Module 5:
Lecture -4 on Stability of Slopes
Sudden drawdown
Determination of most critical slip surface

Criteria for most critical slip surface = Minimum factor of safety

Trial and error approach involves following parameters
a) Center of rotation of the slip surface
b) Radius of slip surface
c) Distance of intercept of slip surface from the toe
d) Minimum factor of safety achieved
Fellenius (1935) proposed empirical approach for cohesive soils ($\phi_u = 0$)

<table>
<thead>
<tr>
<th>Slope ratio</th>
<th>$\alpha$</th>
<th>$\Psi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 : 0.58</td>
<td>29°</td>
<td>40°</td>
</tr>
<tr>
<td>1 : 1</td>
<td>28°</td>
<td>37°</td>
</tr>
<tr>
<td>1 : 1.5</td>
<td>26°</td>
<td>35°</td>
</tr>
<tr>
<td>1 : 2</td>
<td>25°</td>
<td>35°</td>
</tr>
<tr>
<td>1 : 3</td>
<td>25°</td>
<td>35°</td>
</tr>
<tr>
<td>1 : 5</td>
<td>25°</td>
<td>37°</td>
</tr>
</tbody>
</table>

Draw line through corners of slope at angle $\alpha$ and $\Psi$ as per in table.

$O_1$ will be center of rotation for slip circle.
Jumikis (1962) extended the method for $c' - \phi'$ soil

Possible locations of centers for $c' - \phi'$ soil

Center of rotation of critical circle is assumed to lie on PO$_1$ line. Point P is at distance H below the toe in vertical direction and 4.5 H away from toe in horizontal direction.
Comparison of LE methods

Grid and radius option used to search for circular CSS

Entry and exit option used to search for circular CSS
Comparison of LE methods

<table>
<thead>
<tr>
<th>Slope material Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit wt (kN/m^3)</td>
<td>19.64</td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>4.31</td>
</tr>
<tr>
<td>Friction angle (°)</td>
<td>32</td>
</tr>
</tbody>
</table>

Schematic diagram slope cross-section

After Lambe and Whitman, 1969)
Bishop simplified Method (BSM)

Slope stability analysis (Geo-slope 2012)
Slices data (Bishop’s method) for Lambe and Whitman problem

- **Normal stress at the base of slices (kPa)**
- **Shear stress mobilised (kPa)**

**Graphs:**
- Left graph: Normal stress at the base of slices vs. distance from toe of the slope (m)
- Right graph: Shear stress mobilised vs. distance from toe of the slope (m)
Finite element modeling with help of Plaxis 2D

Possible failure surfaces

FOS with FEM = 1.29

Slope stability analysis Lambe and whitman problem
### Comparison of FOS in LEM and FEM

<table>
<thead>
<tr>
<th>Method of analysis</th>
<th>Factor of safety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Limit Equilibrium</strong></td>
<td></td>
</tr>
<tr>
<td>Ordinary method of slices</td>
<td>1.161</td>
</tr>
<tr>
<td>Bishops method</td>
<td>1.289</td>
</tr>
<tr>
<td>Janbu’s method</td>
<td>1.222</td>
</tr>
<tr>
<td>Morgenstern-Price method</td>
<td>1.306</td>
</tr>
<tr>
<td><strong>Finite Equilibrium</strong></td>
<td></td>
</tr>
<tr>
<td>Strength reduction factor</td>
<td>1.29</td>
</tr>
</tbody>
</table>
Aryal (2003)

Minimum FOS
1) BSM = 1.758
2) JSM = 1.590
3) JGM = 1.716
4) M-PM = 1.737

FOS = 1.654
Development of phreatic surfaces within the slope

\[ \frac{u}{\gamma h} \]
Comparison of Phreatic surfaces measured and computed from SEEP/W

$\beta = 63.43^\circ$

$q = 1.98 \text{ m}^3/\text{days}$
Variation of FS with $u/\gamma h$

45 degrees slope; Silty sand; $h = 12$ m
Example 4 for Practice

A cutting 9 m deep is to be excavated in a saturated clay of unit weight 19 kN/m³. The design shear strength parameters are $c_u = 30$ kN/m² and $\phi_u = 0^\circ$. A hard stratum underlies the clay at a depth of 11 m below ground level. Using Taylor's stability method, determine the slope angle at which failure would occur. What is the allowable slope angle if a factor of safety of 1.2 is specified.
Example 5 for Practice

For the given failure surface, determine the factor of safety in terms of effective stress for the slope detailed in Figure, using the Fellenius method of slices. The unit weight of the soil is 21 kN/m$^3$ and the characteristic shear strength parameters are $c' = 8$ kN/m$^2$ and $\phi' = 32^\circ$. 
After Craig (2004)
Rapid Drawdown Condition
Steady state Seepage

After the reservoir or dam has been full for some time, conditions of steady seepage become established through the dam with the soil below the top flow line in the fully saturated state. This condition must be analysed in terms of effective stress with values of pore pressure being determined from the flow net.

Values of $r_u$ up to 0.45 are possible in homogeneous dams but much lower values can be achieved in dams having internal drainage. The factor of safety for this condition should be at least 1.5.
Rapid drawdown

After a condition of steady seepage has become established, a drawdown of the reservoir level will result in a change in the pore water pressure distribution.

If the permeability of the soil is low, a drawdown period measured in weeks may be ‘rapid’ in relation to dissipation time and the change in pore water pressure can be assumed to take place under undrained conditions.
Slope stability analysis in drawdown condition

Response of slope to rapid drawdown

Typical variations in water level during drawdown
Pore water pressure before drawdown at a point \( P \) on a potential failure surface is given by

\[
\begin{align*}
  u_o &= \gamma_w (h + h_w - h') \\
  \text{Change in total major principal stress} &= \text{Total or Partial removal of water above the slope on } P.
\end{align*}
\]
\[ \Delta \sigma_1 = -\gamma_w h_w \]

And the change in pore water pressure is then given by

\[ \Delta u = \overline{B} \Delta \sigma_1 \]
\[ = \overline{B} \gamma_w h_w \]

Therefore the pore water pressure at P immediately after rapid drawdown is:

\[ u = u_o + \Delta u \]
\[ = \gamma_w (h + h_w (1 - \overline{B}) - h') \]
Hence, pore water pressure ratio

\[
\frac{r_u}{\gamma} = \frac{u}{\gamma_{sat} h} \quad r_u = \frac{\gamma_w}{\gamma_{sat}} \left[ 1 + \frac{h_w}{h} (1 - B) - \frac{h'}{h} \right]
\]

- For a decrease in total stresses, the value of \( B \) is slightly greater than 1. An upper bound value of \( r_u \) could be obtained by assuming \( B = 1 \) and neglecting \( h_0 \).

- Typical values of \( r_u \) immediately after drawdown are within the range 0.3–0.4. A minimum factor of safety of 1.2 may be acceptable after rapid drawdown.
The pore water pressure distribution after drawdown in soils of high permeability decreases as pore water drains out of the soil above the drawdown level.

The saturation line moves downwards at a rate depending on the permeability of the soil.

A series of flow nets can be drawn for different positions of the saturation line and values of pore water pressure obtained. The factor of safety can thus be determined, using an effective stress analysis, for any position of the saturation line.
Typical flow net in case of drawdown
*(After Craig, 2004)*
Pore pressure ratio \( (r_u) \) can be used for stability analysis as explained by Bishop and Morgenstern (1960).

This method is based on “effective stress method”. It involves following five parameters:

i) Slope angle, ii) Depth factor, iii) angle of shearing resistance \( (\phi') \), iv) non-dimensional parameter \( (c'/\gamma H) \), and v) pore pressure ratio \( (r_u) \).

Factor of safety can be computed by using charts provided by Bishop-Morgenstern (1960).
Seepage and stability analysis for drawdown condition

Drawdown rate \( (R) = \frac{D}{H} \)

\( R_1 = 1 \text{ m/day (rapid drawdown)} \)
\( R_2 = 0.1 \text{ m/day (slow drawdown)} \)

Submerged slope of height 7m and slope of 1 V: 3H

Schematic diagram of lope (After Berilgen, 2007)
Steady state seepage analysis
(constant hydraulic boundaries i.e. total head)

Transient seepage analysis
(varying hydraulic boundaries i.e. total head)

Stability analysis
(consideration of driving forces for failure
i.e. body forces, pore water pressure, etc.)
Four cases were studied considering two drawdown rates and two types of soil.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit weight (kN/m$^3$)</td>
<td>20</td>
</tr>
<tr>
<td>Coefficient of permeability (m/sec)</td>
<td>$10^{-6}$ and $10^{-8}$</td>
</tr>
<tr>
<td>Cohesion (kPa)</td>
<td>10</td>
</tr>
<tr>
<td>Internal friction angle (degree)</td>
<td>20</td>
</tr>
</tbody>
</table>
Pore pressure contours at the steady state condition

Flow paths during drawdown phenomena
Advanced Geotechnical Engineering

Transient seepage analysis using SEEP/W

Depletion of phreatic surfaces

Drawdown rate
R1 = 1 m/day

Variation of pore water pressure at point “P1”

Pore water pressure dissipation with time
Critical failure surface at the end of drawdown

Critical FOS = 1.497

Factor of safety decreases as drawdown progresses
Effect of drawdown rate

Transient seepage analysis for \( R = 1 \text{ m/day} \)

At the end of drawdown

\( K = 10^{-6} \text{ m/sec} \)

Transient seepage analysis for \( R = 0.1 \text{ m/day} \)

More amount of depletion of phreatic surface

\( K = 10^{-6} \text{ m/sec} \)
Variations of pore water pressure with time at the point “P1”

Higher dissipation of pore water pressure in case of slow drawdown

Prof. B V S Viswanadham, Department of Civil Engineering, IIT Bombay
Variations of factor of safety with seepage time

Higher factor of safety due to dissipation of pore water pressure
Effect of coefficient of permeability of soil

Transient seepage analysis for:
- $k = 1 \times 10^{-6} \text{ m/sec}$
- $R = 1 \text{ m/day}$

$\rightarrow$ Depletion of phreatic surface is marginal for soils with $k$
Variations of pore water pressure with time at the point “P1”

Dissipation of pore water pressure is less for soils with low k

Prof. B V S Viswanadham, Department of Civil Engineering, IIT Bombay
Variations of factor of safety with seepage time

Higher FOS for soils having high coefficient of permeability

Critical FOS = 1
## Total stress analysis

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total stresses in soil mass</td>
<td>Common to both methods</td>
</tr>
<tr>
<td>Strength of soil when subjected to changes in total stress similar to stress changes in field</td>
<td>Accuracy is doubtful, since strength depends upon induced pore pressures</td>
</tr>
<tr>
<td>Requirement</td>
<td>Comment</td>
</tr>
<tr>
<td>-------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Total stresses in soil mass</td>
<td>Common to both methods</td>
</tr>
<tr>
<td>Strength parameters of soil in relation with effective stress</td>
<td>considerable accuracy, since this is insensitive to test condition</td>
</tr>
<tr>
<td>Determination of changes in external loads</td>
<td>Accuracy depends on measurement of pore water pressure</td>
</tr>
</tbody>
</table>
Slopes subject to rainfall
Slope instability is a common problem in many parts of the world, and cause thousands of deaths and severe infrastructural damage each year.

Rainfall has been identified as a major cause for triggering landslides and slope failure.

The mechanism leading to slope failure is that the pore water pressure starts increasing when water infiltrates the unsaturated soil.

The problem becomes severe if the fill material has low-permeability, and cannot dissipate the pore water pressure generated due to rainfall.
To investigate the effect of rainfall on slope stability, a limit equilibrium analysis was carried out by using SLOPE/W, a product of Geostudio (2012) software.

Two slope configurations (45° and 63° inclination) were selected, and were subjected to rainfall of various intensities (2mm/hr-80 mm/hr) for 24 hrs.

Phreatic surfaces were fed into SLOPE/W, and stability analyses were performed at the onset of rainfall, during rainfall, and upto 24 hours after rainfall.
Slope configuration selected (45° inclination)
Soil parameters used in SLOPE/W
(FOS was computed by Bishop’s modified method of slices)

Model: Mohr-Coulomb
Unit Weight: 20 kN/m³
Cohesion*: 3.5 kPa
\( \phi^c: 31.5^\circ \)
\( \phi^B: 22.5^\circ \)
Effect of rainfall intensity on slope stability

Note: Slope stability reduces with increasing intensities of rainfall.
Effect of rainfall intensity on Slope stability

Note: Steeper slopes have lower initial FOS, and the effect of rainfall on such slopes is more devastating as compared to flatter ones.