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Geo-structural stability assessment of surrounding hills of Kuala Lumpur City based on rock surface discontinuity from geological survey data

Ratiranjan Jena[1] · Biswajeet Pradhan[1] · Abdullah M. Alamri[2]

Abstract

Structural field data have been widely used for geological analysis in the past decade. By contrast, structural stability analysis based on surface orientation for large discontinuity planes has received inadequate attention from researchers. This study performs structural stability analysis on Kuala Lumpur (KL) by utilizing surface orientations (1) to investigate the influence of rock stability on the development of transportation corridors and (2) to assess land and infrastructure stability by determining areas susceptible to various rock failures. Data are collected from three parts of KL (east, west and north) that represent different hilly regions. Data from the southern part of the city are not collected because its hilly regions are far from the city. Furthermore, the orientation data of bedding planes, faults and joints are grouped into sets for a thorough understanding. The computed global mean and best fit show that the overall structure of the area is dome- and basin-shaped. Kinematic analysis provides the percentage of potential risk for various rock failures. Our findings show the dominant types of rock failure with high risk around the city and the ranges of probabilities in the eastern, western and northern part of the city, which are 5.22%, 9.8% and 7.37%, respectively. Low probability of wedge sliding, high probability of flexure toppling and medium probability of planar sliding are observed. Results show that the set S(2) with dip angle 55°–60° in the east of KL; S(3), S(4) with dip angle 58°–67° and 65°–70° in the west of KL and S(2), S(6,7) with dip angle 52°–70° and 86°–90° are critical and could contribute to the slope failure risk in the future. It could be understood that rock failures can seriously influence the development of the surrounding agriculture land and infrastructures.

Keywords Geo-structural analysis · Planar sliding · Wedge sliding · GIS · Toppling · Risk

Introduction

Various types of rocks are formed with different mechanisms, which we can understand by investigating their crystal characteristics. Hills around Kuala Lumpur (KL) are covered by forests

with basement as sedimentary rocks. However, sedimentary rocks change to metamorphic and igneous rocks according to the rock cycle due to remarkable stresses. Meanwhile, rocks develop folds, faults, joints, fractures and discontinuities that are separated by planes of weakness due to tectonic stresses (Assali et al. 2014; Oberender and Plan 2015). These discontinuities influence the shape of landscape characteristics and determine the probability of hazards along steep slopes.

The tectonics of the study area reveals an effective explanation that KL and its surrounding hills are present at the western belt, given that the Bentong–Raub shear zone divides the eastern and western belts of Peninsular Malaysia as a part of the stable Sundaland Block (Metcalf 2013). The city is located at a synclinal structure surrounded by hills with igneous, sedimentary and metamorphic rocks. The area surrounding KL is metamorphosed but does not cross the conditions of greenschist facies. The entire area is characterized by western

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and central plutons with sedimentary rock units at the top. High metamorphic rocks can be found in some outcrops in the eastern part of KL. Large outcrops of Ordovician–Silurian rocks separate the granitic plutons from the large shear zone of Bentong–Raub. Some sedimentary outcrops, such as sandstone and limestone, can be found at the middle portion of the hills (Metcalf 2013). The basic lithology in the western part of KL comprises low-grade metamorphic rocks, which are, in turn, characterized by meta-sedimentary rocks. Northern hills are characterized by unmetamorphosed rocks and sandstone and limestone deformed by lagoon-deposited sediments. Limestone caves in the northern region of KL can be found in Batu Caves.

Rock slope failure is a major issue in mountainous regions and threatens road transportation (Clark 1992). Several landslides and rock falls occur in the surrounding hills of KL and produce potential risk for infrastructure and highway users. Geological survey based on developed compass and GPS (Geographical Positioning System) collects rock discontinuity information by conducting direct assessment on the rock layers. The orientation of rocks should be investigated for understanding the direction of beddings, joints and faults (Roncella and Forlani 2005). Many other techniques, such as discontinuity planes from LiDAR (Light Detection and Ranging) and TLS (Terrestrial Laser Scanning) data, have been used for slope stability analysis (Mezaal et al. 2018; Nampak et al. 2018; Rizeei et al. 2016). Several studies have conducted rock stability, hazard, vulnerability and risk analysis on the basis of discontinuity planes (Terranova 1984; Cevasco et al. 2000; Federici et al. 2001; Cevasco 2007; Pradhan et al. 2018; Sameen et al. 2019; Jena et al. 2019; Jena et al. 2020). These studies have used various methodologies to improve the management strategy and to obtain a comprehensive solution for the instability of slope failures. Rock instability analysis is a common subject for coastal areas and regions at high risk of slope failures (Iadanza et al. 2009). Several studies have been conducted on sea cliff erosion, land stability analysis and alteration mineral identification (Andriani and Walsh 2007; Jongens et al. 2007; Ghasemi et al. 2018). Various application approaches, such as high-resolution topographic surveys (Schulz 2007), parametric methods (Budetta et al. 2008) and slope-distributed landslide models, have been used on rock stability analysis (Gunther and Thiel 2009). Fundamental rock slope failures include planar sliding, toppling and wedge sliding (Hoek and Londe 1974). The proposed methodology can be considered a primary method of rock failure analysis (Fell et al. 2008). Therefore, spatial orientation, geometric evaluation and stereographic plotting can provide an overview of discontinuity (faults, joints and beddings) slope failures (ISRM 1978).

Many methods have been used for rock failure analysis. However, we proposed a reliable methodology that has been developed for the preliminary analysis of rock slope failures. Therefore, a feasible methodological flowchart is presented here; it provides a good means of understanding slope characteristics and developing a failure strategy with causal factors. This study aims to evaluate rock mass instability according to orientation data from a geo-structural survey to assess various types of rock failures and to estimate various critical rock slopes for failures. The main contribution of this study pinpoints the use of a large number of rock discontinuity data at a time to assess the slope stability assessment by considering the infrastructure. For the first time, data was collected from the three directions of the Kuala Lumpur metropolitan city to perform this study. Kinematic tests are conducted on various types of slope failures. Therefore, the quality of the proposed methodology, the accuracy of kinematic test and the strength and limitations of the modelling approach should be investigated.

Material and methods

Study area

KL, a city in Selangor District in Peninsular Malaysia, is the country's capital situated at a lat. and long. of 03°08′52″N and 101°41′43″E, respectively (Fig. 1.). The city is characterized by 6891/km^2 of population density. It is also known as the federal territory and the metropolitan city in Malaysia with an average area of 243 km^2. The city typically exhibits syncline structures surrounded by hills from all directions. The geological structure of the study area is dome- and basin-shaped. Beddings are laterally thick with mostly planar surfaces. Well-defined fault planes with a mixture of planar and undulated surfaces can be found in the hills of the city. Joints are also found, but only large joints are considered in our stability analysis. Lithologically, the hills are characterized by sandstone, limestone, granites and schist. The chosen area is vulnerable to slope and wedge failures that creates the motivation to study and analyse.

Data collection and processing

Data was collected through the fieldwork from the east, west and southern part of hills surrounding Kuala Lumpur. First, poles of collected data are clustered with use of stereonets in clustering analysis. Such analysis provides an idea about the clustering of all beds, faults and joint planes and clearly indicates their distribution in a particular region. Next, Terzaghi weighting of the clustered data is outputted. This process modifies the data with a biased angle of 15° and is conducted for an understanding of the clustering. Afterward, kinematic analysis, which is used for the interpretation of spatial interactions of geological structures with respect to slopes, is performed for rock stability assessment. This analysis is suitable for determining the percentage of potential risks for different types of rock failures, such as planar sliding, flexure toppling
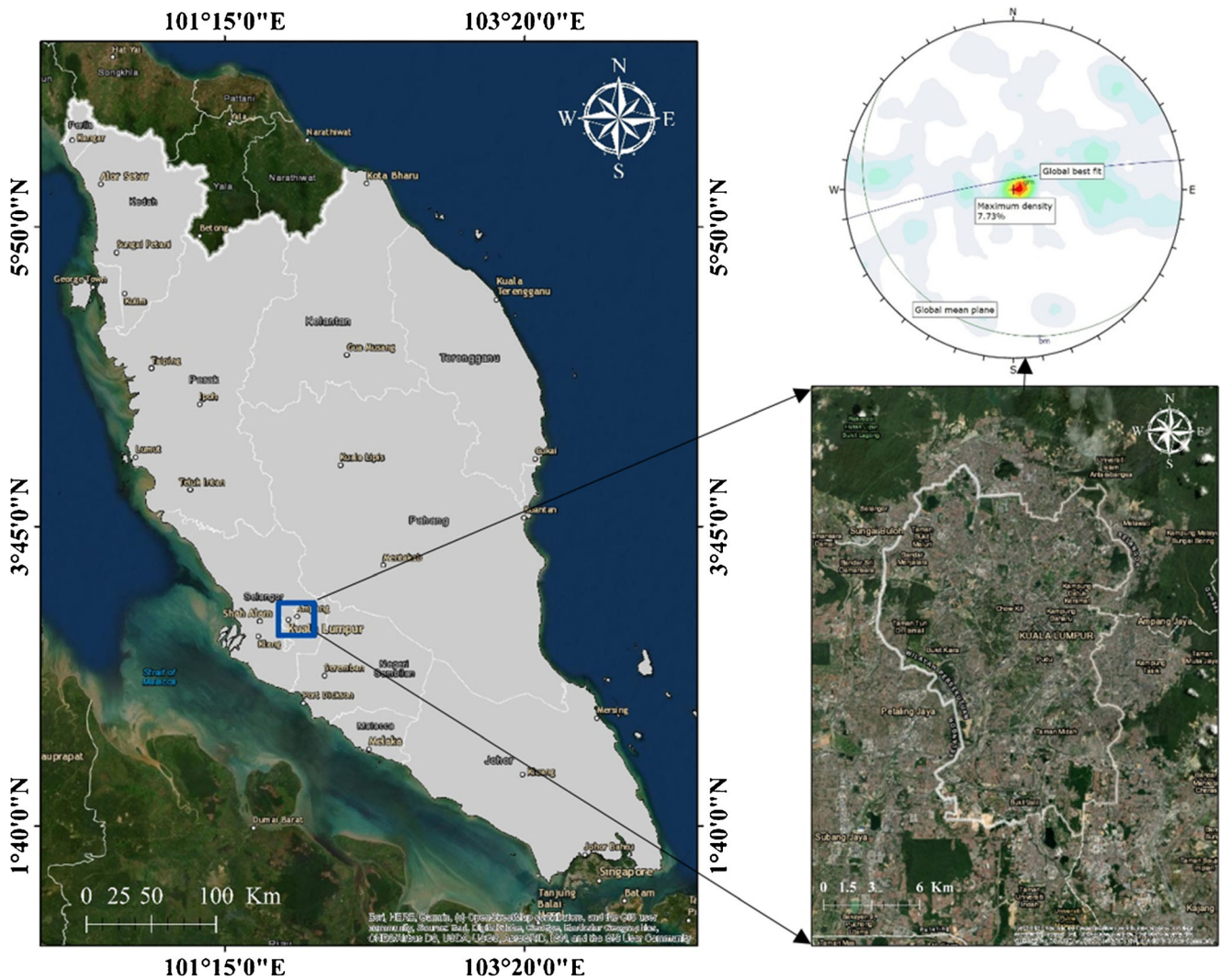
Fig. 1 Study area map with the stereonet presenting the global mean and maximum density of rock discontinuity

and wedge sliding (Sturzenegger and Stead 2009; Babiker et al. 2014; Idrees and Pradhan 2018). Goodman (1989) performed general kinematic analysis for unstable slope identification in Rocscience Dips v6.0. Specific casual factors of slope and friction angles are used for comparing the mean orientation of data. The software computes the intersection of beds, faults and joints to estimate the potential risk of wedge sliding (Admassu 2012). Orientation of all the planes plotted by using equal area stereonet and spatial interrelationship and patterns (sets) among the planes are analysed. The density of discontinuity planes influences the slope failures (Assali et al. 2014). Thus, all the discontinuity planes for kinematic observation are grouped into various sets for three different regions by using a contour plot. According to Rocscience (2010), pole density less than 4% can be considered when the data have high density with variability. However, large amounts of data are used in our stability analysis study without considering small discontinuity planes.

Therefore, pole density less than 1% is ignored for obtaining a good assessment.

The potential risk of slope failure depends on the interaction between slope geometry and friction angle characteristics (Admassu 2012; Idrees and Pradhan 2018). Rocscience (2010) explained that planar sliding only occurs when discontinuity planes dip at an angle of 20° with the slope angle. On the basis of the rules of Rocscience (2010), toppling can occur when steep structural discontinuity planes become parallel to the slope face within 30° (Hoek and Bray 1981). Dipping towards the same direction of the slope and dip angle is less than that in the slope and is more than that in the friction angle along the failure planes when wedge-shaped blocks are formed due to the intersection between discontinuity planes. Therefore, kinematic analysis is performed to estimate the potential risk of planar, toppling and wedge sliding with assumed friction angle of 30° and lateral limit of 30°. The overall methodological flowchart is described in Fig.2

Results and discussion

Orientation of structural discontinuity

The collected field data contain various important information, such as (Dip/dip dir.), strike, shapes of planes, types of planes and geometric properties. The data can be converted into delimited text format by using geological software and GIS (Geospatial Information System). In this study, the entire data are divided into three segments, and each segment is separately analysed on the basis of the geographical area. Large amounts of orientation data are collected without considering small discontinuities. Moreover, an overview of the study area is presented in Figs.1. and . The clustering of poles shows the patchy distribution of points in the stereonet with contour. The pole densities of the three sections are approximately 8.4%, 23.28% and 7.14%, respectively. Pit slope is plotted in the clustering stereonet analysis to obtain a clean visual interpretation. Rosette models are presented for the strikes of all structural discontinuity planes in Fig. 3. This clustering analysis provides important information, which is relevant in evaluating the relationship between the slope direction and rock structure in Fig.3. Best-fit and global mean are plotted to understand the overall structure of the study area.

Terzaghi weighting

Terzaghi weighting is specifically used for bias correction and mostly adopted when the collected data from the study area are planar traverse (Rocscience 2010). However, changes may exist in pole clustering and contour. In our study, Terzaghi weighting is applied in Fig.4 to all three sections of the study area with a minimum bias angle of 15°. Several contour changes can be observed in the eastern and western part of the hills of KL, whereas no changes are observed in the northern region.

Rock structure and fold analysis

Geological discontinuity orientation data are useful for folding assessment analysis. Several hundreds of data are collected in the study area. The variation of dip angle and dip direction reflected in the slope cutting cross-sections identifies rocks
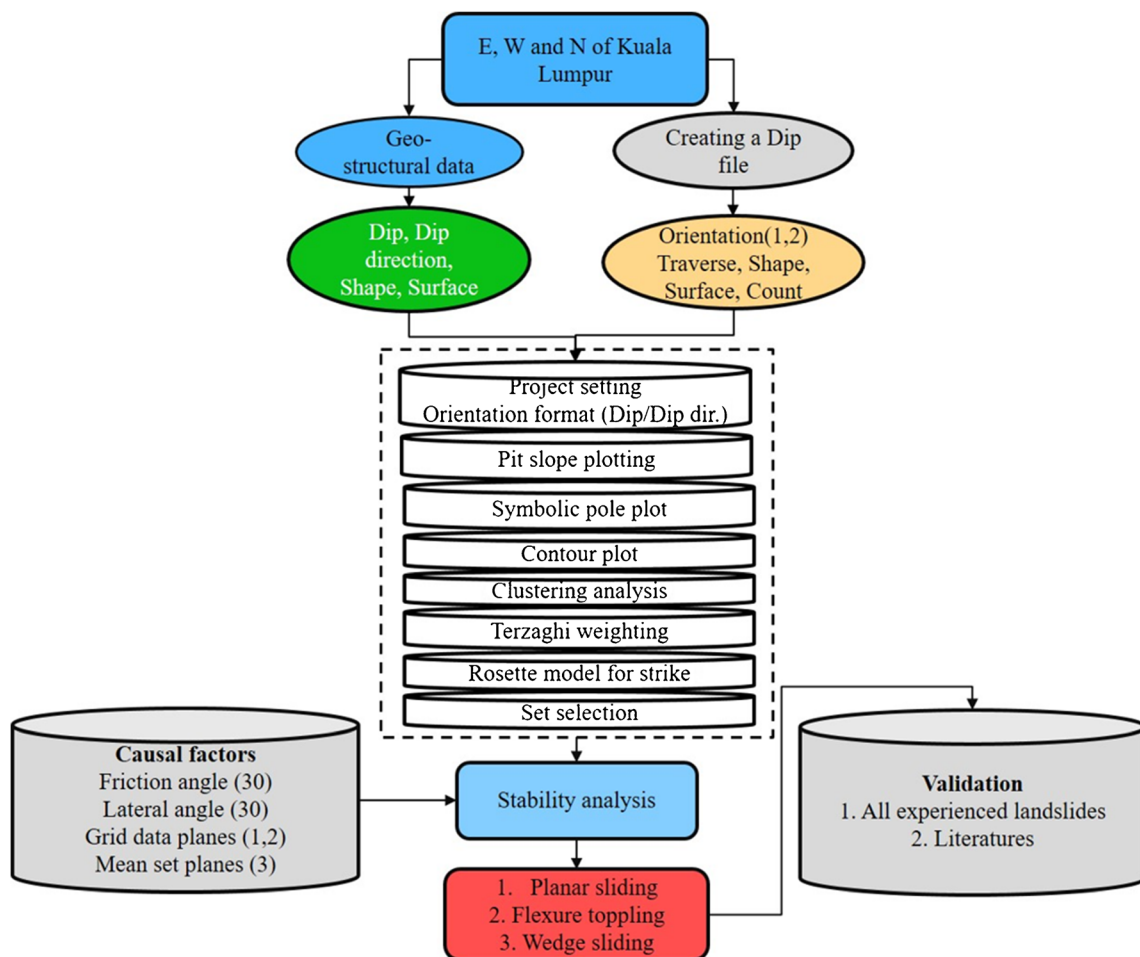

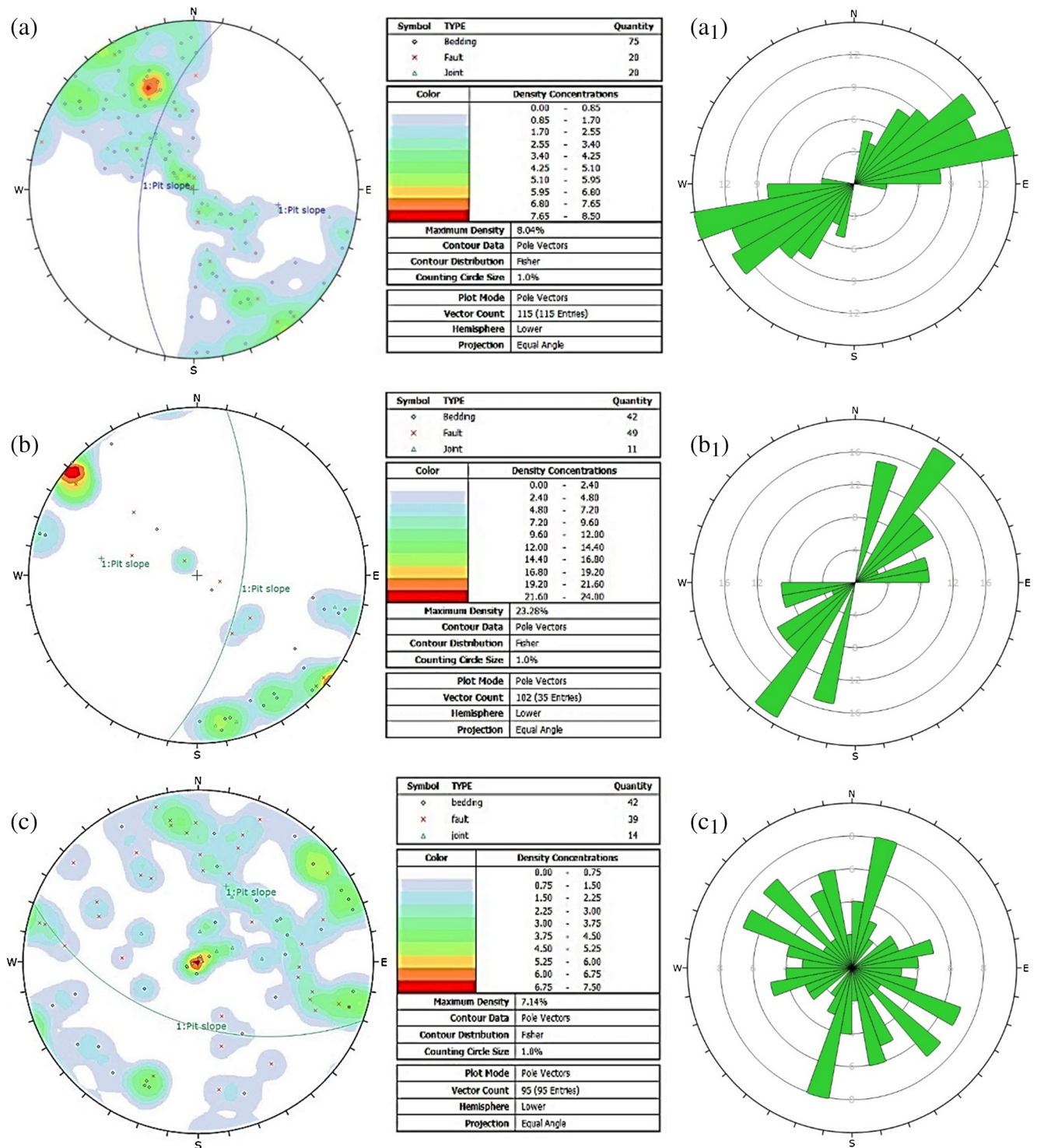**Fig. 2** Methodological flow chart for the kinematic tests

Fig. 3 Clustering analysis in east (a), west (b) and north (c) of KL, while the corresponding rosette models are presented in (a₁), (b₁), (c₁)

with gentle slopes to steep cliffs. The mean orientation data collected from all the sections with 55°, 60° and 60° as dip angles and 280°, 100° and 190° as dip directions are used in the kinematic analysis. Orientation of all the data is plotted in stereonet. This process enables the understanding of mean plane dip, dipping direction, global best-fit and overall maximum density and provides important information that describes the folded bedding planes (Fig 1). Matasci et al. (2015) stated that the fold axis orientation relatively coincides with the best-fit plane. The orientation of global best-fit plane is E–W and contains the bedding planes parallel to the pole vectors. This condition clearly defines that the area is possibly
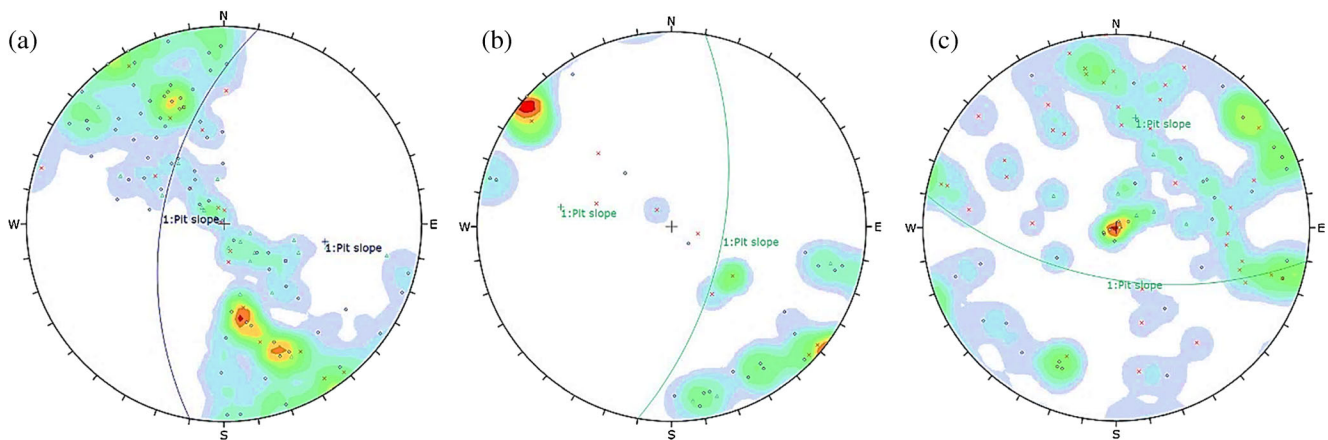
Fig. 4 Bias correction using Terzaghi weighting for the rock discontinuity data in east (**a**), west (**b**) and north (**c**) of KL

folded in the city region that is developing a synclinal structure. Fold analysis reveals the interconnection among the E, W and N parts of the hills. Geologically, hilly regions should be developed dipping towards the city according to their structural orientation characteristics.

Potential slope failures

The orientation pattern clustering of structural discontinuity planes indicates the area of concentration. These areas are highly susceptible to water inflow, which leads to weathering and erosion and thus rock failures (Kohlstedt 2006; Nassir et al. 2010). The favourability of oriented faces and slope failure types is the function of interrelationship between the slope dip directions and slope surface. Clustered poles of different types of discontinuity orientations allow for analysis and estimation of potential risk from planar sliding, flexure toppling and wedge sliding. Failure slopes, such as beddings, faults and joints, are difficult to identify. However, an appropriate evaluation of the mean dip angle on each section can provide information about the types of discontinuity. The general characteristics of data present the beddings, faults and joints in each section. However, the entire data are converted into sets without consideration of discontinuity type.

The percentage of potential risk and the spatial distribution of all susceptible discontinuity planes of the study area are presented in Figs. 5, 6 and 7. According to Goodman (1889), cones with 30° friction angle and slopes with 30° dip direction are generally used in kinematic analysis. Causal factors of 30° lateral plane angle and grid data planes are used for the analysis of planar and flexure toppling, and mean set planes are used for the analysis of wedge sliding. All the sections are under potential risk of slope failures. Different sections are divided into four, five and seven sets in the eastern, western and northern parts of the hills, respectively. The dip and dip direction of all the sets are well-presented in Table 2, in which highlighted sets provide information about

the critical discontinuity planes, which are susceptible to rock failures. Moreover, the critical discontinuity plane sets provide the corresponding dip and dip direction.

Planar failures are basic sliding of beds or rock layers in discontinuity planes. The potential risk of planar failures is well-designed through geological modelling and presented in Fig.5 for all the sections of the study area. However, all the hill sections are susceptible to planar sliding, with total risks of 4.35%, 0.98% and 5.26% over the entire discontinuity planes. Moreover, set 2 of east and northern hills is primarily favourable for planar sliding, with 38.46% and 55.56% on average. By contrast, western hilly regions are unfavourable for planar sliding. Kinematically, the poles of all discontinuity planes that plunge towards the southwest and southeast directions are frictionally unstable and present risks for agriculture lands and KL.

A remarkable potential risk of flexure toppling exists, especially in the western and northern parts of the city (Fig.6 with cliffs steeper than 60°. As shown in Fig. 6, the critical zones of toppling are defined on the basis of stereonet, slip and lateral limits. High risk of toppling can be observed from sets 3 and 4 of west and sets 6 and 7 of north, with the highest values of 89% and 83.33%, respectively. Potentially low risk can be observed from other sets of the study area, especially sets 3 and 6 of the western and northern parts. Moreover, an apparently low risk of toppling can be observed in the eastern part of the city.

The percentage of wedge failure is considerably lower than those of planar and toppling failures. As shown in Fig. 7, crescent-shaped areas are developed for determining the intersecting planes. The critical zone of intersecting planes can be found within the friction cone (30° from the stereonet perimeter). Moreover, the number of intersections represents the total risk for wedge sliding (Rocscience 2010). Therefore, the highest risk can be found in the western hilly regions of KL. According to our analysis, the most important and less number of wedges are formed in the western part of the city.
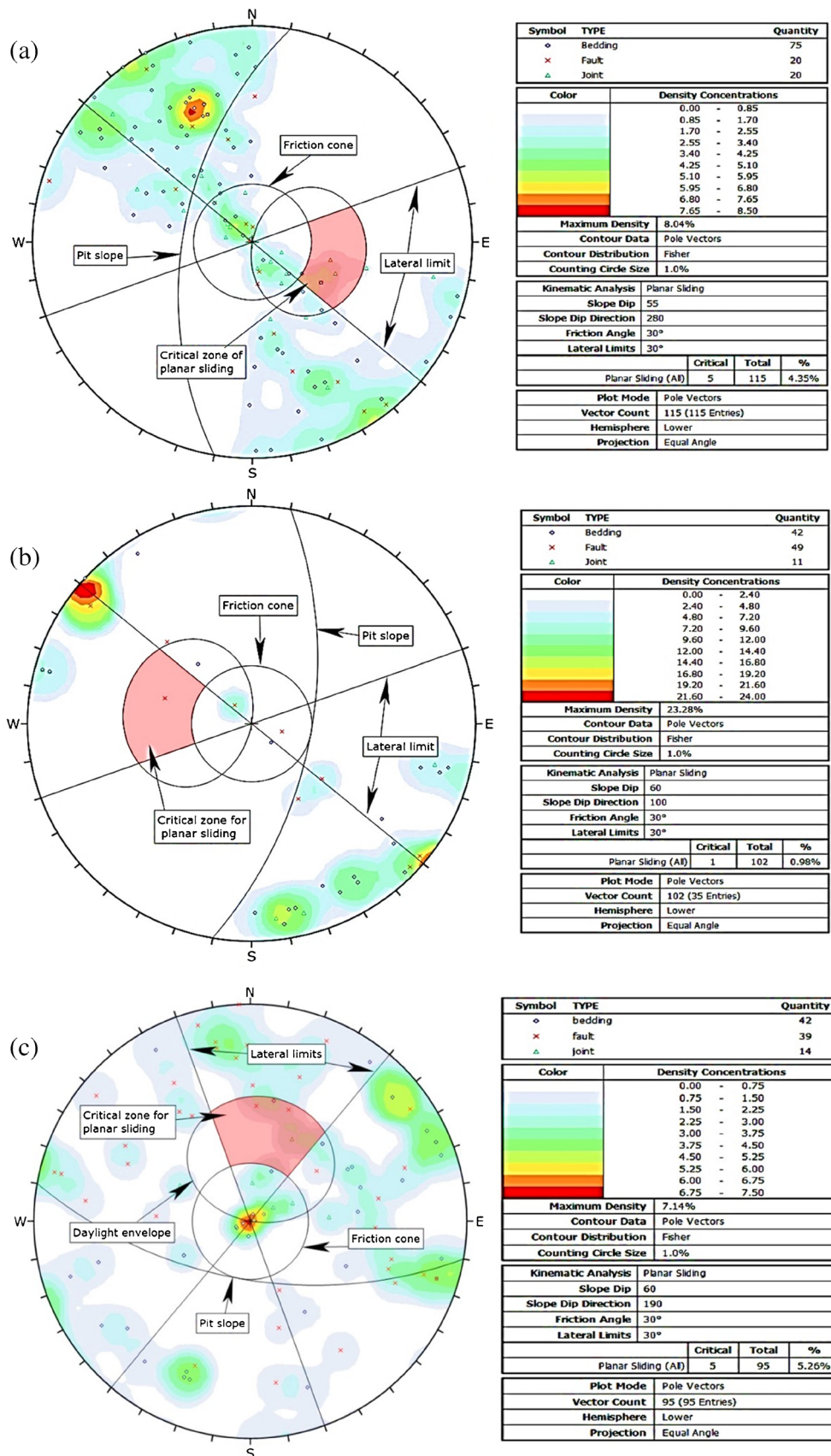
Fig. 5 Kinematic analysis for the planar sliding in east (**a**), west (**b**) and north (**c**) of KL
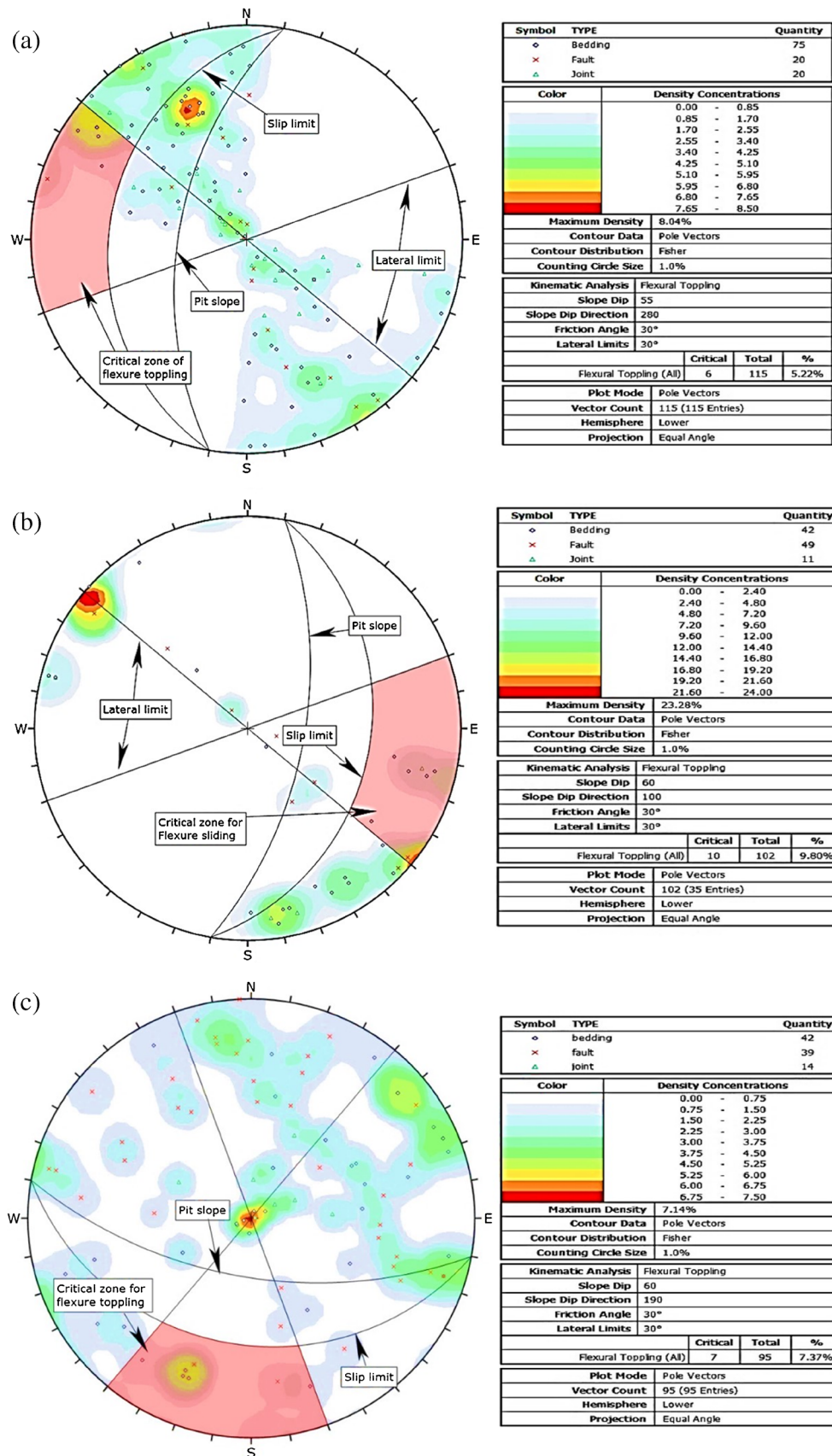
Fig. 6 Kinematic analysis for flexure toppling in east (**a**), west (**b**) and north (**c**) of KL
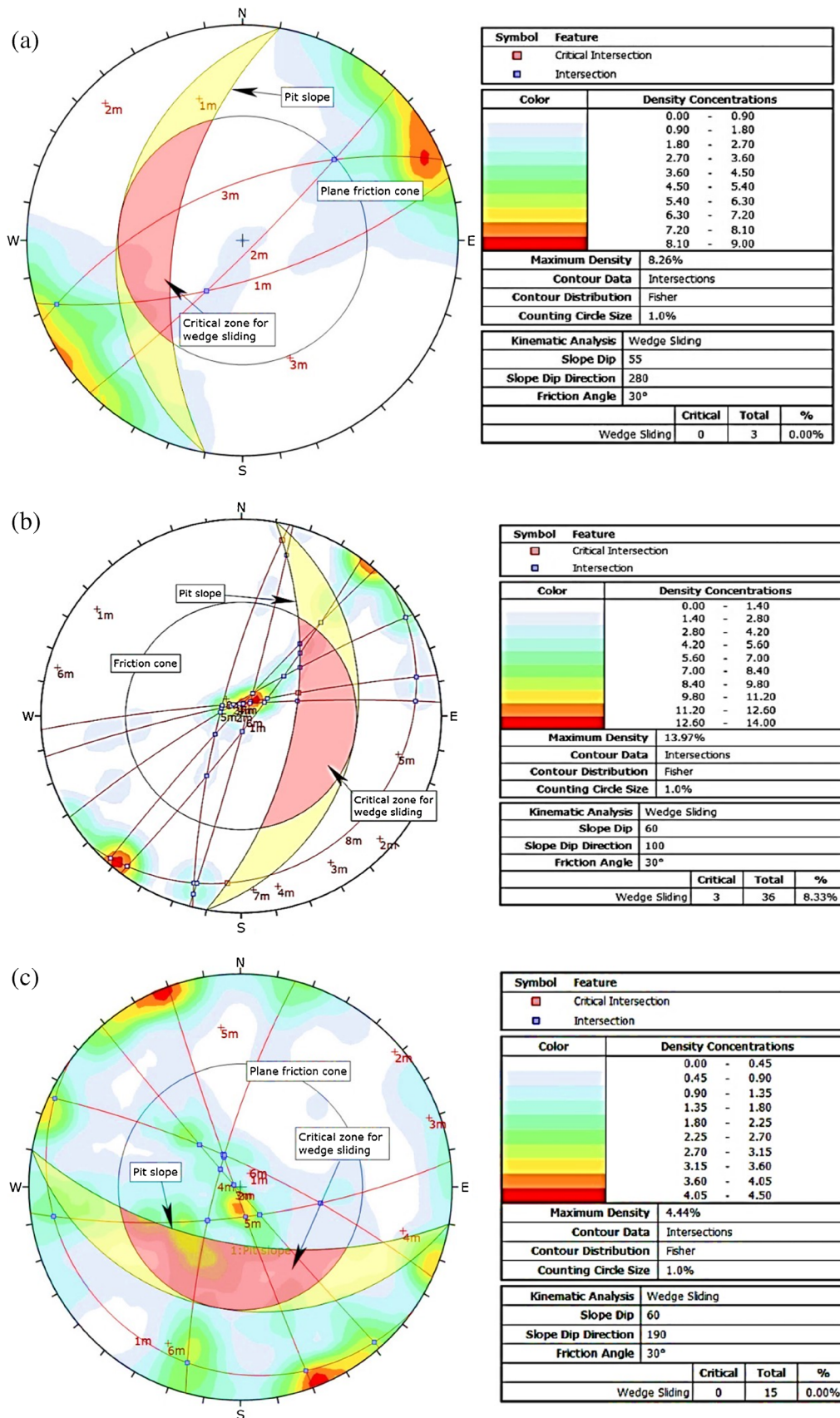
Fig. 7 Kinematic analysis for wedge sliding in east (**a**), west (**b**) and north (**c**) of KL

However, the use of mean set planes can outperform the result of intersection points. Therefore, the risk probability of western hills is 8.33%, which is absolutely less than that of other failures. Moreover, the eastern and northern hills are free from wedge sliding. The risk percentage from wedge failure is relatively small due to the slight intersection of discontinuity planes. Obviously, the discontinuity planes are mostly free from instability and have low risk.

The geological survey data of structural orientation provide valuable information for a good understanding of the structural instability and its influence on engineering structures. The complicated geo-tectonic settings of the study area indicate the basin-shaped structure in which KL is located, and the overall setting clarifies the effect of failure of unstable planes possibly on the city and agriculture lands with major destruction. This condition is because the data used in the study only contain the orientation of large structural discontinuity. The overall structure is possibly steered by strike and dip and is accelerated by compression. The percentage of risk may increase due to localized weathering, erosion and external factors, such as gravity, lithology, high relief and interconnected channels of water flow (Sacchini et al. 2016).

The geometric setup of structural discontinuity in KL, agricultural lands and engineering structures are influenced by the orientation and spatial distribution of major failures. Kinematic analysis of the three sections of the study area reveals the relative severity of slope failures, which project the highest risk and can thus result in major destructions. Regions with high risk of planar sliding are found in the eastern and northern regions, with 38.46% and 55.56%, respectively. Highest toppling probabilities (89% and 83.33%) are found in the western and northern regions of the city. All unstable planes are located under the steep slope faces with dip angles greater than 55° (Table 2). The output of this study is based on geological discontinuity orientation. However, other geological properties of rocks, such as persistence, shear strength, cracks and geological strength index, are not considered. The validation of the resulted model is conducted by using a hill shade map of KL City and its surroundings and the experienced landslides reported in the literature because the collected data are based on the extensive field survey of structural geologists. However, the kinematic analysis can be improved by the collection of a large quantity of data with various factors.

Details of the critical sets that create severe rock slope failures are shown in Table 2. A total of 311 orientation data of bedding planes, faults and joints are used for the kinematic analysis without consideration of the small discontinuity planes. Noticeably, the bedding planes from the data are higher than those of faults and joints, as presented in Table 2. Therefore, the kinematic tests indicate the number of poles located in the critical zone. However, the study reveals that the probability of wedge sliding is small in the western part of KL, and the other parts are totally free from wedge failure. This condition confirms that few discontinuity

planes are interconnected to create wedge-shaped structures. The details of the analysis and results are presented in Table 1.

Figure 8 shows the processed dip direction and the shape of the discontinuity planes. The bar diagrams are presented by using various colours for different sections. In the diagram, the critical processed dip directions are shown, and their corresponding dip angles are listed in Table 2. The quantitative analysis provides the shape of the surface of the discontinuity planes, which are clearly presented using the bar diagram. This condition reveals important information that more planar surfaces than undulated and stepped ones are found in the study area. Therefore, the probability of most of the failures possibly occur in planar surfaces than in stepped and undulated surfaces because other shapes of discontinuity increase the frictional forces. Moreover, all the critical discontinuity planes must have planar surfaces.

Validation

Geo-structural slope failures should be precisely estimated. In our study, the obtained results are validated for supporting the risk calculated from various types of slope failures. However, our study is totally based on the orientation data of discontinuity. Therefore, other parameters that influence rock failure are not covered. In the validation, the information of historical slope failures and landslides experienced in the regions of KL is collected. Generally, a map is constructed as shown in Fig.9 by using a hillshade map of the study area with all historical landslides and our obtained results of various rock failures. The blue boxes in the map are the areas of data collection, and the red circles represent the influenced areas of historical landslides. The validation shows that the obtained results are correct. Moreover, the results can be improved by use of integrated GIS techniques and consideration of additional parameters and factors. This study provides fundamental knowledge about slope failures and can be used as a basis for landscape management. Meanwhile, details of historical landslides can be found in several studies, historical news bulletins and geological surveys of Malaysia.

Table 1   Degree of potential risk obtained from the kinematic tests

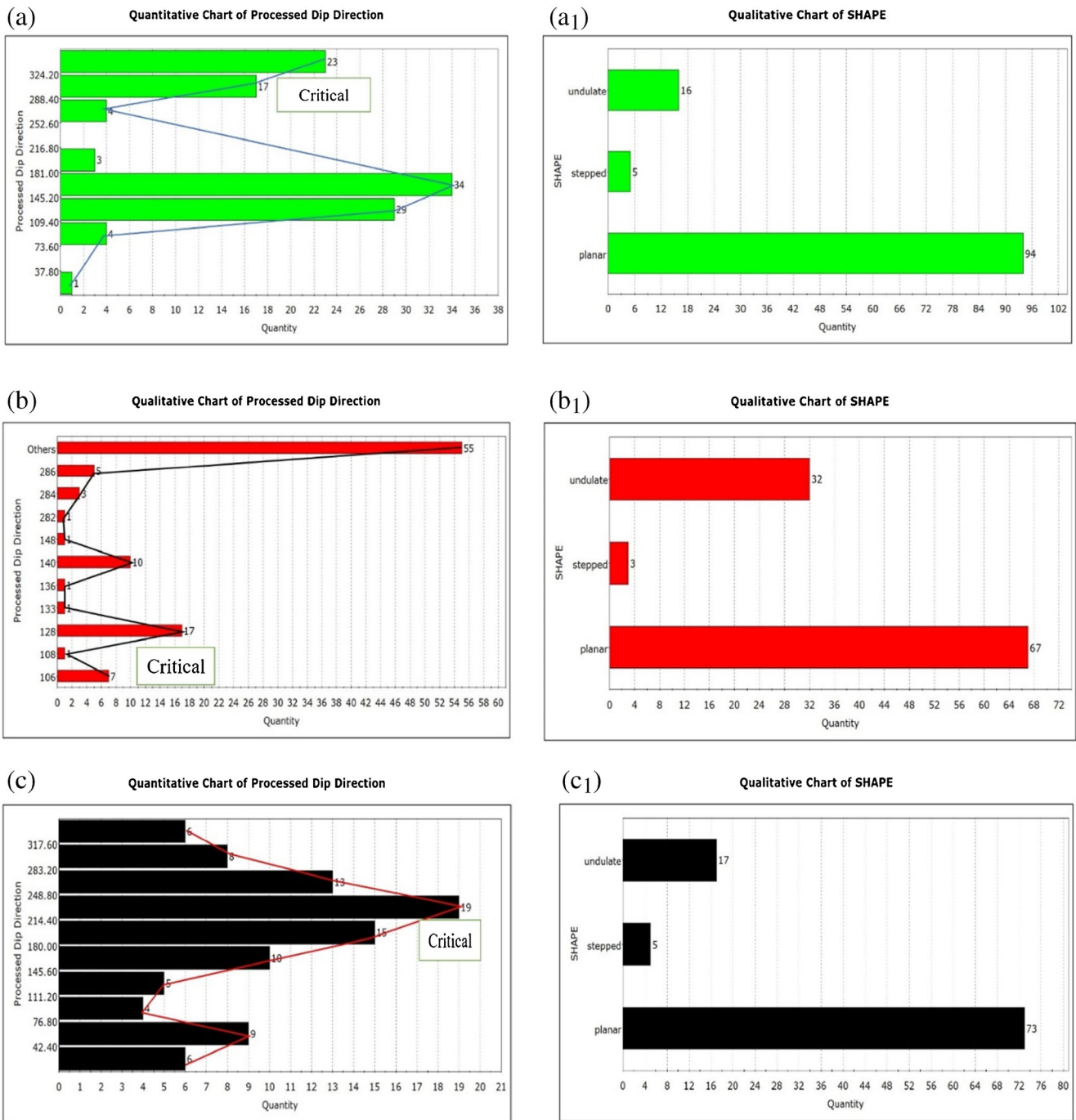| Study area	Degree of potential risk (%)		
	Planar sliding	Flexure toppling	Wedge sliding
East of KL	Total 4.35 Set(2) 38.46	Total 5.22	0
West of KL	Total 0.98	Total 9.80 Set(3) 6.90 Set(4) 89	8.33
North of KL	Total 5.26 Set(2) 55.56	Total 7.37 Set (6) 9.09 Set (7) 83.33	0

Fig. 8 Quantitative charts of critical dip direction east (a), west (b) and north (c) and shape of the surfaces in east (a$_1$), west (b$_1$) and north (c$_1$) of KL, respectively

Conclusion

Orientation data of structural discontinuity planes enabled the measurement of slope failures and rock deformation and evaluation of their impact on the surrounding infrastructures and stability of forests. The increasing trend of geological data usage for various geological and natural hazard surveys motivated us to conduct a broad scientific analysis of slope failures. This method is an interesting approach for structural characterization in terms of processing and efficiency, does not encounter considerable issues given a large amount of available data and overcomes the resolution issues in remote sensing and other techniques. Details of mean plane and global best fit allowed for an understanding of the overall outcrop of the entire region. Clustering analysis with Rosette model for strikes presented the details of pole clustering with
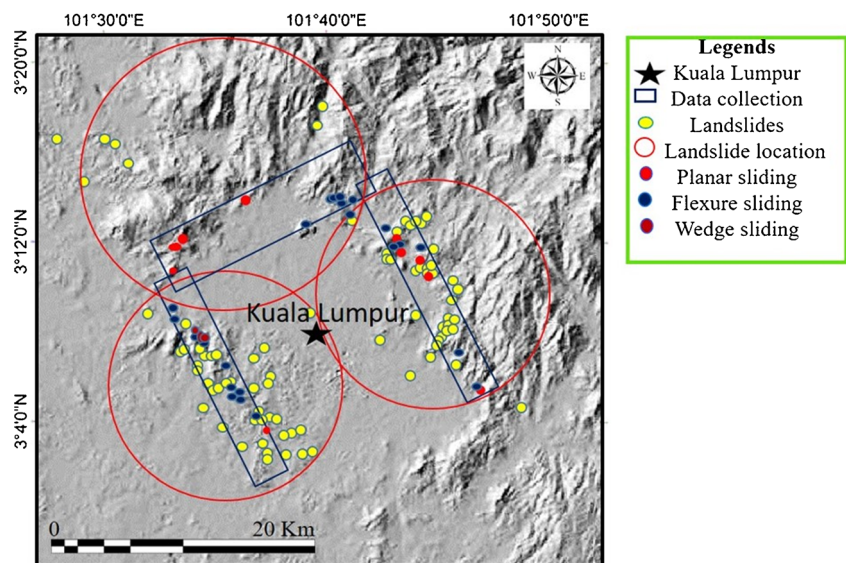
Table 2   Critical sets and their orientation including the data set

Study area	Sets (critical)	Dip (°)	Dip direction	Total data
East of KL	S(1)	6–45	SE	Bedding planes (75)
	S(2)	55–60	W	Faults (20)
	S(3)	60–70	NE	Joints (20)
	S(4)	70–80	NW	
West of KL	S(1)	68–74	N	Bedding planes (42)
	S(2)	50–58	SE	Faults (49)
	S(3)	58–65	SE	Joints (11)
	S(4)	65–70	NW	
	S(5)	70–80	SW	
North of KL	S(1)	4–28	NE	Bedding planes (42)
	S(2)	52–70	SW	Faults (39)
	S(3–5)	72–86	NW	Joints (13)
	S(6, 7)	86–90	SE	

maximum density and the overall trend of all discontinuity planes. Kinematic analysis revealed the mechanism of slope failures by indicating the spatial distribution of discontinuity and unstable direction, including the probability of failures. No inland water flow properties and rock mass composition were obtained in this study. Therefore, geologists and GIS specialists can verify the probability of rock failures detected in the study by conducting field surveys and acquiring satellite imagery. Combination of various data, including major and minor factors, enables measurement of failure magnitude and its effect on surrounding infrastructures. An important future research prospect is surface depression due to tectonic stress or penetration of tree roots, which creates cracks and thus may influence rock failure. Kinematic stability analysis is critical for the survival of important structures, agricultural lands and forests. For the safety of people near probable slope failure regions, the Government of Malaysia should implement risk prevention strategies. Given that KL is a well-developed city, tourists from all over the world visit the tourist places in these hills. Therefore, proper actions against the potential disasters in their large, steep slopes are required for safety. Effective steps must be implemented for protecting the hills and forests, thereby guaranteeing safety. The limitation of the study involves collecting the accurate strike and dip direction information of rocks; however, data collection through fieldwork is time consuming. Moreover, we did not employ any triggering factors such as rainfall intensity, pour pressure and rock quality in this study. Improvements in the slope failure analysis could be performed by employing novel models and by considering all the conditioning and triggering factors. Therefore, future studies could focus on earthquake-induced and rainfall-induced slope failure analysis using the LiDAR cloud points and satellite images by considering all the triggering factors and implementing the deep learning techniques.

Fig. 9 Validation of the results with historical landslides

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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