

Analysis of Highway Slope Failure by an Application of the Stereographic Projection

Chin-Yu Lee and Iau-Teh Wang

Abstract—The mountain road slope failures triggered by earthquake activities and torrential rain namely to create the disaster. Province Road No. 24 is a main route to the Wutai Township. The area of the study is located at the mileages between 46K and 47K along the road. However, the road has been suffered frequent damages as a result of landslide and slope failures during typhoon seasons. An understanding of the sliding behaviors in the area appears to be necessary. Slope failures triggered by earthquake activities and heavy rainfalls occur frequently. The study is to understand the mechanism of slope failures and to look for the way to deal with the situation. In order to achieve these objectives, this paper is based on theoretical and structural geology data interpretation program to assess the potential slope sliding behavior. The study showed an intimate relationship between the landslide behavior of the slopes and the stratum materials, based on structural geology analysis method to analysis slope stability and finds the slope safety coefficient to predict the sites of destroyed layer. According to the case study and parameter analyses results, the slope mainly slips direction compared to the site located in the southeast area. Find rainfall to result in the rise of groundwater level is main reason of the landslide mechanism. Future need to set up effective horizontal drain at corrective location, that can effective restrain mountain road slope failures and increase stability of slope.

Keywords—slope stability analysis, Stereographic Projection, wedge Failure.

I. INTRODUCTION

SLOPE failures along highways usually occur as a result of earthquakes or heavy rainfalls. Slope failures have become one of the main geological disasters in Taiwan due to natural disasters affecting the environment. With such features as joints and cracks, rock slope failures are discontinuous structural destruction. Hoek and Bray categorized rock slope failures into different types based on failure mechanisms, namely: Plane Failure, Wedge Failure, Topples, and Arc Sliding Failure. Factors affecting slope stability can be divided into two main categories: internal latent factors and external inducements. Latent factors include: slope type, property, structure, etc. Inducements include: typhoons, heavy rainfalls, earthquakes, human factors, etc. Internal factors are the most fundamental causes affecting slope stability, especially on rocky slopes. Inducements, on the other hand, are direct causes

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of slope failures. Relatively, wedge sliding occurs more frequently on mountain highway slopes because of the landscape undulation, the failure mechanism of which consists of two or more sets of discontinuous planes with well-developed joints. Wedge failures may occur when the angle between two discontinuous planes is smaller than the dip angle and larger than the friction angle. The regional rock stratum has a significant impact on the stability analysis of slopes, particularly regarding the potential risks of dip-slopes. Spatial plane stratum is usually expressed in strike and dip angle. Usually, mountain highway slope failures occur on rocky slopes. Site investigation should be conducted in the analysis. The stability analyses of slopes are carried out by applying the data of discontinuous planes' stratum and gradient. Also, stereographic projection or slope stability equation may be used to evaluate the stability of highway slopes [1], [2]. Bishop [3] first applied the Equal-Angle Projection Method in slope sliding stability analysis. Philips [4] used the Stereographic Projection Method for judging structural geology. Goodman [5] made use of the Stereographic Projection Method in the joints investigation of rock's discontinuous planes. Hoek *et al.* [6], [7] proposed a complete method to analyze slope wedges. Warburton [8] analyzed the geometrical stability of polyhedron rocks by using vectors. Goodman *et al.* [9] proposed the Block Theory. By segmenting spatial geometries with the set concept in Topology, all of the geometries related to spatial volume can be found systematically. Also, the key block can be found by studying the stratum of failure planes. Goodman [10] on the other hand, illustrated the revolving failure modes of any polyhedron by applying stereographic projection. Yoon *et al.* [11] explained the sliding failure modes of rocks on slopes of multiple free surfaces by using stereographic projection. The scholars mentioned above applied the concept of geometry when studying the geological information and simplified the spatial lines and planes which influence each other. Projecting the three-dimensional lines and planes on two-dimensional planes is an effective approach in the stability analysis of rock slopes. In the analysis of regional rock slope stability, geometries and mechanism of failures can be observed in the site investigation, which is often constrained by height, weak plane, stratum, and length of the slope. However, before slope failures occur, it is necessary to determine how to judge the geometrical volumes which have potential risks, predict the collapse of the slope, and analyze the stability of moving direction based on limited information, all of which are important factors in the task of disaster prevention. Provincial road No. 24 is the main access to Ali Village and Jilou Village in Wutai Township in Pingtung

County, along which disasters such as slope collapse and sliding usually occur whenever there are typhoons or heavy rainfalls (Figure 1). Hence, in order to understand the slope collapse features of this sector of road, geological investigations in the collapse area in this research are based on site investigation and the evaluation of remote survey images. By applying this method, we can understand the landscape undulation, geological materials, geological structures, hydrological environment, and other main linear structures. Also, we can conduct slope stability analyses to better understand the sliding failure mechanism of the area of collapse by applying the Stereographic Projection Method, which is based on structural geology.



Fig. 1 Location of slope collapse and sliding

II. STUDY AREA

Wutai Township is located in northeastern Pingtung County in Taiwan. It is situated on the Central Mountain Ridge with an average altitude of over 1,000m. Wutai Township is neighbored by Jinfong Township in Taitung County in the east and Beinan Township in Taitung County in the southeast. Haocha Village and Jilou Village in Wutai Township are adjacent to the Majia Township in the west across the Ailiao

South River. Wutou Mountain in the northwest with an elevation of 1,200m is part of the Ailiao North River watershed. Neighbored by Wanshan in Maolin Township in Kaohsiung County, Wutai Township is situated in the Ailiao North River watershed, except for Haocha Village, which is located in the Ailiao South River watershed. The location of Wutai is shown in Figure 2.



Fig. 2 Location of Wutai Township (Google Earth)

A. Terrain and Geological Characteristics

With an average altitude of more than 1,000m, the terrain of Wutai Township is rugged with steep slopes. Ali Village is situated in east Wutai with altitudes ranging between 1,180m-1,300m; the level difference of this village is approximately 120m. The overall terrain descends from the east and southeast to the valleys in the north. Neighbored by Jilou Village on the northwestern side, the overall terrain there descends from the south to the north. The average altitude of Jilou Village is between 1,030m-980m, with a level difference of approximately 50m. Pingtung County is divided into two geological zones: the Central Mountain Range Geological Zone and the Hengchun Peninsula Geological Zone. Rocks there are mainly dark grey and grey-black hard shale, slate or phyllite and belong to the region of Tertiary low-grade metamorphic rock. Located at the south end of the Central Mountain Range, the regional geology of Wutai Township mainly consists of slate, which is one kind of metamorphic rock, due to the high temperature and pressure of the Earth's crust. Slopes along Provincial Road No. 24 in the mountains are closely aligned slates which are easy to break or shell off because of external forces, as shown in Figure 3. The rock stratum of the collapse area is shown in Table 1. The active faults in the adjacent area are as follows. With a distance of 11.8 km, the nearest fault is Chauzhou fault, which is followed by Liouguei fault and Cishan fault with distances of 21.64 km and 31.5 km, respectively.



Fig. 3 Brief geological descriptions

B. Climate and Hydrology

Figure 4 shows the average monthly rainfall distribution map at Ali precipitation station over a period of 41 years. The rainfall there is less than that in other mountainous areas and is concentrated in the summer time from May to September. There is less rainfall in the winter, which is the dry season, from October to May. The average temperature is approximately 17°C. This area is often covered in white fog in spring and summer, so it deserves to be called the township of fog.

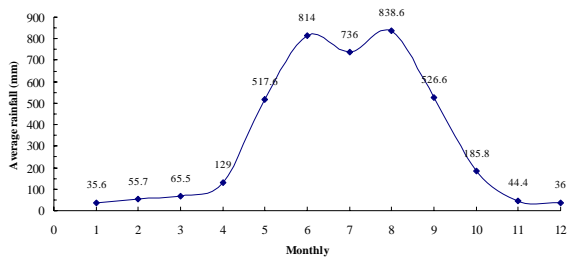


Fig. 4 Average monthly rainfall distribution map at Ali precipitation station

C. Current Situation of Slope Disasters

The main disaster location is situated at Point 46.2 km along Provincial Road No. 24 with the X-Y coordinate of (223202, 2515674) on the border between the tribes of Jilou and Ali. An extensive area of slopes is exposed to the air and failures occurred after several typhoons. Beneath the collapsed area is Ailiao North River. After the site investigation, it was found that several disasters such as serious roadbed loss happened along Provincial Road No. 24. A large collapse happened around Jilou Tribe close to the Point 46.4 km along the road. Continuous masonry rock parapets (Picture 1) were built with slate on the rock slopes. Although short retaining walls were built along the toe of the upper slope, collapse and rockfall still occurred. Construction of slope protection was also conducted on the lower slope with slate (Picture 2). However, it seems that some rocky parts were exposed on both sections. The cracking on that section of road is indicated in Picture 3, while undulation of the road surface is shown in Picture 4.



Picture 1



Picture 2



Picture 3



Picture 4

III. APPLICATION OF GRAPHIC METHOD ON SLOPE STABILITY ANALYSIS

In the research on structural geology, stereographic projection is applied to indicate the rock's structural plane on projection drawings to confirm the relationship between their angles. Stereonet is mainly used to project the three dimensional geological structure on two-dimensional planes. By understanding the distribution of the weak plane, analyses of rock stratum and relative angles are carried out for rock stability analysis; they are most used in stability analysis on rock slopes and tunnels. This method can be applied to rock classification [12], underground excavation [13], and rock slope construction [6], and is most useful in regard to rock slope construction [14]. Stereographic projection drawings simplify complicated and discontinuous three-dimensional space to two-dimensional planes. Although an accurate safety coefficient is not guaranteed, it is the most effective method for evaluating slope stability in the initial planning stage. On one hand, using this method can help to avoid construction on dangerous slopes. On the other hand, slope-related problems can be predicted and protective measures applied. Gokceoglu *et al.* [15] drew risk charts on slope failure in Turkey by using stereographic projection and kinematic analysis. According to different projection methods, stereographic projection can be

differentiated into Parallel Projection, Equal-Angle Projection and Equal-Area Projection. Based on the forms of failures, this research adopted the Equal-Angle Projection Method to proceed with the analysis of slope approaches, gradient, stratum trend, and dip angles. This research also judged rock stability, studied its failure mechanism and direction, and further analyzed slope stability by combining the failure forms of the rock.

A. Graphic Method [7]

Figure 5 shows the recommended terminology for orientation is the dip and dip direction which are defined as follows,

1. Dip is the maximum inclination of a discontinuity to the horizontal (α).
2. Dip direction or dip azimuth is the direction of the horizontal trace of the line of dip, measured clockwise from north (θ).

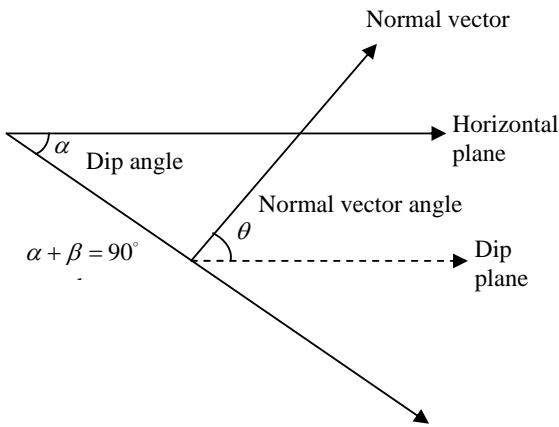


Fig. 5 Isometric view of plane (dip and dip direction)

Figure 6 shows the line of intersection is represented by the point where the two great circles of the planes intersect, and the orientation of the line is defined by its trend (α_i) and its plunge (ψ_i). The inclination of the slope face (ψ_{fi}) is measured in the view at right angles to the line of intersection.

The trend (α_i) and plunge (ψ_i) of the line of intersection of planes A and B can be determined on the stereographic projection, calculation using equations (1) and (2).

$$\alpha_i = \tan^{-1} \left(\frac{\tan \psi_A \cos \alpha_A - \tan \psi_B \cos \alpha_B}{\tan \psi_B \sin \alpha_B - \tan \psi_A \sin \alpha_A} \right) \quad (1)$$

$$\begin{aligned} \psi_i &= \tan \psi_A \cos(\alpha_A - \alpha_i) \\ &= \tan \psi_B \cos(\alpha_B - \alpha_i) \end{aligned} \quad (2)$$

Where α_A , α_B are the dip directions, and ψ_A , ψ_B are the dips of the two planes.

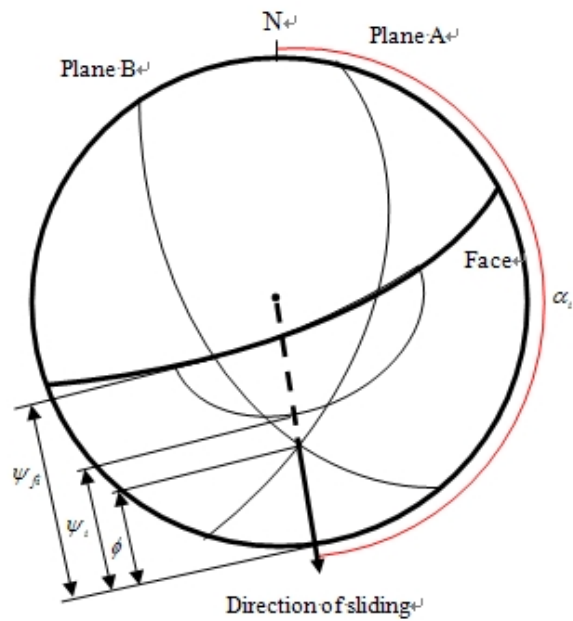


Fig. 6 The orientation of the line of intersection, and the range of the plunge of the line of intersection (ψ_i) where failure is feasible [7]

The factor of safety of the wedge defined, assuming that sliding is resisted only by friction and that the friction angle (ϕ) is the same for both planes, is given by

$$FS = \frac{(R_A + R_B) \tan \phi}{W \sin \psi_i} \quad (3)$$

$$R_A \sin \left(\beta - \frac{1}{2} \xi \right) = R_B \sin \left(\beta + \frac{1}{2} \xi \right) \quad (4)$$

$$R_A \cos \left(\beta - \frac{1}{2} \xi \right) + R_B \cos \left(\beta + \frac{1}{2} \xi \right) = W \cos \psi_i \quad (5)$$

$$R_A + R_B = \frac{W \cos \psi_i \sin \beta}{\sin \left(\frac{\xi}{2} \right)} \quad (6)$$

Hence

$$FS = \frac{\sin \beta}{\sin \left(\frac{\xi}{2} \right)} \times \frac{\tan \phi}{\tan \psi_i} \quad (7)$$

Where R_A and R_B are the normal reactions provided by planes A and B, and the component of the weight acting down the line of intersection is $W \sin \psi_i$. Angles ξ and β are

measured on the great circle containing the pole to the line of intersection and the poles of the two slide planes, the angles ξ and β are define in Figure 7 and Figure 8.

B. Data Analysis of the Discontinuous Plane

The results of rock stratum stereographic projection analysis on site are shown in Figure 9. Based on the stratum data, the stratum trend is northeast while the angle of weak plane is in the same direction as the slope approach. Therefore the failure

mode is judged as dip-slope type. The stratification plane trend and slope approach are independent and discontinuous, and tend to cause more than three sets of wedge failures. The glide direction is southeast, south and southwest. Determining whether the failure happens due to the pressure release of the valley needs further clarification.

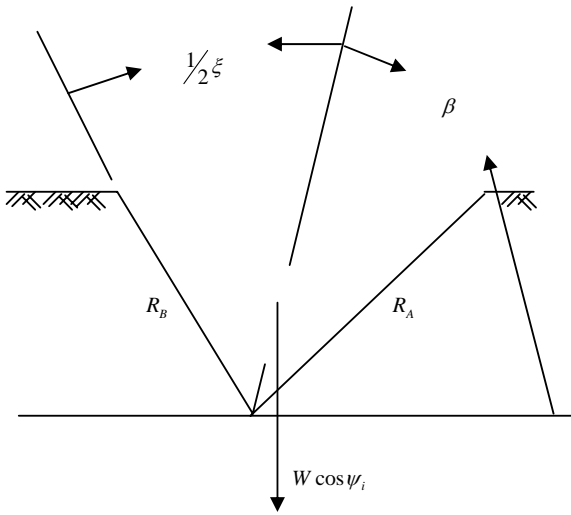


Fig. 7 Definition of angles ξ and β and reactions on sliding planes R_A and R_B [7]

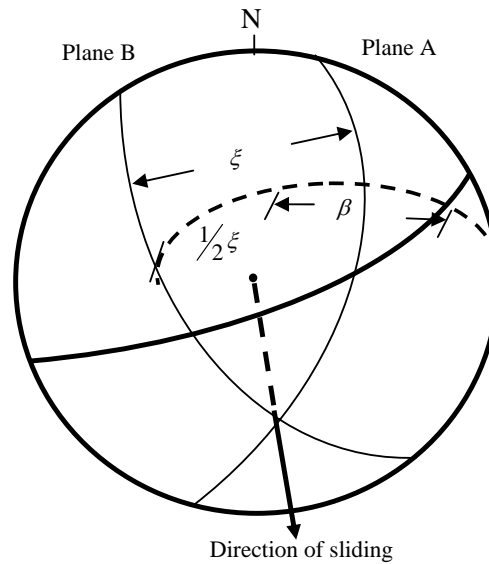


Fig. 8 Measurement of angles ξ and β [7]

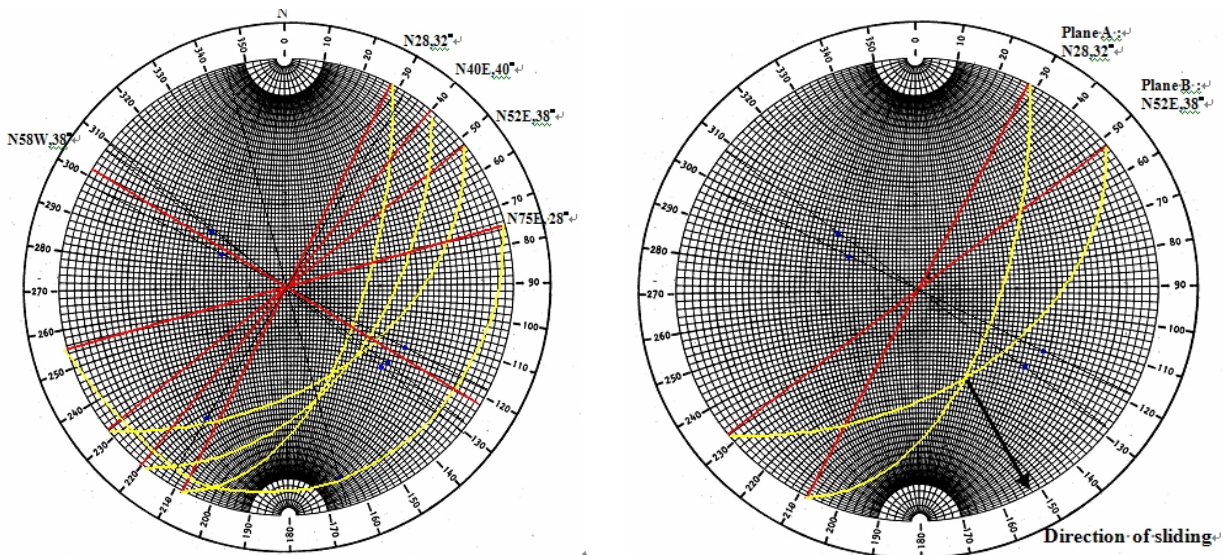


Fig. 9 Rock stratum stereographic projection

IV. DISCUSSION ON THE COLLAPSE FEATURES

Small catchment areas are formed by the undulation of the landscape in this region (Figure 10). Figure 11 shows that the vertical distance of the collapse object's upper slope is 52.5m, while the tilting distance is around 85.1m. The angle of repose is 30° and the length of the side slope is about 163.3m. The dip angles are 23.1° on the left hand side, 36.5° in the middle, and 37.1° on the right hand side. It is evident that sliding continues to occur in this region because the angle on the left hand side is smaller than the angle of repose. Figure 12 shows that the vertical distance of the lower slope is 103m, and the tilting distance is approximately 191m. The dip angle of the slope is 32.1° , which is bigger than the angle of repose. Furthermore, the terrain of the areas along Ailiao North River is cut by the river and meanders are formed. Also, the unstable situation of the side slope is probably caused by the depressurization of the valley. This phenomenon can result from the cracking of the short retaining walls and the road surface. Lastly, it can be judged that the cracking resulting from tension on the top of the upper slope is the key factor which will cause linear structural zoning collapse (Figure 13). Moreover, the geological materials are mostly slate with low weather resistant capabilities. It is possible that large scale collapse may occur if there are any inducements.

Based on the abovementioned analyses, there are four factors related to slope collapse, as follows:

1. The regional geological materials are mostly slate with intensive laminated secondary joints and poor cemented strength. Destruction caused by shearing force tends to occur with cracking along the weak plane.
2. The riverbed of Ailiao North River lies beneath the collapsed area. The side slope tilts toward the river and collapses due to the depressurization of the valley.
3. With the well-developed joints and cleavage, regional rock layers tend to slide along discontinuous latent fracture planes.
4. Rocks gain weight by absorbing water from rainfall. In addition, water pressure in the rock increases while rock shearing strength decreases when water infiltrates through the cracks.
5. Collapse took place because the rock lost its support after the cutting of the stable slope toe caused by the excavation of highway construction; the surrounding environment was also disturbed during the excavation.

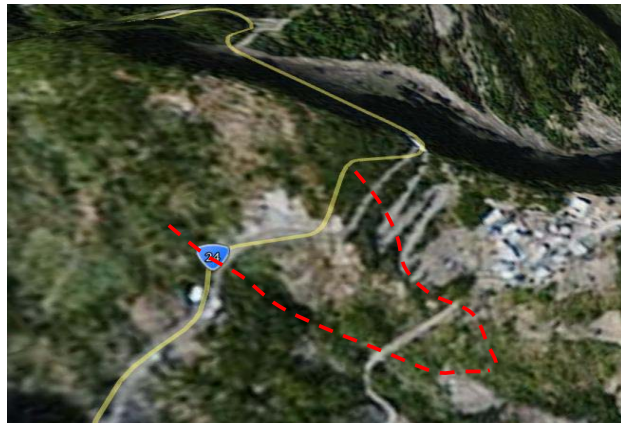


Fig. 10 Regional Small Catchment Area (Google Earth)

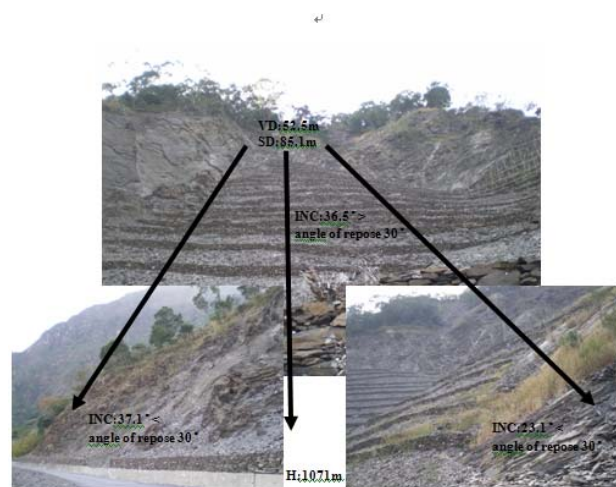


Fig. 11 Ground Stratum of Upper Slope on Collapse Site

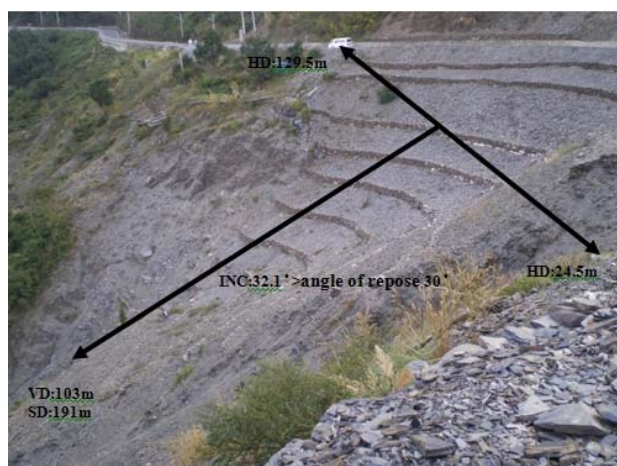


Fig. 12 Ground Stratum of Lower Slope on Collapse Site



Fig. 13 Collapse Zone of Linear Structure (Google Earth)

V. CONCLUSIONS

This research selected the collapsed area in the sector 46k to 47k on provincial road No. 24 as the object of study. By applying site investigation of the ground geology, geological structure analyses and remote survey, this research summarizes the results of every investigation and constructs a complete geological module based on the Stereographic Projection Method. As the result of this research reveals, understanding the stability of the road slope can be fast and easy, with judgments on sliding trends and directions, and simultaneously achieving the goal of site investigation by applying the Stereographic Projection Method through reasonable methods of investigation. However, due to the complexity of factors influencing slope stabilities caused by landslides, it is necessary to proceed with the geological drilling to analyze the information on discontinuous planes' approaches and tilting angles by studying the rock core, in order to derive necessary and fundamental parameters in the analyses. Furthermore, hydraulic piezometers and observation wells need to be distributed on the site to detect the internal pressure variation and survey the height of underground water. The installation of tilt meters is also required to monitor the slope to determine if it keeps sliding. Thereby, the geological conditions of the investigation site can be understood and serve as reference for the site and route selection of future roads as well as the tasks of disaster prevention.

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TABLE I
ROCK STRATUM OF THE COLLAPSE AREA

Location	Joint, Cleavage	Attitude	
		Strike	dip
Left 2		N75E	28
Left 1		N52E	38
Middle top	Average 2-3 group	N40E	40
Right 2		N28E	32
Right 1		N58W	38