Ground Control at MNM Surface Mines:

Highwall Hazards at Quarries
Slope Stability at Sand and Gravel Mines

Northeast
Mine Safety & Health Conference
2017

Presented by Eric Gottheld, Civil Engineer
Mine Waste and Geotechnical Engineering Division
Pittsburgh Safety and Health Technology Center
Directorate of Technical Support
Mine Safety and Health Administration, USDOL

Objectives

To provide an understanding of:

- **How ground control hazards are created,**
- **How to recognize them, and**
- **how to correct these hazards**

Ground control (GC) hazards are created when workers are exposed to highwalls, pit walls, banks, or slopes with the potential for failure.

Exposure can be from above… (falling material)

…or below (loss of support).

Eliminating GC Hazards

1. **Establish mining methods that maintain stability** - through thoughtful planning, evaluation, and design.

2. **Recognize hazardous conditions** - through regular examinations with consideration of changes in geology/ground conditions, seepage, pit wall geometry, rock mass composition, and potential failure modes.

3. **Remediate the condition** – through the application of corrective measures intended to prevent failure or prevent exposure.

4. **Prevent exposure** – through relocating work areas, barriers, protective measures, or monitoring.

What is a Highwall?

- **The unexcavated face of exposed overburden and coal in a surface mine.**
  - Dictionary.com

- **A steeply angled face of naturally occurring <u>rock</u> created by the excavation of adjacent rock and soil.** **– Working Definition**

Highwall failures

- **A highwall failure is generally the unintended loss of material from a highwall.**
- **Two general types of highwall failures:**
  - **Rock Mass Failures – involve a relatively large amount of material on a large portion of a highwall (can be material or structure controlled);**
  - **Rock Falls – involve a discrete number of individual rocks on a small portion of a highwall.**

Rock Mass Failures – Involve a relatively large amount of material on a large portion of a highwall

Highwall Stability

- **Highwalls are composed of rock masses that consist of blocks of intact rock that are separated by structural discontinuities.**

- **Unless the rock is very weak, highwalls fail along structural discontinuities (i.e., joints, cracks, sloping bedding planes and other discontinuities).**

- **The orientation and location of these fracture planes determine the failure type, extent of the sliding rock, and the path that it will take.**

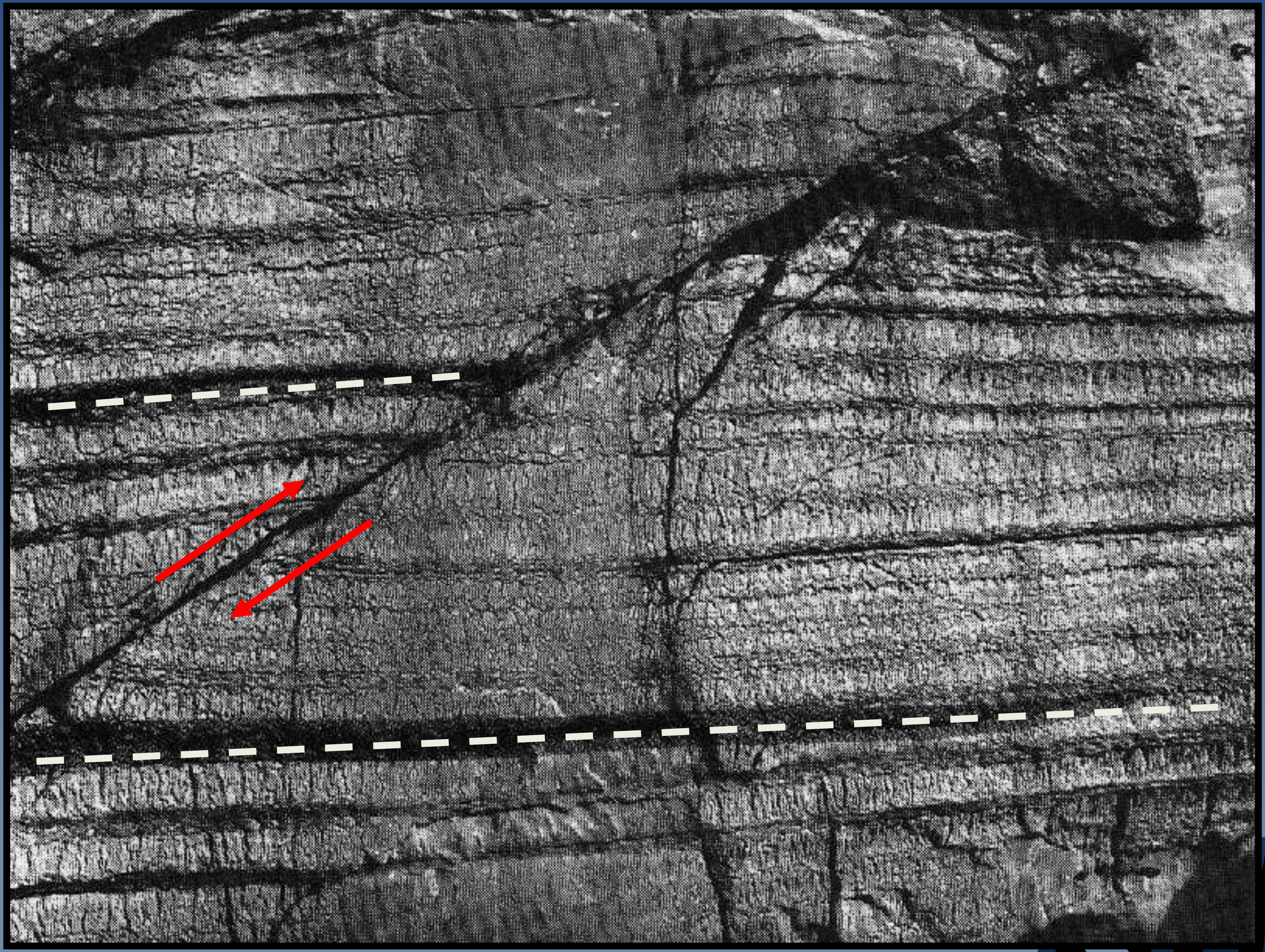
Common Types of Discontinuities

- **Bedding** – a depositional surface found in sedimentary rocks.
- **Joint** – a discontinuity along which no observable displacement has occurred.
- **Fault** – a discontinuity along which displacement has occurred.
- **Fracture** – a generic term applied to a variety of discontinuities.

Bedding

Joints

Fault



Fractured Highwall

Properties of Discontinuities

- Orientation
- Spacing
- Persistence
- Roughness
- Aperture (opening)
- Infilling
- Seepage
- Number of Sets

Rock Mass Failure Modes

- Planar
- Wedge
- Toppling
- Circular


Dip Into Highwall
Dip Into Pit

Planar Failure

Intersecting Discontinuities

Wedge Failure

Joints forming Columns

Toppling Failure

Circular Failure – Before and After

Points to Remember

- Discontinuities can occur at virtually any orientation and spacing.
- The orientation in which discontinuities intersect each other and the highwall face contribute to the failure type and potential.
- Knowledge of discontinuity properties in the mine environment is necessary for evaluation of highwall stability.

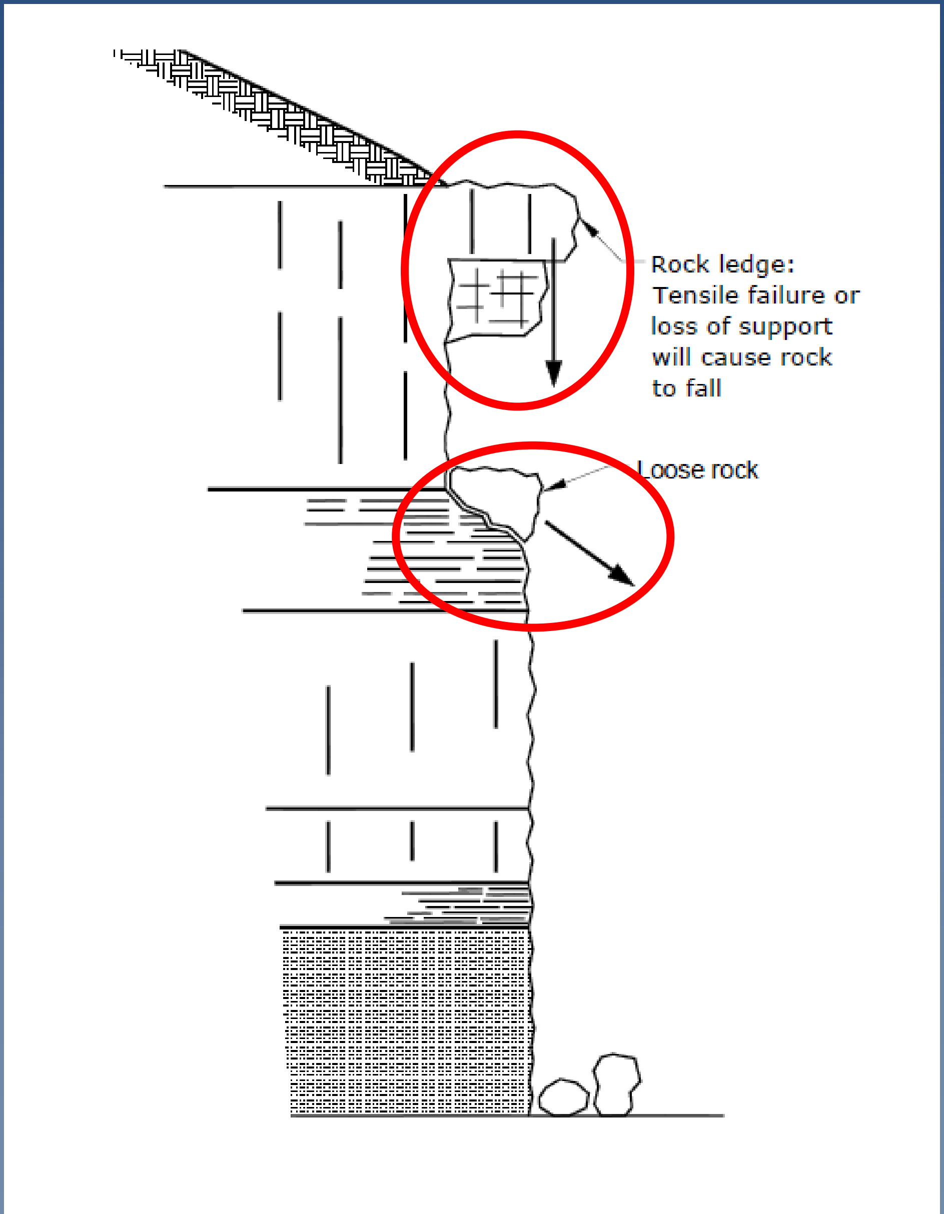
Seepage

Seepage

- Seepage is often a contributing factor to highwall failures.
- Effects of seepage:
  - reduces shear strength of soil/rock,
  - creates driving force in joints,
  - erodes supporting material,
  - adds weight to the potential sliding mass, and
  - formation of ice dislodges loose rock and increases pore pressure

Rock Falls

Rock Falls



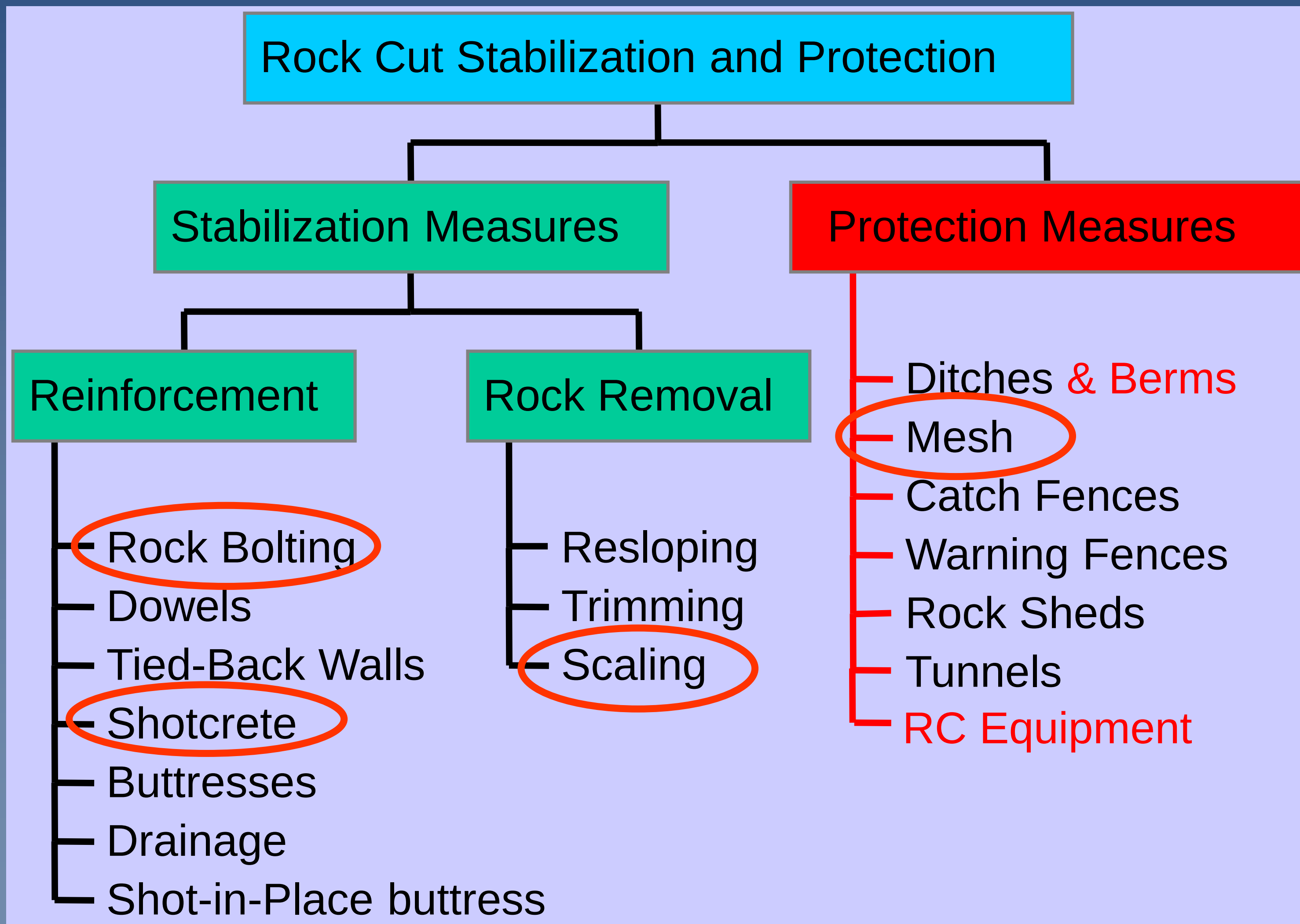
Intact blocks of rock on a fractured highwall are susceptible to falling when they are unconfined.

Trees near the edge of a highwall are also a fall of material hazard.

Loose Rock

Overhangs

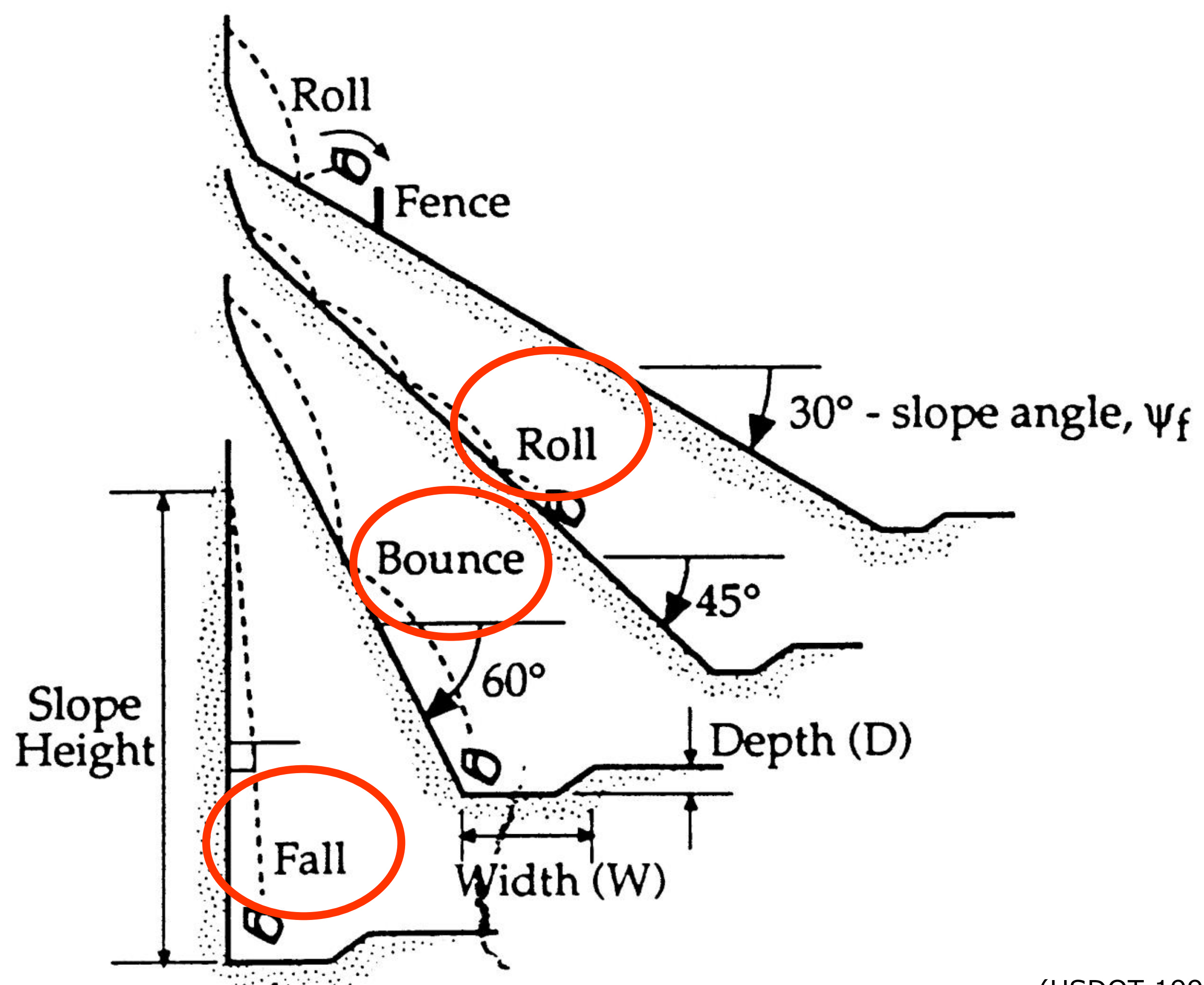
Corrective Measures Intended to Prevent Failure (Stabilization) and Prevent Exposure (Protection) – TRB, 1996



Rock Fall Analysis – for Design of Ditches and Berms

- Geometry and height of the highwall will affect how a rock falls, where it impacts, and where it comes to rest.
- Block size (weight) and drop height will determine the damage potential of a falling rock when it strikes.

Effects of Highwall Geometry on Rock Fall Trajectory



(USDOT 1998)

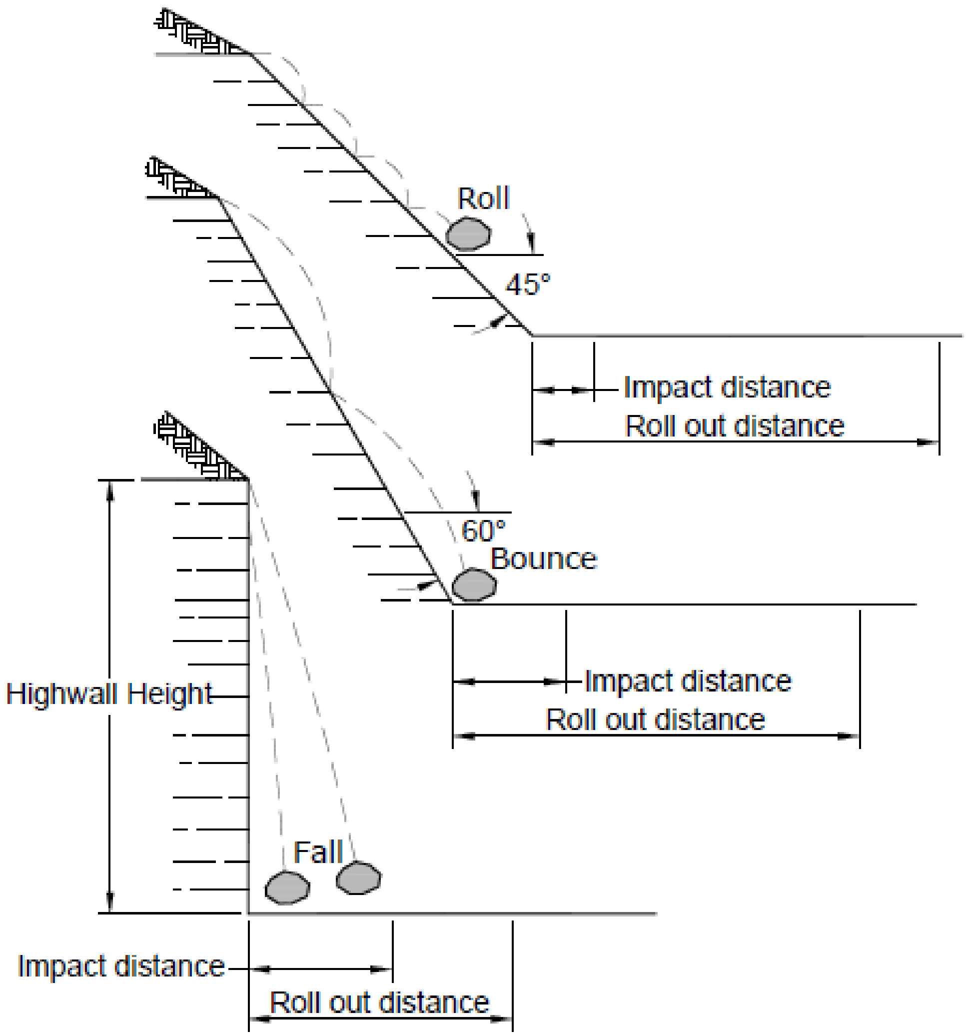
Design of Rock Fall Catchment Areas

Catchment Width (W) Berm Height (D)

Highwall Slope	Highwall Ht. (ft)	W (ft)	D (ft)
Near Vertical	15-30	10	3
Near Vertical	30-60	15	4
Near Vertical	over 60	20	4
0.25H to 0.3H:1V	15-30	10	3
0.25H to 0.3H:1V	30-60	15	4
0.25H to 0.3H:1V	60-100	20	6
0.25H to 0.3H:1V	over 100	25	6
0.5H:1V	15-30	10	4
0.5H:1V	30-60	15	6
0.5H:1V	60-100	20	6
0.5H:1V	over 100	25	8
0.75H:1V	0-30	10	3
0.75H:1V	30-60	15	4
0.75H:1V	over 60	15	6
1H:1V	0-30	10	3
1H:1V	30-60	10	5
1H:1V	over 60	15	6

Ritchie (1963)

Rock Fall: Impact and Roll out Distance



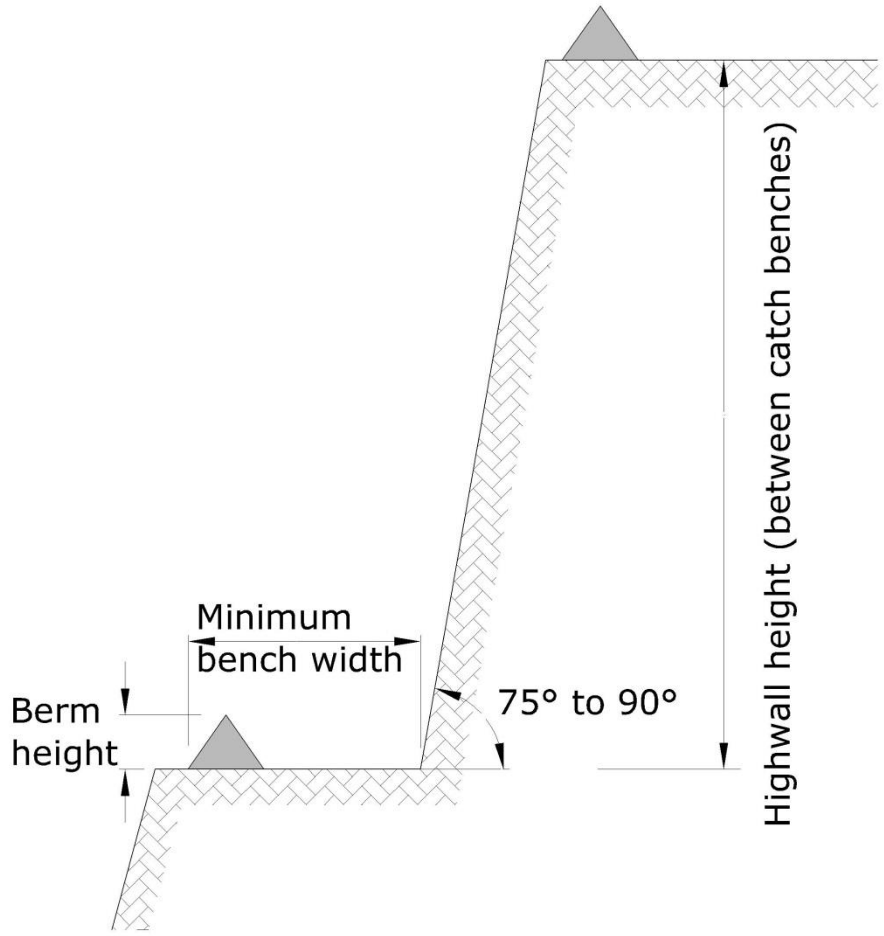
Impact Distances (feet) for 99% of rocks

Highwall Height (ft)	Vertical	0.25H:1V	0.5H:1V	0.75H:1V	1H:1V
40	14	9	6	5	0
50	15	13	11	10	4
60	16	16	15	14	8
70	18	19	17	15	9
80	21	22	19	16	10

Rollout Distances (feet) for 99% of rocks

Highwall Height (ft)	Vertical	0.25H:1V	0.5H:1V	0.75H:1V	1H:1V
40	30	32	48	44	60
50	30	51	56	54	63
60	30	69	66	65	67
70	30	74	67	66	73
80	30	79	68	68	79

Catch Bench Design



- Minimum bench width = 15 feet + (0.2 x highwall height)
- Berm height = 3 feet + (0.04 x highwall height)

(adapted from Call, 1986)

Catch Bench w/Berm
– they do exist

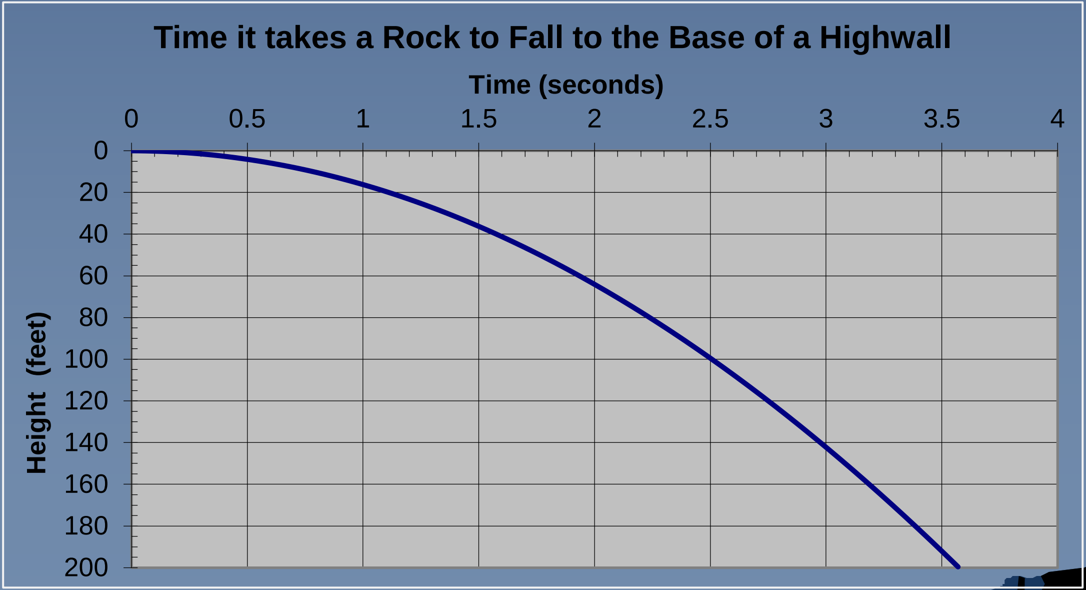
Relatively Small Rocks can pose an Impact Risk to Personnel On-Foot

- 1999 (TN) – Driller at base of 230 ft. highwall
- Rock measured 4" x 4" x 3" & weighed under 3 pounds

Rock Fall: Impact Energy

Height of Rock Fall (feet)	Size of Rock[1] (inches)	Approx. Weight (lbs)	Kinetic Energy (ft-lbs)	Approx. Force of Impact[2] (lbs)	Speed (mph)	Time to Impact (secs)
50	4	6	300	1,200	38	1.8
50	6	20	1,000	4,000	38	1.8
50	12	160	8,000	32,000	38	1.8
100	12	160	16,000	64,000	54	2.5

Hardhats are tested at 40 ft-lbs and FOPS are tested at 8,500 ft-lbs.

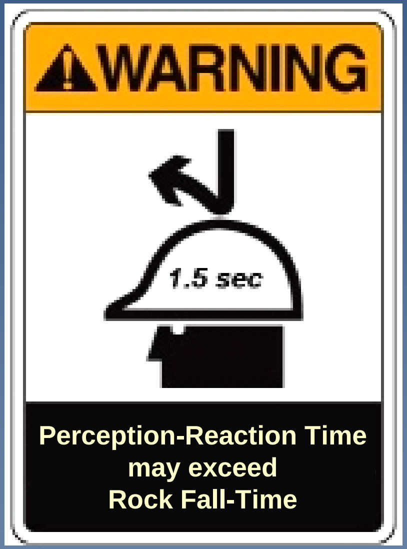


Perception-Reaction Time

- One’s perception-reaction time depends on many factors such as expectancy, attention, visual acuity, decision-making complexity, time of day, fatigue, age, etc.

- Research suggests that the perception-reaction time to brake for a traffic signal varies from about 0.9 to 1.3 seconds.

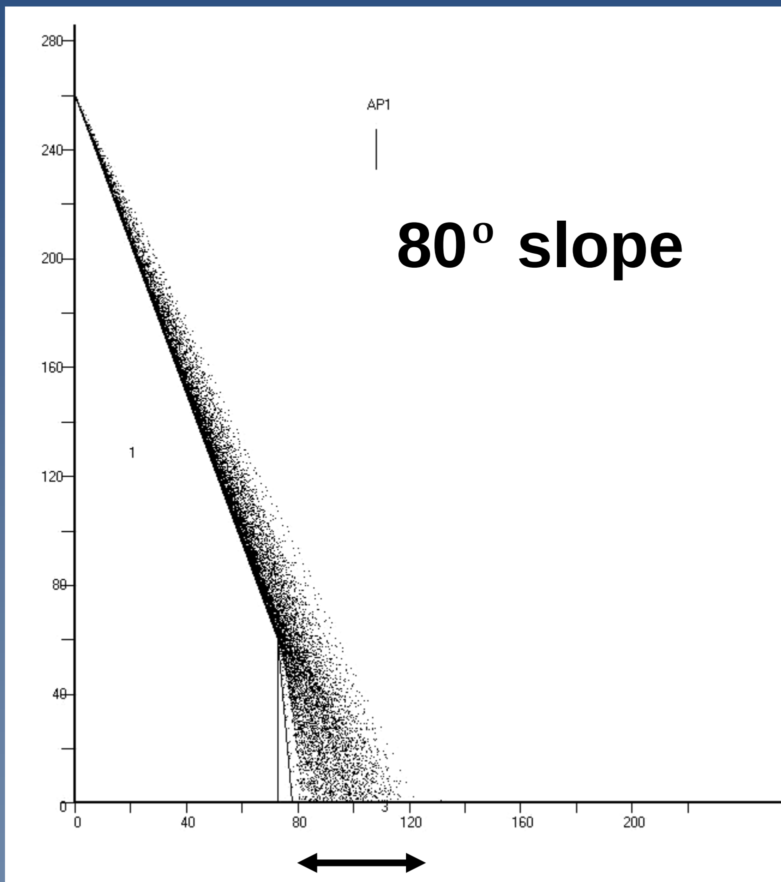
- When using a spotter, the perception-reaction time of the exposed person to the spotter’s alarm is in addition to the perception-reaction time of spotter to the event.



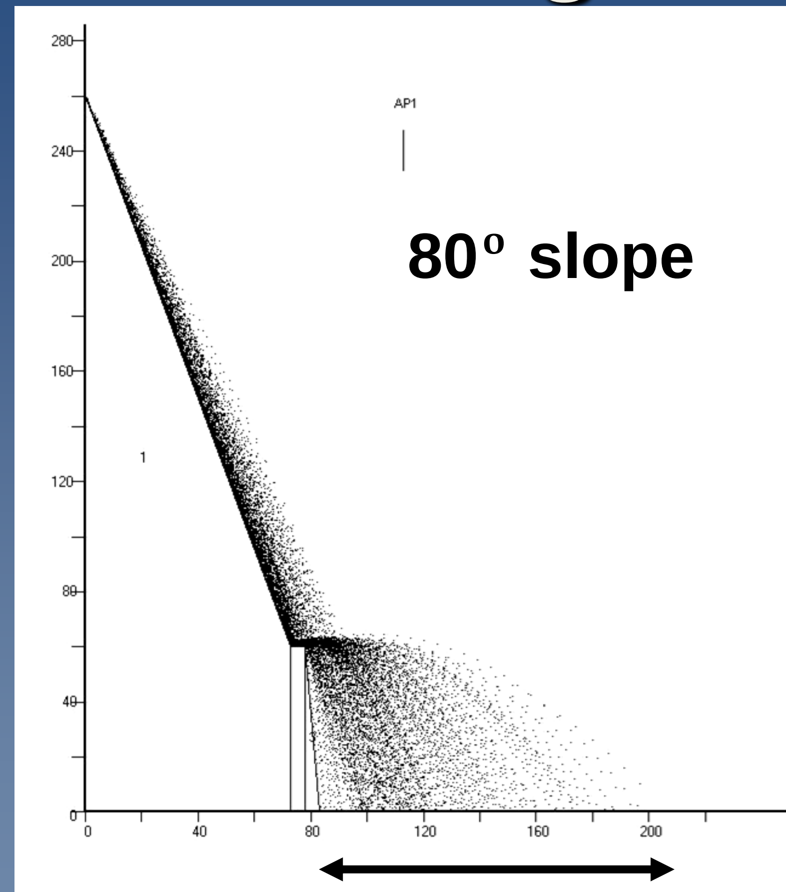
Computer Modeling

- Computer models such as the Colorado Rockfall Simulation Program (CRSP) can be used to design rockfall protection measures.
- Input/assumptions – cross-section, surface roughness, normal and tangential coefficients, rock size and shape.
- Program Advantages/Capabilities:
  - model field conditions such as
  - complex geometry & multi-bench,
  - run many simulations, and
  - analyze various mitigation scenarios.

Highwalls without and with a Ledge



~45-foot impact zone



~130-foot impact zone

Factors that Contribute to the Severity of the Hazard

EXPOSURE

- frequency
- duration
- attention/knowledge

MASS

- volume of material
- size rock
- amount of loose

HEIGHT

- momentum
- examination
- scalability

Sand and Gravel Mining

This specific category of surface mining involves the extraction of sand and gravel from naturally occurring deposits of sediment.

Unconsolidated Overburden (i.e., Soil):

- In geologic terms, unconsolidated overburden or an unconsolidated deposit is composed of sediments or deposits that are not classified as a rock unit (i.e., consolidated unit).
- Soil consist of silts, clays, sand, gravel, and organics.
  - Sediment deposits are soils that have been transported by wind, water, volcanic, or gravity.
  - Residual soils are those soils that have formed in-place from the weathering of rock.

Factors Unique to Sand and Gravel Mining

- **Material** – Sand and gravel is a sediment that generally consists of an un-bonded mixture of solid particles that is much weaker than rock.

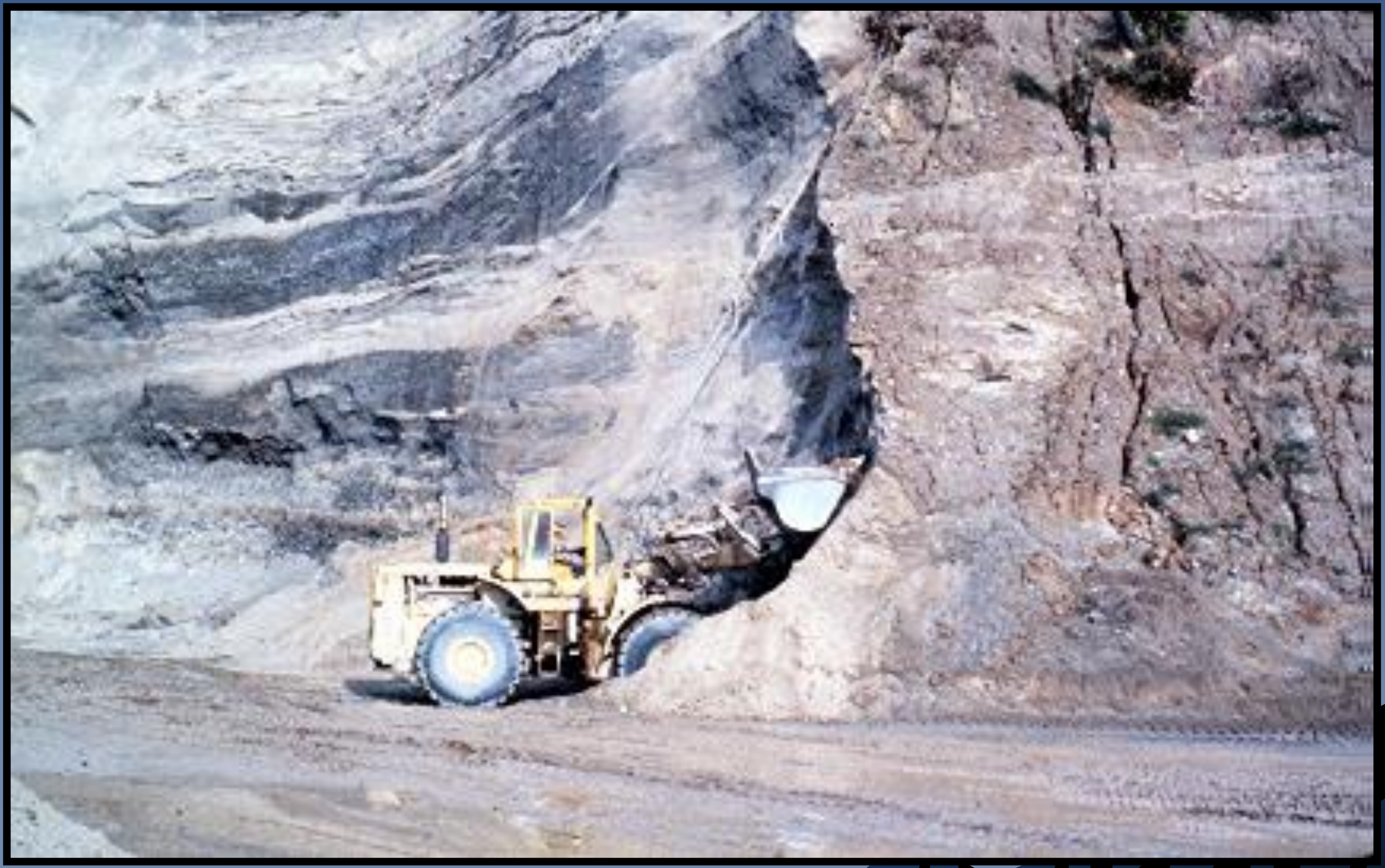
- **Method** – The nature of unconsolidated materials eliminates the need for blasting and permits mining by either direct excavation or dredging.

Direct Excavation

Direct excavation is the mining of material solely through the use of powered equipment such as front-end loaders, excavators, and bulldozers.

Concern in Direct Excavation

The concern in direct excavation is the operation of equipment in the vicinity of slopes that are often excavated steeper than the angle of repose.



Objective

To provide a better understanding of:

- How sand and gravel ground control hazards are created
- How to eliminate these hazards

Ground control hazards in sand and gravel mining amount to Slope Failure.

Eliminating Slope Failure

1. **Establish mining methods that maintain stability** - through thoughtful planning, evaluation, and design.

2. **Recognize hazardous conditions** - through regular examinations with consideration of changing soil composition, weak layers, seepage, potential failure modes, and maintaining a safe slope angle.

3. **Remediate the condition** – through the application of corrective measures intended to prevent failure.

4. **Or Prevent exposure** – through relocating work areas, barriers, protective measures, or monitoring.

Primer to Slope and Bank Stability

Types of Solid Particles

Soils generally contain 4 different types of solid particles:

- Gravel
- Sand
- Silt
- Clay

However, soils can also contain fibrous organic material as well as large blocks of intact rock such as cobbles and boulders.

Particle Characteristics

Solid particles are distinguished by their size and behavior in response to moisture*:

Gravel –	100(~4 in.)-2 mm	Coarse-grained (Granular) Non-Plastic
Sand –	2-0.05 mm	
Silt –	0.05-0.002 mm	Fine-Grained (Powdery) Plastic
Clay –	< 0.002 mm	

Cobbles (~4-12in.)
Boulders (>12in.)

*USDA Size Limits

Cohesive Soil
(High Silt and Clay Content)

Soils with a high silt and clay content tend to exhibit cohesive behavior and are described as cohesive soils.

- **Cohesive soils “stick together.”**
- **Dry samples will not easily break apart.**
- **Moist samples can be rolled into a string.**
- **Molded samples will remain intact when submerged.**

Cohesive Soil Sample

Non-Cohesive Soil
(High Sand and Gravel Content)

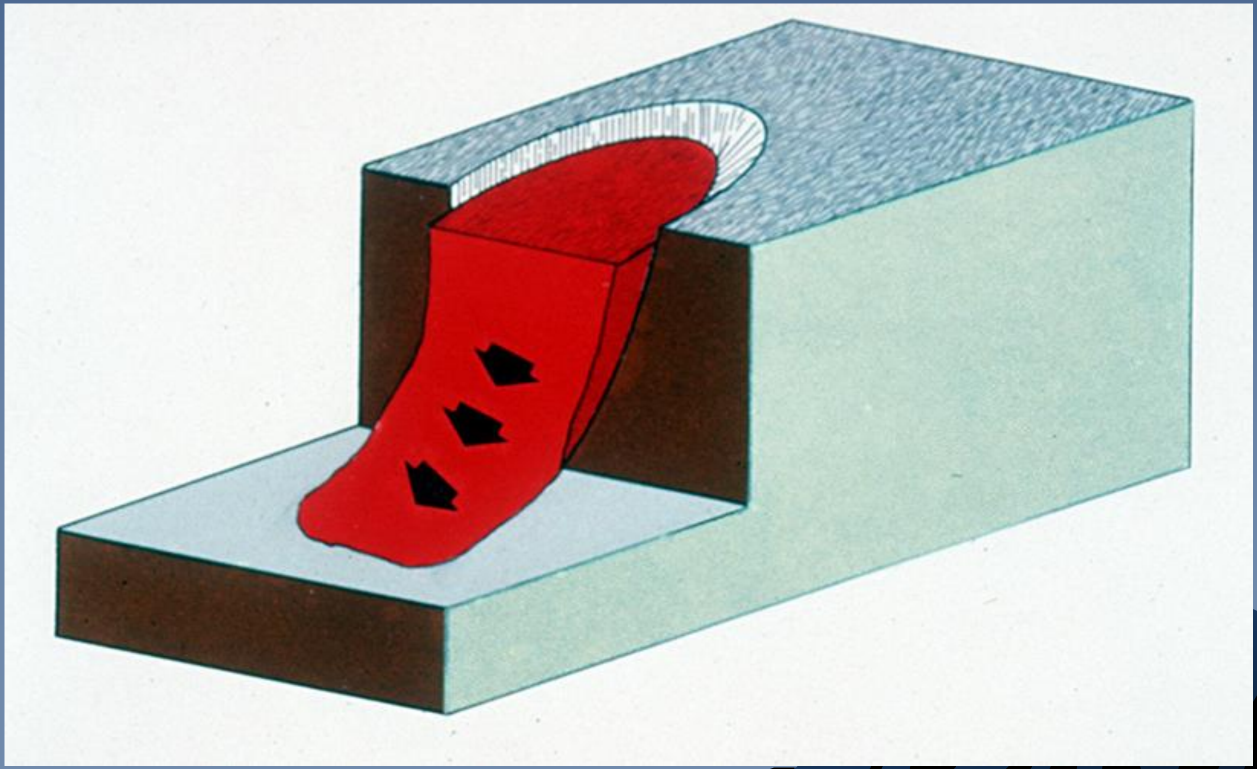
Soils with a high sand and gravel content tend to exhibit non-cohesive behavior and are described as non-cohesive soils.

- **Non-cohesive soils <u>do not</u> "stick together."**
- **Dry samples <u>will</u> easily break apart.**
- **Moist samples <u>cannot</u> be rolled into a string.**
- **Molded samples <u>will not</u> remain intact when submerged.**

Non-Cohesive Soil Sample

Soil Failure Shape

Slope failures in soils involve rotational and sliding movement along a failure surface through the soil mass that often approximates the arc of a circle.



Signs of Potential Slope Failure

Visual signs of a potential soil slope failure include:

- Tension cracks behind the crest
- Vertical displacement of the crest
- Transverse cracks through the slope face
- Bulging at the toe
- Fallen material at the toe
- Active raveling

However, over-steepened, non-cohesive soil slopes ordinarily fail very rapidly and provide very little warning.

Identifying Unstable Conditions

Identifying unstable conditions in sand and gravel mining is therefore largely contingent upon understanding the behavior of non-cohesive soil slopes.

Strength of a Non-Cohesive Soil Slope (High Sand and Gravel Content)

- Strength of a non-cohesive soil slope is primarily due to frictional resistance between the particles.
- Consequently, cohesion (c) for sands and gravels = 0
- Frictional resistance is represented by the friction angle (ϕ).

Friction Angle (ϕ)

The friction angle is a function of:

- Particle surface roughness (smooth, rough)
- Particle size distribution (well graded, uniform)
- Particle shape (angular, rounded)
- Relative density (loose, dense)

For practical purposes, the friction angle in dry, loosely placed, sands and gravels is the "angle of repose."

Angle of Repose

The angle that a dry sand or gravel will form with respect to the horizontal when dumped into place.

Question

Can a non-cohesive soil stand steeper than its angle of repose?

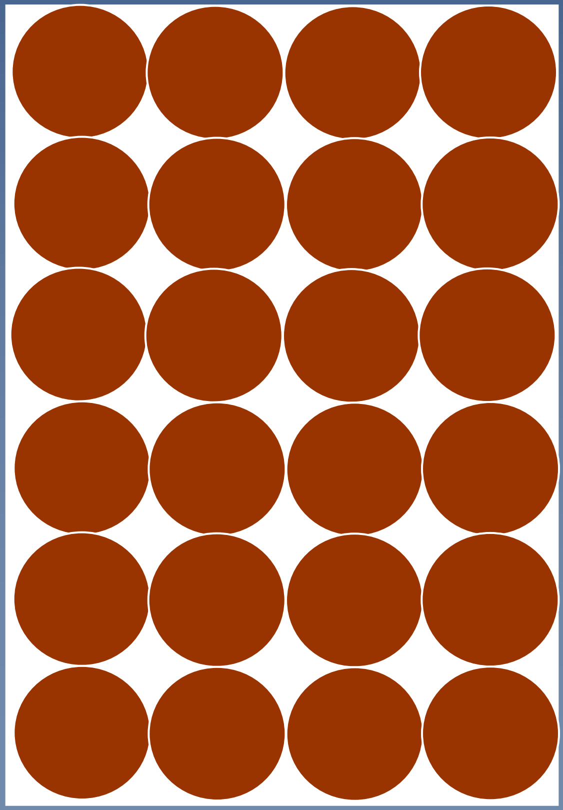
YES !

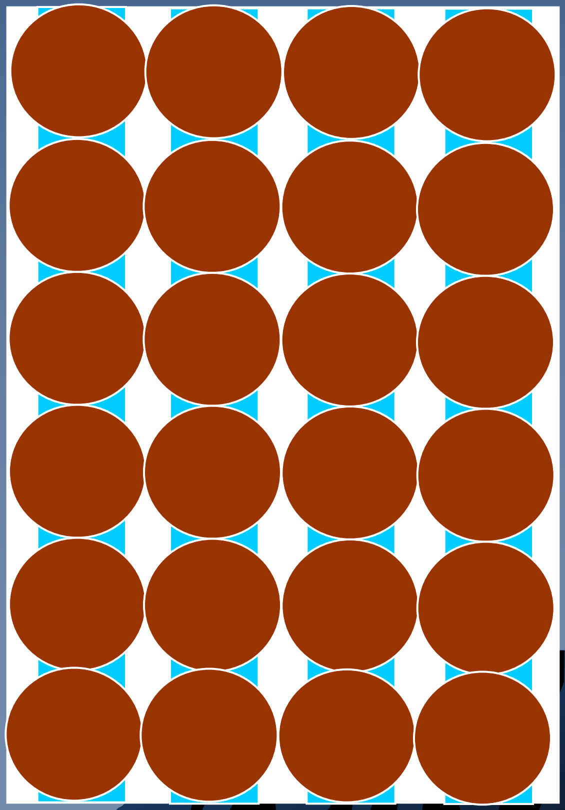
With some moisture and compaction, a non-cohesive soil can stand much steeper than its angle of repose?

Apparent Cohesion

This is partly due to the phenomenon of apparent cohesion where soil particles are held in place by the surface tension of water that is drawn into the pore spaces between the particles.

Dry Soil Sample





Moist Soil Sample

However, Apparent Cohesion is Unreliable

- Strength from apparent cohesion is unpredictable, unsustainable, and should not be relied upon for long-term stability.
- Apparent cohesion is highly dependent on moisture content.
- If the soil dries out or becomes saturated, it will collapse and go back to it’s angle of repose.

Recommended Soil Slopes

Soil Type Classification:

Type A Soils *are cohesive soils with an unconfined compressive strength of 1.5 tons per square foot (tsf) (144 kPa) or greater. Examples of Type A cohesive soils are often: clay, silty clay, sandy clay, clay loam and, in some cases, silty clay loam and sandy clay loam.*

Type B Soils *are cohesive soils with an unconfined compressive strength greater than 0.5 tsf (48 kPa) but less than 1.5 tsf (144 kPa). Examples of other Type B soils are: angular gravel; silt; silt loam; previously disturbed soils unless otherwise classified as Type C.*

Type C Soils *are cohesive soils with an unconfined compressive strength of 0.5 tsf (48 kPa) or less. Type C soils include granular soils such as gravel, sand and loamy sand, submerged soil, soil from which water is freely seeping, and submerged rock that is not stable.*

Maximum Slope for Trench Excavations OSHA (1999)		
Soil type	Horizontal: Vertical (ratio)	Slope angle (degrees)
Type A	¾:1	53°
Type B	1:1	45°
Type C	1½:1	34°
For a maximum overburden of 20 feet; otherwise, perform a stability analysis.		
Type A – Short Term Slope	½:1	63°
For short-term, a maximum overburden of 12 feet; otherwise, perform a stability analysis		

Examinations

- Monitor (i.e., measure) slope angle and piezometers
- Look for cracks on top or bulging of slope
- Look for changes in soil composition or weak layers
- Seepage and sloughing – investigate stability
  - conduct geotechnical evaluation
  - install drains and piezometers
  - flatten slope
  - seepage in erosion gullies
- Control surface runoff to prevent erosion of pit slope
  - Repair erosion where practical
  - Buttress or flatten slope
  - Re-evaluate

Examples of Slope Failures

in Relation to Common Sand and Gravel Mining Methods

Fatal Sand and Gravel Accident
Massachusetts – June 2015

- Mining Method - Direct Excavation
- The victim was operating a front-end loader at the toe of a 128-foot-high sand bank
- The sand bank was over-steepened (slope up to 58 degrees vs. 33 degree angle of repose)
- The victim was fatally injured when about 1,700 cubic yards of sandy soil fell from the highwall and engulfed the loader.
- The narrow mine space contributed to the hazard and consequences.

Fatal Sand and Gravel Accident
Massachusetts – June 2015

Fatal Sand and Gravel Accident

Massachusetts – June 2015

Fatal Sand and Gravel Accident
North Dakota – August 2015

- Handling/Transporting - Direct Excavation
- The victim was operating a front-end loader at the toe of a 39-foot-high stockpile and was fatally injured when about 400 cubic yards of sand and gravel slid from the stockpile
- The victim was outside the loader near the access ladder between the stockpile and the loader
- The stockpile was over-steepened with slopes between 42 and 52 degrees, the angle of repose was 32 to 36 degrees
- The locations of the miner and the equipment contributed to the hazard and consequences.

Fatal Sand and Gravel Accident

North Dakota – August 2015

Fatal Sand and Gravel Accident
North Dakota – August 2015

Common Accident Factors

Direct Excavation

- Slopes were primarily composed of non-cohesive soil (i.e., sand and gravel).
- Highwalls were excavated at slope angles steeper than the soil's angle of repose.
- Highwall stability was unpredictable and unsustainable.
- Compounded exposure to the hazard.
- Failures occurred very rapidly.

Remediating the Hazard
Direct Excavation

- Measures to Prevent Failure:
  – Avoid creating a steep highwall face.
  – Avoid undercutting the highwall face.
  – Limit the highwall height.
- Measures to Prevent Exposure:
  – Mine material from the top down.
  – Move equipment away from the slope, bank, or stockpile before exiting.
  – Do not travel between equipment and the slope/bank/stockpile.

Double Fatal Accident
Mississippi – June 2016

- Mining Method - Direct Excavation
- The victims were an excavator and a haul truck operator working in an incised pit near the toe of a 65-foot-high wall.
- They were fatally injured when the east wall collapsed and about 41,000 cubic yards of saturated tailings inundated the pit and engulfed the equipment.
- The pit was adjacent to a partially-abandoned slurry impoundment (a former mine pit).
- The wall was comprised of hydraulically placed sand, and natural sand and gravel.
- The slope was over-steepened, exhibiting seepage and sloughs of saturated material.

Double Fatal Accident

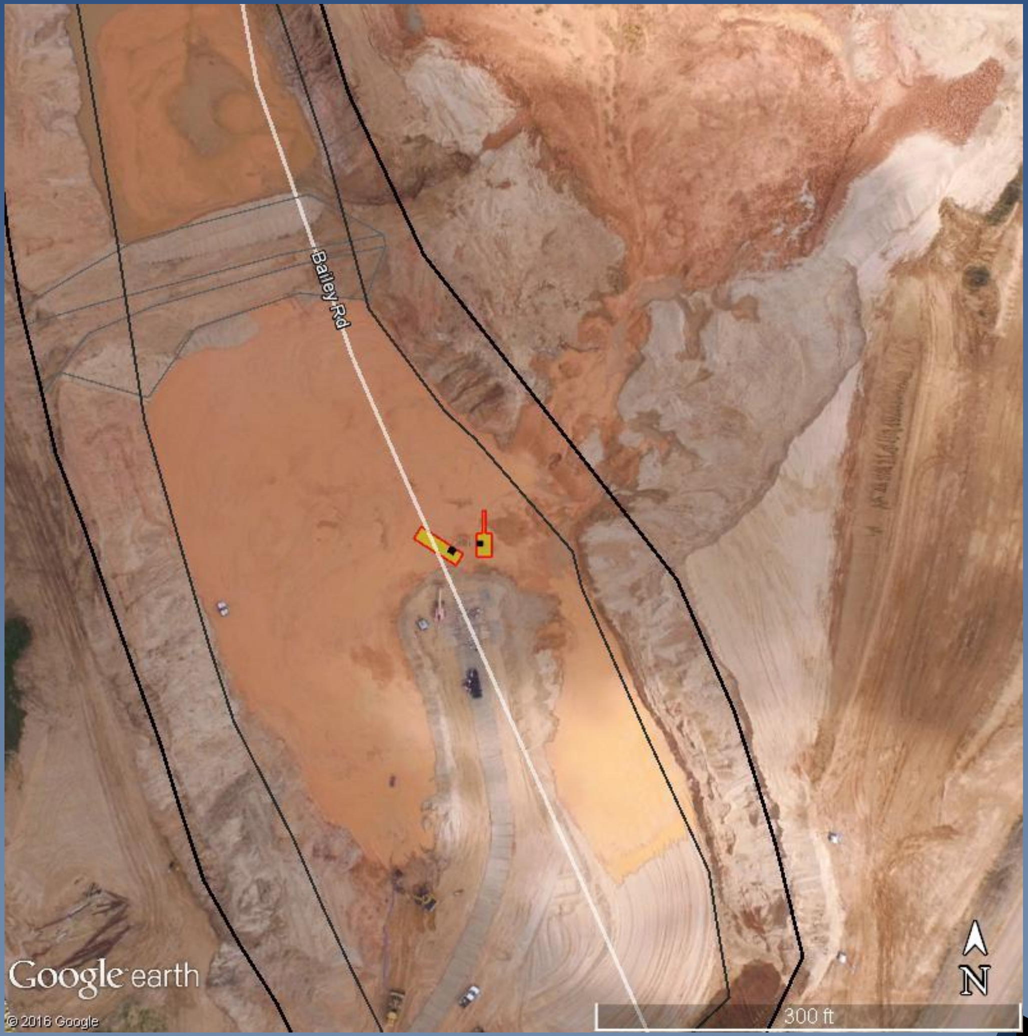
Mississippi – June 2016

Double Fatal Accident
Mississippi – June 2016

Double Fatal Accident
Mississippi – June 2016

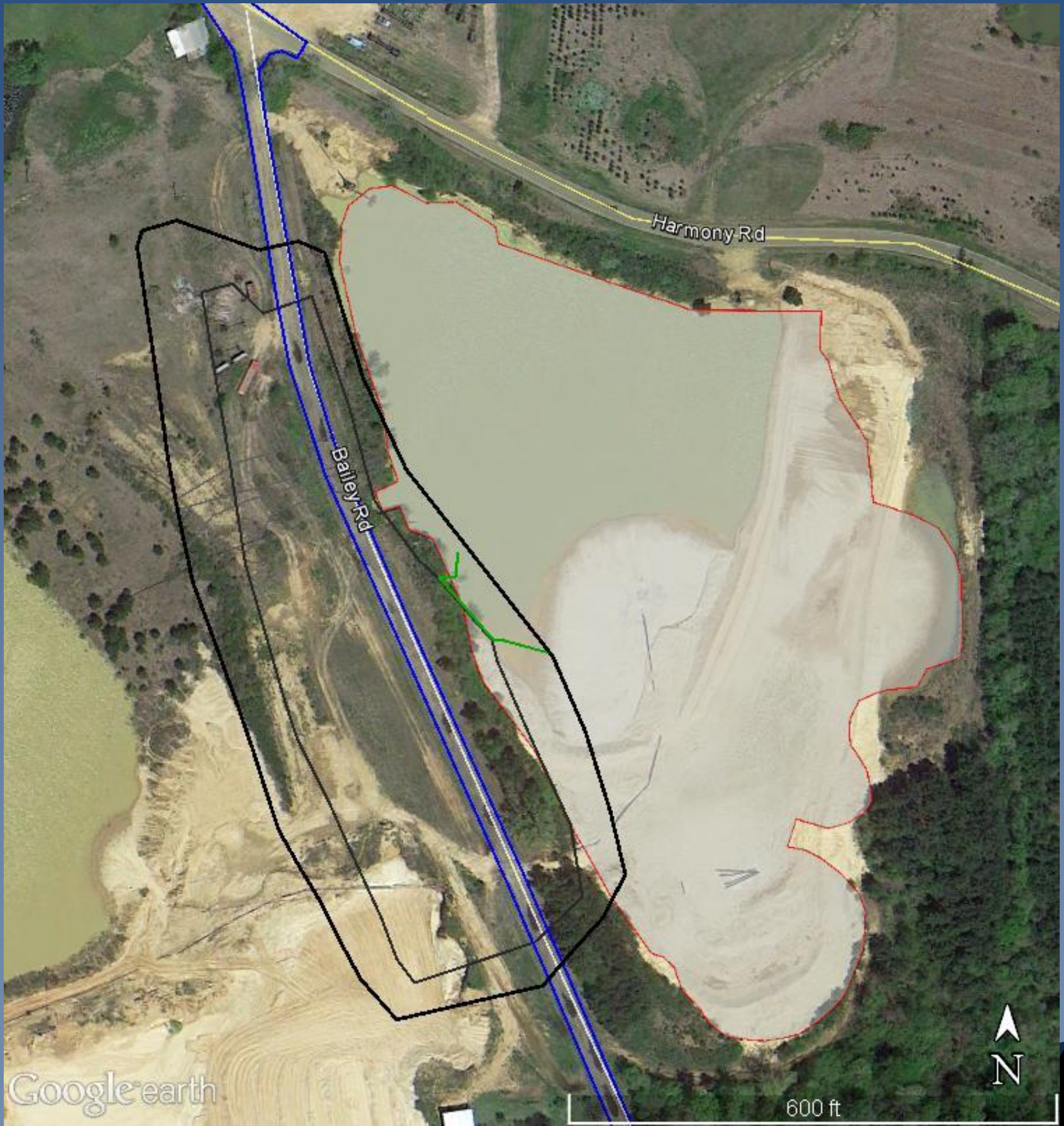
Double Fatal Accident
Mississippi – June 2016

Double Fatal Accident
Mississippi – June 2016



Satellite Image
Mississippi – Dec 2015

Satellite Image
Mississippi – April 2014



Prudent Planning

- Survey adjacent impoundment before reclamation
- Perform geotechnical investigation and evaluation to determine width and slope of natural barrier to maintain
- Install piezometers to monitor ground water
- Build an adequate dam between the pits
  - spigot tailings along proposed barrier to fill with sand
  - monitor and survey beach development for quality control
  - compact sand barrier on a regular basis
  - perform geotechnical investigation on completed sand beach barrier
  - install piezometers
- Establish limits of proposed mining (survey & stake top of final wall)
- Mine top down to establish and maintain the design slope
- Pump out all water or maintain groundwater per design

Summary

- Ground control hazards are created by a combination of the potential for failure and exposure.
- The potential for failure can be greatly reduced by prudent design/planning.
- However, hazards due to changes in conditions can be eliminated by first recognizing and then remediating the hazard using corrective measures intended to either prevent failure or prevent exposure.

For Additional Assistance

Contact Your Local MSHA Office

Or

Stan Michalek
Chief, Mine Waste and Geotechnical Engineering Division
Pittsburgh Safety and Health Technology Center
Mine Safety and Health Administration
(412) 386 - 6974

References

- USDOT (1998): “Rock Slopes,” FHWA HI-99-007, National Highway Institute, Federal Highway Administration, USDOT, Washington, D.C.
- TRB (1996): “Landslides Investigation and Mitigation,” Special Report 247, Transportation Research Board, Washington, D.C.
- Ritchie (1963): Ritchie, A.M., 1963, “An Evaluation of Rockfall and Its Control,” Highway Research Record No. 17, pg. 13–28.
- FHWA (1989): “Rock Slopes: Design, Excavation, Stabilization,” Publication No. FHWA-TS-89-045, Federal Highway Administration, Turner-Fairbanks Highway Research Center, McLean, VA.
- Call (1986): “Cost-Benefit design of open pit slopes.” In: 1st Open Pit Symposium, Antofagasta, Chile, pp 1-18.
- OSHA (1999): Occupational Safety & Health Administration, “Excavations: Hazard Recognition in Trenching and Shoring.” In: OSHA Technical Manual (OTM), Chapter 2, Section V.
- Romana (2003): Romana, M., Serón, J.B., Montalar, E., “SMR Geomechanics classification: Application, experience and validation,” ISRM 2003–Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy.