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Slope Failure studies through Kinematic analysis using Markland's test from Rali-Kashpo village, Himachal Pradesh, India

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Abstract

The slope failure in the mountainous terrain is common, specifically along highways. The areas from Northwest to Northeast are severely affected. Increasing developmental activities have made slopes more prone to failure due to poor slope management strategies. Also, the pattern of precipitation is changing, where the intensity of rain has been increased, which is one of the influential causative factors. Here, the present study is based on the kinematic analysis of hill slopes forming a part of Lesser Himalaya and Higher Himalaya of Himachal Pradesh along National Highway- 5, which is very important from a strategic point of view as it connects the borders of India and Tibet also it is the lifeline for people of Kinnaur district. The problem of instability has been increasing since the beginning of developmental activities like highways and hydropower projects because of ignorance of slope stability issues and inherent geological factors. Those slopes can be better studied, in terms of stability, using kinematic analysis to identify the problematic slopes. Five slopes along NH-5 have been selected for the present study. The relationship of slopes with the discontinuities has been established using stereo-plots and evaluated by applying the conditions of Markland's test stability assessment and modes of failure. Stability and mode of failure were determined using stereo-plots and factor of safety, which resulted in planar, wedge, and planar-wedge failure conditions. Among all one slope shows wedge failure and one slope shows planar failure.

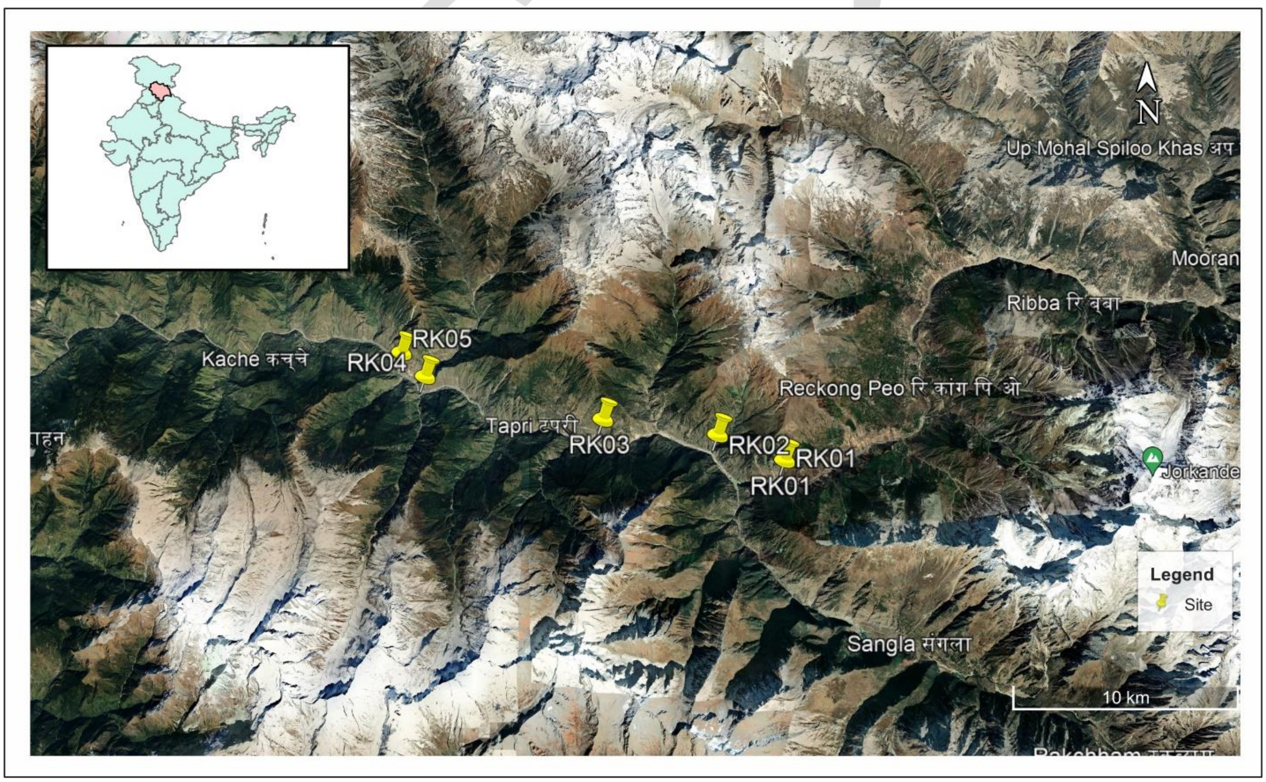
Keywords: Slope failure, Kinematic analysis, planar failure, wedge failure.

Introduction

The hilly regions in India particularly the Himalayas are prone to landslides. Several slope failures have been recorded every year which causes life loss and huge economic loss. The inconvenience due to the blockage of roads hit the lifeline of hilly districts of the Indian Himalaya. Landslides are triggered mainly due to climatical factors and sometimes follow earthquakes or other hazards. Anthropogenic activities such as unplanned road construction, slope modification, cut slopes, poor drainage management, construction waste disposal and deforestation, etc. cause an increase in landslide activities. Due to complex geological and structural settings in the Himalayas, many geoscientists have traversed it to resolve the geological mysteries and many scientists are still working.

Himachal Pradesh is well for its natural beauty which attracts millions of tourists. Tourism is the backbone of this hilly state and many time badly affected by landslides. Many link roads and highways are under threat of land failure. Kinnaur district is one of the most beautiful districts bounded by rugged topography with steep slopes and deep gorges. Landslides in Kinnaur are very common. Urni landslide (Gupta, 2005) or Chooling landslide (Kumar et al., 2017) is one among the other landslides which is more than 3 decades old, in 2022, just 10-20 m away from this slide experienced a heavy landslide which may be the indication of expansion of Chooling landslide. Deformed, jointed, and faulted rock mass makes the slope more vulnerable but road alignment, water outflow through irrigation, and other unplanned construction activities, etc. have increased the danger of instabilities manyfold.

Numerous researchers (Kumar et al., 1999; Kumar and Panigrahi, 2001; Sikdar, 2002; Kastha, 2006; Gupta and Shah, 2008; Gupta, 2010; Sarkar and Singh, 2010; Kahlon et al., 2014; Patra et al., 2015; Sarkar et al., 2016; Kumar et al., 2017; Singh et al., 2017 and others) have studied the slopes on some parts of the Satluj valley with different aspects of landslides analyses techniques in the Satluj valley and their studies define that, to understand the relationship of jointed rock mass and slope, kinematic analysis is the one of the best and effective practice. This can be studied by using stereographic projection which gives the geometrical relationship between the geometry of the discontinuous plane, slope, and angle of internal friction. In this system, three modes of failure in hard rocks are possible to delineate i.e. planar failure, wedge failure and topple failure. In planar failure slope daylight along the discontinuous plane while wedge failure will happen in slopes if two joints or joint sets intersect and form a wedge then the slope fails along the plunging trend of



the intersection line. In hard rock, if a rock mass with forward rotation along a pivot and then moves down as free fall, bouncing, rolling on a surface, can be defined as topple failure. In the present investigation, five slopes from the study area have been considered for this study and only two modes of failure were identified, which are planar and wedge.

Fig. 1: Location map of the study area with sites along the National Highway (NH)-5 from Rali to Kashpo village, district Kinnaur, Himachal Pradesh.

Study Area

The area investigated in the present study, Rali to Kashpo village exists in the Satluj river valley and forms a part of Kinnaur district of Himachal Pradesh shown in Fig. 1 and is situated 180 km from the state capital Shimla towards the Indo-China border along NH-5. The area is well connected through road by NH-5 only. The nearest railway station and airport are situated at Shimla.

Geology of the Area

The present study deals with the slope failure analysis along Rali to Kaspo areas of Himachal Pradesh and comprises a part of lesser Himalayan Crystalline. The rocks exposed in the area belong to Jeori-Wangtu Gneissic Complex (J-WGC) and Karcham Group. The geological boundary between J-WGC and the Kracham Group is marked by Karcham thrust. Karcham thrust is exposed at Karcham and a thrust boundary is formed between gneisses of J-WGC and quartzite of Karcham Group. Graphitic schist is sandwiched between these rocks which are highly deformed and indicate the high stress environment. Gneissic and quartzite rocks have good strength generally >250MPa, but are structurally deformed and along the thrust, rocks are highly deformed. One major fault 'Raura Gad Fault' (RGF) runs across the valley along the Raura Gad near Chooling village and the rocks in the vicinity are highly disturbed and old slided debris can be observed along the left bank of the Raura Gad. The influence of this fault can be seen in that Chooling landslide is an active landslide at a distance less than a kilometer from RGF. 2-3 joint sets are very common throughout the study area and have a strong relationship with slope failures.

Methodology

The field investigation and desk analysis identification and evaluation of modes of slope failure were completed by exhaustive field studies, which involved the identification of the foliation plane (J_0) and other discontinuities present in the rock masses. The structural data including strike, dip amount, and dip direction were determined for each set of joints for each slope. All the collected information such as the attitude of the discontinuous plane and slope face were plotted on the stereo plots and friction circle. Markland's test conditions were used to define the modes of failure according to which condition planar failure shall qualify $\Theta > D_J > \varnothing$ and while $\Theta > P_J > \varnothing$ is the condition for wedge failure where, slope angle is defined by Θ, the dip of the joint plane by D_J, the plunge of intersection of joints by P_J and angle of internal friction or friction angle by $\varnothing$. Several researchers (Hoek and Bray, 1981; Anbalagan et al., 2007; Sarkar et al., 2016; Kumar et al., 2017; Singh et al., 2017 and others) have considered kinematic analysis as important for the

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assessment of slopes. Thus this methodology was adopted in the present research. The following steps have been adopted to carry out the present investigation as shown in the flowchart (Fig. 2).

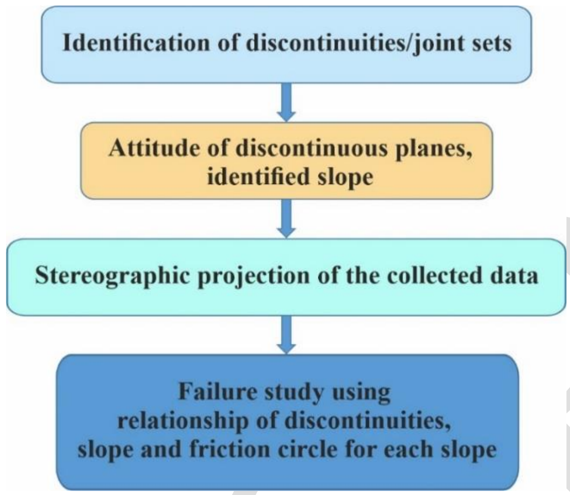

Fig. 2: Flowchart of methodology.

Results and discussion

In this study, five slopes were selected and investigated for identification of failure conditions and their modes of failure based on the orientation of discontinuities and slope information and their possible interaction with the geology. The slopes in the study area are steep to very steep, which makes the slopes critical. The slopes with slope ids RK01 RK02, RK03, RK04, and RK05 detailed in Table 1 were finally analyzed and their structural information was plotted on the stereonets (Fig. 3, 4, 5, 6, and 7). In RK02, RK03, and RK04 as observed the relationship between attitude of discontinuities, slope face, and friction circle did not satisfy the daylight conditions of failure.

Table 1: Location-wise details of lithology, slope information, and mode of failure.

Slope Id	Latitude	Longitude	Lithology	Slope Face	Failure	Mode of Failure
RK47	31.49901	78.20341	Banded Gneiss	85-N195	Partially	Wedge
RK53	31.51106	78.16908	Gneiss	85-N180	No	-
RK66	31.51803	78.10917	Banded Gneiss	70-N195	No	-
RK92	31.53846	78.01475	Augen Gneiss	46-N080	No	-
RK101	31.54997	78.00152	Biotite Gneiss	80-N045	Yes	Planar

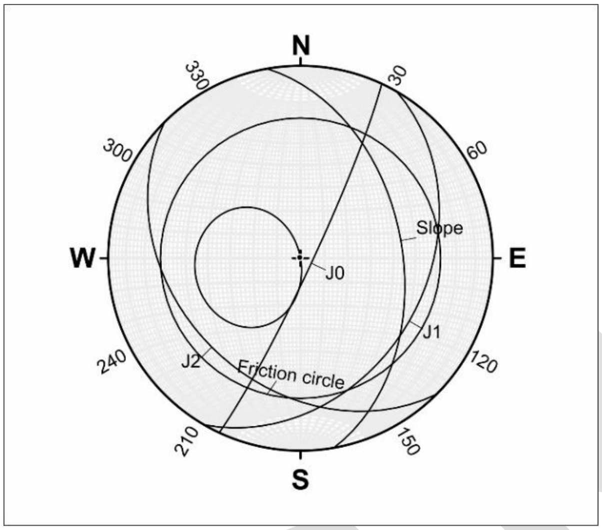

Fig. 3: The stereographic projections of discontinuities and slope data for site RK01.

The structural data of the slope and discontinuities for RK01 are represented in Fig. 3. In this projection wedge formed by the intersection of J1 (second joint set) and J2 (third joint set) does not qualify for any of the conditions. Thus, the slope can be defined as safe as per the method used in the current study. However, J2 can be a problematic discontinuity.

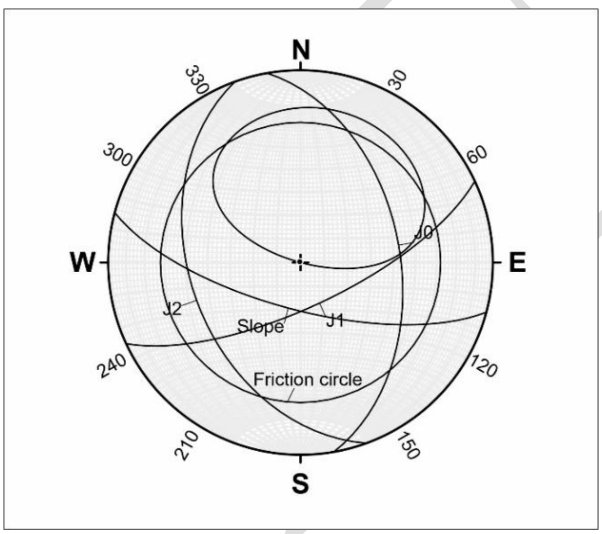

Fig. 4: The stereographic projections of discontinuities and slope data for site RK02.

The structural data of the slope and discontinuities for RK02 is represented in Fig. 4. In this projection only J1 qualifies the first condition of Markland's test where J1 is gentle than slope inclination and steeper than the angle of internal friction, but does not qualify for second condition of Markland's test due to its orientation. Thus it can be said that the slope is critical but did not show any mode of failure. If, in any case, slope daylight under the influence of any other cause, the chance to fail along J1 (planar slide) will be high.

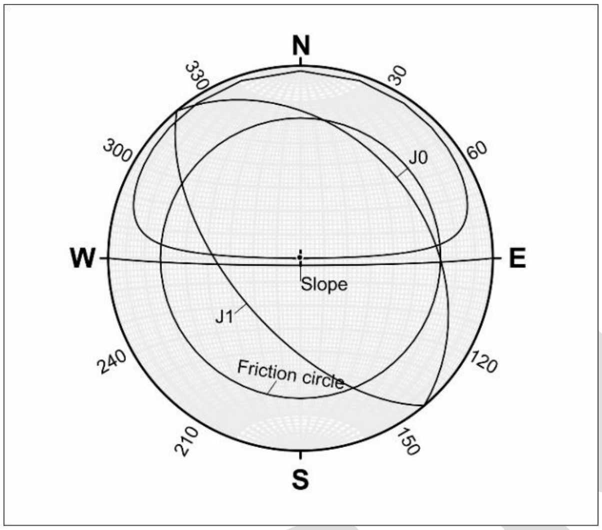

Fig. 5: The stereographic projections of discontinuities and slope data for site RK03.

The structural data of the slope and discontinuities for RK03 is represented in Fig. 5. Three wedges between J0-J1, J0-J2, and J1-J2 were observed after the analysis of field data. In this projection, J2 qualifies for the first condition of Markland's test where the slope is steeper than J2 while the angle of internal friction is gentle as compared to J2, but does not qualify the second condition of Markland's test. In the same way, the wedge formed by the intersection of J1 (first joint set) and J2 (second joint set) but did not satisfy any condition because the plunge of the intersection is more gentle than the angle of internal friction. In the above two cases wedge failure is more prominent as compared to planar failure. Hence, the slope can be defined as critical.

The structural data of the slope and discontinuities for RK04 is represented in Fig. 6. In this projection J1 qualifies the first condition of Markland's test where J1 is gentle than slope inclination and steeper than the angle of internal friction but does not qualify the second condition of Markland's test. Thus it can be defined that slope is critical only. If the slope fails by any other factor (not discussed here) the possibility of failure along J1 (planar failure) will be high.

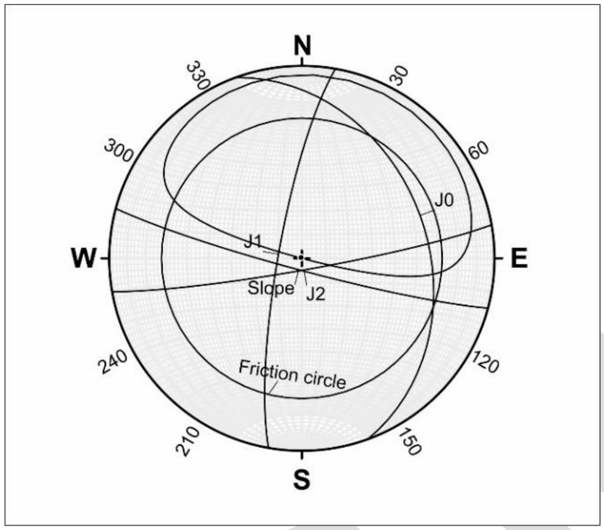

Fig. 6: The stereographic projections of discontinuities and slope data for site RK04.

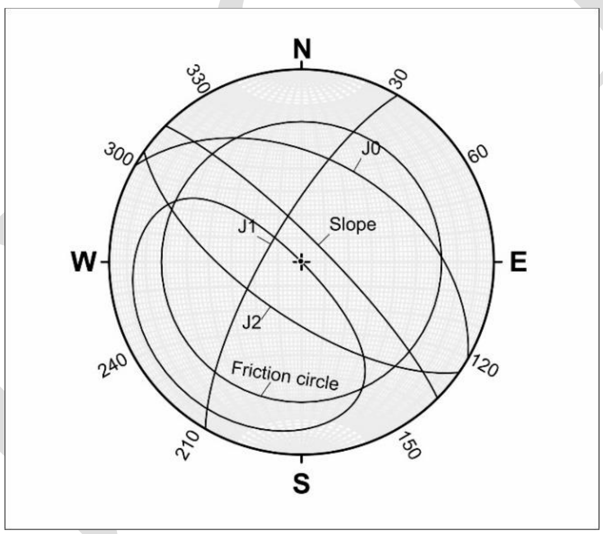

Fig. 7: The stereographic projections of discontinuities and slope data for site RK05.

The structural data of the slope and discontinuities for RK05 is represented in Fig. 7. In the above stereonet there are two cases (1) Wedge formed by J0 and J1, and (2) Planar along J0. Both cases qualify for the first condition of Markland's test, while the first case is disqualified in the second condition. In the second case, the foliation plane dips in a nearly parallel direction to the direction of inclination of slopes. Hence, with this study, the mode of failure is observed as planar failure along J0.

Slopes RK01, RK02, RK04, and RK05 were observed through the relationship between the attitude of discontinuities, slope face, and friction angle and investigated as the planar mode of failure. The slope RK03 shows the wedge mode of failure. RK05 slope is the most problematic slope among the five slopes discussed here in this study.

Conclusion

On the basis of the present field and desk study, it can be concluded that kinematics in assessing slope stability assessment is a quick and effective technique. By using this method slope failure conditions and their modes of failure can be evaluated. If a slope appears stable in the projection again it is a finding that slopes are kinematically safe and stable. The five slopes were assessed in the present study and all slopes are investigated as critical and two modes of failure are evaluated i.e. wedge and planar. One wedge failure and four planar failure modes are delineated. Out of all these slopes, RK05 is the most critical slope and require detailed investigations and adequate slope stability design to avoid untoward incident. Finally, it can be concluded that kinematic analysis is good for quick assessment. Also, the unstable slopes shall be further studied in detail for any construction activities like the excavation of slopes for the construction of new highways or widening of roads so that adequate stability support if required may be provided. Also, road-cut slopes are very critical, and before modification of natural slopes to cut slopes geological, geotechnical, and geomechanical studies must be mandatory, and kinematic study is one among them.

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