS1	Variation	0.79	0.41	1.37	0.03	1.23	0.36	0.80	1.14	0.68	0.36	1.19	0.03	1.19	0.31	0.58	0.95
		OI	5th	6th	1st	8th	2nd	7th	4th	3rd	4th	6th	2nd	8th	1st	7th	5th	3rd
	TS2	Variation	1.69	0.79	3.62	0.11	0.99	0.56	0.41	0.89	1.47	0.69	3.19	0.09	0.98	0.48	0.29	0.73
		OI	2nd	5th	1st	8th	3rd	6th	7th	4th	2nd	5th	1st	8th	3rd	6th	7th	4th
	TS3	Variation	0.70	0.19	2.00	0.15	0.45	0.25	0.05	1.15	0.66	0.18	1.88	0.14	0.44	0.23	0.01	1.08
		OI	3rd	6th	1st	7th	4th	5th	8th	2nd	3rd	6th	1st	7th	4th	5th	8th	2nd
	TS4	Variation	0.16	0.17	0.59	0.02	0.64	0.12	0.26	0.40	0.19	0.14	0.49	0.02	0.64	0.10	0.19	0.32
		OI	6th	5th	2nd	8th	1st	7th	4th	3rd	5th	6th	2nd	8th	1st	7th	4th	3rd
	TS5	Variation	0.71	0.27	0.0	1.86	0.45	0.12	0.21	0.58	0.67	0.25	0.00	1.63	0.45	0.11	0.15	0.50
		OI	2nd	5th	8th	1st	4th	7th	6th	3rd	2nd	5th	8th	1st	4th	7th	6th	3rd
	TS6	Variation	0.74	0.37	1.49	0.04	1.68	0.26	0.22	0.46	0.63	0.32	1.28	0.03	1.52	0.22	0.16	0.38
		OI	3rd	5th	2nd	8th	1st	6th	7th	4th	3rd	5th	2nd	8th	1st	6th	7th	4th
	TS7	Variation	1.96	0.19	0.68	8.38	1.33	0.17	0.47	1.07	1.72	0.17	0.59	7.36	1.21	0.15	0.35	0.92
		OI	2nd	7th	5th	1st	3rd	8th	6th	4th	2nd	7th	5th	1st	3rd	8th	6th	4th
	TS8	Variation	1.06	0.48	2.10	0.67	1.81	0.48	0.48	1.32	1.02	0.42	1.85	0.59	1.78	0.42	0.34	1.13
		OI	4th	8th	1st	5th	2nd	7th	6th	3rd	4th	7th	1st	5th	2nd	6th	8th	3rd
	TS9	Variation	1.71	0.16	0.59	0.21	0.61	0.07	0.46	0.63	171.	0.13	0.50	0.18	0.54	0.06	0.34	0.51
		OI	1st	7th	4th	6th	3rd	8th	5th	2nd	1st	7th	4th	6th	2nd	8th	5th	3rd
	YS1	Variation	1.22	0.43	0.35	0.69	4.67	0.39	0.63	2.24	1.28	0.39	0.31	0.62	4.19	0.35	0.45	2.02
		OI	3rd	6th	8th	4th	1st	7th	5th	2nd	3rd	6th	8th	4th	1st	7th	5th	2nd
Group 2	OG1	Variation	0.84	0.03	3.55	1.87	1.07	0.01	0.91	1.20	0.78	0.03	3.18	1.71	0.95	0.00	0.78	1.07
		OI	6th	7th	1st	2nd	4th	8th	5th	3rd	5th	7th	1st	2nd	4th	8th	6th	3rd
	OG 2	Variation	2.47	0.67	2.73	1.88	1.82	0.36	0.71	2.74	2.36	0.64	2.61	1.79	1.74	0.35	0.58	2.61
		OI	3rd	7th	2nd	4th	5th	8th	6th	1st	3rd	6th	2th	4th	5th	8th	7th	1st
	OG 3	Variation	0.77	0.33	0.09	0.02	0.01	0.03	0.73	0.13	0.65	0.29	0.08	0.02	0.02	0.03	0.59	0.09
		OI	1st	3rd	5th	7th	8th	6th	2nd	4th	1st	3rd	5th	7th	8th	6th	2nd	4th
	OG 4	Variation	0.29	0.16	0.12	0.03	0.04	0.02	0.21	0.19	0.26	0.15	0.11	0.03	0.04	0.02	0.18	0.16
		OI	1st	4th	5th	7th	6th	8th	2nd	3rd	1st	4th	5th	7th	6th	8th	2nd	3rd
	OG 5	Variation	0.26	0.02	0.06	0.13	0.17	0.22	0.71	0.85	0.27	0.02	0.11	0.12	0.14	0.20	0.59	0.75
		OI	3rd	8th	7th	6th	5th	4th	2nd	1st	3rd	8th	7th	6th	5th	4th	2nd	1st
	OG 6	Variation	0.38	0.11	0.32	0.06	0.34	0.54	0.15	1.21	0.38	0.13	0.37	0.06	0.29	0.50	0.09	1.09
		OI	3rd	7th	5th	8th	4th	2nd	6th	1st	3rd	6th	4th	8th	5th	2nd	7th	1st
	OG 7	Variation	0.57	0.55	1.04	18.7	0.40	0.36	0.21	2.16	0.52	0.49	0.96	13.4	0.37	0.35	0.26	2.03
		OI	4th	5th	3rd	1st	6th	7th	8th	2nd	4th	5th	3rd	1st	6th	7th	8th	2nd

values in the F-Table, the difference would be statistically significant (Tull and Hawkins, 2008; Saravanavel, 2007).

The corresponding F-ratios, as presented in Table 6 are found to be statistically significant ($p < 0.01$) for all eight factors/variables (α_f, α_s α_p, α_t, h, C, φ and Z_w) across 17 slopes sections, both under static and dynamic conditions. Thus, it may be concluded that all the 'F' values computed for all eight factors are significant at 99% (Tull and Hawkins, 2008), in determining FoS under both static and dynamic conditions.

4. Discussion

The results in the present study showed that all 17 slope sections have FoS values less than '1' for moderate and full

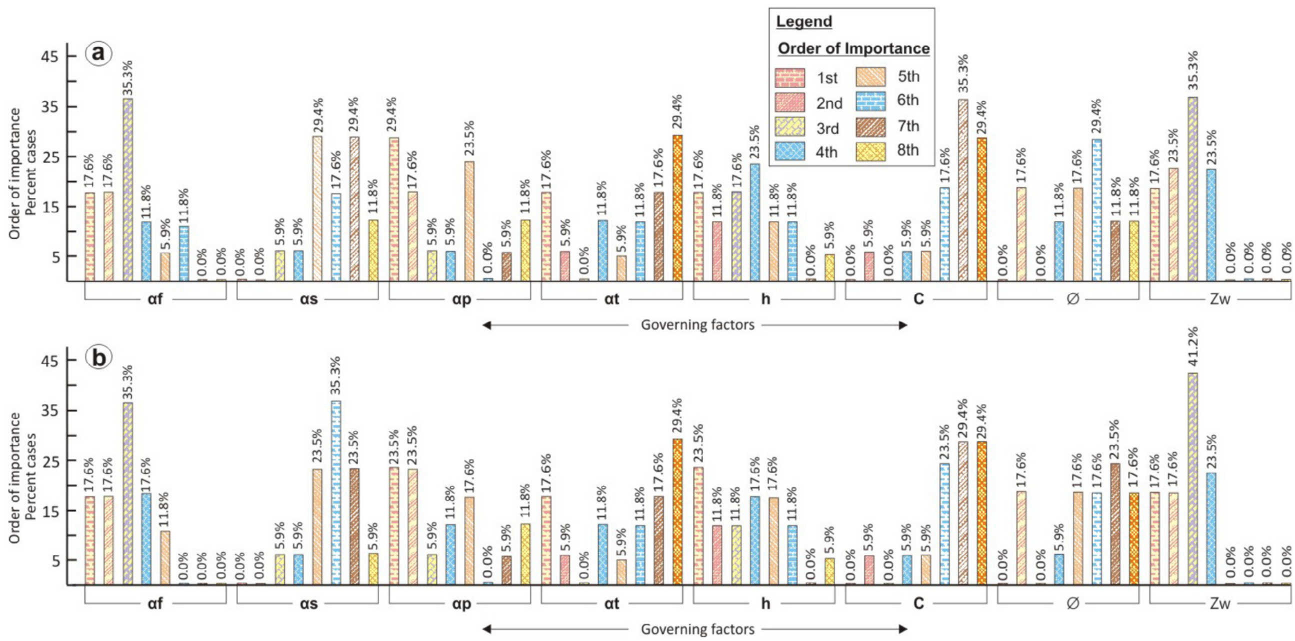

Fig. 4. Percent cases of order of importance (OI) of various governing factors (a) Static case, (b) Dynamic case.

Table 6
Results of Analysis of variance (ANOVA) for governing factors in various slope sections.

Parameters	Source of variation	Static-condition				Dynamic-condition			
		Sum of squares	Degree of freedom	Variance	F-ratio	Sum of squares	Degree of freedom	Variance	F-ratio
Slope angle-(αf)	Between-samples	62.745	16	3.922	8.5	47.497	16	2.969	7.9
	Within-samples	78.182	170	0.460		63.444	170	0.373	
Upper slope angle-(αs)	Between-samples	16.158	16	1.010	61.4	11.427	16	0.714	54.4
	Within-samples	2.797	170	0.016		2.228	170	0.013	
Dip of failure plane-(αp)	Between-samples	41.232	16	2.577	7.4	32.859	16	2.054	6.6
	Within-samples	58.858	170	0.346		52.738	170	0.310	
Dip of tention crack-(αt)	Between-samples	14.510	16	0.907	2496.2	9.950	16	0.622	1924.4
	Within-samples	0.043	119	0.000		0.038	119	0.000	
Height of slope-(h)	Between-samples	53.882	16	3.368	15.1	39.788	16	2.487	13.2
	Within-samples	34.115	153	0.223		28.811	153	0.188	
Cohesion-(C)	Between-samples	13.318	16	0.832	79.7	9.126	16	0.570	67.4
	Within-samples	1.243	119	0.010		1.007	119	0.008	
Angle of friction-(∅)	Between-samples	13.403	16	0.838	26.1	9.229	16	0.577	28.8
	Within-samples	3.816	119	0.032		2.380	119	0.020	
Height of water in tension crack-(Zw)	Between-samples	16.243	16	1.015	3.6	13.314	16	0.832	3.6
	Within-samples	18.934	68	0.278		15.646	68	0.230	

Note-All F-ratio values in table are significant at 99%.

saturation under both static and dynamic conditions (Table 3). Thus, it indicates that all the slope sections are unstable when saturated. Further, about 8 slope sections are unstable in dry static conditions and 11 slope sections are unstable in dry dynamic conditions. Generally, water saturation will reduce the slope stability. However, in the present case many slopes are unstable even in dry conditions. The stability of the slope is defined in terms of FoS which is the ratio between the resisting forces to the driving forces. Therefore, it is possible to have driving forces more than the resisting forces even under dry conditions. Thus, it does not mean that without water saturation slope cannot be unstable. If the other governing factors results into more driving forces than the resisting forces, the slope may demonstrate instability conditions.

The results further showed that, the FoS values reduces as water saturation increases. It clearly shows the role of saturation in inducing instability to the slopes (Raghuvanshi, 2019; Hossain, 2011; Hoek and Bray, 1981). Further, sensitivity analysis results (Table 5 and Fig. 4) also showed that in 41% of the slope sections under static conditions and 35% of the slope sections under dynamic conditions, factor 'Z_w' is 1st or 2nd order important factor which affects FoS. Also, ANOVA results (Table 6) showed that factor 'Z_w' is statistically significant ($F = 3.6$; $p < 0.01$) in determining FoS under static and dynamic conditions.

The sensitivity analysis results further showed that in 47% of the slope sections, 'α_p' is 1st or 2nd order important factor which influence FoS under both static and dynamic conditions (Fig. 4). These results are quite meaningful as the orientation of the potential failure surface and its relation to slope inclination defines the kinematic conditions (Raghuvanshi, 2019; Mulatu et al., 2010; Raghuvanshi and Solomon, 2005; Hoek and Bray, 1981). Besides, ANOVA results (Table 6) also showed that 'α_p' factor is statistically significant for both static ($F = 7.4$; $p < 0.01$) and dynamic ($F = 6.6$; $p < 0.01$) conditions (Kothari, 2009; Tull and Hawkins, 2008). Also, 'α_f' is important factor which influence FoS (Raghuvanshi, 2019; Hamza and Raghuvanshi, 2017). The results showed that in 35.2% of slope sections 'α_f' is 1st or 2nd order important factor which influence FoS under both static and dynamic conditions. Further, 'α_f' was also found to be statistically significant for both static ($F = 8.5$; $p < 0.01$) and dynamic ($F = 7.9$; $p < 0.01$) conditions (Table 6). Another factor that contributes to instability of the slope is the height (h) of the slope (Raghuvanshi, 2019). This fact is reasonably reflected by the results (Fig. 4) as in 29% of the slope sections under static conditions and 35% of the slope sections under dynamic conditions 'h' is 1st or 2nd order important factor which affects FoS. Further, ANOVA results (Table 6) showed that 'h' factor is statistically significant for both static ($F = 15.1$; $p < 0.01$) and dynamic ($F = 13.2$; $p < 0.01$) conditions. All other factors; 'α_t', 'φ', 'α_s' and 'C' do not showed relative influence in 1st or 2nd order importance for FoS, both under static and dynamic conditions. However, ANOVA results showed that, factors 'α_t', 'φ', 'α_s' and 'C' are significant in FoS computations.

The stability condition of slope having plane mode of failure is dependent on various governing factors. These governing factors are responsible to define various resisting and driving forces. The factor of safety (FoS) is a ratio between these resisting and driving forces. The contribution of each of these governing factors on stability condition may vary from slope to slope, as the relationship of governing factors within a slope is a complex process. Thus, the results obtained from the sensitivity analysis are due to this complex relationship. It is really difficult to give reason that why certain governing factors are more significant in order of importance and why others are in lower order of importance. The combined results presented for sensitivity analysis showed that in majority of cases 'αp', 'Zw', 'αf' and 'h' are more significant in higher order of importance. However, it does not mean that other factor 'α_t', 'φ', 'α_s' and 'C' are not significant factors.

Further, Group 1 and Group 2 slopes were analyzed separately. The sensitivity analysis results revealed that 60% of the slope sections in Group 1 have 'αp' factor in 1st or 2nd order of importance, under both static and dynamic conditions. However, in case of Group 2, 28.6% of slope sections, factor 'αp' is 1st or 2nd order important factor for both static and dynamic conditions. Similarly, in Group 1 in 50% slope sections under static condition and 70% under dynamic condition factor 'h' is 1st or 2nd order important factor. However, in Group 2 slope sections factor 'h' does not showed any importance at 1st or 2nd order, both under static and dynamic condition. As can be seen from the Table 2, slope height in Group 1 falls in the range of 68 to 252 m whereas in Group 2 slope height is in the range of 11 to 50 m. As the slope height increases the slope will be more susceptible for instability. As the height of the slope increases the shear stress increases which induces instability in the slope (Raghuvanshi, 2019; Hack, 2002; Anbalagan, 1992; Hoek and Bray, 1981). Group 1 slope sections have more height as compared to Group 2 slope sections (Table 2) therefore, it is reasonable to understand that in Group 1 height of the slope contributes more for instability as compared to Group 2 slope sections. For this reason only in Group 1 in 50% slope sections under static condition and 70% under dynamic condition factor 'h' is 1st or 2nd order important factor and in Group 2 slope sections factor 'h' does not showed any importance at 1st or 2nd order.

Also, in Group 1 in 40% of the slope sections under static condition and 30% under dynamic condition factor 'αf' is 1st or 2nd order important factor, whereas in Group 2, only in 28.6% of slope sections factor 'αf' is 1st or 2nd order important factor for both static and dynamic conditions. In case of Group 2 slope sections 'Zw' and 'αt' showed remarkable importance at 1st and 2nd order. In 57.1% slope sections 'Zw' and in 42.9% of slope sections 'αt' showed importance at 1st and 2nd order both under static and dynamic conditions.

The sensitivity analysis helps to know the order of importance of various governing factors that affects the slope stability conditions (Raghuvanshi and Solomon, 2005; Sharma et al., 1999). Such analysis may be helpful to evolve most appropriate slope stabilization measure. Say for instance if the sensitivity analysis for a given slope section suggests slope inclination 'α_f' and height of water in tension crack (Z_w) to be 1st and 2nd order important factors, respectively. The most appropriate stabilization measures would be slope dressing and drainage improvement. Thus, sensitivity analysis may help in decision making to workout most appropriate remedial measures to stabilize the given slope. Similarly, ANOVA is helpful to know the 'F' value which is the ratio among 'variance between the samples' to 'variance within the samples'. The 'F' value shows whether the difference among several FoS mean values is statistically significant or not. If the calculated 'F' value is greater than the standard 'F' values in the F-Table, the difference would be statistically significant (Tull and Hawkins, 2008; Saravanavel, 2007). Thus, ANOVA helps in understanding general trend and statistical significance of FoS values with respect to various governing factors for anticipated conditions.

5. Conclusion

Plane mode of failure in rock slopes is affected by several governing factors. In the present study attempts were made to understand the influence of these governing factors on slope stability. For this statistical analysis was undertaken on 17 slope sections having potential plane mode of failure. These slope sections were selected from different geological and geographical environment. In order to know the relative importance of these factors on factor of safety (FoS) sensitivity analysis was made for all 17 slope sections. Each of these factors was varied within its permissible limits while keeping all other factors constant and FoS was computed. The relative variation in the FoS values thus formed the basis to workout order of importance of these factors.

The results from sensitivity analysis and ANOVA showed that all 8 governing factors (α_f, α_s α_p, α_t, h, C, φ, Z_w) are significant for FoS computations. However, relative importance of these factors varies from one slope type to another. The present study results also showed that factors 'α_p', 'Z_w', 'α_f' and 'h' are the most statistically significant factors in terms of their order of importance. Further, factors 'α_t', 'φ', 'α_s' and 'C' are also significant however, they are relatively lower in the order of importance, as compared to factors 'α_p', 'Z_w', 'α_f' and 'h'. Further, when Group 1 and Group 2 slopes were analyzed separately it was found that in Group 1 slope sections 'αp', 'h' and 'αf' are the most influencing governing factors whereas in Group 2 slope sections 'Zw' and 'αt' are the most influencing governing factors. Finally, the sensitivity analysis may help to know the order of importance of various governing factors that affects the slope stability conditions. Thus, sensitivity analysis may help in decision making to workout most appropriate remedial measures to stabilize the given slope. Similarly, ANOVA helps in understanding general trend and statistical significance of FoS values with respect to various governing factors for anticipated conditions.

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