ROCK SLOPE STABILITY

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8.1 INTRODUCTION - FAILURE MODES

Rock slopes, whether manmade or artificially created in the process of excavation can be seen many places. Any imbalance of these slopes may cause failure and always a serious concern. The slope may fail in different modes depending on the rock structures and the loading environment. This failures may be gradual with very slow movement of the sliding mass/block or instantaneous without much indication or warning. Usually, there will be some triggering factors which are responsible for the failure. These possible factors are,

1. Increase of seepage pressure due to built-up of hydrostatic pressure in the joints/tension cracks.
2. Due to excavation in the slope toe material
3. Due to increase of surcharge loading and increase of shear stresses
4. Due to slow deterioration of material strength and decrease of shear resistance of the joints planes

Figure 8.1 : Typical rock slopes as seen in the site
Rock slope stability analyses are routinely performed and directed towards assessing the safe and functional design of excavated slopes (e.g. open pit mining, road cuts, etc.) and/or the equilibrium conditions of natural slopes. In general the primary objectives of rock slope stability analyses are:

- To determine the rock slope stability conditions;
- To investigate potential failure mechanisms;
- To determine the slopes sensitivity/susceptibility to different triggering mechanisms;
- To test and compare different support and stabilization options; and
- To design optimal excavated slopes in terms of safety, reliability and economics.

It is well known that the geological structure and strength of rock discontinuities as well as its orientation with respect to the slope face are the essential factors to the failure of rock slope. The pre-existing weak planes or discontinuities with unfavourable orientation are usually the failure surfaces of an unstable rock slope, whereas in soils, it appears generally in the form of a circular arc. The pure sliding is predominantly the failure mode in rock slope engineering.
There are five primary modes of slope failure in rock masses. These are,

(a) PLANAR FAILURE - Planar failure occurs if the joint plane dipping into the excavation forming a well defined weak plane.

(b) WEDGE FAILURE - Wedge failure occurs when two or more weak planes intersect to form a wedge.

(c) CIRCULAR FAILURE - This type of failure happens when in highly disturbed rock with many intersecting weak planes / joints (weathered rock), sliding along a curved surface forming a circular arc, polynomial or logspiral.

(d) TOPPLING FAILURE - This failure is basically the rotation of rock blocks / layers, takes place into the excavation when the critical joint set dips steeply into the rock mass.

(e) BUCKLING FAILURE - When the excavation is carried out with its face parallel to the thin weakly bonded and steeply dipping layers, depending upon the depth of the excavation, these layers may buckle an fracture near the toe and sliding of the upper portion.

These failure modes are shown in figure 8.3.
Figure 8.3: Different possible failure modes in rocks slopes
8.2 PLANE FAILURE

8.2.1 General condition of plane failure

- The plane on which sliding occurs must strike parallel or nearly parallel (within approximately ± 20%) to the slope face.
- The failure plane must daylight in the slope face, means the dip must be smaller than the slope face i.e. \( \psi_f > \psi_p \)
- The of dip failure plane must be greater than the angle of friction of this plane i.e. \( \psi_p > \phi \)

\[ \text{Figure 8.4 : A simple planar slope failure analysis} \]

\[
\text{FOCTOR OF SAFETY} = \frac{\text{STABILISING FORCES}}{\text{DESTABILISING FORCES}}
\]

\[ FOS = \frac{c' A + W \cos \theta \tan \phi}{W \sin \theta} \]

If water is present in the discontinuity, the water pressure reduces the normal stress on the discontinuity and the shear strength of the discontinuity planes reduces. The effect of water pressure can be estimated by determining the effective normal stress.
FOS = $\frac{c' A + (W \cos \theta - U_b) \tan \phi'}{W \sin \theta + U_r}$

when $c'$ and $\phi'$ are effective cohesion and friction angle. 'A' is area of the failure plane per unit thickness. $U_b$ and $U_r$ are the seepage pressures.

### 8.2.2 Plane failure with tension cracks

Effect of a tension crack on stability of slopes with reference to the location and depth determined usually by stability charts (Hoek & Bray, 1977) or empirical equations. If the position of a tension crack is known, its stability analysis can be made based on this existing information. When the position of the critical tension crack position is unknown, it becomes necessary to use an optimization approach to locate the position and depth of the tension crack.

![Figure 8.5: 3D view of the plane failure with tension crack](image-url)
Figure 8.6: Analysis of plane failure with tension crack

The location of the tension crack (figure 4) is expressed by the dimension \( b \) (Hoek and Bray, 1981). When the upper surface is horizontal, the transition from one condition to another occurs when the tension crack coincides with the slope crest. The depth of critical tension crack, \( z_c \) and its location, \( b_c \) behind the crest can be calculated by the following equations:
A simplified model consisting of a measured depth of water in the tension crack is shown in figure 6. It is assumed that the tension crack is vertical and is filled with water to a depth \( z_w \).

It is considered that water enters the sliding surface along the base of the tension crack and seeps along the sliding surface, escaping at atmospheric pressure where the sliding surface daylights in the slope face. For slope stability analysis, a unit thickness of the slice is considered at right angle to the slope face. Under this condition, the water pressure decrease linearly toward and exit at the toe of the slope. This pressure distribution results in a force \( V \) due to water filling in the sub-vertical discontinuity and an uplift force \( U \) due to water flowing at the surface between the block and its base.

\[
\frac{z_c}{H} = (1 - cot\alpha \tan\theta)
\]

\[
\frac{b_c}{H} = \sqrt{\left(\cot\alpha \cot\theta\right) - \cot\alpha}
\]

\[
z = H - (b + H \cot\alpha) \tan\theta
\]

\[
AD = \frac{H - CD}{\sin\theta}
\]

\[
W = \frac{\gamma_r H^2}{2} \left(1 - \left(\frac{z}{H}\right)^2\right) \left(\cot\theta - \cot\alpha\right)
\]

\[
FOS = \frac{cA + w \cos\theta \tan\phi}{w \sin\theta}
\]
\[ Z = H + b \tan \alpha_c - (b + H \cot \alpha) \tan \theta \]

\[ W = \frac{1}{2} \left( H^2 \cot \alpha X + bHX + bZ \right) \]

\[ W = \frac{\gamma_r H^2}{2} \left( 1 - \left( \frac{z}{H} \right)^2 \right) \cot \theta - \cot \alpha + \frac{\gamma_r}{2} (b \times \tan \alpha_c) \]

\[ A = (H \cot \alpha + b) \sec \theta \]

\[ V = \frac{1}{2} \gamma_w Z_w^2 \]

\[ U = \frac{1}{2} \gamma_w Z_w A \]

Factor of safety is given by the equation when water pressure is there,

\[ \text{FOS} = \frac{cA + (w \cos \theta - U - V \sin \theta) \tan \phi}{W \sin \theta + V \cos \theta} \]