Swiss Virtual Campus
“Dealing with Natural Hazards”

Module: Module 03
Topic Group: Process analysis – Rock slopes
Learning Unit: Conventional rock slope analysis
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Objectives

The objectives of this learning unit are to outline and demonstrate the conventional methods used to analyze:

- planar failures
- wedge failures
- toppling failures
- rotational failures

The techniques presented in this learning unit focus on the kinematic feasibility and limiting equilibrium conditions for the different modes of failure.

Introduction

Assessing the stability of natural and engineered rock slopes, which are influenced by natural or induced changes to their environment, can be aided by the application of analytical and numerical techniques.

Both analytical and numerical techniques generally represent a realistic simplification, rather than an exact imitation of reality. The properties of geological materials and their associated mechanical interactions can never be known in detail sufficient enough to allow unambiguous simulated representations.

Rock slope analysis

The stability of a slope depends on its ability to sustain changes in applied load and modification of environmental conditions. Both affect the geological materials mechanically, hydrologically and/or chemically (e.g. through weathering). The analysis of slope stability may be implemented at two distinct stages.

Pre-failure analysis – applied to assess safety in a global sense to ensure that the slope will perform as intended.
Post-failure analysis – also termed back-analysis, should be responsive to the totality of processes which led to failure.

The fundamental requirement for a meaningful analysis, should include the following steps of data collection/evaluation:

- site characterization (geological and hydrogeological conditions);
- groundwater conditions (pore pressure model);
- geotechnical parameters (strength, deformability, permeability);
- instability mechanisms (kinematics or potential failure modes).

<table>
<thead>
<tr>
<th>Situation</th>
<th>complicated geology</th>
<th>simple geology</th>
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<tbody>
<tr>
<td></td>
<td>inaccessible</td>
<td>$$ spent on site investigation</td>
</tr>
<tr>
<td></td>
<td>no testing budget</td>
<td>investigation</td>
</tr>
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| Data               | none               | large data set |

| Approach           | Investigation of failure mechanism(s) | predictive |

Site investigation methods

Desk study – previous investigations, literature review, available data.

Site investigation – field mapping, scanline surveys, observations of instability, hydrological observations.

Laboratory testing – determination of rock strength, material behaviour (discontinuity shear strength evaluation).

Conventional stability analysis – kinematic feasibility, deterministic limit equilibrium (factor of safety), probabilistic sensitivity analysis.


Field monitoring – monitoring of 3D deformations, groundwater & microseismicity.
With a proper site investigation, rock slope stability analysis allows for:

- the determination of rock slope stability conditions and/or instability mechanisms.

- the determination of the slope’s sensitivity/susceptibility to triggering mechanisms (e.g. heavy precipitation, earthquakes, freeze/thaw, etc.).

- the stabilization of unstable or potentially unstable slopes.
• the optimal design of excavated slopes in terms of safety, reliability and economics.

**Continuum V’s Discontinuum**

Rock slope analyses can be performed assuming that the unstable rock mass acts as a homogeneous continuous material (i.e. a continuum) or that discontinuities will control the failure (i.e. a discontinuum).

As a continuum, the failure path passes through the rock mass.

For all but very weak rock materials, the analysis of rock slope stability is fundamentally dependent on a detailed analysis of the rock mass structure.

As a discontinuum, the failure surface is dictated by the presence of specific pre-existing discontinuities.
It is also possible to have intermediate cases where the failure occurs partly along discontinuities and partly through intact rock bridges.

**Discontinuity strength**

Although most soil slope instabilities are of the continuous nature, the majority of rock slope instability problems are controlled by discontinuities. This is because the strength of the intact rock can be high relative to that of any pre-existing discontinuities, which in turn act to form planes of weakness in the rock mass.
Surface irregularities are referred to as asperities, and act to cause interlocking between adjacent discontinuity surfaces (thereby providing increased resistance against shearing).

With increasing normal stresses, there is a transition from dilation to shearing. With increasing normal stress and displacement, asperities are sheared off and the friction angle decreases to a minimum value equal to the residual friction angle of the rock (phi).

Under low normal stress (sn), shear displacements are accommodated by dilation as
asperities opposite one another ride up and over each other. Shear resistance is therefore a function of the asperity angle $i$ and the basic friction angle $\phi$.

**Conventional analysis techniques**

Two types of conventional techniques are currently used to assess rock slope stability:

**Kinematic analysis**
Determines whether a block can move or not. Standard tools include the use of stereonets and key block theory.

**Limit equilibrium analysis**
Constitutes the most widely applied analytical technique used in slope stability analysis. Involves calculation of force and/or moment equilibrium conditions examined on the basis of static mechanics. These analyses require information about material strength, but not stress-strain behaviour (in other words only forces are considered and not displacements).

**Factor of safety**
The output from a limit equilibrium analysis is the “Factor of Safety”, determined from a balance of the static force and/or equilibrium conditions:

$$FS = \frac{\text{resisting forces}}{\text{disturbing forces}} = \frac{\text{shear strength}}{\text{shear stress}}$$

...where $FS > 1.0$ represents a stable situation and $FS < 1.0$ denotes failure

**Application of conventional techniques to slope failure**
Four basic types of slope failure to which conventional techniques of analysis maybe applied are:

planar failure

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wedge failure

toppling failure

circular failure

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Planar sliding – Kinematic analysis

Planar slides generally involve a major discontinuity of lengthy persistence. The case of planar sliding is simple to analyse, in that it is statically determinate.

To consider the kinematic feasibility of plane instability, four necessary but simple criteria are introduced:

- The dip of the slope must exceed the dip of the potential slide plane;
- The potential slip plane must daylight on the slope plane;
- The dip of the potential slip plane must be such that the strength of the plane is reached;
- The dip direction of the sliding plane should lie approximately ±20° of the dip direction of the slope.

Planar sliding – Limit equilibrium analysis

The solution for plane sliding using limit equilibrium analysis requires that the strike of the failure plane and slope are parallel and that no end restraints are present.

Assumptions are incorporated in the solution that...

- define the rock mass as impermeable.
- the sliding block is rigid.
- the strength of the slide plane is given by the Mohr Coulomb criterion.
- all forces pass through the centroid of the sliding block.

Factor of safety equation:

\[
FS = \left\{ \frac{cA + [W(\cos \psi_p - a \sin \psi_p) - U - V\sin \psi_p T \cos \theta \tan \phi]}{[W(\sin \psi_p + a \cos \psi_p) + V\cos \psi_p - T \sin \theta]} \right\}
\]

Wedge kinematic analysis

Wedge sliding can be extended from planar sliding by considering simultaneously sliding along two planes.

To consider the kinematic feasibility of wedge instability, we need to consider three criteria relating to the line of intersection:

- The dip of the slope must exceed the dip of the line of intersection of the two wedge forming discontinuity planes;
• The same line of intersection must daylight on the slope plane;
• The dip of the line of intersection must be such that the strength of the two planes are reached.

**Wedge sliding – Limit equilibrium analysis**

Wedge sliding assumes that the direction of sliding is parallel to the line of intersection of the two sliding planes, forces parallel to this line and perpendicular to the sliding planes can be resolved in order to determine the factor of safety.

\[
FS = \frac{(R_A + R_B) \tan \phi}{W \sin \psi_i}
\]

where:
- \(FS\) is the factor of safety,
- \(R_A + R_B\) is the resisting forces,
- \(W\) is the weight of the wedge,
- \(\sin \psi_i\) is the sine of the angle between the sliding surface and the horizontal plane,
- \(\tan \phi\) is the tangent of the friction angle.

\[
R_A + R_B = \frac{W \cos \psi_i \sin \beta}{\sin 1/2 \delta}
\]

Example: limit-equilibrium and probability analysis for an unstable wedge showing wedge frequency vs factor of safety for possible wedges formed from a discontinuity data set.
Toppling instabilities

**Direct toppling**
Occurs when the centre of gravity of a block lies outside the outline of the base of the block, with the result that a critical overturning moment develops.

![Direct Toppling Diagram]

**Flexural toppling**
Occurs under certain circumstances when a layered rock mass outcrops at a rock slope, and the principal stress parallel to the slope face induces inter-layer slip which causes the intact rock to fracture and the resulting blocks to overturn, however.

![Flexural Toppling Diagram]

...to analyse both the intact rock deformation and inter-layer slip along discontinuities necessary for promoting flexural toppling, more advanced analysis techniques must be employed (e.g. numerical modelling).
Direct toppling – Kinematic analysis

The kinematic-based question in the case of direct toppling is whether a block resting on an inclined surface will be stable, slide, or topple. The nature of direct toppling is determined from considerations of the block geometry and the angle of friction between the block and the surface on which it is resting.

The four categories for equilibrium are...

- **stable block**: \( \psi < \phi \) and \( b/h > \tan \psi \)
- **sliding, no toppling**: \( \psi > \phi \) and \( b/h > \tan \psi \)
- **toppling, no sliding**: \( \psi < \phi \) and \( b/h < \tan \psi \)
- **sliding and toppling**: \( \psi > \phi \) and \( b/h < \tan \psi \)

Direct toppling – Limit equilibrium analysis

To determine whether a block will be stable, slide or topple the following conditions must be satisfied:

- **stable block**: \( \psi < \phi \) and \( b/h > \tan \psi \)
- **sliding, no toppling**: \( \psi > \phi \) and \( b/h > \tan \psi \)
- **toppling, no sliding**: \( \psi < \phi \) and \( b/h < \tan \psi \)
- **sliding and toppling**: \( \psi > \phi \) and \( b/h < \tan \psi \)

Rotational slides – Limit equilibrium analysis

Although rotational failures are primarily associated with failures in soils, such failures may occur in rock if the failure surface is not predominantly controlled by structural discontinuities. If the mode of failure is not structurally controlled and the rock mass strength is of the same magnitude as the induced shear stresses (i.e. stress-controlled), similar techniques as those used in soil slope analysis may be employed.

The most widely used of these being the method of slices, where a critical slip surface is calculated based on the balance of driving forces/moments and resisting forces/moments. Several solutions exist (e.g. Ordinary, Bishop Simplified, Morgenstern-Price, etc.) with each differing in terms of the underlying assumptions taken in the force/moment balance to make the problem determinate.
Curtailed slip surface e.g. changes in lithology, igneous intrusion and mineralization.

In the case of inhomogeneous material, the presence of an underlying bed of hard, strong material can limit the extent of failure.

Slip surfaces nearly planar e.g. heavily broken rock, tailings and some soils.

If the ground has a granular nature with a low cohesive strength, the curvature of the slip surface is less marked (i.e. the surface tends to be planar, and the tension crack is small or non-existent).

Slip surface follows major structural features e.g. bedding planes, joints, faults and shear zones.

If there is a major discontinuity, fault or clay seam in the region of the instability, the slip surface will tend to follow this feature as far as possible.
Limitations of conventional methods

Conventional methods are very useful in rapidly carrying out sensitivity analyses of the parameters affecting slope stability and are also used in back analysis. However, these methods do have significant limitations.

- simple slope geometries and geology.
- homogeneous, isotropic, linear elastic rock masses.
- basic loading conditions (do not incorporate in situ stresses).
- pore-water pressures are treated as a simple phreatic surface.
- do not consider stress state evolution or progressive failure.
- provide little insight into slope failure mechanisms.

Self Evaluation Test

See web.

References

Author: Dr Erik Eberhart, Dr Andrew Kos.
Production: Dr Andrew Kos.

Bibliography


