Analysis of failure behaviour of the anisotropic rocks in the point load index test

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Abstract. The strength and deformational behaviour of rocks under loading conditions are important in underground excavations, mining and every civil engineering constructions as it determines the stability of such structures. This study aims to augment the existing know-how on such behaviour through analysis of point load tests conducted on anisotropic rocks of metamorphic nature. Three types of anisotropic rocks named augen gneiss, granitic gneiss, psammitic schist, and greenschist from different formations of the Lesser and Higher Himalaya of Central Nepal have been investigated. It is observed that the point load index strength of the anisotropic rocks is related to their grain size and the loading angle with respect to the planes of anisotropy. The anisotropic index shows pronounced effects on the surface energy distribution of the samples on the application of stress.

1. Introduction

The strength of the rocks and their behaviour during excavations of varied nature is important for the stability of structures like tunnels, mines and other civil structures. It is therefore imperative to have a complete appraisal of the failure behaviour of rocks in advance, before commencing excavation of a structure in rock. Strength characteristics of rocks varies with their genetic nature and the variation in geo-mechanical properties is distinct in metamorphic rocks. This is primarily due to the strong anisotropy of such rocks. Accordingly, the strength and nature of the failure of such anisotropic rocks change with the orientation of stress. This has a strong bearing on the stability of the underground structures as their orientation with respect to the anisotropy defines the behaviour and stability of the rock mass. One of the methods to determine the geo-mechanical strength characteristics of rocks is the point load index strength test (PLI) that provides valuable information about the mechanical behaviour of rocks. Although indirect tensile testing of the rocks is the preferred test, the PLI is an easy method to arrive at such experimental values.

The anisotropy as proposed by [1] can be determined by testing rock samples in different directions. The anisotropic behaviour of the rocks in different index tests have been identified and studied by many researchers [1–4]. The failure behaviour of anisotropic rocks has been investigated by [1,5–13]. However, relating failure behaviours of anisotropic rocks with actual field conditions is a difficult process, if their directional strength properties are not considered. Therefore, for engineering
projects, it is essential to estimate the strength, stress-strain, shear failure behaviour and failure mechanism of rocks accurately.

In the present study, an effort has been made to understand the strength and failure behaviour of three types of anisotropic rocks named augen gneiss, granitic gneiss, and greenschist from different formations collected from the Lesser and Higher Himalaya of Central Nepal. The rocks were collected from Kathmandu, Sindhupalchowk and Rammechhap districts of Central Nepal. The rock samples belong to the Ulleri Formation [14] - augen gneiss and granitic gneiss [15], Kunche Formation [16] - psammitic schist and greenschist.

The main objective is to determine the rock strength at different loading angles. The rock strength and its behaviour can be used to estimate the strength of the different rocks during an engineering construction and design. Experimental data is used to establish empirical and graphical relationships for the prediction of PLI failure behaviour on different loading angles in the anisotropic rocks. The objective of the study is to augment the existing data and know-how on the failure behaviour of the anisotropic rocks.

2. Methodology

The samples have been taken from the Nepal Himalayan region, which comprises of highly anisotropic metamorphic rock domain and presents a challenge to relate the properties to actual field conditions. This is primarily due to the folded, faulted, crushed and ruptured nature of the rocks present in the Himalayas region.

The intact rock block samples extracted from the above-said areas were taken to the lab for core cutting using the suggested method for the point load index test by [17]. The diameter of the core sample is 51 mm and the ratio of sample length to the diameter is 0.3-0.7. A complete laboratory test study was conducted (figure 1) on such samples and the failure load was used to calculate the PLI values.

![Figure 1. Point load index test](image)

The rock samples were tested at varying orientations, θ, of the foliation planes to the direction of the point load stress with an interval of 15° and the loading angles thus correspond to 0°, 15°, 30°, 45°, 60°, 75°, and 90° with respect to the foliation or anisotropic planes.

Accordingly, the significant failure stress and failure stress analysis in the point load index tests has been performed in the present study.

2.1. Determining the grain size of the rock

Thin sections of the rock samples were prepared in the laboratory and the grain size of the minerals is measured by the image interpretation tool provided by ImageJ by using the particle analysis tool. Different distributions of the particle size were then obtained with the help of relevant methods.
3. Results

In the point load index test, at first compression stress initiates on the application of the point load. With further increase in the stress, the development of the fracture leads to the failure of the specimen that is a continuous process in which the peak strength represents the strength of the specimen. The strength obtained at different loading angle gives different types of curves (Figure 2) for axial loads at different angles mentioned earlier.

![Figure 2. Relationship between I(50) and loading angle.](image)

As is seen in Figure 2, the maximum strength of the rock sample is obtained when the loading angle is perpendicular to anisotropic planes, and the minimum strength is obtained when the loading angle is at 0° and 45°. This means that when the loading angle with respect to the foliation plane changes, there is a drastic reduction in the strength and hence reflects the nature of strength and failure behaviour. The failure behaviour represented by curves in figure 2 is further analysed by calculating the slope and inclination made by the curve in which the minimum strength value in the curve is the dividing point. Accordingly, the analysis is divided into two i.e., analysis for loading angle of 0° to 45° and 45° to 90° as given in Table 1.

| Rock Type        | Loading angle (0°-45°) | Loading angle (45°-90°) | Anisotropic index |
|------------------|------------------------|-------------------------|-------------------|
|                  | Slope                  | Inclination             | Trendline R²      | Slope                  | Inclination             | Trendline R² |                  |
| Green schist     | -0.0319                | 17.47°                  | 0.95              | 0.0451                 | 24.58°                  | 0.99          | 2.29             |
| Augen gneiss     | -0.0445                | 26.73°                  | 0.94              | 0.0508                 | 28.31°                  | 0.94          | 2.45             |
| Granitic gneiss  | -0.0681                | 35.21°                  | 0.97              | 0.0782                 | 38.76°                  | 0.99          | 2.44             |

Table 1 shows that the slope and inclination angle of the curve is higher for the gneiss rock type than the schist. Also, an anisotropic index is high for the gneiss than the schist. To relate this results in micro-scale, it is further correlated in the mineral grain size to the loading angle because it showed the relationship between rock type and anisotropic index in which the anisotropic index is decreasing with an increase in the denseness of the foliation than mineral grain size.

As observed above, the minimum PLI is obtained when the loading angle is at 45° and the maximum is obtained when the loading angle is normal or either parallel to the foliation plane due to a change in the cross-sectional area. This can be further explained with the help of figure 3. During the loading angles change, stress applied from the cross-sectional area (A) transforms to the anisotropic plane area (A/cosθ).
Figure 3. Axial loading mechanism with respect to the anisotropic angle where inclined lines represent the foliation of the rock.

The relationship of change in the anisotropic plane area when an inclined plane of the core sample is:

\[ A' = A / \cos \theta \]  

(1)

Where the \( A \) is the cross-section area of the sample and the anisotropic plane area is \( A' \) anisotropic plane area is in Figure 3.

The anisotropic plane areas at different loading angles are presented in the Table 2.

Table 2. Change in the anisotropic plane area with respect to cross-sectional area varying in loading angles

| \( A \) (in mm\(^2\)) | loading angle (\(^\circ\)) | \( A' \) (in mm\(^2\)) |
|-----------------|----------------------|-----------------|
| 2042.82         | 0º                   | 2042.82\(^1\)   |
| 2042.82         | 15º                  | 2114.94         |
| 2042.82         | 30º                  | 2358.92         |
| 2042.82         | 45º                  | 2889.01         |
| 2042.82         | 60º                  | 4085.64         |
| 2042.82         | 75º                  | 78934.33        |
| 2042.82         | 90º                  | \( \infty^2 \)  |

The nature of the graph is similar to the basic cosine functions graph. In normal (stress applied in 90º angle) or parallel (stress applied in 0º angle) to the plane, the cosine function is 0 and 1. However, there is no effect of anisotropic plane effect on the rock samples in 0º and 90º so the sum of the normal stresses acting on perpendicular and parallel faces for a stress element is constant, independent of loading angle (\( \theta \)).

\[ y \approx \cos \theta \]  

(2)

Strength development in the rock sample is a complicated process, which begins at the micro-level (atomic level to grain-size level) and ends with the development of single or several macroscopic fractures, which split the sample into several pieces. The behaviour can be understood by using figure 4.

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\(^1\) \( \cos \theta \) is 1 on the 0º loading angle so there is not any change in anisotropic plane area.

\(^2\) The area of the rock cylindrical sample never can be infinitive because the rock sample size has fixed H/D ratio which explains that there is not effect of loading angle on the 90º.
Figure 4. Strength nature of the point load index to the cross-sectional area change from 0° to 75°. (The dashed line in the figure shows that the strength break point)

In Figure 4, the graph is divided into the two-parts due to the different nature shown by the curve of the rock sample test results, in which the dividing point is the minimum strength obtained (Loading angle 45°) during the point load index test. In Figure 4, the effect of cross-sectional area change is different from 0° to 45° and 45° to 75° loading angles. The obtained curve shows that the failure behaviour of the rock in the PLI test is different from the right part and left part from the minimum strength obtained by the PLI test.

| Rock Type      | Loading angle (0°-45°) | Loading angle (45°-90°) |
|----------------|------------------------|-------------------------|
|                | Equation               | R-Square                | Equation               | R-Square                |
| Green schist   | 16.32e-9E-04x          | 0.92                    | 0.0003x+0.40           | 0.92                    |
| Augen gneiss   | 9.49e-6E-04x           | 0.81                    | 0.0002x+1.22           | 0.92                    |
| Granitic gneiss| 26.48e-9E-04x          | 0.84                    | 0.0004x+1.4            | 0.96                    |

In Table 3, the failure behaviour of rock form during the PLI test 0° to 45° loading angles is an exponential relationship with the cross-sectional area change because the curve is continuous, y>0, and the graph passes from the (0,1) to the dividing point. But, from 45° to 90°, it has a linear relationship with the cross-sectional area change. Therefore, the strength is maximum at 90° and 0° and the minimum at 45° due to the effect of the stress applied in the anisotropic plane.

The study of failure behaviour of anisotropic rocks to loading angle shows the cross-sectional area controls in the strength of anisotropic rocks. During stress induced in the sample, stress transfers in the form of the energy from the atoms to atoms that is surface energy where it depends on the cross-sectional area.

$$\gamma = \frac{\text{Energy}}{\text{Area}} \quad (3)$$

Where $\gamma$ is the surface energy that is inversely proportional to the area i.e., an increase in the area leads to a decrease in surface energy and vice-versa.

Therefore, with changing loading angle in the anisotropic rocks, the cross-sectional area changes with changing the loading angles that can be seen in Table 2. Except for 0° and 90° loading angles, the area in the equation (3) can be replaced by $A/cos\theta$

$$\gamma = \frac{\text{Energy}}{A} \quad (4)$$

Further, the anisotropic index relationship is established with the slope of the curve and average grain size determined by the particle analysis. The analysis of the grain size in µm to the grain size
frequency is shown in the histogram that is in Figure 6. The frequency of the grain size is higher between 1000 \( \mu m \) and 1500 \( \mu m \) and is further analysed in Figure 7.

![Figure 5. One example of a photomicrograph of augen gneiss for grain size analysis.](image_url)

The particle sizes were plotted in the histogram to their frequency distribution is shown in Figure 6. The selected sampling interval with the range particles size was plotted (Figure 7) with the frequency of the grain size. After this the, obtained curve was fitted with the Gaussian transformation function to determine the average grain size of the selected samples.

![Figure 6. Histogram of grain size of augen gneiss sample.](image_url)

The obtained frequency count of the grain size is further plotted in Figure 7 to determining the average grain size of the mineral by the transformation by curve fitting. The nature of the graph is symmetrical, bell-shaped with a single peak that matches with the gaussian function so that gaussian transformation is applied. The obtained results and parameter characteristics are shown in Table 4.
Figure 7. Gaussian transformation for determining the average grain size of the augen gneiss sample.

Table 4. Obtained Gaussian transformation parameters characteristics for the augen gneiss.

| Parameters   | Characteristics |
|--------------|-----------------|
| Model        | Gaussian        |
| Equation     | $y = y_0 + \frac{A}{\sqrt{2\pi}w} e^{-\frac{1}{2}ln(2)(x-x_c)^2}$ |
| Plot        | Counts          |
| $y_0$       | $6.56 \pm 3.98$ |
| $x_c$       | $1175.88 \pm 145040.12$ |
| $A$         | $148898.71 \pm 1.34314E9$ |
| $w$         | $114.26 \pm 343521.1$ |
| Reduced Chi-Sqr | 126.89 |
| R-Square (COD) | 0.999 |
| Adj. R-Square | 0.989 |

Similarly, the calculation of the grain size is done for the granitic gneiss and green schist and the obtained results are shown in Table 5.

Table 5. Obtained the grain size of the rock

| Rock type    | Grain size (mm) | R-Square |
|--------------|-----------------|----------|
| Augen gneiss | 1.175           | 0.99     |
| Granitic gneiss | 1.017       | 0.99     |
| Green schist | 0.511           | 0.99     |

The obtained grain size is plotted with the strength parameter of the rock i.e., an anisotropic index that will represent the failure behaviour of the rock. Also, the slope of the curve is correlated with the anisotropic index in which the slope of the curve represents the overall nature of the strength value obtained from the PLI test.

Figure 7 represents the main effect of the slope of the curve from 0°-45° loading angle and grain size of the rock with anisotropic index as a response because it is the strongest factor. It has a linear response with the anisotropic index. With increasing grain size, the strength also increases and the slope made by the strength also increases.
In general, grain size controls the roughness of the rock surface made by the grain size i.e., in nature gneiss has high roughness of grains than slate, phyllite or schist. Also, the mineral grain affects the friction produced by the interlocking of the grains on the rock during the stress applied and hence the failure behaviour.

![Figure 8](image)

**Figure 8.** Main effect plot of the grain and slope (0°-45°) of the graph to the anisotropic index by differing the rock types.

Similarly, the main effect plot (Figure 9) of the loading angle 45°-90° has the same relationship as Figure 8.

![Figure 9](image)

**Figure 9.** Main effect plot of the grain and slope (45°-90°) of the graph to the anisotropic index by differing the rock types.

It is evident from the above analysis that the strength behaviour of the rock samples in the point load index tests is substantially governed by anisotropic planes and the size of the grains present on them. The failure process initiates in the rock samples and is, to a very large extent, controlled by the tensile strength of intact rock or of its component grains.

4. Conclusion
This study presents the characteristics of the failure behaviour of anisotropic rocks in the PLI test. When the loading angle is parallel to perpendicular to the anisotropic planes, failure stress and failure stress analysis are lower than those in other loading directions. It is observed that the strength due to anisotropic plane change with respect to cross-sectional area at varying loading angles with respect to the anisotropic plane. The slope and inclination of the curve made by strength in different loading angles depend on the anisotropic index and the grain size of the rock.

From Eq.(1, 3and4), the change in anisotropic plane area in different loading angles is related to surface energy change that is changing with the intermolecular forces at the interface between minerals grain to grain and relates to the density of bonds per unit area. In the mineral grain analysis,
the slope of the curve to the strength parameter i.e., the anisotropic index also supports the role of the loading angle and mineral grain control over the strength of the rock as the formation of the anisotropic plane is controlled by mineral orientations. The size and the granularity of the mineral and the friction generated by the roughness of the material determine the material's reaction after stress during the index test.

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