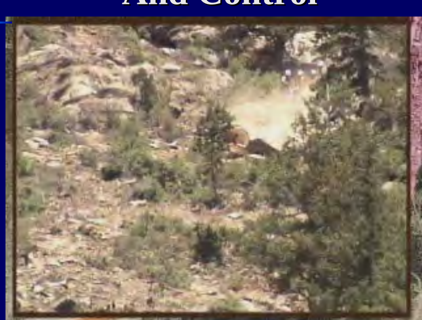
Rockfall Mitigation Workshop

Rockfall Characterization And Control

1	Intro/Executive Summary	800 to 825
	Break	825 to 830
2	Types and Causes	830 to 1000
3	Recognition of Rockfall Hazards	
4	Site Characterization	
5	Monitoring	
6	Analysis	
	Break	1000 to 1015
7	Mitigation	1015 to 1200
7a	Avoidance	
7b	Stabilization	
7c	Protect on	
	LUNCH	1200 to 1300
8	Current Events	1300 to 1630
8a	F exible Rockfall Fences	1300 to 1430
8b	Wire and Cable Mesh Drapery	
8c	Anchored Wire Mesh	
	BREAK	1430 to 1445
9d	Analysis	1445 to 1600
9e	Rockfal Hazard Ratings	
10	Open Forum	1600 to 1630

Rockfall Characterization And Control



Executive Summary

- With a Systematic Approach to we will
  - Improve Public Safety
  - Increase Mobility
  - Reduce Tort Liability Exposure

Improve Public Safety

- Reduce overall costs because we will have a systematic approach statewide
- Experienced people currently in place to solve the problem

Increase Mobility

- Through Systematic approach
  - Right fix first time
  - Identify problems before they become problems
  - Every rockfall impairs traffic flow
  - Reduce incidents of rockfall you increase mobility

Reducing Tort Liability Exposure

- This system reduces that exposure
- Effective system
- Proven

Reducing Tort Liability Exposure Improve Public Safety

- Between January 1, 1994 and December 31, 2007 there have been seventy (70) rock cases filed against Caltrans that have been resolved.
- Of the seventy (70) cases, there were
  - eighteen (18) wrongful deaths,
  - five (5) quadriplegic injuries,
  - two (2) paraplegic injuries,
  - eight (8) brain injuries
  - and the remaining thirty three (33) cases had a variety of lesser injuries.

Reducing Tort Liability Exposure Improve Public Safety

- Thirty two (32) of the cases were dismissed or resulted in a defense verdict with Caltrans paying zero.

Reducing Tort Liability Exposure Improve Public Safety

- Thirty eight (38) cases resulted in either a settlement or a judgment with a combined payout of
- 

Attorneys settle lawsuit over rockslide

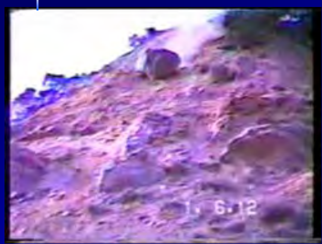
Rockfall presents these problems for the motorists

- Rock hitting car
- Car avoiding rock running off road or hitting car
- Car hitting rock

What is a Rockfall

- "Rockfall" is the movement of rock of any size from a cliff or other slope that is so steep the mass continues to move down slope. Movement may be by free falling, bouncing, rolling or sliding.

Rockfall



- Very Rapid to Extremely Rapid Event
- 10 feet per second and higher
- TRB 247 Landslides Analysis and Control 1996 Velocity Class 7.

Executive Summary

- There are Specialists who are trained in the discipline of rockfall
- Like all disciplines to do this work requires experience and practice which can only be acquired by doing projects under the tutelage of experienced practitioners and attending training classes.

Objectives in this course for Geotech

Project Management

- Awareness of rockfall issues
- Develop plans and specs
- Timeline of projects
- Resources
- Purpose and Need

Maintenance

- First response
- Awareness
- Reduce Workload Cost Savings
- Help Project initiation
- Help identify the problems
- Provide History

Construction

- Rapid response
- Awareness
- Educate on Products
- Solutions
- Resource to solve problems

There is a process! A systematic approach

- Types
- Ratings
- Investigation
- Instrumentation
- Analysis
- Mitigation
- Construction

ROCKFALL SOURCES AND CAUSES

- Rockfall occurs on slopes steeper than 33° (1.5:1) that have loose rock on the slope surface. Gravity assisted by other mechanisms causes loose rock to move down slope. The following is a brief review of rockfall sources and causes.

ROCKFALL SOURCES

- Fractured Rock
  - Internal fracture orientations influence slope stability
- Blocky Deposits
  - Weak Or No Matrix
    - Colluvium
    - Talus
    - Volcanic Ash Deposits
    - Glacial Till
    - Others

ROCKFALL SOURCES

FRACTURED ROCK

- Common Failure Types
  - Planar
  - Wedge
  - Toppling
  - Buckling
  - Circular
- Localized Failures
  - Discontinuous fracture planes limit failures to a few blocks
- Deeper Seated Failures
  - More continuous fracture planes causes some or all of slope to fail

ROCKFALL SOURCES

FRACTURED ROCK

- Adversely Oriented Fractures
- Orientation Steeper Than Friction Angle

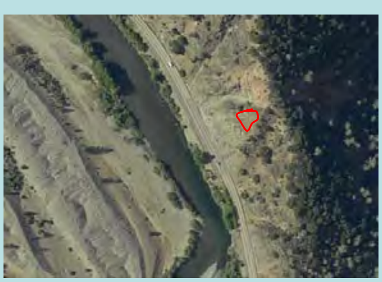
ROCKFALL SOURCES

FRACTURED ROCK

- Differential Erosion
- Decomposition / Weathering

FRACTURED ROCK - Rockfall Sources

SLOPE FAILURES



- Slow moving slides
- Toe over-steepens and fails
- The mass breaks apart and becomes rockfall

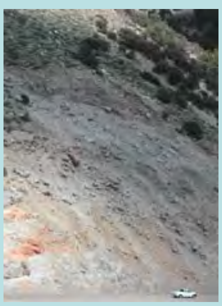
FRACTURED ROCK - Rockfall Sources

DEEP SEATED FAILURES

- Dormant slides
  - Marginally stable slide mass occasionally fails as rockfall in unusual storm events
- Reactivating
  - Rockfall can be the first indicator that a dormant slide is reactivating

Rockfall Sources

BLOCKY DEPOSITS



- Many deposits at angle of repose
- Raveling
- Boulder Fall

Rockfall Sources

BLOCKY DEPOSITS

- Differential Erosion
- Weak Matrix

ROCKFALL CAUSES

CLIMATE

- Rain
- Groundwater
- Freeze-thaw
- Wind
- Thermal Expansion
- Snow Load

ROCKFALL CAUSES

WATER

- Springs and Seepage
- Channeled Runoff
  - Cut Slope Riling
  - Large Channels / Drainage
  - Water Shed Erosion
- Snow Melt

ROCKFALL CAUSES

BLASTING AND VIBRATION

- Overshot Slopes
- Earthquakes
- Truck Vibrations
- Construction Activities / Equipment
- Train Vibrations – harmonic vibration

ROCKFALL CAUSES

NATURAL AND EXCAVATED SLOPES

- Relaxation of the Rock Mass
- Slopes Age

ROCKFALL CAUSES

OUTSIDE INFLUENCES

- Burrowing Animals
- Tree Roots
- Wild Animals
- Humans
- Fires

Recognition of Rockfall Hazard

- Maintenance
- Legal
- Citizens
- Construction
- CHP
- TASAS Traffic Accident Surveillance Analysis System - Accident History
- Ethically

Recognition of Rockfall Hazard

- Maintenance
  - On the highway daily observing slopes
  - Perform Rock patrols in mountainous regions
  - Typically first CT responders to accidents involving rockfall

Recognition of Rockfall Hazard

- Legal
  - Are aware of pending litigation for accidents involving rockfall.

Recognition of Rockfall Hazard

- Citizens
  - Reports directly from highway drivers to the District Office or local maintenance yard of areas where rockfall has occurred.
  - Reports from citizens that live adjacent to an area where a rockfall has occurred.

Recognition of Rockfall Hazard

- Construction

Recognition of Rockfall Hazard

- CHP
  - Respond to accidents involving rockfall.
  - Receive public complaints about potential hazardous conditions along the highway.
  - Patrol sections of the highway and may have concerns of their own

Recognition of Rockfall Hazard

- TASAS Traffic Accident Surveillance Analysis System - Accident History

Method of Evaluation of Rockfall Hazard

- Risk Based Assessments
  - Historical and literature review of recognition approaches – including aerial and ground based methods (including photography, remote sensing, LIDAR, GIS, and creating a rock slope data base.
- Hazard Rating-CT

Rockfall Hazard Rating Systems Tool to Prioritize

- Rock slope rating procedures
  - Basic concepts
  - Historical development
  - Rock slope inventory and database management
  - Accommodating climate regimes
  - Maintenance program documentation

Inventories and Hazard Ratings Systems

- The Rockfall Hazard Rating System
  - RHRS Rockfall Hazard Rating System (Nationally Funded Pooled fund study)
  - NY DOT Rock Slope Rating Procedure
  - Penn DOT Geotechnical Problem Inventory Program
  - Colo Geo Survey Site Specific Hazard Rating System
  - CDOT
  - Tenn DOT
  - AZ DOT
  - Golder And Assoc.
  - Hong Kong

Caltrans Adopted Method – RHRS Rockfall Hazard Rating System

Caltrans RHRS

- In order to achieve conformity and consistency within the Department when the occasion requires a quantitative ranking of rockfall generating slopes it is Geotechnical Services policy that the Rockfall Hazard Rating System (RHRS) be used as the standard.

RHRS Rockfall Hazard Rating System

- The development of RHRS was funded through a HPR pooled fund study of which Caltrans was a contributor and served on the Technical Advisory Committee (TAC). Caltrans Engineering Geology staff not only served as technical advisors but also evaluated the system for statewide application. Caltrans staff has used RHRS as a method of prioritizing rockfall mitigation projects since it was published in 1990.

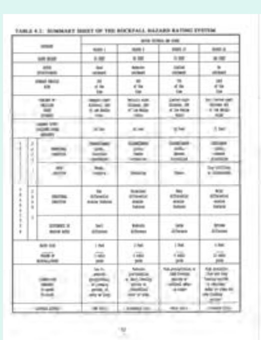
RHRS
Field Rating

- Field Rating utilizing RHRS
  - A quick assessment of rockfall concerns can be made in the field utilizing a simple points rating system assigning either 3,9,27 or 81 points for each condition that needs to be recorded to complete a RHRS study.

RHRS
Final Rating

- Final Rating Utilizing RHRS
  - Uses a combination of data collected in the field and supporting data collected in the office setting.
  - Some categories are quantified utilizing mathematical equations.

RHRS
Components of Rating System



- Slope Height
- Ditch Effectiveness
- Average Vehicle Risk
- Percent of Decision Site Distance
- Road width Including Shoulders
- Geologic Character
- Block Size/Quantity of Event
- Climate and Presence of Water on Slope
- Rockfall History

RHRS Components
Slope Height

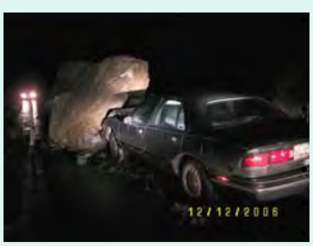
- Slope height is the maximum vertical height of the slope in which rockfall can occur.

RHRS Components
Ditch Effectiveness

- Effectiveness
  - –The key word is EFFECTIVENESS

  No matter what type of ditch or catchment area it is, this is a rating of how well the area contains the rocks that come down the slope and prevents them from reaching the traveled way

RHRS Components
Average Vehicle Risk - AVR



Average Vehicle Risk take into account the following three items.

Average Daily Traffic (ADT)

Slope Distance (SD)

Speed Limit (SL)

AVR= (ADT X (SD/5280) / 24) / SL X 100

RHRS Components
Percent of Decision Site Distance

Table 201.7
Decision Sight Distance

Design Speed (mph)	Decision Sight Distance (ft)
30	450
35	525
40	600
45	675
50	750
55	865
60	990
65	1,050
70	1,105
75	1,180
80	1,260

- Percent of Decision Site Distance is the required site distance for a given speed divided by the actual site distance.
  - Sight distance should be measured in the field approaching the rockfall location from both directions and the shortest distance obtained should be utilized in the equation.
  - Table from Section 201.7 Caltrans Highway Design Manual, 6th edition.

RHRS Components
Road width Including Shoulders

- This is obtained by measuring the paved area.
- Why it is important?
  - This identifies where a vehicle may swerve to avoid a rockfall.

RHRS Components
Geologic Character

- Case 1 - Structural Condition
  - Typically caused by adverse joint sets, fractures and bedding planes.

RHRS Components
Geologic Character

- Case 2 Differential Erosion
  - When competent rock blocks are contained within a weaker matrix material that is more susceptible to erosion.
  - Matrix can be comprised of soil as in glacial till.

RHRS Components
Block Size/Quantity of Event

- A rockfall where quantity would be described in block size.

- A rockfall where quantity could be described in either block size or volume.

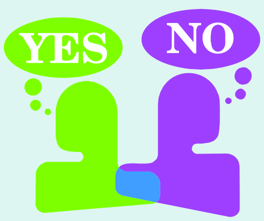
RHRS Components
Climate and Presence of Water

- RHRS divides Climate and Presence of Water into three areas
  - Precipitation
  - Ground water
  - Freeze thaw

RHRS Components
Rockfall History

- RHRS divides rockfall history in to four categories
  - Few Falls
  - Occasional Falls
  - Many Falls
  - Constant Falls

RHRS



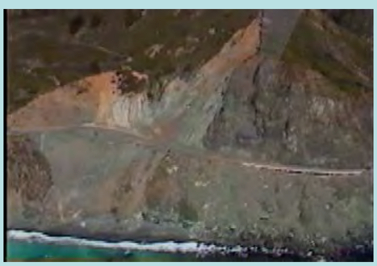
- It is important to maintain the statewide data base of rockfall ratings in the same scoring system and language. This is the language of rockfall and allows practitioners statewide to compare projects, evaluate sites, and make decisions.

Site Characterization

- The three components of many rock-fall hazard assessments are
  - a determination of the relative susceptibility of rock outcrops to rock-fall initiation,
  - identification of travel paths of potential rock falls,
  - and an evaluation of the depositional zone (sometimes referred to as rock-fall runout).

Site Characterization

- Regionally
- Globally
- Locally



Site Characterization

- You have to get out of the car
- Experience
- Training
- Field Partner

Site Characterization

- *Is there evidence of rockfalls in the area?* Although a site is below a bluff or steep slope it does not mean there is rockfall activity. Typically there will be field evidence such as impact marks, broken trees or individual rocks or rock accumulations scattered throughout the area. But there also may be no rocks on the slope indicating rocks are not traveling far from the base of the slope or falling at all.

Site Characterization

- Its OK to not have a rockfall problem!

Site Characterization

- Literature Review
- Climate
- Maintenance History
- Rock Structure Implications
- Photo Interpretation
- Geologic Field Mapping
- Rockfall Characteristics
- ALL Part of the DPGR and GDR

Site Characterization

- Geologic Field Mapping
  - Evidence of Past Instability
  - Slope Geometry
  - Rock Type and Weathering
  - Structural Geology-Rock Slope Discontinuity Analysis
  - Rockfall Characteristics
  - Field Trials – Rock Rolling

Site Characterization

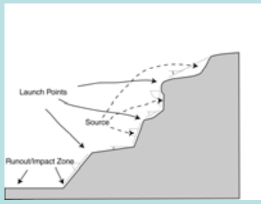
- **Evaluating the Initiation Zone**
- **Evaluating the Travel Zone**
- **Evaluating the Run out Zone**

Site Characterization

- **Data Collection**
  - There are many useful onsite data collection techniques that can supplement information gathered from a literature review.
    - visual examination,
    - outcrop mapping,
    - scanline and window surveying, and
    - slope mapping.

Site Characterization

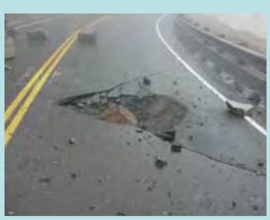
- **Evaluation of the Travel Paths**
  - slope height
  - topographic profile
  - variable slope angles
  - potential launch points
  - rock type variations
  - soil cover
  - vegetative cover
  - potential runout areas
  - impact zones.



Site Characterization-Travel Paths

Site Characterization

- **Evaluation of the Travel Paths**
  - They also largely affect the mode of travel:
    - Rolling
    - Bouncing
    - free falling.
  - Existing impact locations on structures, trees or other impediments allow rudimentary estimates of bounce heights and launch points.
  - Slope height, angle and the frictional resistance ultimately determine the energy of the rock motion.

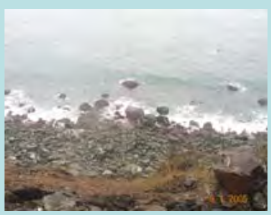


Site Characterization

- **Depositional Zones**
  - Analyzing rockfall deposits involves reviewing fallen rock material in the runout zone near the base of the slope as well material deposited on the slope.
  - Information such as the size, density, and shape of the projectile rocks should be observed.

Site Characterization

- Additionally, the mode of failure and cause of failure should be identified.
- Maintenance reports and eyewitness accounts are also good information sources.
- For many of the transportation agencies, maintenance records of rockfall on roadway and ditches and can be the best source of identifying the locations of reoccurring rock fall.



Site Characterization

- Single source area or random source areas
- What size rock typically reaches the base of the slope
- Max bounce height
- Maximum velocity/energy

Site Characterization

- Nature of event single or group of rocks
- Hit other rocks and destabilize those rocks
- Rock Avalanche

Instrumentation

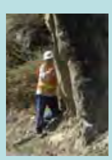
Rockfall Investigation

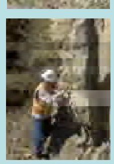
Monitoring

- Visual Inspection
- Video CAMs
- Direct Crack Monitoring
- Remote Monitoring
- Tilt Movement
- SSR (Slope Stability Radar)
- Indirect Monitoring
  - IMMS

Monitoring

- Visual Inspection
  - Check bedding and joint orientation.
  - Review the rock type at the site.
  - Review surroundings for signs of rockfall activity
    - Broken limbs
    - Holes in pavement
    - Damage to structures

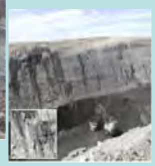




Monitoring

- Video CAMs





Monitoring

- Direct Crack Monitoring



Monitoring

- **Tripwire at brake rings**
  If an event occurs, the brake rings will contract and the tripwire will be torn out of the Impact Sentinel Unit which will then trigger the alarm.
  The alarm signal is transmitted wirelessly from the sensors to the data logger where it is evaluated and then forwarded to the person in charge via **Text Messaging or Radio Data Communications**.

- **Can be used permanently or temporarily**
  Impact Sentinel can be used permanently, for instance, **in remote areas** or temporarily, for instance, to help secure construction sites.

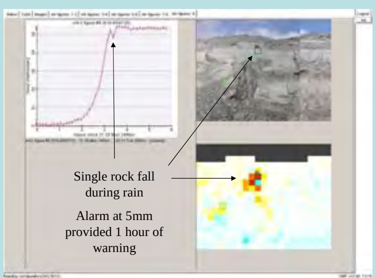
Monitoring

- Tilt Movement

Rockfall Investigation

Monitoring

- SSR



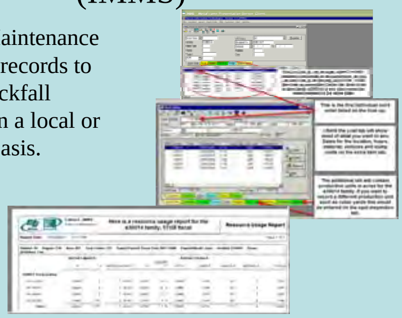
Rockfall Investigation

Monitoring

- Rock Patrols

Indirect Monitoring (IMMS)

- Utilizing Maintenance work order records to monitor Rockfall Problems on a local or Statewide basis.

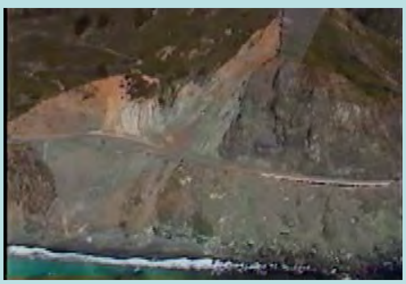


Rockfall Analysis

- Selection and design of effective protection measures requires the ability to predict rockfall behavior.

Rockfall Analysis

- Consider
  - Globally
  - Locally



Rockfall Analysis

- Rockfall behavior is defined in three phases:
  - an initiation zone,
  - a travel zone,
  - and the depositional zone.
- At the initiation point a rock has potential energy that becomes kinetic energy that is dissipated as the rock bounds down slope and eventually comes to rest.

Rockfall Analysis

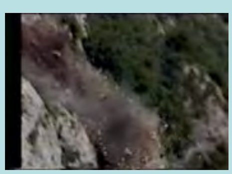
- In many cases, for example, when dealing with boulders on the top of slopes, the rockfall hazards are obvious.
- In other cases rockfall hazards are not so obvious as in the case where rock failure occurs when a block is suddenly released from an apparently stable face in the surrounding rock mass.

Rockfall Analysis

- Initiation Zone
  - Rock Mass
    - Kinematics
  - Soil
    - Method of Slices
  - Transitional Materials
    - Slices
    - Erosion Rates

Rockfall Analysis

- Analytical solutions to determine travel path and run out zones are determined by
  - computer simulations where rockfalls are modeled
  - or from empirical data where rocks are rolled down a slope.



Rockfall Analysis

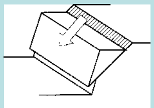
- The results of these analyses, together with geological data on block sizes and shapes, can be used to determine the potential of a rockfall occurring and estimate the dimensioning of mitigation such as the height of a barrier or width of a catchment ditch.

Rockfall Analysis

- For very weak rock where the intact material strength is of the same magnitude as the induced stresses, the structural geology may not control stability, and classical soil mechanics principles for slope stability analysis apply.

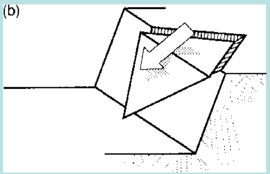
- Transitional Materials
  - Residual Soils
  - Colluvium
  - Talus
  - Other Degradable Materials

Rockfall Analysis



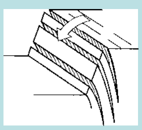
- **Types Of Rock Slope Failures**
  - **Planar failures** are governed by a single disconti-nuity surface dipping out of a slope face.
  - Rock Pack
  - Rock Science

Rockfall Analysis



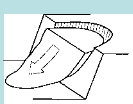
- **Types Of Rock Slope Failures**
  - **Wedge failures** involve a failure mass defined by two discontinuities with a line of intersection -that is inclined out of the slope face.
  - Rock Pack
  - Rock Science

Rockfall Analysis



- **Types Of Rock Slope Failures**
  - **Toppling failures** involve slabs or column, rock defined by discontinuities that dip steeply into the slope face.
  - Rock Pack
  - Rock Science

Rockfall Analysis



- **Types Of Rock Slope Failures**
  - **Circular failures** occur in rock masses that are either highly fractured or composed of material with low intact strength.
  - Slope W
  - STABL

Rockfall Analysis

- **There are two principle methods of analyzing rockfall travel and run out zone.**
  - **One is to perform field tests whereby rocks are rolled and the behavior of the falling rock is observed for different slope characteristics.**
  - **The second is to do a computer simulation. This is typically done using the various computer programs developed for that purpose.**

Rockfall Analysis

ENERGY

- Kinetic Energy (KE)
    - Foot tons
    - Kilo Joules
  - Translational KE
    - $\frac{1}{2} mv^2$
  - Angular KE
    - $\frac{1}{2} I \omega^2$
  - Total KE
  - $\frac{1}{2} mv^2 + \frac{1}{2} I\omega^2$
  - KE Cannot be greater then

Rockfall Analysis

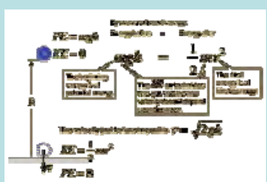
- Mass and Weight
  - m= w/g
  - $(SG_{rock})(\gamma_{water}) = (\gamma_{rock})$
- Velocity
  - ν- distance / time
  - ω = radians / time

Rockfall Analysis

- All collisions between macroscopic bodies are inelastic. Total kinetic energy therefore lessens by some amount. The kinetic energy of a system cannot increase without work being done by some outside agent.
- A rockfall on a slope is inelastic. In any non-perfectly elastic (inelastic) collision, kinetic energy is lost.
- In the case of a rock impacting a slope, the component of kinetic energy parallel to the slope and the rotational energy are attenuated by friction along the slope and collisions with features perpendicular to the slope.

Rockfall Analysis

- The Conservation of Energy principle asserts that in a closed system energy is conserved.
- When an object is at rest at some height, *h*, then all of its energy is *PE*. As the object falls and accelerates due to the earth's gravity, *PE* is converted into *KE*.
- When the object strikes the ground, *h=0* so that *PE=0*.



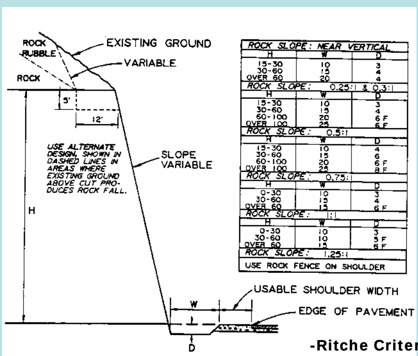
Rockfall Analysis

- **EMPIRICAL ANALYSIS OF ROCKFALL**
  - Over the years there have been numerous rockfall studies where rocks have been rolled down slopes for the purpose of understanding rockfall trajectories.
  - Some of these tests have been solely for rockfall observation while others have been combined to evaluate the performance of protection systems.
  - In every case a unique source of rock rolling data has been collected for various slope characteristics. This information is a valuable guide to practitioners and researchers in understanding rockfall behavior.

Rockfall Analysis (60's)

- **Ritche Criteria**
- An early study of rock falls was made by Ritchie (1963), who drew up empirical ditch design charts related to the slope dimensions
- Ritche described the various modes of travel as;
  - on slopes flatter than 1:1 rocks rolled down a slope,
  - on slopes up to ½:1 rocks bounced down slope
  - on slopes ¼:1 or steeper rocks trajectories were described as a fall.
- The Ritchie Criteria was developed and perhaps the most famous and widely used empirical data, and one of the first to study rockfall trajectory present rockfall catchment ditch geometry's that prevent rocks from free falling or rolling onto the traveled way. The criterion is based on the slope height and slope angle

Rockfall Analysis



-Ritche Criteria

Rockfall Analysis

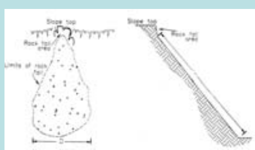
- **Caltrans Rockfall Field Test, 1985.**
  - The purpose of these tests were to study the effectiveness of protective measures that were already in place along the state's highways.
- **Caltrans Rockfall Field Tests, 1986, 1995, 2005, 2008, 2009.**
  - The purpose of these tests were to study the rockfall trajectories at project sites along the state's highways.
- **Caltrans Rockfall Barrier Field Tests, 1988 to 1989, 1993, 1995, 1996, 1998, 2000.**
  - Detailed measurements on angular velocity and translational velocity

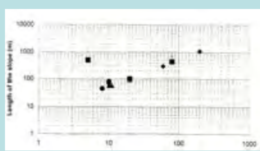
Rockfall Analysis

- Example Devils Slide
- Measured
  - V
  - m

Rockfall Analysis (90's)

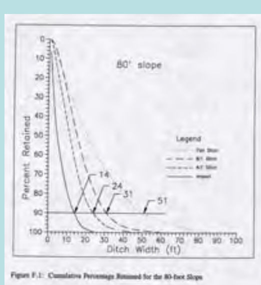
- **Azzoni Rockfall Field Tests, 1995**
- During these tests data was collected for the assessment of the restitution coefficient, rolling coefficient block shape and dimension, and lateral Dispersion of the Trajectories.





Rockfall Analysis

- **National Pooled Fund Study by Oregon DOT**
- Rockfall Catchment Area Design Guide, 2004
  - http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/RockfallReportEng.pdf



Rockfall Analysis

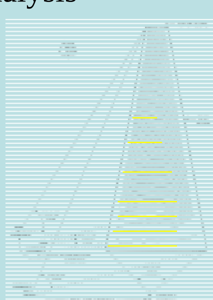
- **Other rock rolling tests around the world**
  - CDOT
  - Switzerland
  - Taiwan
  - China
  - France
  - Germany
  - Canada
  - Italy

Rockfall Analysis

- Whenever possible, rolling rocks in the field will provide the most accurate information for rockfall analysis.
- Obtaining good test data for rockfall analysis requires careful preparation.
  - A measurement of the rocks to be rolled is needed together with a properly prepared test slope.
  - And most importantly, film and video equipment should be in place and operational.

Rockfall Analysis

- Field Tests
  - Test Slope
    - Ground based Lidar
  - Test Rocks
  - Data Collection
  - Computer Modeling

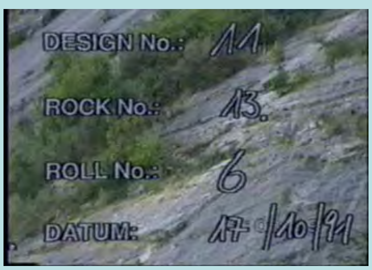


Rockfall Analysis

Caltrans Field Tests

Rockfall Analysis

- Swiss Field Tests



Rockfall Analysis

- **COMPUTER SIMULATION OF ROCKFALL**
  - Computer modeling allows designers and investigators to observe dozens or even hundreds of simulated rockfall events.
  - The 1990’s experienced a renaissance of rockfall computer modeling. These models attempt to predict rockfall behavior and describe rockfall in terms of trajectory and energy.

Rockfall Analysis

- **COMPUTER SIMULATION OF ROCKFALL**
  - The majority of the models used today are two-dimensional calculating horizontal and vertical movements along a single cross sectional segment.
  - Three-dimensional models additionally calculate lateral movement across a slope and although available have yet to achieve wide spread use due in part to the considerable data input requirements.

Rockfall Analysis

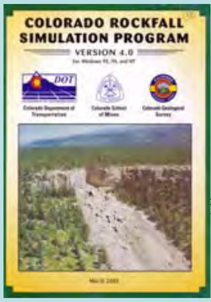
- **COMPUTER SIMULATION OF ROCKFALL**
  - Most of these rockfall models include a Monte Carlo simulation technique to vary the parameters included in the analysis. This technique, named after the gambling casinos of Monte Carlo, is similar to the random process of throwing dice - one for each parameter being considered.

Rockfall Analysis

- **COMPUTER SIMULATION OF ROCKFALL**
  - CRSP – USA
  - Rocfall - Canada
  - Rockfall - Europe

Rockfall Analysis

•



fall

Rockfall Analysis

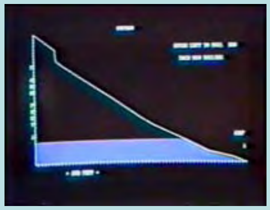
- The development of CRSP was funded through the Colorado Department of Transportation in cooperation with the U.S, Department of Transportation, and Federal Highway Administration. Caltrans Engineering Geology staff evaluated initial test versions of the program and contributed rock rolling data to its development
- CRSP is used by most State Departments of Transportation and many countries around the world. FHWA supports and encourages the use of CRSP through Chapter 6 of Rockfall Mitigation manual and the National Highway Institute (NHI) training class (NHI Course No. 13219).

Rockfall Analysis

- The Colorado Rockfall Simulation Program (CRSP) was developed for the purpose of modeling rockfall behavior and to provide statistical analysis of probable rockfall events at a given site.
- The program is based upon field studies of actual rockfalls and upon the principles of physics that apply equations of gravitational acceleration and conservation of energy to describe a body in motion..

Rockfall Analysis

- Since its official release in 1988 Caltrans staff has used CRSP almost exclusively to help design rockfall mitigation projects statewide.



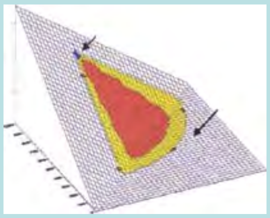
Rockfall Analysis

- Computer Simulation
  - Influencing Factors
    - Requires careful field work and experience to collect and use the appropriate factors.
  - This is a tool to be used in conjunction with other field data and site history

Rockfall Analysis

- Computer Simulation-Influencing Factors
- Slope Characteristics
  - Cross Section
    - Slope Length and Slope Inclination
  - Slope Surface
    - Surface Roughness
  - Slope Material Properties
    - Slope & Rock Coefficients Rt and Rn
      - 1. Soft Soil Slopes-pictures
      - 2. Talus and Firm Soil Slopes
      - 3. Most Bedrock and Boulder Fields
      - 4. Smooth Hard Surfaces and Paving
- Rock Characteristics
  - Durability, Size, Shape, Mass

Rockfall Analysis

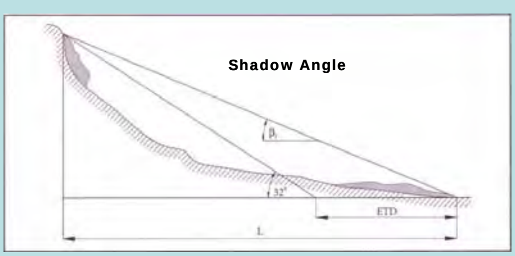


3-Dimensional Simulations
CONEFALL Model
Others
Europe
Japan
US (the new CRSP)

Rockfall Analysis

- **Shadow Angle**
  - The shadow angle is defined by the apex of the slope and not by the rockfall source area above the slope.
  - This is an angle between the horizontal line and the line connecting the highest point of talus and the point where the rocks stop.
  - This approach does not require the knowledge of the precise location of each rockfall release, because the rockfall activity is integrated in time by taking into account the largest distance traveled by blocks.

Rockfall Analysis



Rockfall Analysis

- **Shadow Angle**
  - The minimum shadow angle is the smallest shadow angle of an area.
  - Minimum values were given by several authors and are between 22° and 30°. Research in British Columbia came to a conclusion that the shadow angle is at least 27.5°, regardless of rock face height, trajectory length and slope gradient. Where talus slope is rather smooth, researchers suggest lower values (23°-24°).
  - The minimum shadow angle should be used only for the first assessment of the rockfall runout distance.

Rockfall Analysis

- Importance of Field Experiments
- Uncertainties

ROCKFALL MITIGATION METHODS

ROCKFALL MITIGATION METHODS

- Selection Criteria
  - Complexity
  - Effectiveness
  - Durability
  - Constructability
  - Special Expertise
  - Road Closure/Traffic Restrictions
  - Environmental Limitations
  - Aesthetic Impacts
  - Cost
  - Maintenance Requirements

ROCKFALL MITIGATION METHODS

- **Relocation**
- **Stabilization**
- **Protection**
- **Management**

Rockfall Mitigation Methods

RELOCATION

Avoiding the site is sometimes the cheapest and safest long-term solution to its rockfall problem

Rockfall Mitigation Methods

RELOCATION

- Reasons
  - Public safety
  - Maintenance cost
  - Construction safety
  - Length of road closures
  - No other reasonable alternatives

Rockfall Mitigation Methods

RELOCATION

RELOCATION - Rockfall Mitigation Methods

VIADUCT/BRIDGE

- Elevate roadway to allow rockfall to pass under structure
- Structure supports must be protected or out of rockfall impact zone
- Move alignment away from slope to create rockfall catchment area

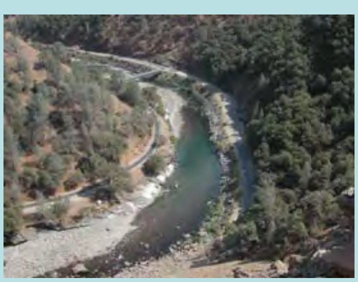
RELOCATION - Rockfall Mitigation Methods

TUNNELS

- Avoids rockfall by moving roadway into hillside
- Tunnel portals must be outside of rockfall impact zone

RELOCATION - Rockfall Mitigation Methods

REALIGNMENT



- Move roadway away from rockfall area
- Sometimes the nearby terrain does not allow realignment

RELOCATION - Rockfall Mitigation Methods

CASE HISTORIES

- Viaduct/Bridge
  - Forest Boundary
  - Pitkins Curve
- Tunnel
  - Devils Slide
- Realignment
  - Confusion Hill
  - Ferguson
- Hybrid
  - Emerald Bay

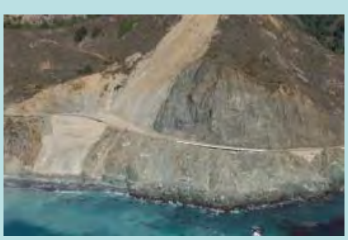
VIADUCT CASE HISTORY - Relocation Rockfall Mitigation Methods

FOREST BOUNDARY-Viaduct

- Viaduct allows unstable material to pass under the structure
- Since then at this site there have been no road closures
- No cleanup of rock fall debris required

VIADUCT CASE HISTORY - Relocation Rockfall Mitigation Methods

PITKINS CURVE-Bridge



- 1998 traffic was disrupted for 5 months, $5 million to restore roadway
- 2000 traffic was disrupted for 2 months, $3.4 million to restore roadway
- Since that time the yearly average has been 10 days of road closure and the maintenance cost has been $1 million

VIADUCT CASE HISTORY - Relocation Rockfall Mitigation Methods

PITKINS CURVE-Bridge

- $19 Million
- 2.5 years for public comment and design
- 4 years for construction
- $100 million estimated savings in maintenance costs during the bridge 50 year lifespan

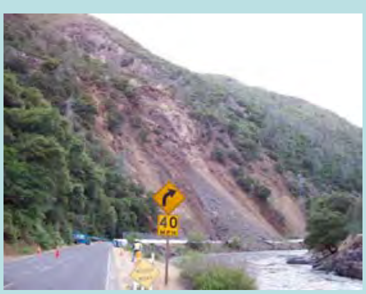
REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

Ferguson Rockslide

- Memorial Day 2006 rockfall from the slide buried 600 ft of Highway 140
- Slide plane 200 feet above roadway
- Continuing rockfall from the slide makes it unsafe to remove the rockfall debris from road

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

FERGUSON SLIDE



- Rockfall was so active that it was unsafe to reopen the highway

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

Ferguson Rockslide

- One of the proposed alternative alignments would be a 2200 ft long tunnel
- Single bore two lane
- Would require lighting and ventilation
- $230 Million
- Geotechnical investigation would take 1 year

TUNNEL CASE HISTORIES - Relocation Rockfall Mitigation Methods

DEVILS SLIDE

- Long history (since it was built in the '40's) of rockfalls, slides and road closures
- Closed for 158 days in 1995
- $3 million to repair roadway

TUNNEL CASE HISTORIES - Relocation Rockfall Mitigation Methods

DEVILS SLIDE

- Scarps produce rockfalls
- Individual blocks are up 6 feet in diameter
- Storms and earthquakes cause rockfalls

TUNNEL CASE HISTORY - Relocation Rockfall Mitigation Methods

DEVILS SLIDE

- Years of public input and engineering work
- Site will be bypassed with two inland tunnels

TUNNEL CASE HISTORY - Relocation Rockfall Mitigation Methods

DEVILS SLIDE

- It will cost $250 million
- Twin 30 foot diameter bores
- 4,200 foot long
- 1,000 foot long bridge
- On-site Operations and Maintenance facility
- Construction will take 5 years

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

CONFUSION HILL

- Maintenance cost was $33 million for the last ten years
- Over 100 days of road closures in 2005

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

CONFUSION HILL

- Five alternative alignments
- Common Elements
  - Two Bridges
  - Connecting Cut

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

CONFUSION HILL

- One year was required to obtain necessary permits for this project from other agencies
- FHWA approved emergency relief funds
- Design and Geotechnical work took two years

REALIGNMENT CASE HISTORIES - Relocation Rockfall Mitigation Methods

CONFUSION HILL

- Project cost will be $65 million
- Construction will require 3 years for completion

HYBRID CASE HISTORIES - Relocation Rockfall Mitigation Methods

EMERALD BAY

- Erosion of glacial till caused rockfall
- In the mid 80's a project that included a minor realignment was completed

HYBRID CASE HISTORIES - Relocation Rockfall Mitigation Methods

EMERALD BAY

- A viaduct was used to realign the roadway out away from the slope
- A concrete retaining wall was used to create a rockfall catchment area
- The catchment area requires periodic cleaning

Avoidance

Mitigation Selection

Summary of Engineered Mitigation Measures

- Tunnels
  - Purpose: Avoids road hazards by moving the roadway inside the rock mass away from external rockfall forces.
  - Limitations: Hazards associated with traffic in confined space. Long tunnels require lighting and special ventilation. Expensive.
- Realignment
  - Purpose: Full road realignment or facility relocation to move away from rockfall area.
  - Limitations: Often the old road must be maintained for existing access. Commonly there is limited space for this option. Expensive.
- Elevated Structures
  - Purpose: Used to span the anticipated rockfall paths allowing rockfalls to pass beneath.
  - Limitations: The structure must completely span the active area to avoid being damaged by rockfalls. Expensive.

STABILIZATION

- Rock anchors and strands
- Rock Dowels/ Shear Pins
- Shotcrete, Gunite and Mtn. Grout
- Anchored Mesh
- Cable Lashing
- Buttressing
- Retaining Walls
- Rock Slope Protection
- Drainage
- Dental Work
- Polyurethane Resin (PUR)
- Slope sculpting/slope flattening

STABILIZATION

- Rock anchors and strands

STABILIZATION

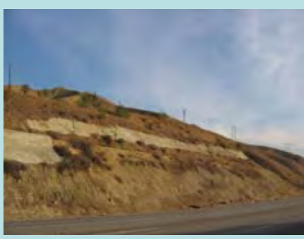
- Rock Dowels

STABILIZATION

– Shear Pins/Dowels

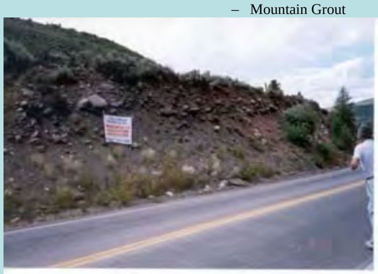
STABILIZATION

– Shotcrete and Gunite



STABILIZATION

– Mountain Grout



STABILIZATION

- Anchored Mesh
- Caltrans utilizes double twisted wire mesh and cable nets in anchor wired mesh installations.

STABILIZATION

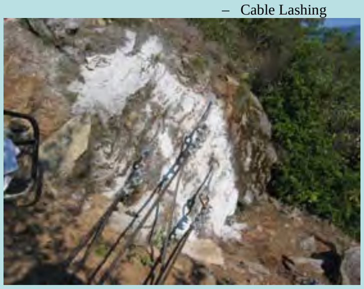
- Anchored Mesh

STABILIZATION

- Cable Lashing

STABILIZATION

– Cable Lashing

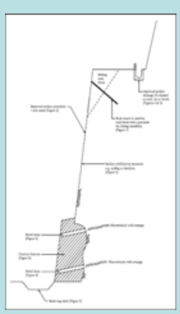


STABILIZATION

– Buttressing

STABILIZATION

– Buttressing



STABILIZATION

– Buttressing

STABILIZATION

– Retaining Walls

STABILIZATION

– Rock Slope Protection

STABILIZATION

– Rock Slope Protection

STABILIZATION

– Drainage

STABILIZATION

– Drainage

STABILIZATION

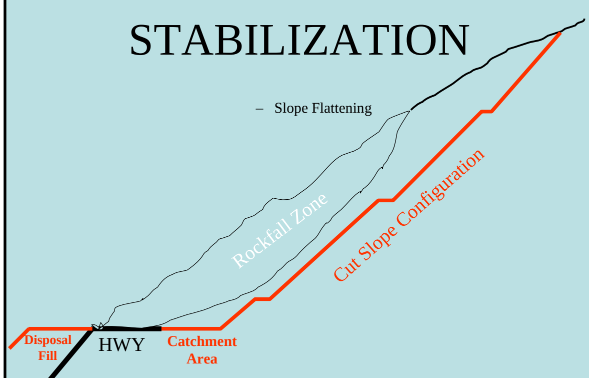
– Dental Work

STABILIZATION

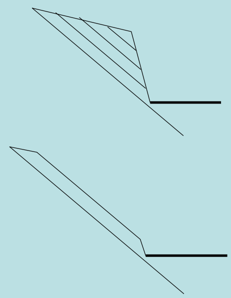
– Polyurethane Resin Injection (PUR)

STABILIZATION

– Slope Flattening



STABILIZATION



- Slope Flattening
  - Slope flattening does not always mean leveling an area. It may be as simple as decreasing the slope ratio to match appropriate planes that prevent the movement of rock.

STABILIZATION

- Slope Flattening/Slope Sculpting

STABILIZATION

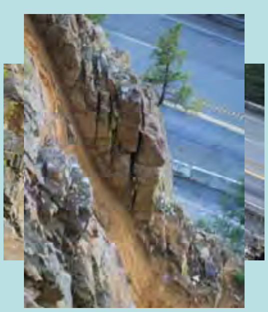
- Slope Sculpting

STABILIZATION

- Scaling
  - Scaling is the removal of loose and marginally stable rock from a slope face, utilizing hand methods
  - Scaling is considered a temporary stabilization technique when performed on a routine basis can be utilized for long term stabilization.

SCALING

SCALING and TRIM BLASTING



Scaling

- Should be done by experienced contractors
  - Proper Gear
    - Mobile, quick and safe
  - Understand Rockfall
    - Do not do excessive scaling
  - Right Tools
    - Right tool for the right job
      - Air bags, light scaling bars, hydraulic jacks
  - Appropriate Experience
    - Many State DOT's have experience requirements in their specifications.

STABILIZATION

- When it comes to slope stabilization it is not a one technique fits all slopes.
- Many different techniques maybe utilized in conjunction with one another to stabilize slopes.
- Requires little to no maintenance effort after completion.

STABILIZATION

Mitigation Selection

Summary of Engineered Mitigation Measures

- **Removal:**
- Scaling
  - Purpose: Removal of loose rock from slope by means of hand tools and/or mechanical equipment. Commonly used in conjunction with most other design elements.
  - Limitations: A temporary measure that usually needs to be repeated every 2 to 10 years as the slope face continues to degrade.
- Rock Removal/ Blast Scaling
  - Purpose: Removal of loose rock or large rock blocks from slope by means of blasting or chemical expanders.
  - Limitations: Damage from fly rock and rockfall, and possible undermining or loss of support by key-block removal.
- Trim Blasting
  - Purpose: Used to remove overhanging faces or protruding knobs that may act as launch features on a slope.
  - Limitations: Difficulties with drilling, debris containment, and safety.
- Re-sloping
  - Purpose: Cutting the rock slope at a flatter angle to improve slope stability and rockfall trajectories.
  - Limitations: May have right-of-way or environmental issues.

STABILIZATION

Mitigation Selection

Summary of Engineered Mitigation Measures

- **Reinforcement 1/2:**
- Dowels
  - Purpose: Untensioned steel bars/bolts installed to increase shear resistance and reinforce a block. Increases normal-force friction once block movement occurs.
  - Limitations: Passive support requires block movement to develop bolt tension. Slope-access difficulties.
- Shear Pins
  - Purpose: Provides shear support at the leading edge of a dipping rock block or slab using grouted steel bars.
  - Limitations: Cast-in-place concrete needed around bars to contact leading edge of block. Access difficulties.
- Rock Bolts
  - Purpose: Tensioned steel bars/bolts used to increase the normal-force friction and shear resistance along potential rock-block failure surfaces. Applied in a pattern or in a specific block.
  - Limitations: Less suitable on slopes comprised of small blocks. Difficult to access slope.
- Shotcrete
  - Purpose: Pneumatically applied concrete requiring high velocity and proper application to consolidate. Primarily used to halt the on-going loss of support caused by erosion and spalling. Also helps retain small supporting rock blocks.
  - Limitations: Reduces slope drainage. Can be unsightly unless sculpted or tinted. Wire mesh or fiber reinforcement required. Needs a minimum 2-inch (5-cm) thickness to resist freeze/thaw. Quality and durability are very dependent on nozzleman skills.

STABILIZATION

Mitigation Selection

Summary of Engineered Mitigation Measures

- **Reinforcement 2/2:**
- Buttresses
  - Purpose: Provide support to overhanging rock or lateral support to rock face using either earth materials, cast concrete or reinforcing steel.
  - Limitations: Height limitations. May form a roadside hazard and be unsightly.
- Cable Lashing
  - Purpose: Anchored, tensioned cable(s) used to strap a rock block in place. May be used in conjunction with cable nets or wire mesh. Also used as a temporary support during rock-bolt/dowel drilling activities.
  - Limitations: Due to slope and/or block geometry, typically movement must occur for full cable resistance to develop.
- Whalers/Lagging
  - Purpose: Anchored beams or steel straps used to hold rock blocks in place between bolt locations. Also used as a temporary measure to provide support during rock-bolt/dowel drilling activities.
  - Limitations: Unsightly as a permanent application. Movement must occur for full tensioning/resistance to develop.
- Anchored wire mesh/cable nets/ high tensile strength steel mesh
  - Purpose: Free-draining, pinned/anchored-in-place nets or mesh. Used to apply an active retention force to retain rocks on a slope.
  - Limitations: May form pockets of loose rock as rockfall debris accumulates. Can be difficult to clean out.

STABILIZATION

Mitigation Selection

Summary of Engineered Mitigation Measures

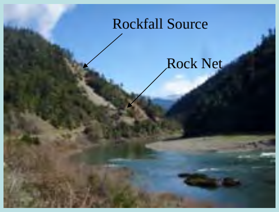
- **Drainage:**
  - Weep Drains
    - Purpose: Reduces water pressures within a slope using horizontal drains or adits. Commonly used in conjunction with other design elements.
    - Limitations: Difficult to quantify the need and verify the improvements achieved.

PROTECTION

- The application of protection measures inherently accepts the occurrence of rockfalls and strives to mitigate the associated hazard by
  - Stopping
  - Controlling
  - Deflecting.

PROTECTION

- Conditions that typically warrant protection measures include:
  - rockfall source areas that lie beyond boundaries of the facility
  - aerial extent or nature of the source area is impractical or excessively costly to stabilize or,
  - not practical or excessively costly to relocate the facility to avoid the hazard.



PROTECTION

- Protection measures are inherently passive systems.
  - Provide a barrier
  - control the trajectory
  - reduce energy
  - provide a catchment
- The most common protection measures include:
  - catchment areas
  - barriers and fences
  - draped slope protection

PROTECTION

- Protection measures can often be
  - more cost-effective,
  - involve simpler construction,
  - be constructed within the boundaries of the facility,
  - And result in less environmental impacts.
- For these reasons, protection measures are probably more widely applied for remedial rockfall mitigation than stabilization and avoidance measures.
- Protection measures, however, are not the panacea for all rockfall hazards.

PROTECTION

- Rigid
  - Rock Sheds
  - Timber Walls
  - Concrete Walls
  - Jersey Barrier (K-rail)
  - Earthen Berms and Buttresses
  - Catchment Ditches
- Flexible
  - Cable Nets
  - Wire fences
  - Wire Drapery
  - Cable Drapery

PROTECTION

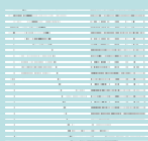
- **Catchment Ditches**
- catchment areas are designed to stop moving rocks before they reach the facility by dissipating their energy on flat or negatively sloped ground.

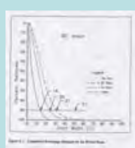
PROTECTION

- Properly designed rock Catchment Ditches will prevent most falling rock from reaching the road.
- There are three general design strategies for catchment ditches:
  1. Ritchie ditch (Ritchie, 1963; FHWA, 1989),
  2. Rockfall Area Design Guide (Pierson et al., 2001),
  3. and computer modeling and dimensioning.

PROTECTION

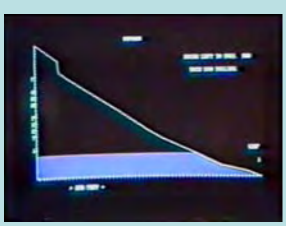
- The Ritchie Ditch
  - incorporates slope height and inclination to dimension the ditch and provide for a rock protection fence, if needed
- **Rockfall Catchment Area Design Guide, 2004**
  - **http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/RockfallReportEng.pdf**





PROTECTION

- **Computer modeling**
  - This design approach would be employed for rock falls generated from irregular natural slopes and compound cut slopes or those that exceed the heights defined in previous design methods.



PROTECTION

- **Mid Slope Benches**
  - With improved characterization of rock mass conditions and the use of controlled blasting, many designers dropped their use opting for uniform steep cuts that account for potentially adverse structural control combined with ditches.

PROTECTION

- Barriers
  - can deflect or contain rockfall, depending on their location and orientation with respect to the rockfall trajectory.
  - function either by being sufficiently stiff to withstand or flexible to attenuate the kinetic energy of the rockfall impact.

PROTECTION

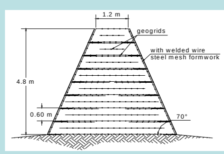
- The most common barriers in North America for permanent applications include:
  - earthen berms
  - concrete barriers
  - structural walls
  - Fences and draperies
- Mass (m) is the property a body has of resisting any change in its state of rest and is a measure of inertia of the rock body.

PROTECTION

- **<u>Earthen berms and Buttresses</u>**
  - Piled earth
  - Fortress buttress
  - MSE structure with vertical walls

PROTECTION

- Full scale test of geogrid-reinforced MSE wall with a 10,000 kg mass traveling at approximately 30 m/s demonstrates the high capacity (4500 kJ / 1660 ft-tons of this protection measure



ROCKFALL MITIGATION-Protection

Testing

- **<u>Concrete barriers</u>** are widely applied to improve ditch effectiveness, but all systems have their limitations

PROTECTION

- **Structural Walls**
  - Walls incorporate a variety of structural elements to withstand the often very high impact energy associated with rock falls, while striving to minimize the footprint of the protection structure.

PROTECTION

- **Gabions**
  - Rock-filled wire baskets that can be stacked to form gravity walls and barriers for rockfall protection.
  - Gabions also have well demonstrated performance of withstanding high impact energies although their capacity has not yet been well quantified.

PROTECTION

- **Rock Sheds**
  - The basic configuration of a shed consists of a near-horizontal roof covered with a layer of energy-absorbing material
  - An alternative configuration consists of an inclined, relatively lightweight roof that directs the rock falls across the shed with little impact force

PROTECTION

- Rigid
  - Rock Sheds

PROTECTION

- **Fences,** like nearly all barriers, are used to create a rockfall catchment area. A fence is a structure able to maintain a net on a slope in a position to intercept the highest number of moving rock blocks.

PROTECTION

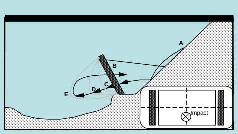
- The blocks' stopping involves the fence to deform so that it dissipates the kinetic energy of the block with a suitable safety factor.

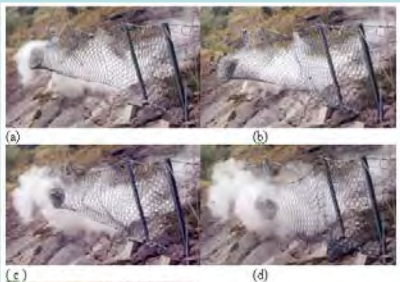
  Impact Force
  Force = Mass x Acceleration

  $F = m a$

  $F = m\, \delta v/\delta t$

  $F = m (v_2 - v_1)/(t_2 - t_1)$





•It is a fences flexibility that gives the fence a distinct advantage over all other barriers in terms of costs, design and construction.

PROTECTION

- Flexible Barrier

PROTECTION

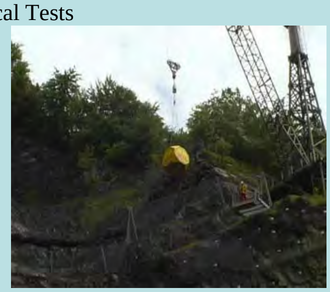
- NCHRP 20-7
  - Recommended Procedures for the Testing of Rockfall Barriers-
    - Switzerland, USA, and European Union
    - **MEL-Maximum Energy Level**
    - **SEL-Service Energy Level**
    - Proof Testing under Ideal Conditions
    - Compare Products
    - Not a Real World Test

PROTECTION

- Why do we test? Buyer Beware

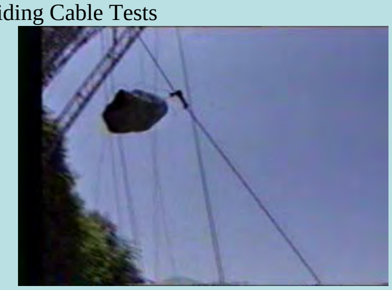
PROTECTION

- Vertical Tests



PROTECTION

- Sliding Cable Tests



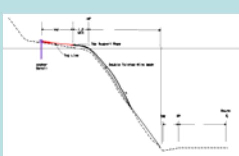
PROTECTION

- Actual Field Tests – 960 kilo-joules

PROTECTION

- at energy levels below 500 kilo-joules fences stop rocks effectively requiring only annual cleaning and associated minor maintenance.
- Above this energy level maintenance requirements increase but not dramatically until energy levels reach 1000-kilo joules and above.
- At these levels rocks are effectively stopped but maintenance is significant and in some cases replacement is necessary.

PROTECTION



- **<u>Drapery Systems</u>**
  - Drapery systems entail only anchoring a mesh along the top of the slope, allowing rockfalls to occur between the slope and the mesh, and controlling their falls into a containment area at the base of the slope/installation.

PROTECTION

- Drapery systems have been installed on moderately inclined to overhanging slopes and in excess of 120 m (400 ft) in height.
- Systems have been successfully applied to very uniform slopes and highly irregular slopes.
- Systems are generally exposed to rockfall trajectories and impacts in the plane of the fabric.

PROTECTION

Research Report

http://www.wsdot.wa.gov/biz/mats/Geotech/WA-RD612.1WireMesh.pdf

Design Guidelines

http://www.wsdot.wa.gov/biz/mats/Geotech/WA-RD612.2WireMesh.pdf

PROTECTION

- **Double-Twisted Wire Drapery**
- Double-twisted hexagonal mesh has demonstrated an upper range of effectiveness for block sizes up to about 2 ft
- Analyses and case histories bear out that standard drapery systems cannot sustain loads much in excess of 10 cubic yards of debris

PROTECTION

- **Cable Drapery**
- Cable nets have proven effective for block sizes up to about 4 ft
- Analyses and case histories bear out that standard drapery systems cannot sustain loads much in excess of 10 cubic yards of debris

PROTECTION

- The slope on the left in photo (A) was draped in 1992 with little attention to slope interface contact. The center slope was draped in 2005 with careful attention to slope interface contact. In photo (B) taken in 2007 the slope on the left is still lightly vegetated while the center slope is heavily vegetated

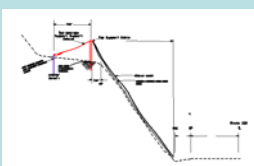
PROTECTION

- The slope in the top photo was draped in 2008 with careful attention to slope interface contact. In the bottom photo, taken in 2010, the slope is re-vegetating the slope is stabilizing and the mesh well camouflaged.

PROTECTION

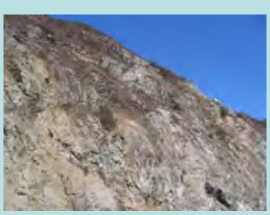
- Hybrid Drapery Systems
  - Provide the added benefit to a standard drapery of intercepting rock falls sourced upslope of the installation by lifting the top of the system off the ground.
  - Such systems can be impacted with considerable energy out of the plane of the mesh.
  - By not restraining the base of the mesh, the fabric has the ability to deform and attenuate the energy and control the trajectory into a suitable containment area at the bottom of the installation

PROTECTION



PROTECTION

Hybrid cable net drapery system. Big Sur Coast. Color coating “Desert Tan”.



PROTECTION
Mitigation Selection
Summary of Engineered Mitigation Measures

- Catchment Areas/Sheds
  - Ditches and Berms
    - Purpose: A shaped catchment area at the base of the slope used to contain rockfall.
    - Limitations: Tall Slopes require wide fallout areas. May have ROW or environmental issues.
  - Rockfall Sheds
    - Purpose: A covered structure used to intercept and divert rockfalls.
    - Limitations: Expensive, hazards associated with traffic in confined space. Must consider down slope issues.

PROTECTION
Mitigation Selection
Summary of Engineered Mitigation Measures

- **Barriers**
  - Rigid Barriers
    - Purpose: Used to intercept falling rock and restrict the rocks to a prescribed fallout areas.
    - Limitations: Rigid systems are more prone to damage by higher energy events. Complicates debris cleanout and snow plowing.
  - Flexible Barriers
    - Purpose: Wire mesh panels with energy absorption capacity supported by posts and anchor cables with braking elements. Typically proprietary systems.
    - Limitations: Require room for barriers to deflect during impacts. Must be cleaned out periodically. Complicated snow plowing.

PROTECTION
Mitigation Selection
Summary of Engineered Mitigation Measures

- **Mesh/Cable Nets**
  - Draped Mesh Slope Protection
    - Purpose: Placed on slope face to slow erosion, control the descent of falling rocks, and restrict the rocks to the catchment area.
    - Limitations: Require a debris collection ditch area. Must consider debris and snow loads. Typically limited to 4 ft (1.2 m) rocks.
  - Suspended Systems
    - Purpose: Mesh suspended by posts or suspended across chutes. The fence intercepts the attenuates falling rocks initiating upslope, and directs the rocks beneath the mesh and into catchment areas.
    - Limitations: Require a debris collection ditch area. Must consider debris and snow loads. Typically limited to 4 ft (1.2 m) rocks.

PROTECTION

- Protection Measures
  - Have limitations
  - Require Maintenance
  - Not a Panacea for all rockfall

Management

- Warning systems
- Signs
- Monitoring
- Rock Patrols
- Rockfall Management program

ROCKFALL MITIGATION

MANAGEMENT

Mitigation Selection

Summary of Non-engineered Mitigation Measures

- **Warning Signs**
  - Purpose: Alert users to the potential for rockfall and for fallen rocks to be encountered on the roadway.
  - Limitations: Users become accustomed to presence of signs and ignore warnings.
- **Road Patrols**
  - Purpose: Roadway inspections during periods of higher rockfall activity to find and remove fallen rocks.
  - Limitations: May encompass too many miles of road to manage in a timely manner.
- **Ditch Cleaning**
  - Purpose: Removal of accumulated rockfall debris from ditches to maintain their effectiveness in capturing rocks.
  - Limitations: Temporary measure requiring repeated action by maintenance crews and a suitable disposal site.
- **Monitoring**
  - Purpose: Use of instruments to detect incipient rockfalls.
  - Limitations: Lead time to events can be short.

SUMMARY

- Questions?
- This Afternoon
  - Current Events
    - Flexible Rockfall Fences
    - Wire and Cable Mesh Drapery
    - Anchored Wire Mesh
    - Analysis
    - Rockfall Hazard Ratings
    - Field Work
  - Open Forum