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Study of shear strength of rocks from Kohat Formation

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Abstract

Shear strength plays a vital role in the designing of mining and civil structures within or on the rocks. The shear strength parameters can be determined either through direct or indirect methods. Many mining and civil structures have been constructed and many are under consideration in the area comprising limestone. Shear strength of the rocks in the study area has been determined using indirect methods previously. However it is extremely necessary to apply direct methods for comparison purposes. In this study shear strength of Kohat limestone was determined from direct method using shear box apparatus. Tests were carried out under Constant Normal Load Condition (CNL). Nine samples were tested under normal load condition up to 0.020% of uniaxial compressive strength. Barton Model was fitted to laboratory test data. Joint Wall Roughness Coefficient (JRC) was obtained from the impression of joint wall roughness and compared with Barton standard profiles. Since these were fresh joints therefore Uniaxial Compressive Strength (UCS) was used as Joint Wall Compressive Strength (JCS). JRC and JCS values were same for all the samples. Microsoft Excel built in optimization tool so called "Solver" was used to optimize the basic friction angle. Analysis of the results was compared with indirect method for determination of the said parameter. It was observed that the frictional angle determined for Kohat limestone using direct method is close to that from indirect methods but the later is on higher side.

Keywords: Shear strength; Direct method; Barton model; Constant normal load condition; Joint wall compressive strength (JCS); Friction angle.

1. Introduction

Shear strength plays a vital role in any structural facility constructed within or on rocks. Different civil and mining structures have been constructed while many are proposed on and in the rocks of Kohat ~~Formations~~ having limestone as a major rock type. Kohat Tunnel-I is constructed in the area on Indus Highway but due to increasing traffic trend another Tunnel called Kohat Tunnel-II is under consideration (NHA, 2003). The area is a valley and access roads require slopes. Many other civil structures are also under consideration. For all these designing problems a detailed analysis of shear strength of the rocks from the area especially major rock component is important. Shear Strength and its parameters of major rock type have been determined by indirect methods (Feroz Din et al., 1993; Feroz Din et al., 1995; Din, 2009; Tahir, 2010), however a detailed study of shear strength of these rocks by direct method is essential for comparison purpose and to get more refined results. The main objective of this study is to determine shear strength of the major rock type, i.e., limestone by direct method and its comparison with indirect method.

2. Geology of Kohat Limestone

The geological column of the area shows that in the North and North-West of the Kohat, the exposure of rocks is ranging from Jurassic to Pliocene in age while in the Southern part they belong to age ranging from Eocene to Pliocene. The Eocene succession comprises of Limestone, Shale and Gypsum. These lithologies form low lying hills and somewhere high sky lines. The Eocene limestone has an industrial application as well and used a raw material for Ordinary Portland Cement. The predominant limestone is creamy, light grey and pink in color and highly fossiliferous characterized by abundance of Nummalites and other forams. The thickness is variable and average thickness is about 500 feet. It is observed during excavation of Kohat tunnel and access roads that the limestone is unweathered and joints are fresh (NHA, 2003; Ahmad et al., 2001; Tahir et al., 2011).

3. History of previous work in the area

Shear strength of rocks can be determined in laboratory using either direct or indirect methods. Shear strength is directly determined in laboratory using shear box apparatus. The most common indirect methods are graphical methods using tensile and compressive strength data, fitting of linear failure criteria on laboratory triaxial tests data and fitting of non-linear failure criteria on laboratory triaxial test data. Shear strength of various rocks of Khyber Pakhtun-Khuwa was determined using graphical method including limestone and sandstone of Kohat Formation. In this indirect method shear strength was calculated by graphical method from uniaxial compressive strength and uniaxial tensile strength. From the common tangent of the two circles shear strength was obtained (Feroz et al., 1993).

Shear strength of limestone from the area was also determined from triaxial study using Mohr's Circles (Feroz et al., 1995). Design parameters were determined for limestone of the area but it was also an indirect approach (Din, 2009).

Using Triaxial, Uniaxial and Tensile tests data Tahir (2010) fitted modified version of Hoek - Brown failure criteria and its variants and determined shear strength parameters of Kohat limestone using Roclab software builtin tool "Mohr-coulomb fit to Hoek – Brown failure criteria", techniques developed by Hoek (1994) and Douglas (2002). No attempt has been made to determine the shear strength of Kohat limestone using direct methods. Therefore the current research work was undertaken to determine the shear strength of fractured limestone of Kohat tunnel area using portable shear box assembly in rock Mechanics lab at the Department of Mining Engineering University of Engineering and Technology Peshawar, Pakistan.

Some limestone samples were tested using direct method by National Highway Authority for Kohat tunnel and access road project but under low normal load condition. The results of these tests are also included in the analysis of shear strength parameter especially friction angle ϕ.

4. Strength of discontinuities

Rock masses generally contain natural defect and are composed of intact rock pieces separated by discontinuities such as joints, bedding planes, fractures and faults. The nature of these defects controls the mechanical behavior of rock mass. An authentic and precise estimation of mechanical properties plays a vital role in the design of excavation with in or on the rock. Reliable information about the behavior of discontinuities is necessary for stability analysis especially in the numerical analysis. The most common mechanical property of the rock is its shear strength that can be obtained from the laboratory using direct shear box test. The shear strength of discontinuities is important for design and stability analysis of civil and mining structure at shallow depth where the stability is mostly controlled by sliding of rock blocks along plane of discontinuities, such as tunnels in discontinium rock mass at shallow depth, rock slopes and dam foundations (Geertsema, 2003).

Shear box apparatus is a common test apparatus that determines direct shear strength of discontinuities. Improvements have been brought to enhance the capacity of the shear box apparatus with maximum shear force of 1000 kN with dynamics (Konietzky et al., 2012). However such an apparatus is a requirement of higher stress environment and an apparatus with a capacity of 200 kN to 300 kN is sufficient in majority of circumstances.

The shear behavior can be investigated under both constant normal load (CNL) (Potton, 1966; Barton et al., 1977; Wang et al., 2003; Asadollahi et al., 2010) and constant normal stiffness (CNS) conditions (Kodikara et al., 1994; Haque, 2000). The conceptual difference between the two conditions is: in the former the normal load remains constant during shearing allowing the joint to dilate while in the later the dilation is restrained due to which the normal load on joint increases.

5. Shear strength models of discontinuities

Cutnell and Johnson (2001) has explained the principal of shear along the discontinuity surface as when a normal load is acting on discontinuity surface and a load F is applied parallel to the surface that tends to shear then resistive frictional force fs has the following properties:

- The resistive force fs have equal magnitude as F (component of F parallel to the surface in case F is not parallel to the surface) but opposite in direction.
- When the force F tends to slide the body the maximum frictional resistive force is given as by equation 1.

fs maximum = μs N....................................(1)

Where μs is coefficient of static friction and N is normal load acting

- The value of equation 1 is transition and sliding starts when the value of F or component of F parallel to the surface (When F is not parallel to the sliding surface) exceeds the value of equation 1 and for kinematics frictional force, μs is replace by kinematics coefficient of friction μk.

Joint surfaces are mostly rough and undulating like coastline and joint roughness is an important parameter in determination of shear behavior of discontinuities. Joint wall compressive strength, tensile strength, weathering, and infilling materials etc are among the definitive parameters that should be considered. Some of many empirical and theoretical constitutive models are of Potton (1966a), Goodman (1974), Barton and Choubey (19770, Bandis et al. (1981), Swan (1981), Heuze and Barbour (1981), Desai and Fishman (1987, 1991), Kana et al. (1996), Samadhiya et al. (2008) and Ghazvinian et al. (2012). Most of the models address joint roughness in different ways such as Barton (1977) termed this parameter as Joint Roughness Coefficient JRC. Among all, Potton (1966a) model is initiative as it was the first ever theoretical approach to define the shear strength of rock joints. Barton and Choubey (1977) model is most widely accepted due to its user friendly nature and simplicity, therefore majority of the researchers have used this model as a bench mark.

Based on surface roughness Potton (1966a) derived a relationship as given in equation 2 from shear test on SAW Tooth samples.

$\tau = \sigma_n \tan(\O_b + i)$...(2)

Where σn is normal load, ϕb is basic frictional angle and i is the angle of asperity with the surface as shown in Figure 1a.

The asperity angle tends to dilate or increase the volume of sample. Figure 1b shows the shear strength envelope of Potton model. On certain normal load the asperity angle diminishes and the envelope represents the shear strength of smooth surface.

Barton and Choubey (1977) presented their updated version of empirical criterion for joint shear strength based on Joint Roughness Coefficient JRC as given by equation 3.

$$\tau = \sigma n \tan\left(\phi b + JRC \log \frac{JCS}{\sigma n}\right) \text{.................(3)}$$

Where JCS is joint wall compressive strength or compressive strength of intact rock and σn is normal stress.

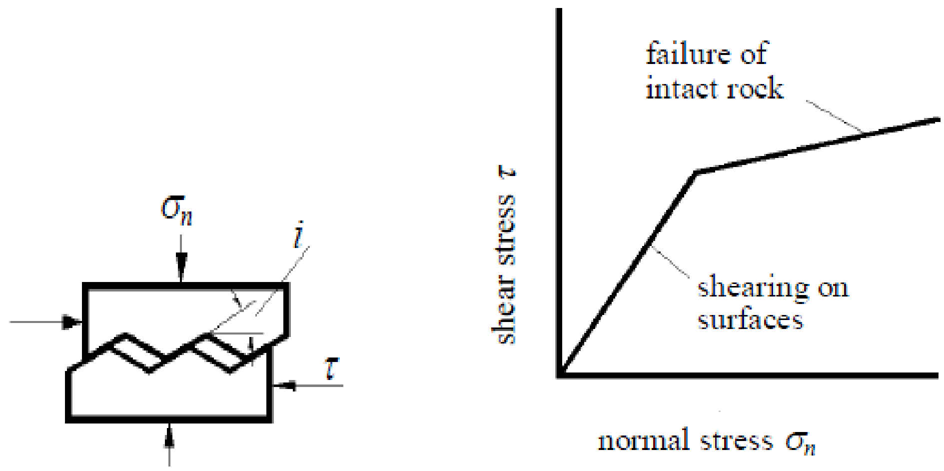
JRC is obtained from comparing the discontinuity surface with standard profile produced by Barton and Choubey (1977). The model is similar to the Potton model but more comprehensive as the term for asperity angle is replaced with the term as by equation 4.

$$i = \left(JRC \log \frac{JCS}{\sigma n}\right) \text{......................................(4)}$$

It is indicated from equation 4 that the asperity angle is normal stress dependent. This term makes the model non linear as shown in Figure 2.

The joint wall compressive strength may be identical or different and are called discontinuities with identical joint wall compressive strength (DIJCS) and discontinuities with different joint wall compressive strength (DDJCS) respectively. Barton model is widely accepted as an empirical criteria based on DIJCS.

It is revealed from the work of Haberfield et al. (1999) that shear strength of discontinuity with identical joint wall compressive strength is quite different form discontinuity with different joint wall compressive strength. However Ghazvinian et al. (2012) founded that results from DDJCS are very close with that from DIJCS.



a. **b.**

Fig. 1a. Shear Model for saw tooth surfaces, Fig. 1b) Shear strength envelope of Patton model (after Hoek et al., 1993)

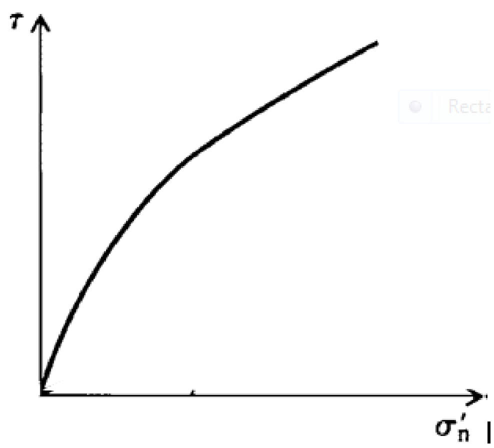


Fig. 2. Shear strength envelope for Barton model (after Barton and Choeby, 1977)

For Barton model the joint wall compressive strength (JCS) is determined from rebound test. However the term can be obtained using the uniaxial compressive strength of intact rock pieces in case of fresh joints.

Basic friction angle is the key quantity in estimating the joints shear strength of rocks. It is either calculated from the direct shear strength tests of saw cut or ground surfaces or can be obtained directly from the list provided by Barton and Choubey (1977).

Joint roughness coefficient is the term in Barton model that is addressed in many researches. Barton (1977) have provided one dimensional standard profile as shown in Figure 3, but a clear picture can be obtained from 2D and even 3D analysis (Grasselli, 2003). However, as an engineer we prefer accurate approximation than exact value and the original standard profile comparison is an easy, fast and economical method for such an accurate approximation.

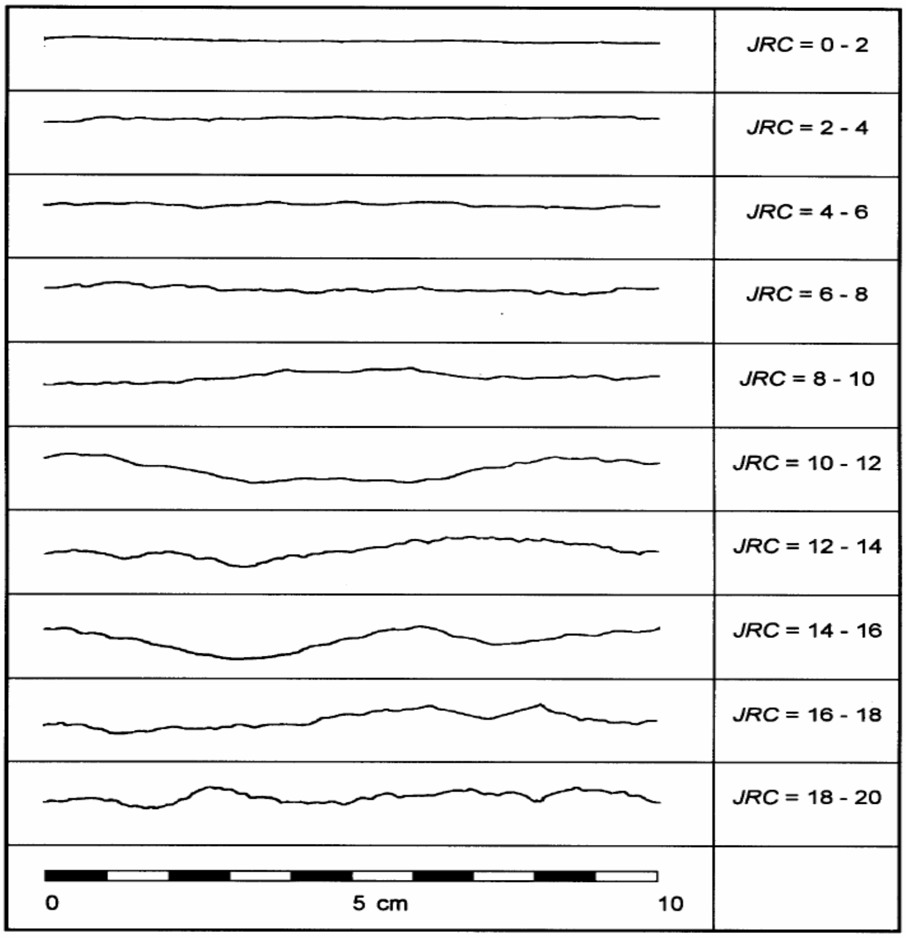


Fig. 3. Standard profiles for Joint Roughness.

Fig. 3. Moulded sample for Shear box

6. Shear tests on Kohat Limestone using shear box

For testing limestone of the research area shear box assembly in rock mechanics laboratory in the department of Mining Engineering (UET), Peshawar, Pakistan is used. Limestone samples were collected from Kohat tunnel site from different locations. The longer dimension of the rock samples was approximately 0.9 meter. Through cutting by saws and cutters rectangular blocks having 50mm x 50mm size and 100mm length were prepared from these boulders. Since there was no shear plane in the intact samples, therefore shear planes were produced in the samples using geological hammer. The shear plane or surface roughness was noted through wax impression on the paper. The samples were bounded through cotton thread to protect the shear planes from disturbance during sample moulding and loading. The bounded samples were gripped in the jaws of clamp in such a manner that the shear plane was aligned and parallel to the shear load and moulded using Quick Settling Cement and sand mortar. Figure 4 depicts molded sample for the shear box test.

A total of nine (09) samples were prepared and tested in shear box apparatus and Results are given in Table 1. When the sample was loaded completely, two vertical displacement gauges were attached to the upper box through magnetic stand on both sides. The vertical gauges are attached to measure the vertical displacements. One of the yoke was attached to the horizontal ram which is a shear load ram. One horizontal gauge was attached to the lower section of the box to measure the horizontal displacements during the test.

Table 1. Laboratory test results using shear box

Sample No	Applied constant Normal Stress (MPa)	Peak Shear Stress (MPa)
1	0.38	0.55
2	0.57	0.62
3	0.76	0.87
4	1.13	0.92
5	1.51	1.21
6	2.27	1.48
7	3.02	2.31
8	4.45	4.49
9	6.06	4.63
10	6.24	5.74
11	6.96	8.91
12	7.32	4.39
13	7.88	6.14
14	8.29	5.72
15	10.79	8.76
16	11.42	6.77

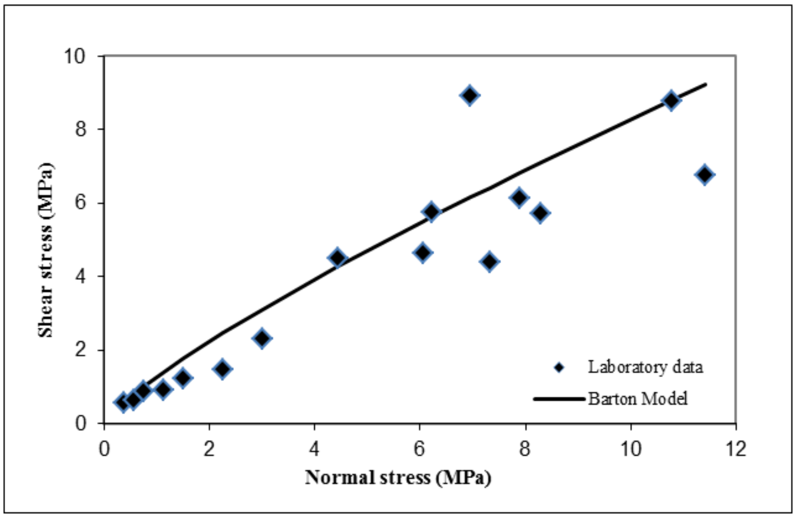


Fig. 4. Fitting of Barton model to Laboratory data.

Table 2. Optimized parameters of Barton model using Solver.

Basic Friction Angle	*Φb*	31.00°
Joint Wall Compressive Strength	JCS	52.2 MPa
Joint Roughness Coefficient	JRC	12
Sum of squares		21

Table 3. Angle of internal friction of limestone from Kohat Formation

Direct Method	**Indirect Methods used by Tahir, 2010**		
Barton model	Roclab software	Hoek, 1994	Douglas, 2002
31°	41.98°	31.55°	43.39°

The vertical load was applied using hydraulic hand pump and portable air pump. The load is applied in such a manner that the maintainer edge is at half way up to the viewing ports on the outer body. The load was increased step by step and then was kept constant at the required value. The readings of the vertical displacement gauges were noted constantly.

After approaching the required value of normal load the gauge reading was noted and shear load was applied with the help of hydraulic pump. After this the readings of normal movements and shear displacements were noted at the same time from the vertical and horizontal gauges respectively. The shear load was applied constantly after reaching the peak shear strength values to get the residual shear strength. To reach residual values the horizontal displacement values in different tests ranged from 5-10 mm from the starting point. For residual strength the weight of upper value and the ram friction were taken as zero errors. The maximum normal load applied to the sample is within the limit of 0.02% of uniaxial compressive strength.

Barton model was applied to laboratory tests data as shown Figure 4. For Barton model joint roughness coefficient (JCS) is obtained from the comparison of joint wall roughness with standard profiles, its value is 12 for all the samples. The joints were fresh and unweathered therefore Uniaxial compressive strength of limestone is used as joint wall compressive strength (JCS). JCS and JRC values are same for all the samples. Excel solver is used to optimize the basic friction angle keeping the JCS and JRC constant. Table 2 shows the best fit values of different parameters of Barton model. The optimized friction angle obtained is 31° with minimum residuals of 21.

The optimized basic friction angle was compared with the value determined using indirect method by Tahir (2010). Table 3 shows a comparision of fractional angle values obtained from both direct and indirect methods. It is revealed from the comparison that both the values are very close but the later is on higher side.

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