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Development of Kinematic Criterion for Undercutting Induce Rock Failures

Luqman Ahmed[a]*, Mian Sohail Akram[a]

[a]*Institue of Geology, University of the Punjab, Quaid-e-Azam Campus, Lahore 54590, Pakistan*

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Abstract

The interlayered soft and hard rocks exhibit difference in weathering rate. This differential weathering leads to various failure modes such as rockfall, rock-slides, plane fall/slide and wedge fall/slide in upper lying hard units, which is eventually induced by the erosion of the underlying weaker lithologies. However, the geometry and orientation of joints in hard rock play an essential role in causing these failures that were not reported previously. The current research focuses on developing a kinematic criterion for these undercutting-induced rock slope failures. In this study, the discontinuity data were gathered from the thirteen cut slopes along the Islamabad-Muzaffarabad Dual carriageway, Pakistan, where the rocks of Murree Formation of Miocene age are exposed. The discontinuity data was analysed in the DIPS software that indicated the three orthogonal joints along the slopes with the bedding of the rock unit dipping into the hill. The horizontal and into the slope orientation of the major joint is generally considered favourable; however, the field evidence is depicted otherwise in the interlayered lithologies. The results of this research showed that the undercutting is more pronounced along gentler bedding joints either into or out of the slope; on the other hand, it has less effect on the slope where the strike is across the hill, dipping on either side at steep to very steep angles.

1. Introduction

The interlayered lithologies are typical in sedimentary origin rocks, resulting from transgression and regression processes (Blatt, 1982; Crook, 1960; J.A. Franklin & Chandra, 1972; Potter et al., 1980; Wood & Deo, 1975). These rocks are commonly present all around the globe and have been reported by Akram et al. (2018); Cano & Tomás (2013); Hussain et al. (2015); Miščević & Vlastelica (2014); Shakoor &

* Corresponding author
E-mail address: luqman.phd.geo@pu.edu.pk

Weber (1988); and Zhang et al. (2016). Undercutting due to differential weathering is frequently observed in these rocks (Admassu et al., 2012; Admassu & Shakoor, 2013; Gautam & Shakoor, 2016; Niemann, 2009; Shakoor, 1995; Shakoor & Weber, 1988). The soft blocks of rock such as of shale, claystone, mudstone are more susceptible to weathering and erode at higher rates than the hard lithologies such as of sandstone, siltstone and silt-shale (Dick et al., 1994; Z.A. Erguler & Shakoor, 2009; J.A. Franklin & Chandra, 1972; Heidari et al., 2018; Koncagül & Santi, 1999; Selen et al., 2020). This differential weathering shape overhangs in the upper lying hard lithologies (Shakoor & Rodgers, 1992). The lower-lying soft lithologies stop supporting them due to the higher erosion rate. Hence, it speeds up the movements of planes and wedges, which eventually changes into the falling and sliding mode of blocks. Shakoor & Weber (1988) initially reported such types of rockfall and slide failures. Similarly, the crack initiation in the upper competent block and depth of undercutting is discussed in detail by (Zhang et al., 2016).

The differential weathering is always associated with the slaking nature of rocks, and at a laboratory scale, the slaking nature of rocks is assessed by the slake durability test (ASTM, 2008, 2016; Zeynal Abiddin Erguler & Shakoor, 2009; John A Franklin & Chandra, 1972). However, various tests, such as the jar slake test (Santi, 1998) and the nail penetration test (Özdemir & Erguler, 2021), are used for these lithologies in the field (Zeynal Abiddin Erguler & Shakoor, 2009). Similarly, the methodology to design the ditch to limit the rock falling mode induced in these slopes is discussed by Admassu (2010); Admassu et al. (2012); Admassu & Shakoor (2013). Despite the extensive studies carried out in the line to restrict these undercutting induced failures, however, in the light of kinematic analyses, the failures are not available in the literature. The other kinematic criterion for different failure modes, such as the plane, wedge, and topple, are reported in the literature (Hudson & Harrison, 2000; Wyllie & Mah, 2014). The kinematic criterion for plane failures along slopes is defined as the failure is likely along slopes where one of the joint strike parallel or sub-parallel to the slope face. The dip direction of the failure plane is gentler than that of the slope face. In addition, the friction angle of the rock must be smaller than the dip of the failure plane.

Similarly, the Markland test is commonly used for wedge failures (Markland, 1972, 1974). According to the test, the criterion for the wedge failure along slopes is explained as follows: a wedge should be formed by the two intersecting joints that should daylight on the slope face and marked by the line of intersection. The strike of the line of intersection of two joints must be parallel to the strike of the slope face joint. The dip of the line of intersection should be greater than the friction angle. Lastly, the kinematic criterion for toppling failure is defined as the toppling failure is likely along the slope if the dip direction of the joint plane is parallel or sub-parallel to the dip direction of the slope face. The other joints must dip at steep or very steep angles dipping into the slope. There should be another joint set that defines the height of the block. The most convenient way to study these rock failures along slopes is by drawing the great circles on the stereo nets (Goodman & Shi, 1985; Lisle & Leyshon, 2004). It should be noted that these kinematic criteria are for the slopes where one rock unit is exposed and are not likely to define the failures in interlayered lithologies especially comprising hard and soft lithologies side by side. This study aims to develop a kinematic criterion for undercutting induced failures and identify the region of major rock failure induced by its geometry. In the present research, a similar method of stereographic projection techniques is utilized to define the limits of the undercutting induced rock failures.

2. Geology of the Study Area

This study is carried out along the cut slopes of Islamabad Muzaffarabad Dual Carriageway (IMDC), Pakistan, where the rocks of the Murree Formation of the Miocene age comprise interlayered sandstone /siltstone /silt-shale and shale/ mudstone/ claystone are exposed (Akram et al., 2018; Iqbal & Shah, 1980; Kazmi & Jan, 1997; Shah, 1977) (Figure1). According to the regional geological map of the study area, the sequence of synclines and anticlines are present in the area trending in the northeast-southwest. The competent rocks comprise sandstone, siltstone, and silty shale, while incompetent units are shale, mudstone, and claystone. The competent rocks are massive to blocky, while incompetent rocks are thinly bedded to laminated. The sandstone of purple to greyish brown with subordinates beds of reddish-brown siltstone, mudstone, and claystone. The Murree Formation is comprised of a monotonous sequence of dark red and purple clay and purple grey and greenish-grey sandstone. The name Murree Formation is designated to the rocks of Mari Group of Wynne (1874), and Murre Series of Pilgrim (1910). The upper contact of Murree Formation is with Kamlial Foramtion which is transitional, while the lower contact is unconformable. The slaking nature of various rocks units of the formation is variable.

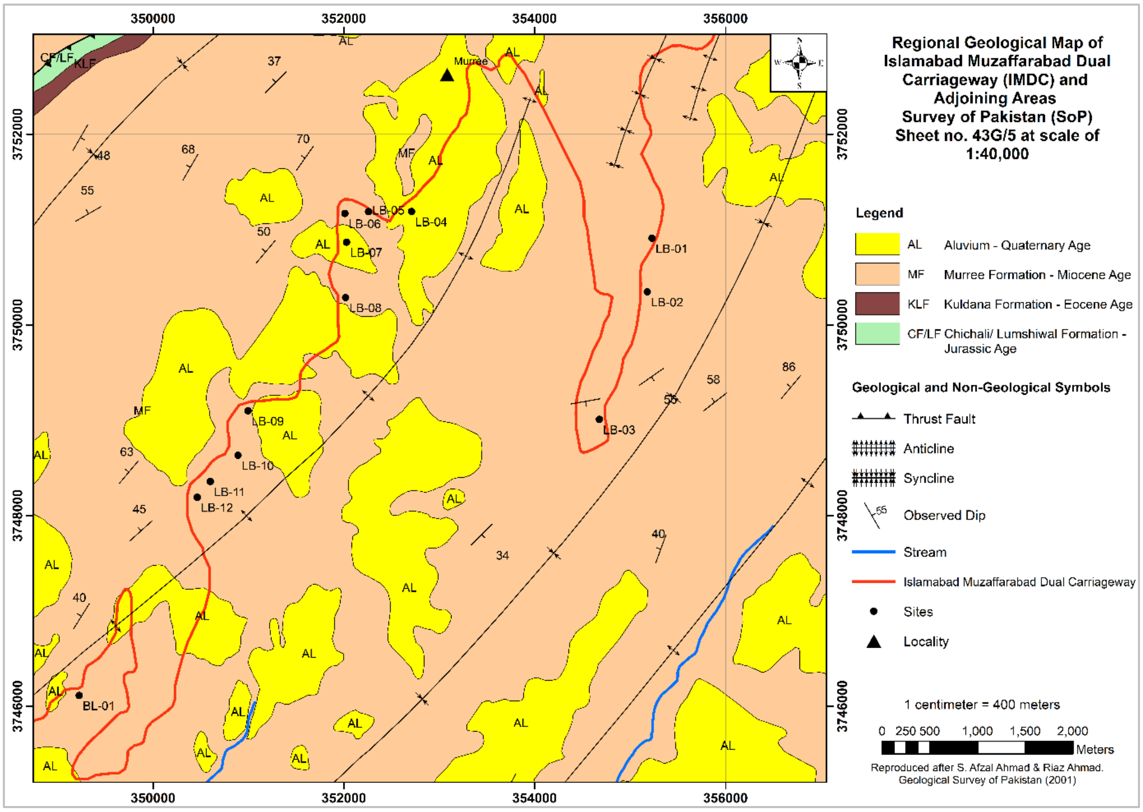

Fig. 1. The geological map of the study area (reproduced after Ahmad & Ahmad 2001).

3. Methodology

The methodology adopted for the current research comprises collecting the field orientation data from various cut slopes using the window and scan line sampling techniques (Cawood et al., 2017; Delaney et al., 2019; Fisher et al., 2014; Piteau & Martin, 1977; Wyllie & Mah, 2004) and collecting samples for friction angle tests. In the field, it is observed that the sub-horizontal to horizontal bedding joint is dipping into the hill throughout the project area with a change in the strike. The sandstone and siltstone are massive to blocky, while shale is thinly bedded to laminated. In addition, the likely state of failure mode was also recorded in the field performa. In the laboratory, the friction angles were determined by tiltmeter test (Alejano et al., 2018; Pérez-Rey et al., 2016). The average friction angle of sandstone and siltstone is 30º with a range from 29º to 31º, whereas the average friction angle of claystone is found to be 25.5º with a range from 24º to 27º. The Rocscience suite DIPS were used for the interpretation of respective failure modes in the slopes. Akram et al. (2018) previously reported these failure modes with conventional kinematic for plane, wedge and toppling for similar sites. The primary modes of failure were plane and wedge along the slopes, and the toppling mode of failure is absent in the slope. In the light of the field data and observations, laboratory testing and detailed failure results, the kinematic criterion was proposed for the undercutting induce rock failures.

4. Development of Kinematic Criterion

The kinematic criterion was developed based on the field orientation data plotted on the lower hemisphere stereo-net with a fixed and normalized steep slope face of 70º. The orientation data of every window were rotated to this fixed slope face, and the poles of the joints were marked as per the poles plotting on the stereo-nets. The modes of failure observed in the field were used to designate the zone of likely failure on the stereo-net. Based on the analyses, three zones were identified for undercutting induced rock failures (Figure 2). It was observed that the undercutting is more pronounced along gentler bedding joints either into or out of the slope; on the other hand, it has less effect on the slope where the strike is across the hill, dipping on either side at steep to very steep angles. It should be noted that the kinematic criterion is developed for the interlayered lithologies and should be used with precaution for other lithologies.

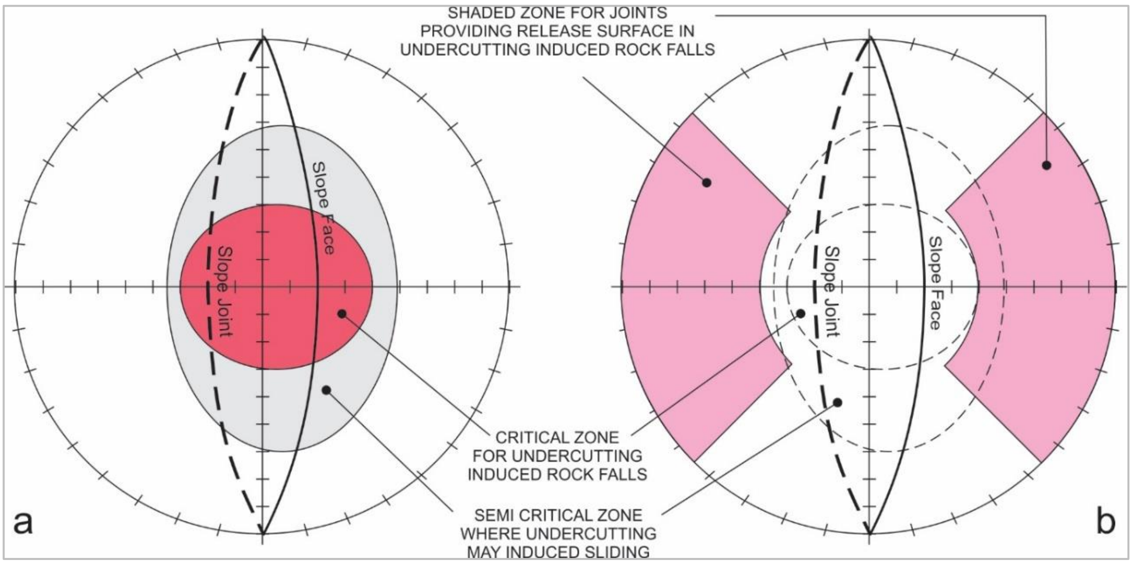

Fig. 2. The proposed criterion for undercutting induced rock failures.

5. Conclusions

The present research was carried out for the development of a kinematic criterion for undercutting induced rock failures that were not identified in the conventional kinematic criterion for plane, wedge and toppling. The kinematic criterion is developed on the lower hemisphere equal area equatorial stereo-net. These three zones can be explained as;

(1) The undercutting-induced rock fall's critical zone covers the centre of the stereo-net (marked with red colour in Figure 2).
(2) The Semi-critical zone surrounding the critical zone is in an oval shape, and the likely mode of failure is undercutting indue sliding (marked with grey colour in Figure 2).
(3) Shaded zone for joints that provide release surface in undercutting induce rockfalls (marked with pink colour in Figure 2).

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References

Admassu, Y. (2010). Developing design methodology for cut slopes in Ohio. August, 618.

Admassu, Y., & Shakoor, A. (2013). Cut Slope Design Recommendations for Sub-Horizontal Hard Sedimentary Rock Units in Ohio, USA. Geotechnical and Geological Engineering, 31(4), 1207–1219. https://doi.org/10.1007/s10706-013-9644-4

Admassu, Y., Shakoor, A., & Wells, N. A. (2012). Evaluating selected factors affecting the depth of undercutting in rocks subject to differential weathering. Engineering Geology, 124, 1–11.

Ahmad, S. A., & Ahmad, R. (2001). Geological Map of Murree Quadrangle Rawalpindi District Punjab and a part of Abbottabad District N.W.F.P. Pakistan [sheet 43 G/5 1:50,000]. Geological Survey of Pakistan.

Akram, M. S., Ahmed, L., Farooq, S., Ahad, M. A., Zaidi, S. M. H., Khan, M., & Azhar, M. U. (2018). Geotechnical evaluation of rock cut slopes using basic Rock Mass Rating (RMR basic), Slope Mass Rating (SMR) and Kinematic Analysis along Islamabad Muzaffarabad Dual Carriageway (IMDC), Pakistan. Journal of Biodiversity and Environmental Sciences, 13(1), 297–306.

Alejano, L. R., Muralha, J., Ulusay, R., Li, C. C., Pérez-Rey, I., Karakul, H., Chryssanthakis, P., & Aydan, Ö. (2018). ISRM suggested method for determining the basic friction angle of planar rock surfaces by means of tilt tests. Rock Mechanics and Rock Engineering, 51(12), 3853–3859.

ASTM. (2008). Standard Test Methods for Slake Durability of Shales and Similar Weak Rocks (D4644-08). In Annual Book of ASTM Standards (Vol. 4, pp. 880–882).

ASTM. (2016). Standard Test Method for Slake Durability of Shales and Other Similar Weak Rocks (D4644-16).

Blatt, H. (1982). Sedimentary petrology. W.H. Freeman,San Francisco, CA.

Cano, M., & Tomás, R. (2013). Characterization of the instability mechanisms affecting slopes on carbonatic Flysch: Alicante (SE Spain), case study. Engineering Geology, 156, 68–91.

Cawood, A. J., Bond, C. E., Howell, J. A., Butler, R. W. H., & Totake, Y. (2017). LiDAR, UAV or compass-clinometer? Accuracy, coverage and the effects on structural models. Journal of Structural Geology, 98, 67–82.

Crook, K. A. W. (1960). Classification of arenites. American Journal of Science, 258(6), 419–428.

Delaney, R., Shakoor, A., & Watts, C. F. (2019). Comparing Unmanned Aerial Vehicle (UAV), Terrestrial LiDAR, and Brunton Compass Methods for Discontinuity Data Collection. IAEG/AEG Annual Meeting Proceedings, San Francisco, California, 2018-Volume 1, 267–273.

Dick, J. C., Shakoor, A., & Wells, N. A. (1994). A geological approach toward developing a mudrock-durability classification system. Canadian Geotechnical Journal, 31(1), 17–27. https://doi.org/10.1139/t94-003

Erguler, Z.A., & Shakoor, A. (2009). Quantification of Fragment Size Distribution of Clay-Bearing Rocks after Slake Durability Testing. Environmental and Engineering Geoscience, 15(2), 81–89. https://doi.org/10.2113/gseegeosci.15.2.81

Erguler, Zeynal Abiddin, & Shakoor, A. (2009). Quantification of fragment size distribution of clay-bearing rocks after slake durability testing. Environmental and Engineering Geoscience, 15(2), 81–89. https://doi.org/10.2113/gseegeosci.15.2.81

Fisher, J. E., Shakoor, A., & Watts, C. F. (2014). Comparing discontinuity orientation data collected by terrestrial LiDAR and transit compass methods. Engineering Geology, 181, 78–92.

Franklin, J.A., & Chandra, R. (1972). The slake-durability test. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 9(3), 325–328. https://doi.org/10.1016/0148-9062(72)90001-0

Franklin, John A, & Chandra, R. (1972). The slake-durability test. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 9(3), 325–328.

Gautam, T. P., & Shakoor, A. (2016). Comparing the Slaking of Clay-Bearing Rocks Under Laboratory Conditions to Slaking Under Natural Climatic Conditions. Rock Mechanics and Rock Engineering, 49(1), 19–31. https://doi.org/10.1007/s00603-015-0729-7

Goodman, R. E., & Shi, G. (1985). Block theory and its application to rock engineering.

Heidari, M., Momeni, A., & Mohebbi, Y. (2018). Durability Assessment of Clay-Bearing Soft Rocks By Using New Decay Index. Periodica Polytechnica Civil Engineering. https://doi.org/10.3311/PPci.11284

Hudson, J. A., & Harrison, J. P. (2000). Engineering rock mechanics: an introduction to the principles. Elsevier.

Hussain, G., Singh, Y., & Bhat, G. M. (2015). Geotechnical Investigation of Slopes along the National Highway (NH-1D) from Kargil to Leh, Jammu and Kashmir (India). Geomaterials, 05(02), 56–67. https://doi.org/10.4236/gm.2015.52006

Iqbal, M. W. A., & Shah, S. M. I. (1980). A guide to the stratigraphy of Pakistan (Vol. 53). Geological Survey of Pakistan.

Kazmi, A. H., & Jan, M. Q. (1997). Geology and tectonics of Pakistan. Graphic Publishers.

Koncagül, E. C., & Santi, P. M. (1999). Predicting the unconfined compressive strength of the Breathitt shale using slake durability, Shore hardness and rock structural properties. International Journal of Rock Mechanics and Mining Sciences, 36(2), 139–153. https://doi.org/10.1016/S0148-9062(98)00174-0

Lisle, R. J., & Leyshon, P. R. (2004). Stereographic projection techniques for geologists and civil engineers. Cambridge University Press.

Markland, J. T. (1972). A useful technique for estimating the stability of rock slopes when the rigid wedge slide type of failure is expected. Interdepartmental Rock Mechanics Project, Imperial College of Science.

Markland, J. T. (1974). The analysis of principal components of orientation data. International Journal of Rock Mechanics and Mining Sciences And, 11(5), 157–163. https://doi.org/10.1016/0148-9062(74)90882-1

Miščević, P., & Vlastelica, G. (2014). Impact of weathering on slope stability in soft rock mass. Journal of Rock Mechanics and Geotechnical Engineering, 6(3), 240–250. https://doi.org/10.1016/j.jrmge.2014.03.006

Niemann, W. L. (2009). Lessons learned from rates of mudrock undercutting measured over two time periods. Environmental and Engineering Geoscience, 15(3), 117–131. https://doi.org/10.2113/gseegeosci.15.3.117

Özdemir, S., & Erguler, Z. (2021). Investigation of the slaking behavior of weak geological units in terms of undercutting rate. Bulletin Of The Mineral Research and Exploration, 1–22. https://doi.org/10.19111/bulletinofmre.898013

Pérez-Rey, I., Alejano, L. R., Arzúa, J., & Muralha, J. (2016). The role of tilting rate and wear of surfaces on basic friction angle testing. Rock Mechanics and Rock Engineering: From the Past to the Future–Ulusay et Al (Eds) Taylor and Francis, London, 235–240.

Pilgrim, G. E. (1910). Notices of new mammalian genera and species from the Tertiaries of India. Records of the Geological Survey of India, 40, 63–71.

Piteau, D. R., & Martin, D. C. (1977). Description of detailed line engineering mapping method: Rock Slope Engineering. Part G, Federal Highway Administration, Reference Manual FHWA-13-97-208, Portland, Oregon, 29p.

Potter, P. E., Maynard, J. B., & Pryor, W. A. (1980). Sedimentology of Shale. In Springer-Verlag, New York. Springer.

Santi, P. M. (1998). Improving the Jar Slake, Slake Index, and Slake Durability Tests for Shales. Environmental & Engineering Geoscience, IV(3), 385–396. https://doi.org/10.2113/gseegeosci.IV.3.385

Selen, L., Panthi, K. K., & Vistnes, G. (2020). An analysis on the slaking and disintegration extent of weak rock mass of the water tunnels for hydropower project using modified slake durability test. Bulletin of Engineering Geology and the Environment, 79(4), 1919–1937. https://doi.org/10.1007/s10064-019-01656-2

Shah, S. M. I. (1977). Stratigraphy of Pakistan. Geol. Surv. Pakistan Rec., 12.

Shakoor, A. (1995). Slope stability considerations in differentially weathered mudrocks. Reviews in Engineering Geology, 10(1), 131–138. http://reg.gsapubs.org/lookup/doi/10.1130/REG10-p131%0Apapers3://publication/doi/10.1130/REG10-p131

Shakoor, A., & Rodgers, J. P. (1992). Predicting the rate of shale undercutting along highway cuts. Bulletin of the Association of Engineering Geologists, 29(1), 61–75.

Shakoor, A., & Weber, Mi. W. (1988). Role of shale undercutting in promoting rock falls and wedge failures along Interstate 77. Bulletin of the Association of Engineering Geologists, 25(2), 219–234.

Wood, L. E., & Deo, P. (1975). A Suggested System for Classifying Shale Materials for Embankments.

Wyllie, D. C., & Mah, C. (2004). Rock slope engineering. CRC Press.

Wyllie, D. C., & Mah, C. (2014). Rock slope engineering. CRC Press.

Wynne A B. (1874). Notes from the progress of report on the geology of parts of upper Punjab.,. Indian Geol Surv. Recs.

Zhang, K., Tan, P., Ma, G., & Cao, P. (2016). Modeling of the progressive failure of an overhang slope subject to differential weathering in Three Gorges Reservoir, China. Landslides, 13(5), 1303–1313.