Kinematic Analyses of Different Types of Rock Slope Failures in a Typical Limestone Quarry in Nigeria

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Abstract
Kinematic analyses of planar discontinuity sets in a limestone deposit in Western Nigeria were carried out to ascertain the degree of slope stability. Discontinuity orientations in the rock mass were mapped using compass clinometers. Kinematic analyses of the discontinuities were carried out using DIPS software. The results of the investigation revealed evidence of potential slope failures from the two joint sets identified in the study area. From the result of the analyses, face 1 of the limestone quarry is susceptible to both plane and wedge failures as all the geometrical conditions associated with the occurrence of such failures were noticeable. However there was no indication of any toppling failure from the analyses. Face 2 of the limestone quarry is not susceptible to wedge failure, but some part of it (40%), faces the risk of plane failure while up to 50% of it faces the risk of toppling failure. It can be concluded that analyses of discontinuity orientation in relation to cut face direction in rock excavation is essential for mine planning to forestall mine accidents.

Keywords: Discontinuity, orientation, limestone, slope failure

INTRODUCTION
With the usage of rock materials being significant in the various engineering applications and the need for increased production, a more effective approach is needed to solve its exploitation problems. The safe condition of working environment for both mine workers and the equipment of any mining industry should be a paramount concern of all the stakeholders of the industry, hence, the need to critically investigate from time to time the problems that may be associated with the exploitation of the deposit with a view to proffering solutions. Slope stability investigation in mines is critical to the profitability of the mines in relation to slope failures. Kinematic analysis is one of the analytical methods used for the investigation.

“Kinematics” refers to the motion of bodies without reference to the forces that cause them to move (Goodman, 1989). Many rock cuts are stable on steep slopes even though they contain steeply inclined planes of weakness with exceedingly low strength; that happens when there is no freedom for a block to move along the weak surface because other ledges of intact rock are in the way. Should the blockage be removed by erosion, excavation, or growth of cracks, the slope would fail immediately. This deals with an approach to slope design making use mainly of the directionality of the discontinuous rock mass to insure that there is always rock “in the way” of potentially failure blocks. Only minimal reference made to the strength parameters of the rock for the principal considerations are the orientations of the planar weaknesses in relation to the orientation of the excavation.

In the determination of mean orientation of planar discontinuities, each structural domain is characterized by a single stereonet displaying the mean orientation of set. During data acquisition, the orientation of the sampled areas has to be noted, because contouring procedures can bias the fracture density sampling. It is possible for data sampled along a scanline to be biased since the discontinuity frequency is dependent on the angle between the discontinuity set and the scanline. The density point of the stereonet can be corrected using Terzaghi correction (Terzaghi, 1965; Priest, 1993). Mean number of traces in a sampling window is usually difficult to obtain because third dimension of the structure is not easily accessible, hence, surface observations are the only obtainable data. Trace lengths may be estimated from a sampling window by dividing the total length of the traces that appear in the window by the number of contained traces. Discontinuity spacing is the perpendicular distance between adjacent discontinuities and is usually expressed as the mean spacing of a particular set of joints. The spacing of discontinuities determines the sizes of the blocks making up the rock mass. The mechanism of deformation and failure can vary with the ratio of discontinuity spacing to excavation size.
Engineering properties such as cavability, fragmentation characteristics and rock mass permeability also vary with discontinuity spacing. It is to be expected that, like all other characteristics of a given rock mass, discontinuity spacing will not have uniquely defined values but, rather, will take a range of values, possibly according to some form of statistical distribution. Priest and Hudson (1976) made measurements on a number of sedimentary rock masses in the United Kingdom and found that, in each case, the discontinuity spacing histogram gave a probability density distribution that could be approximated by the negative exponential distribution. Thus the frequency, \( f(x) \), of a given discontinuity spacing value, \( x \), is given by the function:

\[
\begin{align*}
  f(x) &= \lambda e^{-\lambda x} \\
  \text{Eq. 1}
\end{align*}
\]

Methods for Sampling the Geometrical Characteristics of Discontinuities

Mining condition vary widely from mine to mine, therefore stability problems must be handled with care since rock is a discontinuous material, non-homogeneous and strength parameters of the rock massif are very variable (Olaleye 2009). The geometrical characteristics of discontinuities, such as spacing, trace length, means and distributions can be determined by several methods yielding more or less detailed information. A review of the main methods can be found in Priest (1993). Trace lengths have been estimated by employing distribution assumptions (Priest and Hudson, 1976). In these cases, they can be estimated by counting them on rectangular (Pahl, 1981) or circular windows (Mauldon et al., 2001). Other methods using two or more photographs of an outcrop allow the estimation of orientation, fracturing density and trace length (Thomas et al., 1987; Crosta, 1997). Detailed digital elevation model may be used to characterize discontinuity sets (Froldi, 2000). A more sophisticated and time consuming approach employs the use of software which allows a complete characterization of discontinuities using numerical simulations (Baroudi et al., 1990; Starzec and Andersson, 2002). The present method uses simple estimates of the mean characteristics of discontinuity sets. The first step consists in defining homogeneous structural domains, where geological structures, lithologies and fracturing show constant properties, i.e. orientation, spacing, trace length, undulation, infilling material and aperture. In other words, this is an area where rock instabilities are driven by an identical mechanism that could also be controlled by slope morphology. The second step consists of a field survey of the discontinuities (Hoek and Bray, 1981; Priest, 1993; Jaboyedoff et al., 1996). This survey can be more or less detailed, depending on the goal of the study. An estimation of the fracturing density requires three parameters for each discontinuity set: the mean orientation, mean spacing and mean trace length (Del’eze et al., 2003).

LOCATION OF STUDY AREA

The study area is the limestone deposit at Obajana in Kogi State, Nigeria which is within longitude 6°20 E and 6°28 E and latitude 7°48 N and 7°56 N. Figure 1 shows the location map of the study area. The rock type in the study area includes schist, pegmatite, quartz, limestone, granite and granulites. The limestone having roughly NE-SW trend and thinning out in the western direction is of gray to white in colour, mainly coarse grained in nature with few mica specks. In some places mica and granulites intrude the limestone. The limestone is overlaid with 8 metres thick overburden soil as revealed from the surface.

DISCONTINUITY DATA COLLECTION AND INTERPRETATION

According to Olaleye and Jegede (2006), one of the most important aspects of rock slope analysis is the systematic collection and presentation of geological data in such a way that it can easily be evaluated and incorporated into stability analysis. Two faces of the limestone quarry were mapped and there were two major joint sets observed at the faces. The third joint set was random and scanty in term of density, hence it was neglected. At face 1, the dominant joint set was joint set 1 while in face 2, the dominant joint set was joint set 2. However during processing using directional cosine to calculate mean orientation, the joints in each face were classified according to their
sets. For instance joint set 1 in face 1 was analysed separately, also joint set 2 in face 1 was analysed separately to get the correct mean of each joint set. The same was used for analyses of joint sets in face 2. DIPS software was used to plot the data and also used for both statistical and kinematic analyses of the orientation data to determine the stability of the slopes under study and results were presented in Figures 1-6. Tables 1-4 contain the processed orientation data of the two bench faces (1 and 2) for 150 and 100 sub-parallel fractures respectively. Fracture orientation data were collected along a 200m straight scanline on a rock slope which was tagged, face one (1) and 100m straight scanline tagged, face two (2). At Obajana limestone quarry, two joint sets were identified on each of the faces. Figures 1 and 2 show the fracture normal in lower hemisphere projection. The fractures are thought to be of approximately the same size, and orientations to follow the Fisher distribution. Orientation of cut faces 1 and 2 are 89/100 and 88/230 respectively. Since all fractures belong to a well-defined set, the “Terzaghi bias” associated with sampling along a straight scanline (Priest, 1993) is approximately the same for all fractures, and is therefore neglected here. With the aid of spread sheet, a basic program with Microsoft excel was written to process the data. However DIPS software has inbuilt program for statistical analyses, but sometimes it is not always handy hence the basic excel program was very useful.

RESULTS AND DISCUSSION

Results

Tables 1-4 contain the processed orientation data of the two bench faces (1 and 2) for 150 and 100 sub-parallel fractures respectively. Figures 2-7 depict the orientation data of the discontinuities in the limestone deposit.

Table 1: Summary of orientation data for joint set 1 fracture on quarry face 1

<table>
<thead>
<tr>
<th>Direction cosine</th>
<th>( \frac{\text{sin dip}}{\text{dir* cos dip}} )</th>
<th>( \frac{\text{cos dip}}{\text{dir.cos dip}} )</th>
<th>( \text{sin dip} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
</tbody>
</table>

Number of joint sets, \( N = 96 \) for J1 in face 1

Table 2: Summary of orientation data for joint set 2 fracture on quarry face 1

<table>
<thead>
<tr>
<th>Direction cosine</th>
<th>( \frac{\text{sin dip}}{\text{dir* cos dip}} )</th>
<th>( \frac{\text{cos dip}}{\text{dir.cos dip}} )</th>
<th>( \text{sin dip} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
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<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
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<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
</tbody>
</table>

Number of joint sets, \( N = 45 \) for J2 in face 1

Table 3: Summary of orientation data for joint set 2 fracture on quarry face 2

<table>
<thead>
<tr>
<th>Direction cosine</th>
<th>( \frac{\text{sin dip}}{\text{dir* cos dip}} )</th>
<th>( \frac{\text{cos dip}}{\text{dir.cos dip}} )</th>
<th>( \text{sin dip} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
</tbody>
</table>

Number of joint sets, \( N = 63 \) for J2 in face 2

Table 4 Summary of orientation data for joint set 1 fracture on quarry face 2

<table>
<thead>
<tr>
<th>Direction cosine</th>
<th>( \frac{\text{sin dip}}{\text{dir* cos dip}} )</th>
<th>( \frac{\text{cos dip}}{\text{dir.cos dip}} )</th>
<th>( \text{sin dip} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sum</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
<td>( \sum_{i=1}^{n} )</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
<tr>
<td>Vector Mean</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
<td>( \frac{\sum_{i=1}^{n}}{N} )</td>
</tr>
</tbody>
</table>

Number of joint sets, \( N = 37 \) for J12 in Face 1.

DISCUSSION

From Figure 2, the pole friction cone of plunge 90 degree and angle 35 degree is roughly estimated to represent friction angle of limestone. On the stereonet, a daylight envelope is visible. Any pole that fall outside the cone represents a plane which could slide if kinematically possible. From the analyses, there is indication that joint set 2 is susceptible to plane failure. The red crescent outline zone outside the pit slope enclosed by the friction cone represents the zone of wedge (intersection) sliding. Any plane intersection which falls within this zone will be unstable. In Figure 3, planes 1 and 2
intersect outside the pit slope but enclosed by the friction cone. Hence, the intersection falls within critical area which makes wedge failure to be possible on the face. From Figure 4, any pole that falls within pole toppling region indicates a toppling risk. From visual estimation, there is no pole within this region; hence toppling failure is unlikely. The crescent formed by failure envelope on friction cone only in Figure 5 affected roughly 40% of joint set 1 in face 2, therefore, it is not of much concern that plane failure will be experienced. Intersection of planes 1 and 2 fall outside the crescent (critical area) produced by overlapping cut face and friction angle by a very small margin in Figure 6. This indicates that wedge failure is not expected and very unlikely to happen. Face 2 is more stable kinematically than face 1 as far as wedge failure is concern. Joint set 2 in face 2 of the quarry is susceptible to toppling if other factors favour it. 50% of the joint set 2 falls within pole toppling region as indicated in Figure 7.

CONCLUSION
The importance of discontinuity orientation to stability of slopes in the study area was considered and the fracture pattern in the limestone deposit was studied. Results show that there are two major joint sets at the limestone quarry with average orientation of 87/218 for face 1 and 68/95 for face 2. The quarry face 1 is susceptible to both plane and wedge failures from kinematic analysis. There is no indication of any toppling failure from the analyses. Face 2 of the quarry is not susceptible to wedge failure, but some part of it (40%) face the risk of plane sliding and up to 50% of the face also face the risk of toppling. The parameters that can be varied to avoid slope failures are orientation of cut face, bench height and drainage of flooded pits. Fracture orientation is a natural geologic activity, hence attention should be paid to the orientation of the cut faces and proper analysis should be done using the right tools and techniques so as to avoid turning a profitable mine to a loss.

REFERENCES


Figure 2: Stability analyses of quarry face 1 for plane failure using daylight envelope and friction cone

Figure 3: Stability analyses of quarry face 1 for wedge failure using intersection of planes

<table>
<thead>
<tr>
<th>Orientations</th>
<th>ID</th>
<th>Dip / Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>89</td>
<td>100</td>
</tr>
<tr>
<td>1 m</td>
<td>87</td>
<td>228</td>
</tr>
<tr>
<td>1 w</td>
<td>87</td>
<td>228</td>
</tr>
<tr>
<td>2 m</td>
<td>72</td>
<td>096</td>
</tr>
<tr>
<td>2 w</td>
<td>72</td>
<td>096</td>
</tr>
</tbody>
</table>

Number of Poles
- 1 pole
- 2 to 3 poles
- 4 to 5 poles
- 6 to 7 poles
- 8 to 9 poles
- 10 to 11 poles
- 12 to 13 poles
- 14 to 15 poles
Figure 4: Toppling failure analyses of quarry face 1

Figure 5: Stability analyses of quarry face 2 for plane failure using daylight envelope and friction cone

Figure 6: Stability analyses of quarry face 2 for wedge failure using intersection of planes
Figure 7: Toppling failure analyses of quarry face 2