Slope Stabilization Methods
Learning Objectives

• Understand driving and resisting components of slope stability and leverage these concepts towards landslide repair.
• Understand common means of repairing and mitigating slope failures.
Slope Stabilization Methods

• Seldom used independently
• Most efficient method is usually some combination of methods
• Drainage is always part of slope stabilization
• Should not be (finally) selected until the subsurface model is complete
• Should be selected based on desired level of performance
• Safety during construction and for the life of the structure should be the first consideration
Stabilizing Approaches

• Decrease driving force
  • Change geometry
  • Lower groundwater

• Increase resisting force
  • Change geometry
  • Lower groundwater
  • Increase shear strength of soil mass

• Surface Erosion Protection

• Soil Improvement
  • Densification
  • Dynamic Compaction
  • Stone columns
  • Vibrocompaction
Stabilizing Approaches

- Soil improvement
  - Consolidation
    - Surcharge loading
    - Drains
  - Soil reinforcement
    - Geosynthetic reinforcement
    - Soil nailing
    - Micropiles
- Physicochemical Changes
  - Chemical grouting
  - Lime stabilization
  - Cement stabilization
Stabilizing Approaches

- Column Supported Embankments
- Earth retaining systems
  - MSE walls
  - Gravity walls
  - Soldier beams and lagging
  - Soldier beams and shotcrete
  - Tangent pile walls
  - Secant pile walls
Changing Slope Geometry

Increase resisting shear stresses and/or decrease driving stresses.
Stabilizing Methods – Changing Geometry

Unstable

Stable
Unloading

Unload Slide Mass
(Reduce Driving Force)
Unloading
Unloading – Light Weight Fill

Common Embankment Material Used to Encapsulate Lightweight Materials to Prevent Degradation.

Embankment Material Removed and Replaced with Lightweight Fill.

Soils used for embankment Construction Typically Range from 95 to 115 lbs/ft³ Lightweight Fill Materials, Commonly Constructed from Wood Chips, are Typically 30 to 35 lbs/ft³ Foam Blocks that are currently being considered for use are about 1 lb/ft³.
Unloading – Light Weight Fill
Buttressing and Shear Keys

Increase shear resistance and increase shear strength.
Increasing shear strength – shear key
GWT drawn from springline at upslope inclination

Landslide Scarp

New Slide boundaries to match
Changed Cross Section

Two soils in these slices

Rockfill Friction angle in this slice

Buttress extends below shear surface to preclude deeper failure
Buttressing

Construct Buttress and Shear Key
(Increase Resisting Forces)

- Rock Buttress to Resist Slide Movement
- Road Grade
- Toe Grate to Remove Water from Base of Slide
- Shear Key - Provides Shear Resistance to Sliding
Drainage

Increasing shear strength.
Stabilization Method – Lower groundwater
Drainage

Drainage
(Reduce Driving Force, Improve Resisting Forces)
Interceptor Drain

![Diagram of an interceptor drain](image)
Reinforced Slopes and Walls

Recreating a new slope with higher shear strength and controlled drainage.
Soil Reinforcement

• Geosynthetic Reinforced Soil Slopes
• In-situ Soil reinforcement – soil nailing
• MSE Walls
Reinforced Soil in a Nutshell

- Soil: **Strong** in compression, **weak** in tension

- Reinforcement can carry tensile stresses

- Soil + Reinforcement $\Rightarrow$ Structure strong under both compression and tension

- Analogous to reinforced concrete
History: Reinforced Soil Structures

3000 B.C. - Mesopotamia
“Reeds” placed in horizontal layers used to reinforce soil

Great Wall of China – in western desert
How Does Reinforcement Work?
Components of an MSE Wall

- Facing
- Reinforced Fill
- Reinforcement
- Retained Backfill
- Drain
- Leveling Pad
- Foundation Soil

Components of an MSE Wall:

- Facing: The outer layer of the wall, often made of concrete or other materials.
- Reinforced Fill: Soil or gravel reinforced with geosynthetic materials to enhance stability.
- Reinforcement: Geosynthetic materials such as geogrids or geotextiles embedded in the fill to provide additional strength.
- Retained Backfill: The area behind the facing where the retained soil or material is placed.
- Drain: A drainage system to prevent water buildup behind the wall.
- Leveling Pad: A layer of compacted soil or gravel at the base of the wall to level the foundation.
- Foundation Soil: The naturally occurring soil or sand in which the MSE wall is constructed.
Reinforced Soil Slope

Secondary Reinforcement (Typ.)

Erosion Protection

Primary Reinforcement

Reinforced Fill

Retained Backfill

Drain
Major Advantages

**MSEW**
- Simple and rapid construction
- Cost effective
  - Less site preparation
  - Unskilled labor and small equipment
  - Reduced ROW acquisition
  - Less space needed in front during construction
  - No deep foundations
- Technically feasible to heights > 100 ft

**RSS**
- Cost effective where ROW is available
- Can use lower quality reinforced fill + higher seismic accelerations than MSEW
Potential Disadvantages

- Requires large space behind facing
- Requires select fill (MSEW)
- Requires considerations of reinforcement corrosion/degradation
MSEW / RSS Components

**Major Components**
- Reinforced fill material (soil)
- Reinforcement
- Facing

**Other Components**
- Joint Materials
- Leveling Pads
- Coping
- Drainage
- Membrane (salts)
- Connections
- Traffic Barrier
- Ground Improvement (if needed)
Common Facing Systems

- Precast concrete panels (wet cast)
- Modular blocks (dry cast)
- Gabions
- Welded wire mesh
- Cast-in-place
- Timber
- Shotcrete
- Vegetation
- Geosynthetic: wrap around, geocells
Soil Nails and Micropiles
Increase resisting stresses.
Micro-Pile Wall Roadway Stabilization
H Pile and Lagging Tieback Wall
Typical Tieback
H Pile and Shotcrete
Soil Nails

• Soil Nailing - an in situ technique for reinforcing, stabilizing and retaining excavations and deep cuts through the introduction of relatively small, closely spaced inclusions (usually steel bars) into a soil mass, the face of which is then locally stabilized.
• The “nails” are passive – they required soil movement to mobilize their strength.
• Reinforced earth looks similar, but the fill material in which the reinforcement is placed is fill rather than insitu soil.
• Earth Anchors look similar, but they are active elements – tensioned.
EXCAVATION BY STEPS

RETAINING STRUCTURES

SLIDING ZONE

SLOPE STABILIZATION
Construction Process

Step 1. Excavation

Step 2. Nail Installation

Step 3. Shotcreting

Step 1. Excavation
Soil Nail system – full length grouting of nails – no initial load.

Earth Anchor system – only the portion of the anchor behind the assumed failure surface is grouted to provide load transfer – anchors are tensioned.
Applications

- Slumps, creeping slopes, often used for cuts and fills
- Vertical or near vertical cut construction (i.e. road widening projects)
- Tunnel portals
- Repair existing walls (i.e., MSE )
MSE Remediation
What are the advantages of Soil Nailing?

- Incorporation of temporary support in final structure
- Reduction in cut excavation
- Potential reduction in right-of-way
- Rapid construction
- Large # of nails - redundant system
- Cost effective
What are the disadvantages of Soil Nailing?

- Permanent underground easements may be required
- Difficult to construct wall with high groundwater
- Utility conflicts
- Nail capacity may not be economical in highly plastic clays
- Ground displacements
- Durability of shotcrete with respect to freeze thaw
- Soil face must exhibit sufficient stand up time
Soil Nail Design – Failure Modes

- External Failure
- Internal Failure
- Mixed Failure
- Crossing the Nails
Internal Failure Modes

(d) Nail-Soil Pullout Failure

(e) Bar-GROUT Pullout Failure

(f) Nail Tensile Failure

(g) Nail Bending and/or Shear Failure
Construction: ~5 feet increments
Good Root Reinforcement
Grout, then...
Wire mesh and drain behind face
Happily apply shotcrete
What are common issues/problems with soil nailing?

• Not economical in soils with poor standup time or requiring cased drill holes
• Not economical in cohesive soils with low to medium strength below groundwater table
• May require freeze-thaw consideration in northern climates
• Deformation
Note wetness - freeze impact
Vegetation and Surface Protection

Decreasing erosion potential and oversteepening (decreasing driving forces).
The Role of Vegetation in Slope Stability

Hydrologic Effects
1. Foliage intercepts rainfall reducing the rate at which water seeps into the subsurface. Absorption and evaporation reduce the amount that reaches the soil
2. Roots and stems increase surface roughness, increasing infiltration
3. Roots extract moisture from the soil which is transpired to the atmosphere
4. Soil moisture depletion can dessicate the soil and cause cracking that allows increased infiltration

Mechanical Effects
5. Roots reinforce the soil, increasing shear strength
6. Tree roots may anchor into underlying rock, supporting the overlying soil
7. Weight of trees surcharges the slope. Increasing normal and down-slope force components
8. Vegetation exposed to wind transmits dynamic forces into the slope
9. Roots bind soil particles at the ground surface and increase surface roughness which reduces erosion.

From Cornforth, 2005
Surface Protection
Surface Treatments
Stabilization Method – Erosion Control
Stabilization Method – Erosion Control
Stabilization Method – Erosion Control
Avoidance
Addressing Toe Erosion of Buttresses
Reinforcement
Earth Retention Structures

Construct Retaining Wall
(Increase Resisting Force)
Tieback Wall Construction
Rockfall Mitigation
Avoidance
Slope/Catchment Design
No Catchment
Catchment Modification
Rockfall Catchment Area Widths For Various Cut Slope Rates And Ditch Slope Configurations For 90% Retention

Basis of data is ODOT's Nov. 2002 Rockfall Catchment Area Design Guide. For each cut slope rate and ditch slope configuration, 100 1", 75 2", and 75 3" rocks were assessed. Rock sizes were +/- 6".
Scaling – Trim Blasting
Slope Mats
Rock Fences
Rock Bolts
Other Mechanical Methods

1. Reinforced concrete shear key to prevent loosening of slab at crest.
2. Tensioned rock anchors to secure sliding blocks along crest ($l_b$—bond length; $l_u$—unbonded length).
3. Tied-back wall to prevent sliding on fault zone.
4. Shotcrete to prevent raveling of zone of fractured rock.
5. Drain hole, oriented to intersect water-bearing joints, to reduce water pressure within slope.
6. Concrete buttress to support rock above cavity.
Questions?