Effects of Discontinuous Properties on the Stability of Tunnels

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Abstract: Many failures of underground openings during excavation are closely related to discontinuous properties of the surrounding rock mass and they affect differently to the stability of underground openings. In this research, attempts have been made to study the effect of discontinuities over the rock mass stability with various infilling materials, dip angles and strikes by using laboratory scaled models. Specimens were casted using cement concrete mixture and five different dip angles (30^0, 45^0, 60^0, 75^0, 90^0) and three infilling materials (quarry dust, kaolin and graphite) have been selected for the study. Models were tested to determine their uni-axial compressive strength. The results indicate that the dip angle of the joints and the orientations of the tunnel axis have significant impacts on the stability of the tunnel. The dip angle at 90^0, perpendicular to the tunnel axis shows a higher stability while the angle at 45^0, shows the lowest stability. The tunnels excavated with axis parallel to the discontinuous plane should be avoided as much as possible. If it is unavoidable in any circumstances, well designed support system should be used. Types of infilling materials also affect the stability of the tunnel with graphite being the most unfavourable among the selected materials.

Key words: Dip angle, Infilling, Strike, Tunnel axis.

1. Introduction

Tunnel is an underground route or a passage, excavated through various types of materials from soft clay to hard rocks, where the method of excavation depends mainly on the ground conditions. Discontinuities, stresses and strength of rocks and ground water conditions are the major influencing factors in tunnelling. The strength of the rock mass is dependent on both strength of intact rock material and the discontinuities. Discontinuities drastically alter the behaviour of the rock mass by decreasing the ultimate strength and increasing the deformability of the whole system (Ni and Ove Stephansson 1990). The jointed rock masses exhibit a complicated mechanical behaviour with varying strike, dip orientations and the infilling materials. These factors have been mainly considered in rock mass classification systems because they help to decide the tunnel excavation method, direction of the tunnel axis, types of support systems and eventually the cost of the tunnelling.

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Model testing and numerical analysis are reliable ways of determining the deformation and failure characteristics in rock masses. In this research, the main objective was to determine the effect of rock strength and discontinuities on the stability of the tunnel with various infilling materials, joint dip orientation and rock strengths.

2. Methodology

2.1 Strength testing for different compositions.

Two separate concrete mixtures with varying compositions were selected and four cubes of size 2″×2″×2″ were prepared out of each composition (Table 1).

Table 1 - Material ratios of the compositions

Composition no	cement	Sand <1.7mm	Aggrega -tes 2-5 mm
Com A	1	2	3
Com B	1	2	4

2.2 Strength testing for infilling conditions.

Based on the composition A, 6″ ×6″ ×6″ size cubes were prepared under different infilling conditions, with a circular 1.5 inch diameter tunnel incorporated. Infillings of clay, graphite and crushed rock were selected with the desired thickness of 2mm infilling layer (Figure 1).

Four cubes under each condition were prepared with changing joint orientation for both parallel and perpendicular to the tunnel axis with a dip angle of 60^0. The joint spacing and the dip angle were kept constant for each block.

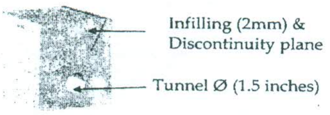

Figure 1 - Joint orientation of the concrete model with infilling

2.3 Strength testing for different joint strikes and dip angles.

Based on the composition A, 6″ ×6″ ×6″ size cubes were prepared under following conditions of dip and strike.

- Joint strike perpendicular to the tunnel axis with dip angles - 30^0,45^0,60^0,75^0,90^0
- Joint strike parallel to the tunnel axis with dip angles - 30^0,45^0,60^0,75^0,90^0

Under each of the above conditions (2.1, 2.2, 2.3), all the blocks were soaked and cured for 28 days and tested by using the Uni-axial Compressive Strength (UCS) machine. The ultimate load at failure was recorded and the test results were analyzed.

3. Results and Discussion

3.1 Results of the strength test with blocks of size (2˝×2˝×2˝)

Table 2 - Strength of cubes with different compositions.

Composition C: S: A	Average failure load (MPa)
1: 2: 3	9.59
1: 2: 4	1.80

Composition A has the highest strength and it was selected for further testing.

3.2 Results of strength test for different dip angles, strike perpendicular and parallel to the tunnel axis.

When the joint plane is perpendicular to the tunnel axis (and that is dip angle = 90^o), the effect of the joint or the discontinuity plane is negligible because parts of the block act as two seperate columns. But if there are any frequent movements between the hanging wall and the foot wall, shear zones can be develop along the discontinuity plane and they will adversely affect to the stability of the tunnel.

Composition: 1:2:3 and Size 6″×6″×6

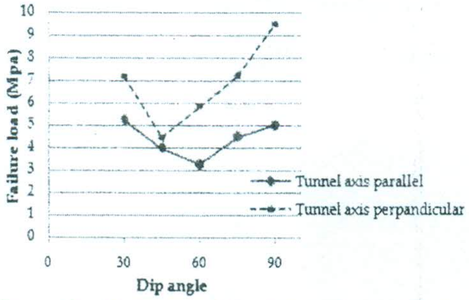

Figure 2 - Variation of the failure load with the dip angle and the strike

On the other hand during the loading period of the cube with TA⊥ 75^0(Discontinuity plane perpendicular to the tunnel axis with dip angle 75^0) and TA⊥60^0, the two portions of the cube again act as columns to a certain extent. But a considerable part of the load is transferred to the foot wall by hanging wall of the cube. So they will fail under low value of load due to the high influence of the forces on the upper part of the cube.

When it comes to the angles of 45^0 and 30^0, two portions of the block act nearly as two separate parallel horizontal beams. Therefore, the bearing capacity of the block against the forces is higher than the previous cases and in angle 30^0, the plane is closer to the horizontal than in the angle 45^0. Therefore, the strength of the block TA⊥30^0 is greater than that of TA⊥45^0 (Figure 2).

When the discontinuity exists along the tunnel axis, the simulated stress conditions are totally different from the earlier condition (strike perpendicular). The effect of the discontinuity on the stability of tunnel is extensively greater than the ealier case.

The total stress distribution of a circular excavation can be implimented in terms of σ_{rr}, $\sigma_{\theta\theta}$, $\sigma_{r\theta}$. The stresses on the excavation boundary are given as;

$$\sigma_{\theta\theta} = P[(1+K) + 2(1-K)Cos2\theta] \qquad (4.1)$$

$\sigma_{r\theta}=0$, $\sigma_{rr}=0$

According to the above equation, the maximum and minimum boundary stresses occur at the side walls (θ=0) and the crown (θ=π/2) of the excavation.

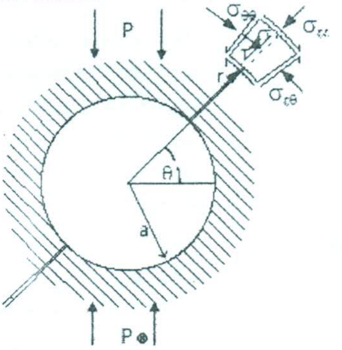

Figure 4 - An inclined, radially oriented pale of weakness intersecting a circular excavation

Above expressions can be coverted into equation 4.2 where it represents a uni-axial stress field parallel to the y-axis when K=0.

$$\sigma_{\theta\theta} = P[1 + 2Cos2\theta] \qquad (4.2)$$

$\sigma_{r\theta}=0$, $\sigma_{rr}=0$

The stress distribution around the circular opening generated due to the uni axial field (K=0) can be implimented as follows.

$$\sigma_{rr} = \frac{P}{2}[\left(1-\frac{a^2}{r^2}\right) - \left(1-\frac{4a^2}{r^2}+\frac{3a^4}{r^4}\right)Cos2\theta] \qquad (4.3)$$

$$\sigma_{\theta\theta} = \frac{P}{2}[\left(1+\frac{a^2}{r^2}\right) + \left(1+\frac{3a^4}{r^4}\right)Cos2\theta] \qquad (4.4)$$

$$\sigma_{r\theta} = \frac{P}{2}[\left(1+\frac{2a^2}{r^2}-\frac{3a^4}{r^4}\right)Sin2\theta] \qquad (4.5)$$

(Brady and Brown 1999)

The equation 4.2 agrees with the graph given in the figure 2.

3.3 Results of strength test for different infillings with strike perpendicular and parallel to the tunnel axis.

Composition: 1:2:3, Size 6″×6″×6″ and dip angle 60^0

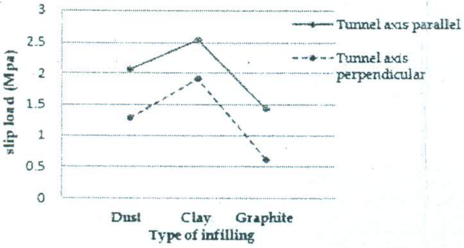

Figure 3 - Variation of the slip load with infillings.

The study was carried out on three infilling materials, as quarry dust to simulate weathered and crushed rock particles, kaolin and graphite which are very common filling materials often found in joints and fractures. Quarry dust is coarser than clay and graphite where air can be trapped within the particles. Therefore, when the load is applied, dust particles tend to move easily than the clay particles. These freely mobile particles may cause a reduction in friction due to rolling. Kaolin is cohesive, weak and non-frictional material. But when the load is applied, it will get compacted due to its cohesiveness and increase the bond between its particles as well as the rock-filling interface. Hence it will increase the slip load with quarry dust. Graphite on the other hand is very weak and posses lubricant properties. Therefore it's obvious that it shows a marked decrease in the strength (Figure 3).

The above expalnation is common for both conditions where tunnel axis perpendicular and parallel to the discontinuity plane.

4. Conclusion

According to the results, the tunnels excavated with axis parallel to the discontinuity plane should be avoided as much as possible. If it is unavoidable in any circumstances, well designed support system should be used since the stability of the tunnel vary (Figure 2). Tunnels excavated with axis perpendicular to the discontinuity plane is the best option where a classification system can be suggested (Table 3).

Table 3 - Strength classification for different dip angles that are perpendicular to the tunnel axis

Dip Angle				
30^0	45^0	60^0	75^0	90^0
Favourable	Unfavorable	Favourable	Much favourable	Very favourable

Furthermore the stability of rock mass mainly depends on the type of infilling material and, it is always lower than that of open joints with no filling. Graphite is an unfavourable filling material, because it reduces the stability of the rock mass drastically due to its lubricant properties.

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