

**Rockfall
Mitigation
Design
Packet**

CURRENT EVENTS

- ROCKFALL TECHNICAL TEAM
- FLEXIBLE ROCKFALL FENCES
- WIRE AND CABLE MESH DRAPERY
- ANCHORED MESH
- SCALING
- ROCKFALL ANALYSIS
- HAZARD RATING
- FIELD WORK
- LONG TERM PERFORMANCE OF MITIGATION SYSTEMS
- OPEN FORUM

CT Rockfall Technical Advisory Committee

- John D. Duffy – Chairperson
 - Bill Webster – Committee Member
 - Charlie Narwold – Committee Member
 - Scott Lewis – Committee Member
 - Grant Wilcox – Committee Member
 - Gustavo Ortega – Committee Member
 - Friends of the Committee

DES Geotechnical Discussion Board

- [http://cap1.dot.ca.gov/forum/Geotechnical Services/index.php](http://cap1.dot.ca.gov/forum/Geotechnical%20Services/index.php)
 - This is the location to open dialog between Committee Members and staff that is non-urgent or comment on policies being proposed or implemented.
 - CRSP
 - RHRS

Action Items

- Rockfall Web Page
- Statewide Inventory of Mitigation GIS Based
- Emergency Response Team
- nSSPs to SSPs

• RTT GOALS

– Develop and Implement for Rockfall



- A Systematic Approach
- Guidelines and Procedures
- Standard Special Provisions
- Training

• RTT GOALS

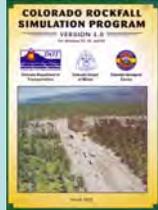
– Adopt Cut Slope Design and Development and Implement



- A Systematic Approach
- Guidelines and Procedures
- Standard Special Provisions
- Training

• RTT CURRENT STATUS

- Rock Scaling Training
- Rockfall Mitigation Workshop
 - District 8
 - HQ Geotech
- Standards and Policy
 - Rockfall Hazard Rating System
 - Computer Simulation



• FUTURE PROJECTS

- Cut Slope Design Procedures and Workshop and FHWA Rock Slope Design NHI Training
- Rockfall Hazard Rating System FHWA NHI Training
- Emergency Response Team
- Standard Special Provisions
- Inventory of Statewide Systems GIS Based
- Geotechnical Web Site for ROCKFALL and Cut Slope Design

New TRB Manual

- Rockfall Mitigation and Control
- Expected Publication Date July 2010

TRB Rockfall Manual

- **Chapter 1: Introduction**
– *AUTHORS: A.K. Turner, R.L. Schuster & G.P. Jayaprakash*
- **Chapter 2: Rockfall Types and Causes**
– *AUTHORS: J.D. Higgins & R. Andrew*
- **Chapter 3: The Rockfall Hazard Rating System**
– *AUTHORS: Larry Pierson*
- **Chapter 4: Implementation and Modification of Rockfall Hazard Rating System Concepts to Reflect Regional Variations**
– *AUTHORS: Larry Pierson & A.K. Turner*

TRB Rockfall Manual

- **Chapter 5: Quantitative Risk Assessment of Rockfall**
– *AUTHORS: A.K. Turner (& W.J Roberds & A.T. Moon??)*
- **Chapter 6: Site Characterization**
– *AUTHORS: Rick Andrew & J.D. Higgins*
- **Chapter 7: Instrumentation**
– *AUTHORS: Rick Andrew*
- **Chapter 8: Evaluation of Rockfall Mechanics**
– *AUTHORS: A.K. Turner & J. Duffy*

TRB Rockfall Manual

- **Chapter 9: Modeling and Prediction of Rockfall**
– *AUTHORS: J. Duffy & A.K. Turner*
- **Chapter 10: Energy Adsorption Considerations**
– *AUTHORS: J. Duffy & J.D. Higgins*
- **Chapter 11: Mitigation Selection**
– *AUTHORS: Michael Vierling & Larry Pierson*
- **Chapter 12: Avoidance of Rockfall Areas**
– *AUTHORS: Tom Badger and John Duffy*

TRB Rockfall Manual

- **Chapter 13: Stabilization of Rockfall**
– *AUTHORS: R. Andrew & Larry Pierson*
- **Chapter 14: Selection of Rockfall Protection Measures**
– *AUTHORS: Thomas C. Badger & John Duffy*
- **Chapter 15: Rockfall Catchment Fences**
– *AUTHORS: John Duffy & Thomas C. Badger*
- **Chapter 16: Drapery Systems**
– *AUTHORS: Thomas C. Badger & John Duffy*

TRB Rockfall Manual

- **Chapter 17: Maintenance, Monitoring and Response**
– *AUTHORS: Thomas C. Badger and Michael P. Vierling*
- **Chapter 18: Rockfall Management Programs**
– *AUTHORS: Steve M. Lowell and Norman I. Norrish*

**FLEXIBLE
ROCKFALL
FENCES**

Flexible Rockfall Barriers

- Ground Anchors
- MEL – Maximum Energy Level
- SEL – Service Energy Level
- 500 kj and 1000 kj
- Maintenance

Flexible Rockfall Fences

- 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.

Flexible Rockfall Fences

Considerations in designing active measures

Impact Force

Force = Mass x Acceleration

$$F = m a$$

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

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

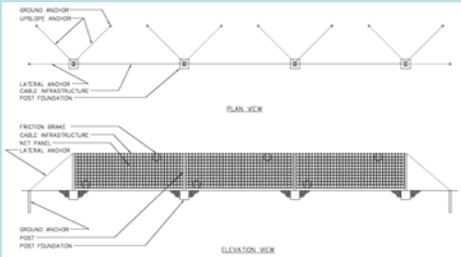
Flexible Rockfall Fences

- 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.
 - Another factor in a barrier performance is the inertia the rockfall has to overcome. The heavier the mesh the more inertia.

Flexible Rockfall Fences

• Four Major Components

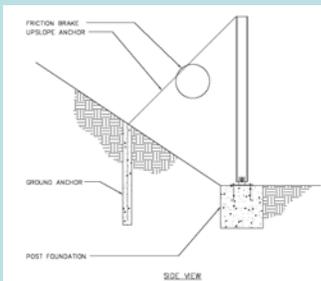
- Cable Mesh
- Posts and Post Foundations
- Anchors and Brakes
- Cable Infrastructure



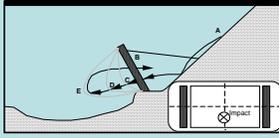
• Dissipation of Energy

Net Panel Deforms
 Cable Infrastructure Elongates
 Brakes Activate

➡ Rock Decelerates



Flexible Rockfall Fences



- The ideal impact for any flexible barrier is a center-fence impact. A center impact allows the fence to fully flex, thereby efficiently absorbing energy with minimal damage.
- The fence flexibility increases the time for the rock to decelerate, therefore decreasing the total force on the system and increasing the fence's ability to absorb high energies with minimal maintenance.



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

Flexible Rockfall Fences

- Flexible Barrier



Flexible Rockfall Fences

- NCHRP 20-7
 - Recommended Procedures for the Testing of Rockfall Barriers
 - Vertical Drop Tests
 - Sliding Cable Tests
 - Actual Field Tests

Flexible Rockfall Fences

- Why do we test?



Flexible Rockfall Fences

- Vertical Tests



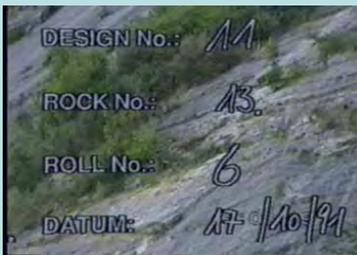
Flexible Rockfall Fences

- Sliding Cable Tests



Flexible Rockfall Fences

- Actual Field Tests



Flexible Rockfall Fences

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

Flexible Rockfall Fences

- MEL
 - Maximum Energy Level
- SEL
 - Service Energy Level
 - Swiss and US
 - SEL = MEL/2
 - EU
 - SEL = MEL/3

Post Foundations for Flexible Rockfall Fences

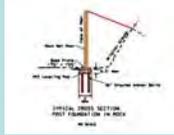
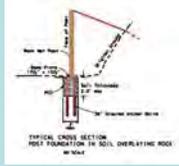
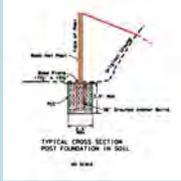
Posts

- Maintain Catchment Height
- Replaceable Connections
- Pinned vs. Fixed



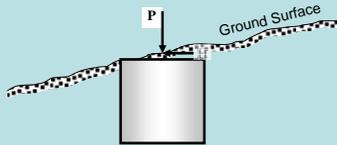
Post Foundation Design

- Site Reconnaissance
- Typical Foundation Conditions



Post Foundation Design Continued

- Design Loads
 - Predicted Foundation Loads
 - Isofer/Rotec
 - Measured Foundation Loads
 - Maccaferri MAC.RO. CTR-500-B System



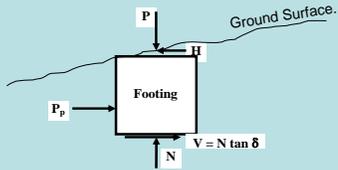
Experience

- Caltrans 1990-Present
 - 85 Flexible Rockfall Fences
 - 12,750 Linear Feet of Fence
 - 731 Posts and Foundations
 - **0 Foundation Failures**



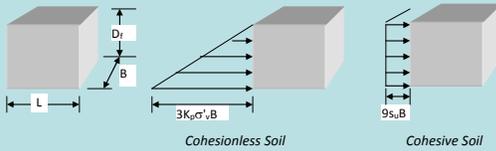
Foundation Design and Analysis

- Axial and Shear Loads
- Foundation Resistance



Foundation Design Example

- Measured Loads from Maccaferri Test
- Typical Caltrans 500 kJ Foundation
- 2½-foot x 2½-foot x 2½-foot Unreinforced Concrete
- Cohesionless Soil Overlying Rock
- Brom's Method for Approximating Ultimate Passive Resistance



Foundation Design Example Continued

Axial compressive force and shear force acting on the footing (measured):

$$P = 12.88 \text{ kips} \quad H = 7.55 \text{ kips}$$

Shear resistance at the base of footing:

$$V = P \tan \delta = 9.88 \text{ kips} \tan(35^\circ) = 9.02 \text{ kips}$$

Coefficient of passive earth pressure:

$$K_p = \tan^2(45^\circ + 35^\circ/2) = 3.69$$

Resultant of passive resistance:

$$P_p = \frac{1}{2} B [3 K_p \sigma'_v B]$$

$$P_p = \frac{1}{2} 2.5 \text{ ft} \times [3 (3.69) (2.5 \text{ ft}) (120 \text{ pcf}) (2.5 \text{ ft})] = 10.34 \text{ kips}$$

Summation of resistances:

$$V + P_p = 9.02 + 10.34 = 19.36 \text{ kips} > 7.55 \text{ kips}$$

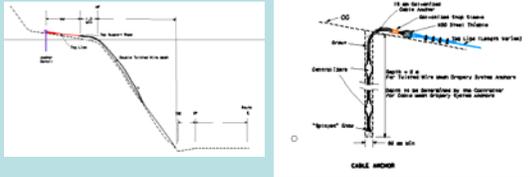
Footing is stable

**WIRE
AND
CABLE
MESH DRAPERY**

- Drapery**
- Mesh
 - DTWM
 - Chain Link
 - High Tensile Steel Wire - Spider Nets
 - High Tensile Steel Wire - Tecco
 - Low Strength – 9 gauge mss wire
 - Cable Nets
 - Ring Nets
 - Anchors
 - Sole Sourcing/Proprietary

- Wire and Cable Mesh Drapery**
- Drapery Systems
 - 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.

Wire and Cable Mesh Drapery



Wire and Cable Mesh Drapery

- 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.

Wire and Cable Mesh Drapery

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>

Wire and Cable Mesh Drapery

- 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



Wire and Cable Mesh Drapery

- 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





Cable Mesh



Ring Mesh



Spider and Tecco Mesh



Wire and Cable Mesh Drapery

- **Material Specifications**

- Unit Weight
- Large Panel Puncture Strength
- Simple Element Strength/Materials
- Isotropic Flexibility
- Corrosion Protection

Wire and Cable Mesh Drapery



- 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.

Wire and Cable Mesh Drapery

- **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

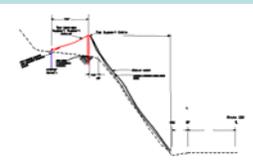
Wire and Cable Mesh Drapery

- **Two design Approaches with Hybrids**

- As a Flexible Fence Design
 - Absorb dynamic loads
 - High velocity impacts
- As a Drapery design
 - Catch and control
 - Low velocity impacts

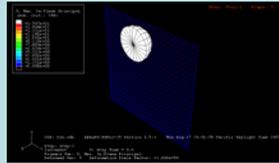
Wire and Cable Mesh Drapery Hybrids

As a Flexible Fence Design
Absorb dynamic loads
High velocity impacts



Wire and Cable Mesh Drapery Hybrids

- Finite Element Modeling of Hybrid Drapery Systems
- The top two corners are fixed.
- The hemisphere weighs 1000lbs and moves at a velocity of 25ft/s.



Wire and Cable Mesh Drapery Hybrids



San Bernardino 330
California State 330 San Bernardino County Post Mile 31.8

Wire and Cable Mesh Drapery Hybrids

Hybrids can be used to slow rocks down to more manageable energies.

Wire and Cable Mesh Drapery Hybrids

- Hybrids as a Drapery
 - Catch and control
 - Low velocity impacts



ANCHORED MESH

Anchored Mesh

- DTWM
- Cable mesh
 - Spider Mesh
 - Ring Nets
 - Cable Mesh
- Anchor Spacing and Loads
- Ruvolum method and myths

Design Limitations

Anchorage
Slope stability

Mesh
retains unstable fragments between anchorages.

Design Limitations

The mesh does not interfere with the overall stability of the slope

The calculation of the mesh is in relation with the spacing between the two anchors.

The potential anchor rupture is in relation with the overall stability of the slope.

MESH
GLOBAL STABILITY

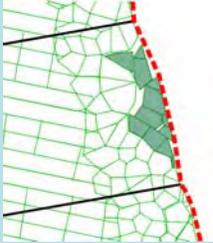
Design Limitations

The deformation of the mesh is very high.

The mesh is not a beam which transmits loads.

The mesh is **FLEXIBLE** and **DEFORMABLE**

Design Limitations



The mesh does not introduce forces in the geotechnical stability before any movement of rocks.

The mesh is a **passive** device.

The mesh only reacts after the movement of the rocks.

The system mesh and anchorages are **PASSIVE SYSTEMS**

Anchored Wire Mesh



- Caltrans Design
 - Anchor Spacing 10 feet
 - DTWM
 - Cable Nets

Anchored Wire Mesh



Anchored Wire Mesh

– Anchored Mesh



Testing



**ROCKFALL
ANALYSIS**

CRSP

- Widespread CT use again gives us a language
- Not perfect
- All models are only tools

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

- **There are two principle methods of analyzing rockfall trajectories.**
 - 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
 - $\frac{1}{2} mv^2 + \frac{1}{2} I \omega^2$



Rockfall Analysis

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



Rockfall Analysis

- Moment of Inertia for Rectangular Parallelepiped
 - $I_{xx} = 1/12 m (a^2 + b^2)$
 - $I_{yy} = 1/12 m (c^2 + b^2)$
 - $I_{zz} = 1/12 m (a^2 + c^2)$
- for a Sphere
 - $I_{zz} = 2/5 mr^2$

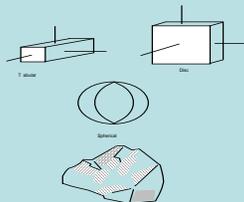


Figure 1. Common Rockfall Shapes: Rectangular Parallelepiped, Disk, and Sphere

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

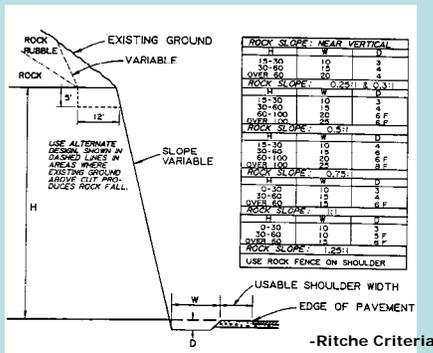
- **EMPIRICAL ANALYSIS OF ROCKFALL**
 - Empirical methods are based on experience and/or derived from testable observations and are verifiable by means of scientific experiment.
 - Over the years there have been numerous rockfall studies where rocks have been rolled down slopes for the purpose of understanding 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

• 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
- Ritchie described the various modes of travel as:
 - on slopes flatter than 1:1 rocks rolled down a slope,
 - on slopes up to 1/2:1 rocks bounced down slope
 - on slopes 1/4:1 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

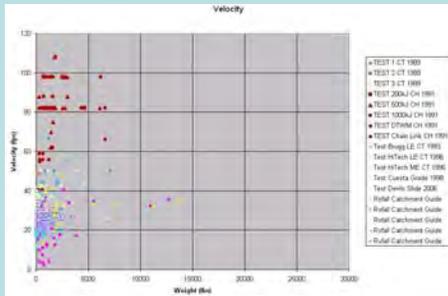
Rockfall Analysis



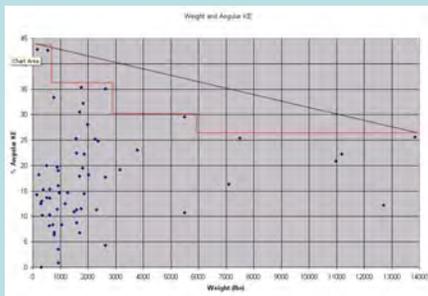
Rockfall Analysis

- **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

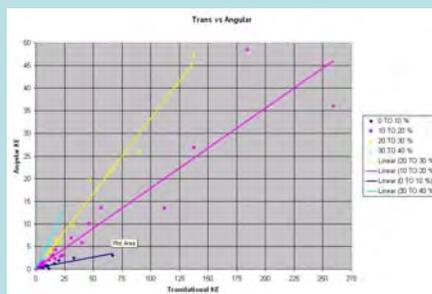
Velocity for all slopes vs Rock Weight



% Angular KE vs Rock Weight

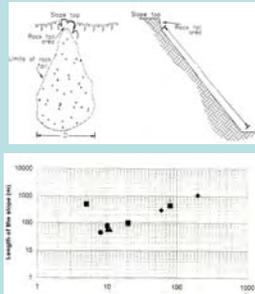


Translational KE vs Angular KE



Rockfall Analysis

- **Azzoni (Italy) 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

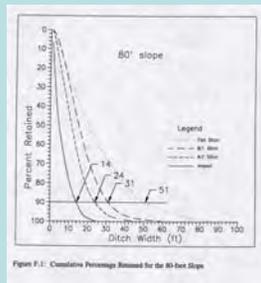


Figure P.1: Cumulative Percentage Retained for the 50 box slope

Rockfall Analysis

- **Other rock rolling tests around the world**
 - Caltrans
 - 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.

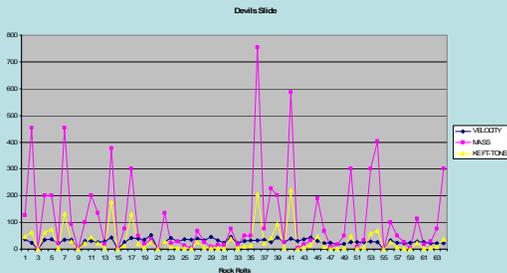
Rockfall Analysis

- Example - Devils Slide



Rockfall Analysis

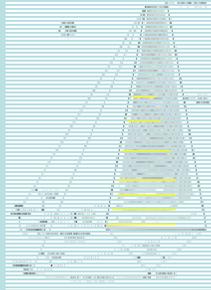
Example Devils Slide



Rockfall Analysis

- Field Tests

- Test Slope
- Test Rocks
- Data Collection
- Computer Modeling



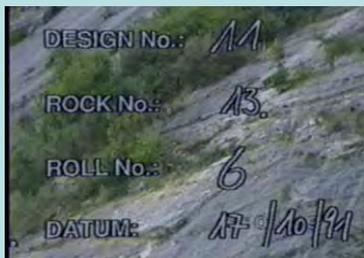
Rockfall Analysis

- Caltrans Field Tests



Rockfall Analysis

- Swiss Field Tests



Rockfall Analysis

- **Hand Calculations**

- As an object falls from rest, its gravitational **potential energy** is converted to kinetic energy. Conservation of energy permits the calculation of the velocity just before it hits the surface.

- Velocity $(v) = \sqrt{2gh}$
- Mass $(m) = \text{weight}/g$ (acceleration of gravity)
- $\frac{1}{2} m \cdot v^2 = \text{KE}$ (Kinetic Energy)

- **Hand Calculations**

- Japanese practitioners have done experiments evaluating the relationship between the velocity of a free fall and the smaller velocity of a falling rock on a slope from the same height. Generalized ratios were established from 0.60 to 0.85 for talus and from 0.85 to 0.96 for rock slopes

- **Hand Calculations**

- Caltrans practitioners use these equations to calculate the maximum velocity and energy a falling object could achieve (potential Energy). This is sometimes used in emergency situations where a quick analysis is required but can also be use to cross check computer simulations.

Rockfall Analysis

- **Hand Calculations**

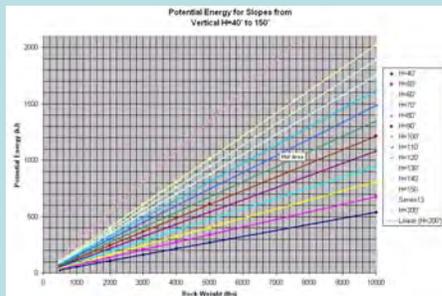
- You are called out to investigate a rockfall.

- Slope height = 60 feet
 - Rock size 2 feet in maximum dimension
 - Estimate Energy?

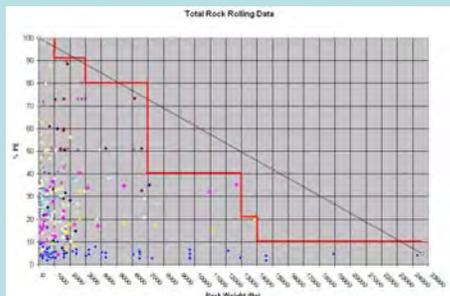
- Note

- » Free Falling Object
 - » $(Velocity)^2 = 2gh$
 - » Mass = weight/g (acceleration of gravity)

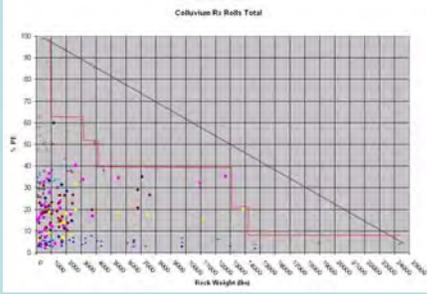
Potential Energy for vertical slope heights from 40 to 200 feet vs Rock Weight



% Potential Energy for all slopes vs Rock Weight



% Potential Energy for Colluvial (soft) slopes vs Rock Weight



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.

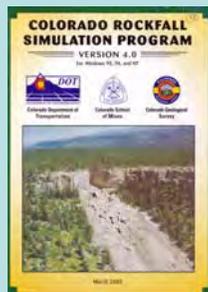
Rockfall Analysis

- **COMPUTER SIMULATION OF ROCKFALL**

- CRSP – USA
- Rocfall - Canada
- Rockfall - Europe

Rockfall Analysis

- In order to achieve conformity and consistency within the Department when the occasion requires a rockfall computer simulation it is Geotechnical Services policy that the current version Colorado Rockfall Simulation Program (CRSP) be used as the standard.



Rockfall Analysis

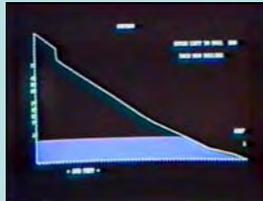
- The development of CRSP was funded through the Colorado Department of Transportation in cooperation with the U.S. Department of Transportation, and Federal Highway Administration. Caltrans Engineering Geology staff evaluated initial test versions of the program and contributed rock rolling data to 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.

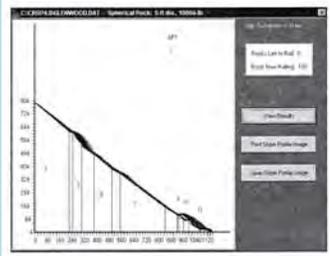


Rockfall Analysis

- Input
 - Cross Section with Individual Cells
 - Surface Roughness and Hardness
 - Rock Size and Shape
 - Rockfall Initiation Location
 - Height of Initial Fall
 - Analysis Location

Rockfall Analysis

Output



Rockfall Analysis

• Output

The screenshot shows a software window titled "A.P. 1 Statistical Analysis - C:\CRSP\M\GLENWOOD.DAT". It displays a table with the following data:

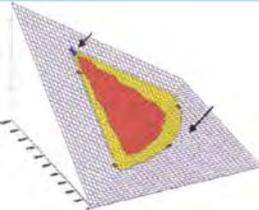
Cumulative Probability	Velocity (ft/sec)	Energy (ft-lb)	Source Height (ft)
50%	98.5	198220	2.82
75%	91.73	1962376	4.99
90%	86.42	2022195	7.59
95%	82.24	2119000	9.93
99%	72.41	2227995	11.45

Note: Velocity and kinetic energy are analyzed assuming a normal distribution.
Source height is analyzed assuming a log distribution.

Rockfall Analysis

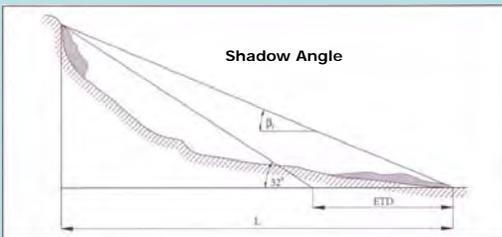
- Run Program

Rockfall Analysis



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

Rockfall Analysis



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

- **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



Caltrans Adopted Method – RHRS Rockfall Hazard Rating System



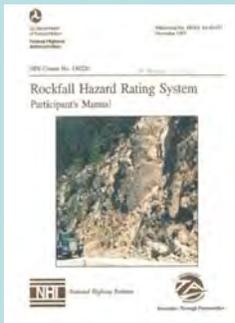
- In order to achieve conformity and consistency within the Department when the occasion requires a quantitative ranking of rockfall generating slopes it is Geotechnical Services policy that the Rockfall Hazard Rating System (RHRS) be used as the standard.

RHRS

- A common language for rockfall practitioners similar to N Blow Counts
- Not mandated statewide
- Good field investigative tool
- Use and begin a data base
- RHRS Components
- Slope Height
- Ditch Effectiveness
- Average Vehicle Risk
- % Decision Site Distance
- Road Width
- Geologic Character
- Block Size
- Climate and Presence of Water
- History

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 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)
 $AVR = (ADT \times (SD/5280) / 24) / SL \times 100$

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	825
60	900
65	1,050
70	1,200
75	1,350
80	1,500

- 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.

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
 - Rating of Structural Condition is broken into two classifications.
 - Classification 1 describes the joint/fracture/bedding length and inclination towards the highway.
 - Classification 2 describes the rocks frictional characteristics.

RHRS Components Geologic Character

- Case 2 Differential Erosion
 - Rating of Differential Erosion is broken into two classifications.
 - Classification 1 describes the amount of erosion features that exist on the slope.
 - Classification 2 describes the difference in erosion rates of differing material making up the slope.



RHRS Components Block Size/Quantity of Event



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



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

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

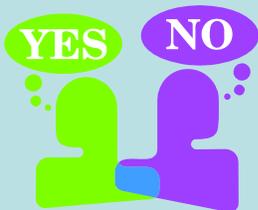
- Few Falls
- Occasional Falls
- Many Falls
- Constant Falls

RHRS Components Rockfall History



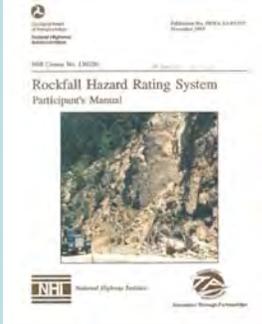
- Maintenance
- Legal
- Citizens
- Construction
- CHP
- TASAS Traffic Accident Surveillance Analysis System - Accident History

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.

RHRS



- RHRS is supported by the Federal Highway Administration (FHWA) and has been adopted by many State Departments of Transportation. FHWA supports and encourages the use of RHRS through a manual and the National Highway Institute (NHI) training class (NHI Course No. 130220).

FIELD WORK

- You have to get out of the car
- There is abundant evidence in the field
- Field Guides
 - RHRS
 - CRSP

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

- *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
- Structure Implications
- Photo Interpretation
- Geologic Field Mapping
- Rockfall Characteristics
- Computer Analysis
 - Influencing Factors
 - Slope Characteristics
 - Rock Characteristics
 - Slope Characteristics
 - Cross Section
 - Slope Surface
 - Slope Material Properties

The image shows a portion of the RHR Field Rating form. It includes fields for 'SLOPE RATING', 'ROCK RATING', and 'TOTAL RATING'. Below these are several tables for recording field observations, such as 'SLOPE OBSERVATIONS', 'ROCK OBSERVATIONS', and 'VEGETATION OBSERVATIONS'. Each table has columns for 'TYPE', 'LOCATION', 'DESCRIPTION', and 'RATING'.

RHR Field Rating

Field Rating utilizing RHR

– 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 RHR study.

The image shows the RHR Final Rating form. It is a large table with multiple columns and rows, designed for calculating the final rating. The columns include 'FIELD RATING', 'OFFICE RATING', and 'FINAL RATING'. The rows are organized into sections for 'SLOPE', 'ROCK', and 'VEGETATION', each with sub-sections for different types of observations.

RHR Final Rating

Final Rating Utilizing RHR

– Uses a combination of data collected in the field and supporting data collected in the office setting.

– Some categories are quantified utilizing mathematical equations.

Long Term Performance Of Rockfall Mitigation Systems

Inventory of Systems per District to Date.

D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	TOTALS	Mitigation
4	1	0	1	31	1	1	3	0	0	4	2	48	Flexible Rockfall Fences
1	0	1	2	14	0	0	10	0	0	0	0	28	Debris Flow Barriers
8	14	3	0	2	0	0	0	0	0	0	0	37	Chain Link Fence
0	0	0	0	1	0	0	0	0	1	0	0	2	Temporary Flexible Rockfall Fence
1	2	0	0	2	0	0	9	0	0	0	0	14	Hybrid Cable Nets
0	0	0	0	0	0	0	1	0	0	0	0	1	Hybrid Tecco
3	2	0	0	5	1	9	3	0	2	1	0	26	Cable Net Drapery
6	4	5	6	12	1	11	5	1	0	0	7	58	Double Twisted Wire Mesh Drapery
0	0	0	0	1	0	2	0	0	0	0	0	3	Chain Link Mesh Drapery
2	0	0	2	3	0	3	0	0	0	0	0	10	Anchored Tecco Mesh (Ruvolum)
1	0	0	5	2	1	1	0	0	0	0	1	11	Anchored Double Twisted Wire Mesh
0	0	0	0	1	0	0	0	0	0	0	1	2	Anchored Cable Nets
0	0	1	0	4	0	0	1	0	0	0	0	6	Rock Slope Protection Barriers
												246	
26	23	10	16	78	4	27	32	1	3	5	11	246	

System Performance

- Selection Criteria
- Design Features
- Corrosion
- Foundations
- Ground Anchors
- Maintenance

Flexible Barriers

- Flexible Rockfall Fences - 87
 - Cables
 - Rings
 - Wire
- Debris Flow Barriers- 28
 - Cables
 - Rings
- Hybrid Barriers- 15
 - Cables
 - Wire

Flexible Barriers



Flexible Barriers



Flexible Barriers

Above MEL Impacts



Flexible Barriers



SEL Impacts

Hybrid Flexible Barriers



D2 Feather River Canyon



D8 San Bernardino Mountains

Flexible Barriers



Santa Barbara County



Monterey County

Ground Anchors



Corrosion



Corrosion



Drapery (unsecured) Systems

- Chain Link - 3
- Double Twisted Wire Mesh - 58
- Cable Nets - 26

Cable Net Drapery



Maintenance



DTWM Drapery



DTWM Drapery



Corrosion



Anchored (secured) Systems

- Anchored Double Twisted Wire Mesh
- Anchored Cable Nets
- Anchored Tecco Mesh
- Anchored Chain Link Mesh

Anchored (secured) Systems



Anchored Tecco and DTWM



Anchored Tecco Mesh

Anchored (secured) Systems



Tecco Mesh



DTWM Mesh



Anchored (secured) Systems



Anchored Chain Link Mesh



Anchored Tecco Mesh

What have we learned?

- Flexible Barriers
 - >1000 kJ High Maintenance
 - <500 kJ Minimal Maintenance
 - Use cable ground anchors
 - CT foundations work
- Draperies
 - Standard Criteria Work
 - Weight per unit area is important
 - Ground contact is important
- Anchored Mesh
 - Is it a passive or active system?
 - Wire (high strength and low strength) and cable are working!

Draperies “weight per unit area”

