MACCAFERRI

Design Guide for Rockfall Fences

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Why deformable rockfall barriers

1) Barrier destroyed by a boulder of 1.5 m^3 (estimated velocity 3 - 5 m/s – 55 kJ energy)
2) Barrier pierced by a boulder of 0.04 m^3 (estimated velocity 12-14 m/s, 18 kJ energy)

$$F\,\Delta t \quad = \quad M\,\Delta v$$

The capacity of a “non deformable” barrier is related to the elastic deformability of its components.

Since its components are stiff (cable, post), the “non deformable” barrier must reduce the velocity (Δv) in a very short time ($\Delta t = 0$).

Then the force F of impact

$$F = \frac{M\,\Delta v}{\Delta t}$$

is huge.

So the stiff barrier is broken even if the energy level is low.

ETAG 27 code

ETAG 27 requires 2 tests

MEL = Maximum Energy Level

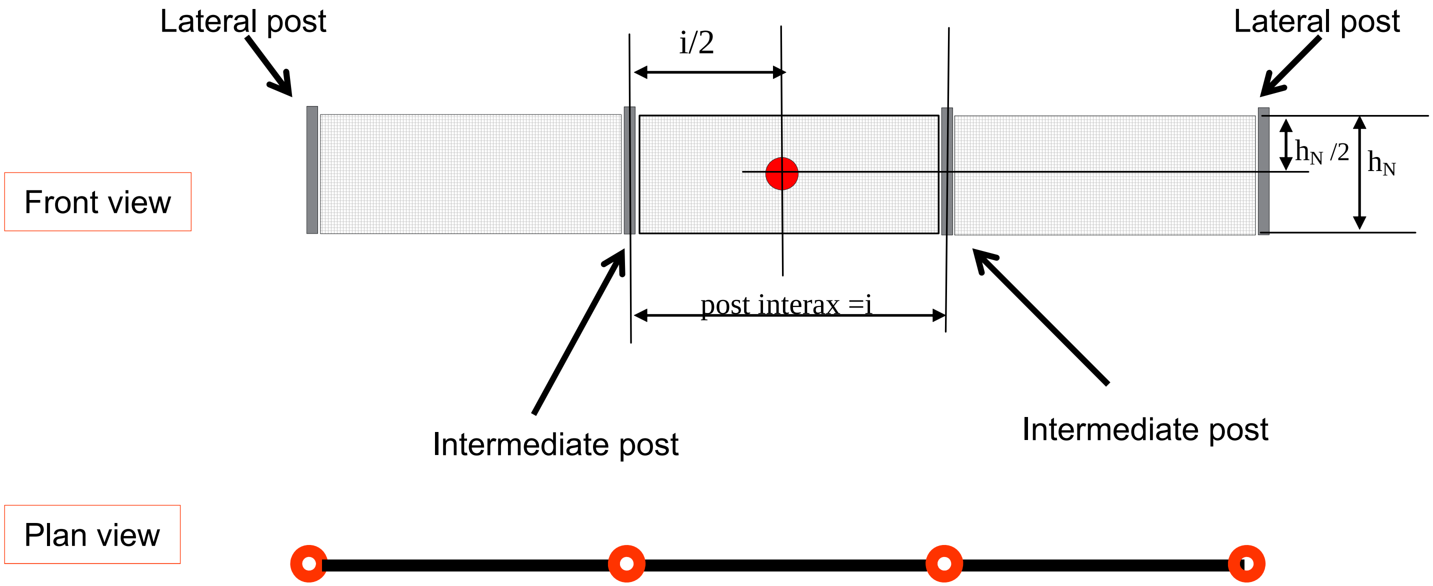
The barrier has to catch a boulder with the maximum energy level (100%). The residual height of the panel after the impact indicates the quality level of the barrier.

SEL = Service Energy Level

The barrier has to catch two impacts of a boulder with 1/3 of the MEL energy without damage. The residual height after the first impact must be greater than 70%. The second impact needs only to catch the boulder.

The field test is conducted on a barrier with 3 modules in a straight line, that is why 3 modules are the suggested minimum length of a barrier

Configuration of the Crash test barrier



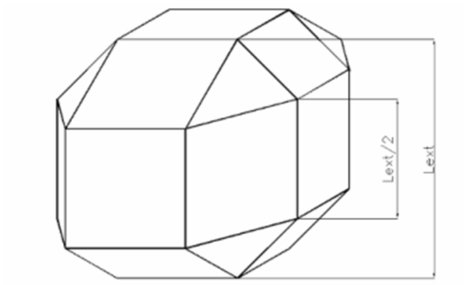
FIELD TEST

Inclined field test

Vertical field test

Falling velocity >= 25 m/s

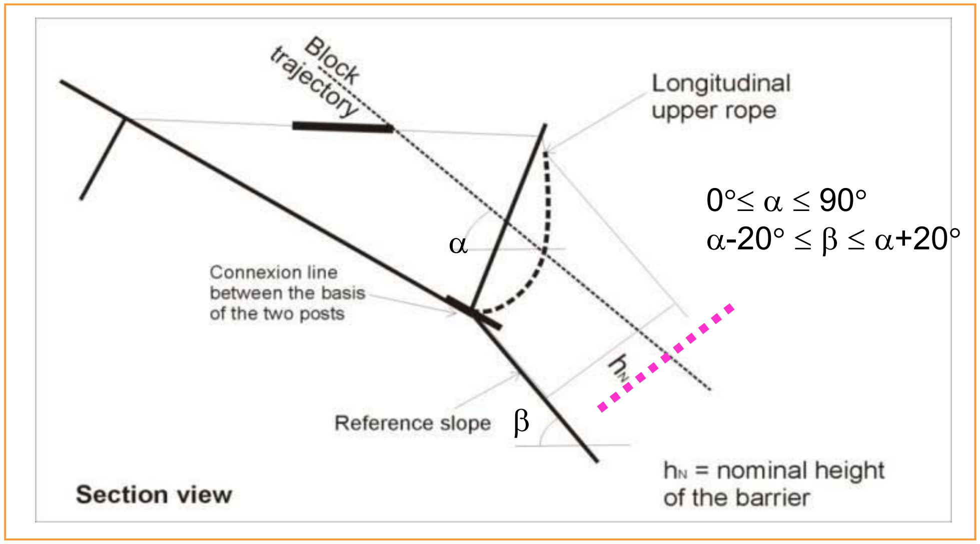
Block size



Energy $$E_c = \frac{1}{2}\cdot m\cdot V_{impact}^{2}$$

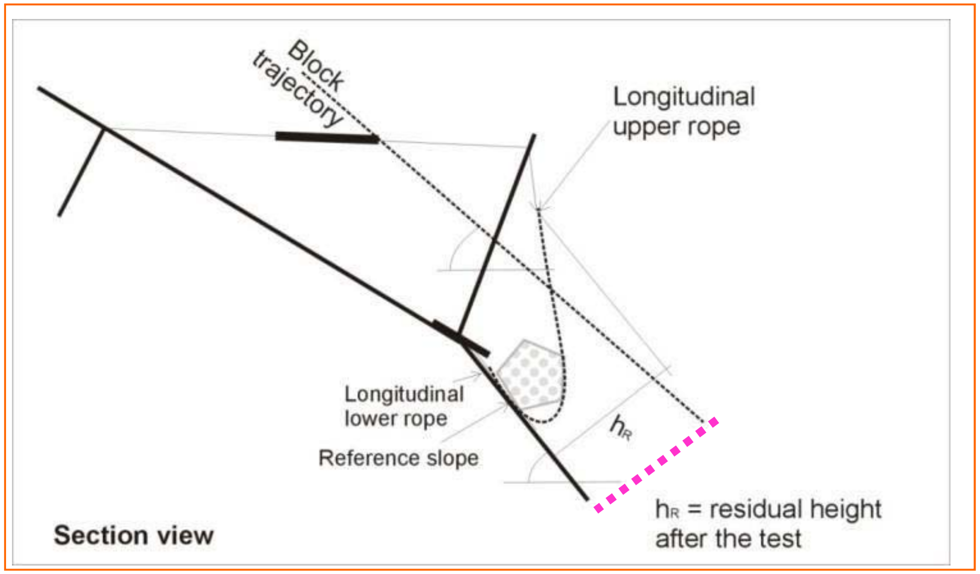
ETAG 27 code

ETAG 27 code

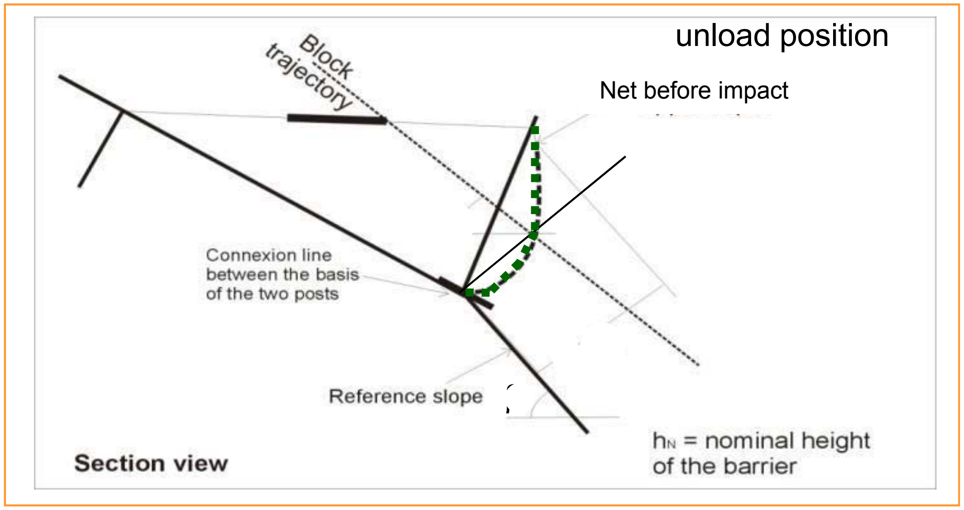


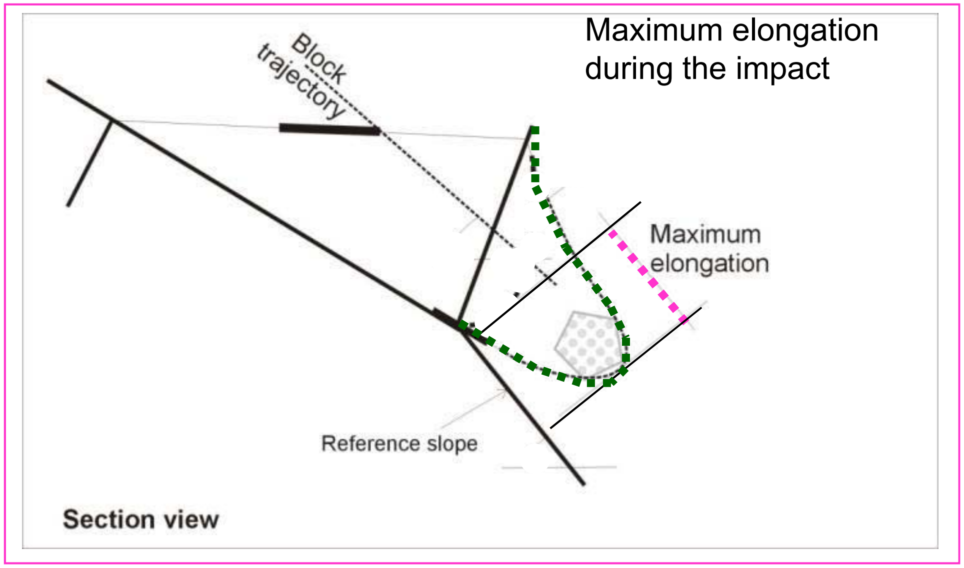
$0° \leq \alpha \leq 90°$
$\alpha-20° \leq \beta \leq \alpha+20°$

Nominal height of the barrier



Residual height (after impact)





Elongation after impact

Falling rock protection kit classes

A classification for residual height for **MEL** is as follows:

Category A : Residual Height ≥ 50 % nominal height
Category B: 30% nominal height < Residual Height < 50 % nominal height
Category C: Residual Height ≤ 30 % nominal height

Design of barriers

Design approach for rockfall protections

The design of a barrier for Ultimate Limit State means to refer the design to MEL (Maximum Energy Level of crash test)

Maximum capacity of the barrier must be utilized.
Design based on a single hits
Frequent inspections and maintenance on site are possible and convenient.
Higher cost for the maintenance

The design of a barrier for Serviceability Limit State means to refer the design to SEL (Service Energy Level = 1/3 MEL)

No Damages on the barrier after impact
There are multiple hits on the barrier during test
Frequent inspections and maintenance works on site are more difficult to do.
Maintenance cost is minimum

NEW Design approach for rockfall Barrier

Energy level of Barrier $\geq \frac{1}{2} m_d v_d^2 + \xcancel{\frac{1}{2} I_d \omega_d^2}$

Reduce the “energy” of the barrier with coefficients in relation with the index test

Add safety factor on the components in relation with the data precision

Distance between infrastructure and barrier >= **Elongation of barrier**

Increase the elongation of the barrier with coefficient

Height barrier >= **Height of the trajectories**

Reduce the height of the barrier of the upper free border

Increase the height with coefficient

Barrier Design

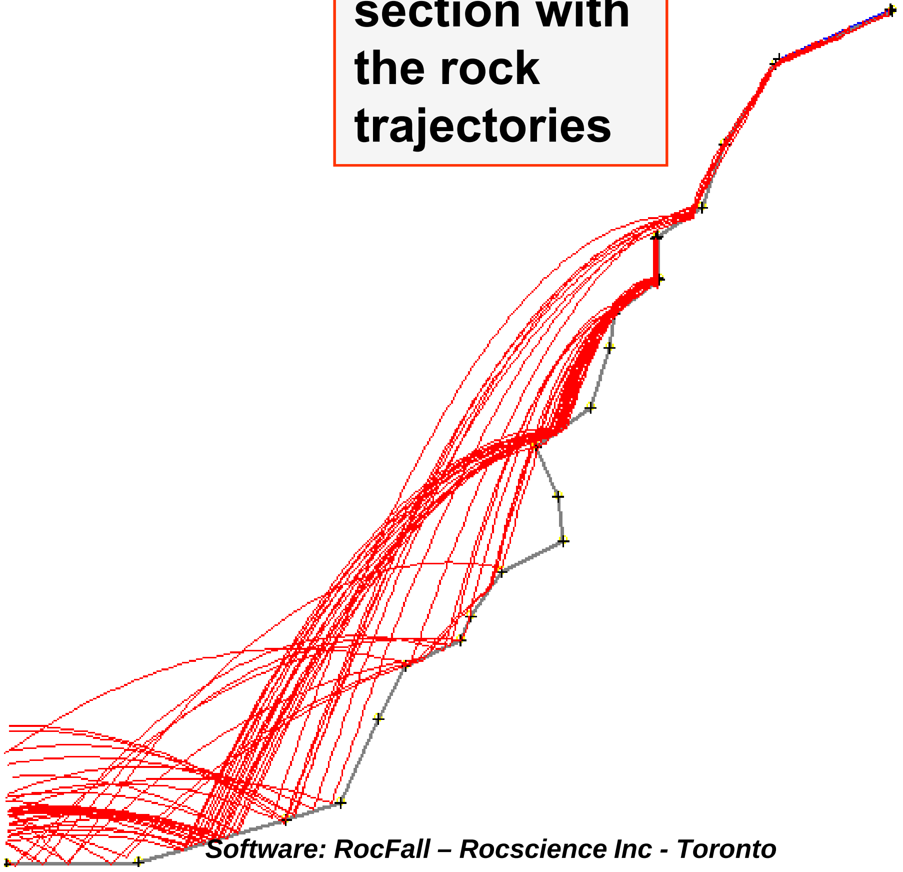
Rockfall Simulation Software

DESIGN OF ROCKFALL BARRIERS WITH NUMERICAL SIMULATIONS

The main questions are:

Which is the best position for the barrier?

What is the statistical distribution of velocity and height in that position?



Topographic section with the rock trajectories

Software: RocFall – Rocscience Inc - Toronto

PARAMETERS USED IN CODES

The main parameters are:

Topographic slope section;

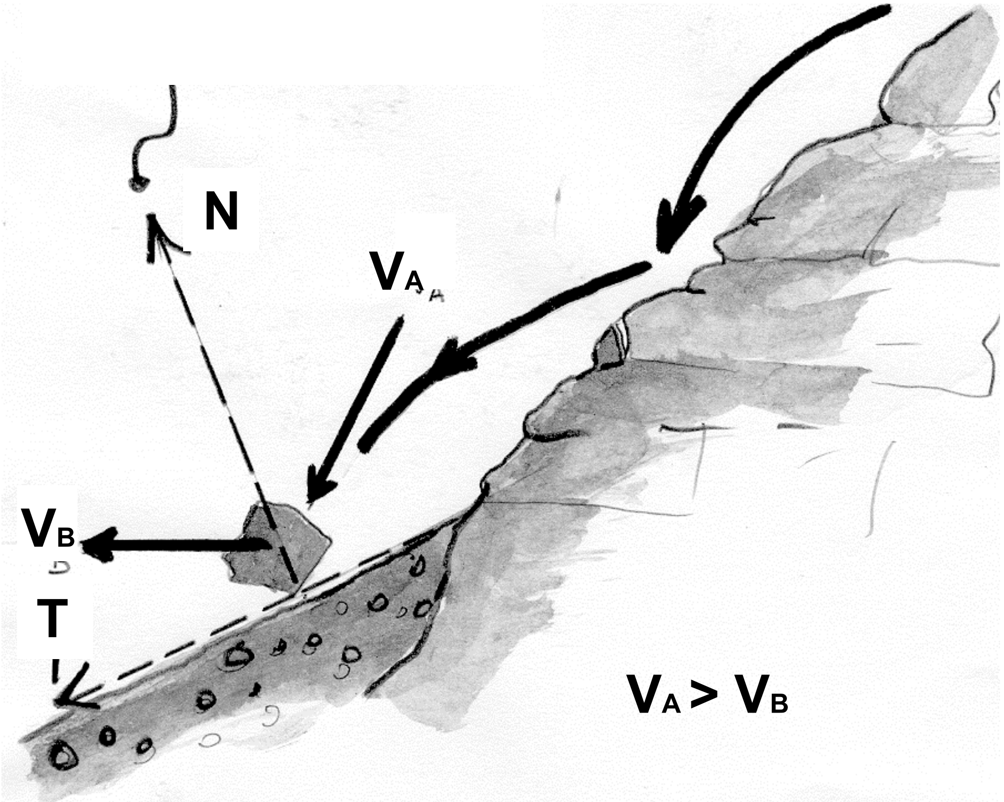
Coefficients describing the energy dissipation after the block impact;

Coefficients describing the rolling of the block along the slope;

Boulder size.

N = axis perpendicular to the slope

T =axis tangent to the slope

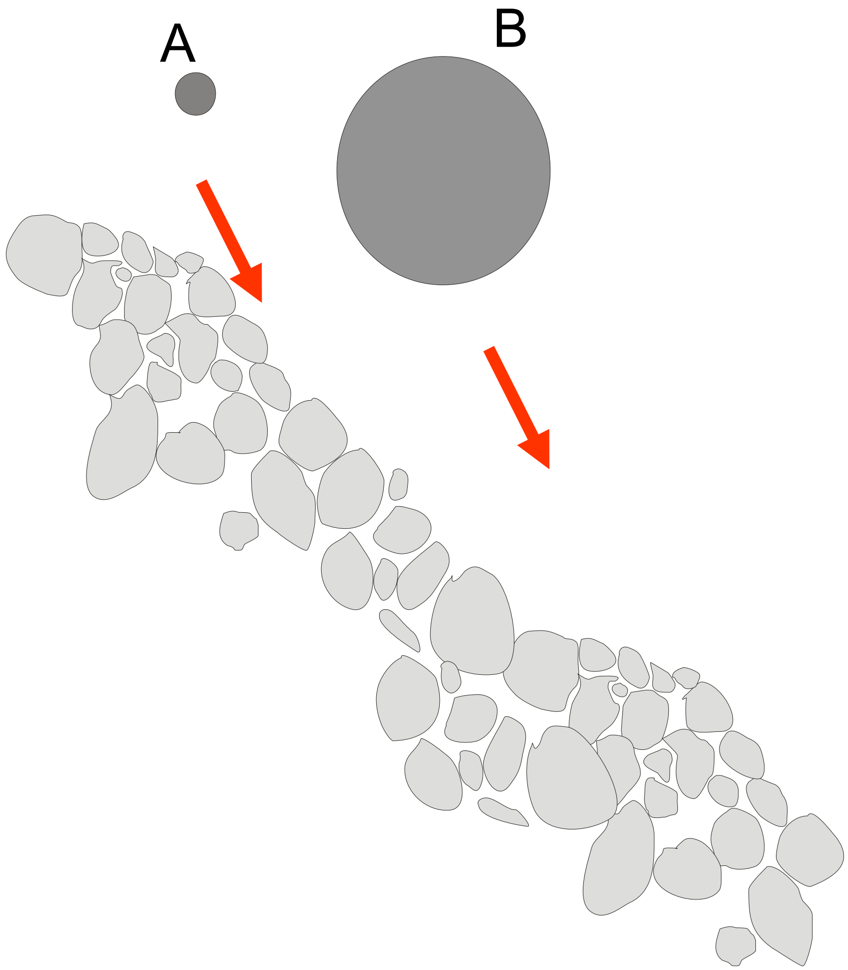


Will the impact be on an hard or soft soil ?

“Soft” and “hard” depend on the size of the boulder.

Case A) the soil is hard

Case B) the soil is soft



The values of Rt and Rn suggested by the bibliography can only be accepted as an initial suggestion.

They must be verified with a back analysis.

HEIGHT OF IMPACT

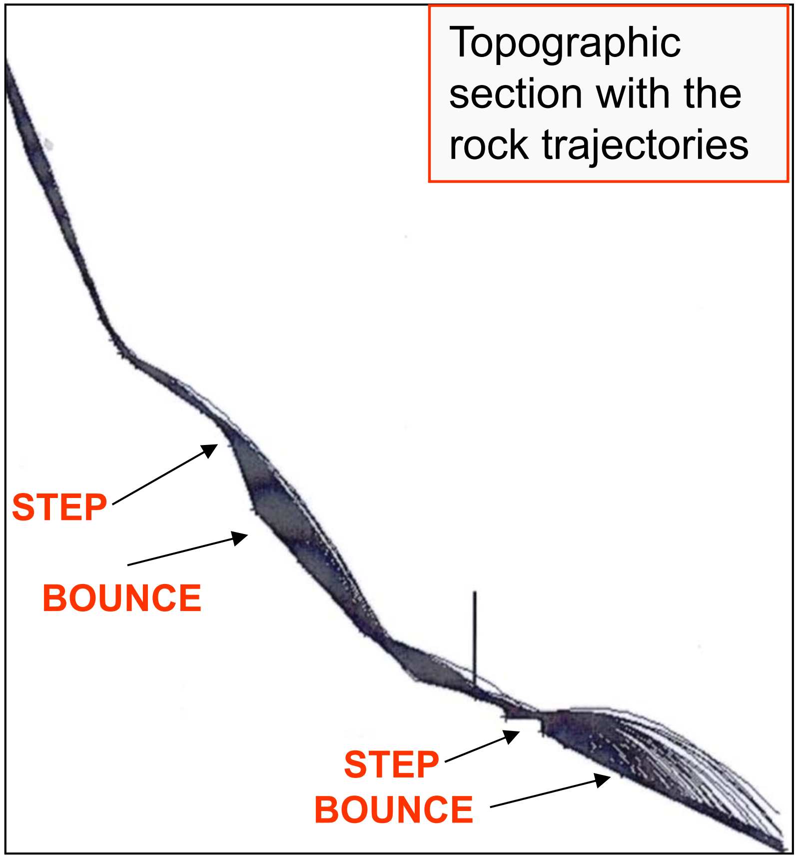
The barriers must be higher than the path of falling boulders.

We must take into account:

A) A statistical approach cannot forecast 100% of the events

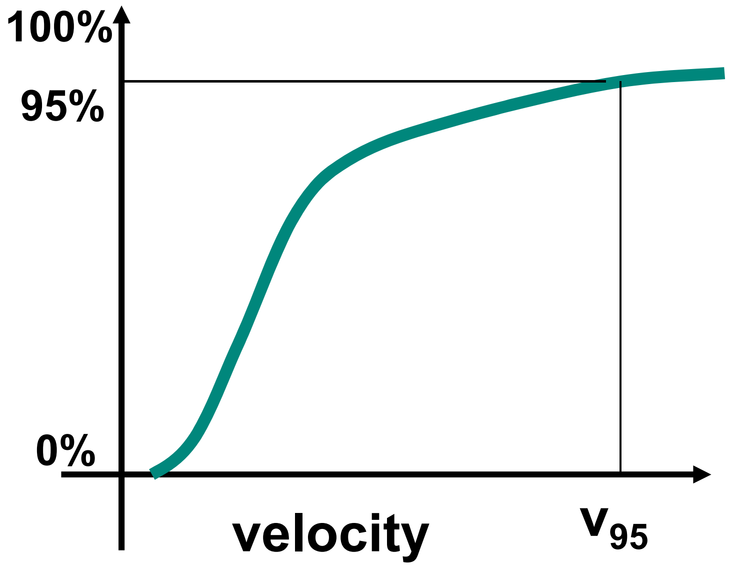
B) Simulation gives the trajectory without considering the actual boulder dimensions.

C) There is a relation between the height of a rockfall barrier and its capacity for energy dissipation.

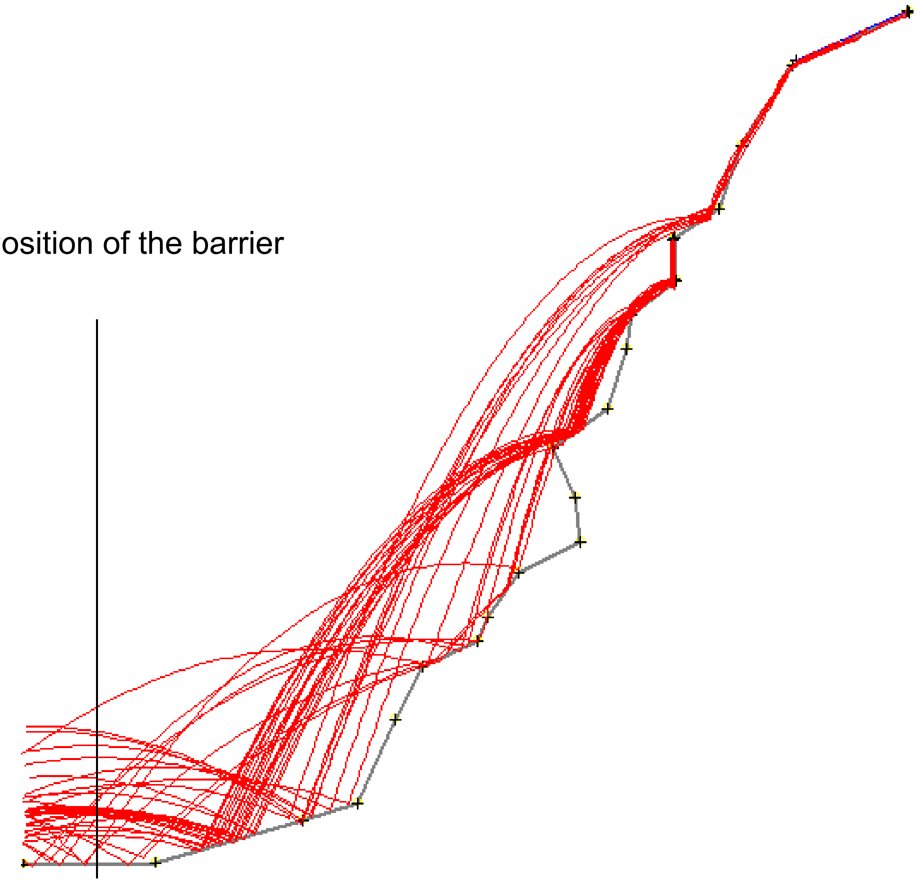

Topographic section with the rock trajectories

Rock fall simulation is required to get velocity and height of the trajectories

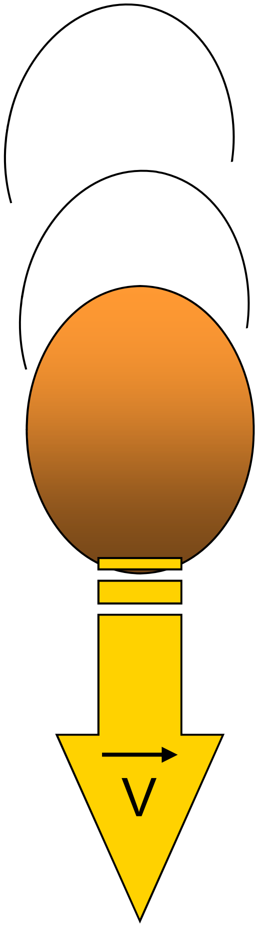
CUMULATIVE PROBABILISTIC CURVE



Position of the barrier



Velocity of the design boulder



The velocity **v_{95}** is taken at the **95%** of the calculated velocities and multiplied per the safety coefficient γ_F:

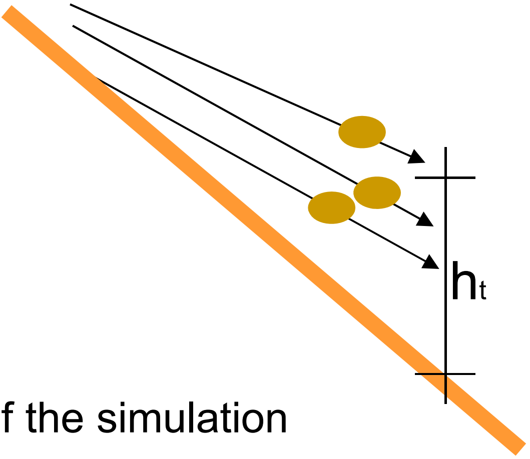
$$v_d = v_{95}\,\gamma_F = V_{95}\,(\gamma_{Tr}\,\gamma_{Dp})$$

γ_{Tr} = safety coefficient depending on the reliability of the simulation
= 1.02 for 2D and 3D simulation calibrated by back analysis;
= 1.07 for 2D simulations on the basis of bibliographic values;

γ_{Dp} = safety coefficient for precision of the slope:
= 1.01 for slope traced on the bases of topographic survey;
= 1.07 slope traced with low precision.

Height of the rock trajectory of design h_p

The height **h_{95}** is taken at the **95%** of the calculated trajectories and multiplied per the safety coefficient γ_F:



$$h_d = h_{95} \quad \gamma_F = (\gamma_{Tr}\, \gamma_{Dp})$$

h_{95} = height of boulder trajectory over the slope

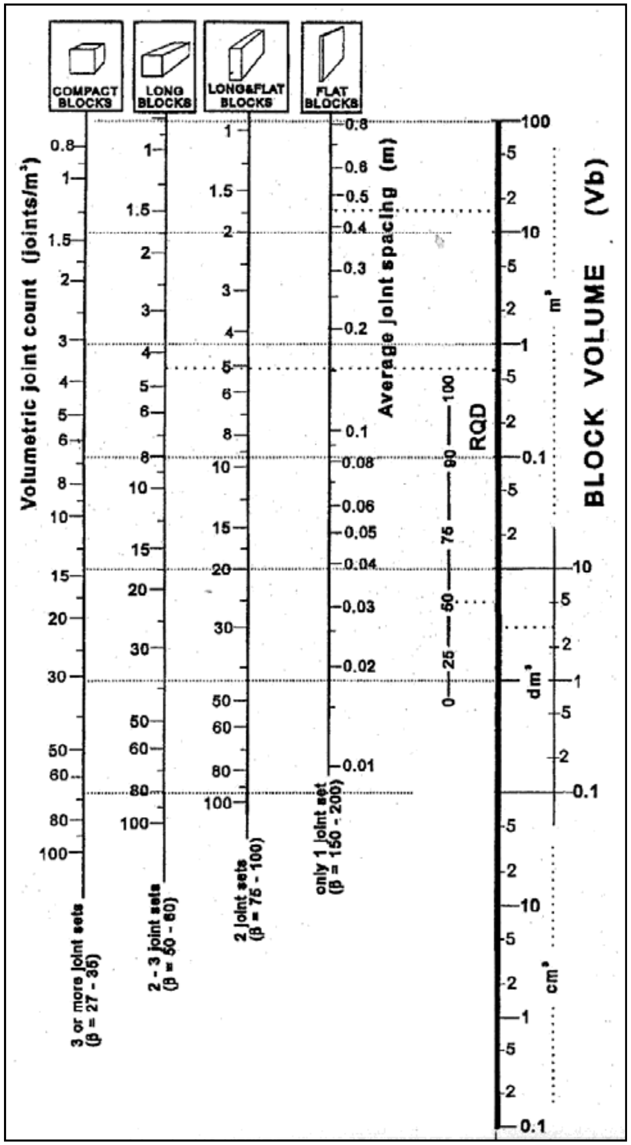
γ_{Tr} = safety coefficient depending on the reliability of the simulation
= 1.02 for 2D and 3D simulation calibrated by back analysis;
= 1.07 for 2D simulations on the basis of bibliographic values;

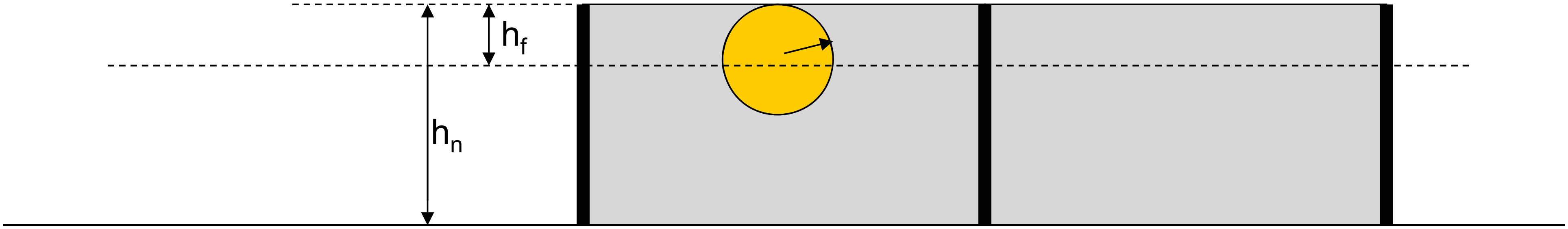
γ_{Dp} = safety coefficient for precision of the slope:
= 1.01 for slope traced on the bases of topographic survey;
= 1.07 slope traced with low precision.

Size of the design boulder

It is useful to look at the rock mass which the blocks originate.

But the best is to look at the debris and choose the largest diameter among the more frequent blocks.





Evaluations of the height of the fence

$$(h_d - h_f) \leq 0$$ **where**

$$(h_d - h_n + h_b \gamma_b) \leq 0$$

h_n nominal height according to ETAG 027

h_f free border, that is the height of non impact zone on the border of the panel

h_b average radius of the falling boulder

γ_b coefficient of safety for the radius of the boulder, generally 1.5

h_d design height of the barrier

Evaluation of the position of the barrier on slope near infrastructure

$$(d_d - d_A) = (d_d - d_{maxMEL}\,\gamma_D) \geq 0$$

d_A maximum deformation of the barrier MEL ($d_{maxMEL}\,\gamma_D$)

γ_D safety coefficient

= 1.3 if there is the deformation of crash test MEL only.

= 1.20 if there is calculation to verify the impact on post and free zone (lateral and upper)

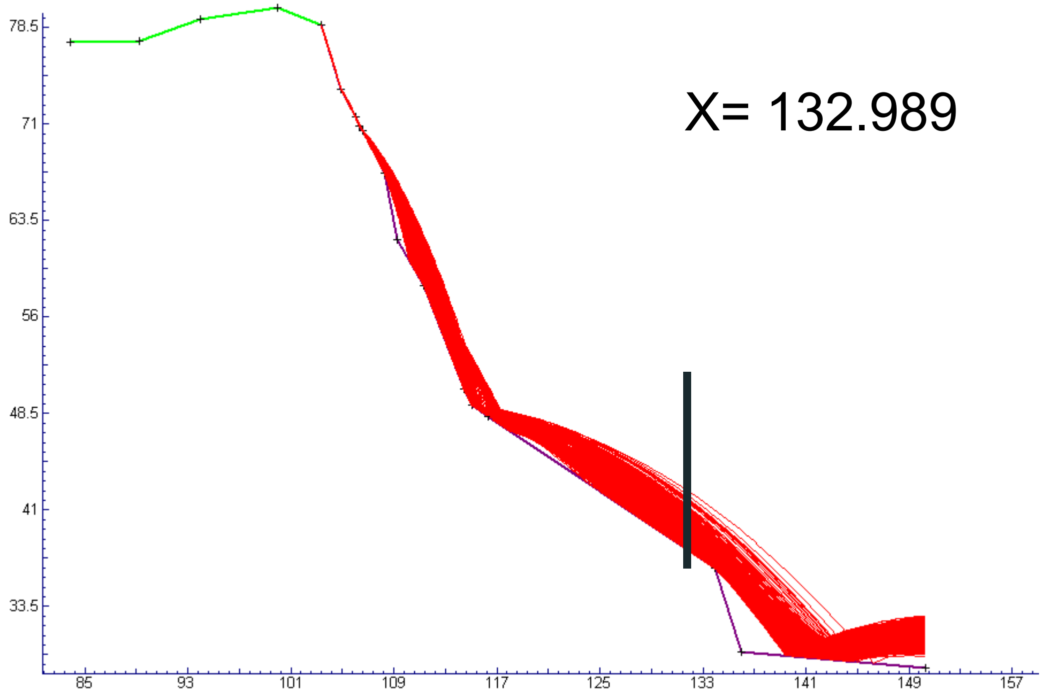
d_d minimum design distance between barrier and infrastructure

Evaluation of energy level of the barrier

$$(E_d - E_{BTE,barrier} / \gamma_E) \leq 0$$

E_d	energy level calculated via simulation $(0.5\, v_d^2\, m_d)$
v_p, m_p	velocity, mass of design
$E_{BTE,barrier}$	energy level measured on crash test
γ_E	safety coefficient
	in case of MEL design :
	= 1.2 if there is the energy level measure on crash test only;
	in case of SEL design : = 1.00

Design Example

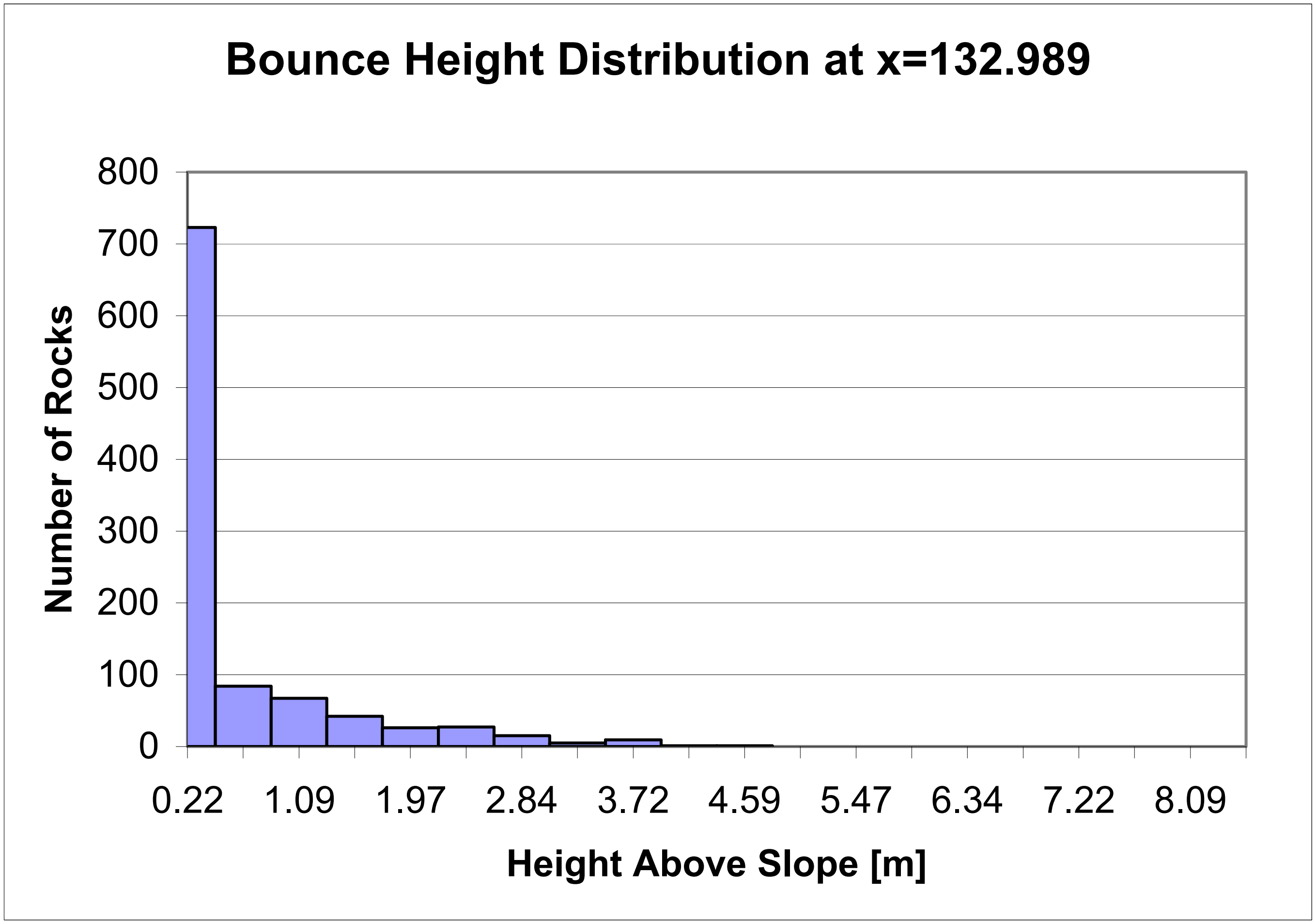


X= 132.989

Software Simulation

Minimum distance between barrier and infrastructure	**6.00**	**[m]**
Slope - Clean Rock		
Estimate Rock Size	**0.85**	**[m3]**
Density of the Rock	**2500.00**	**[kg/m3]**

Bouncing Height



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Bouncing Height

Height Statistics of Raw Data at x = 132.989

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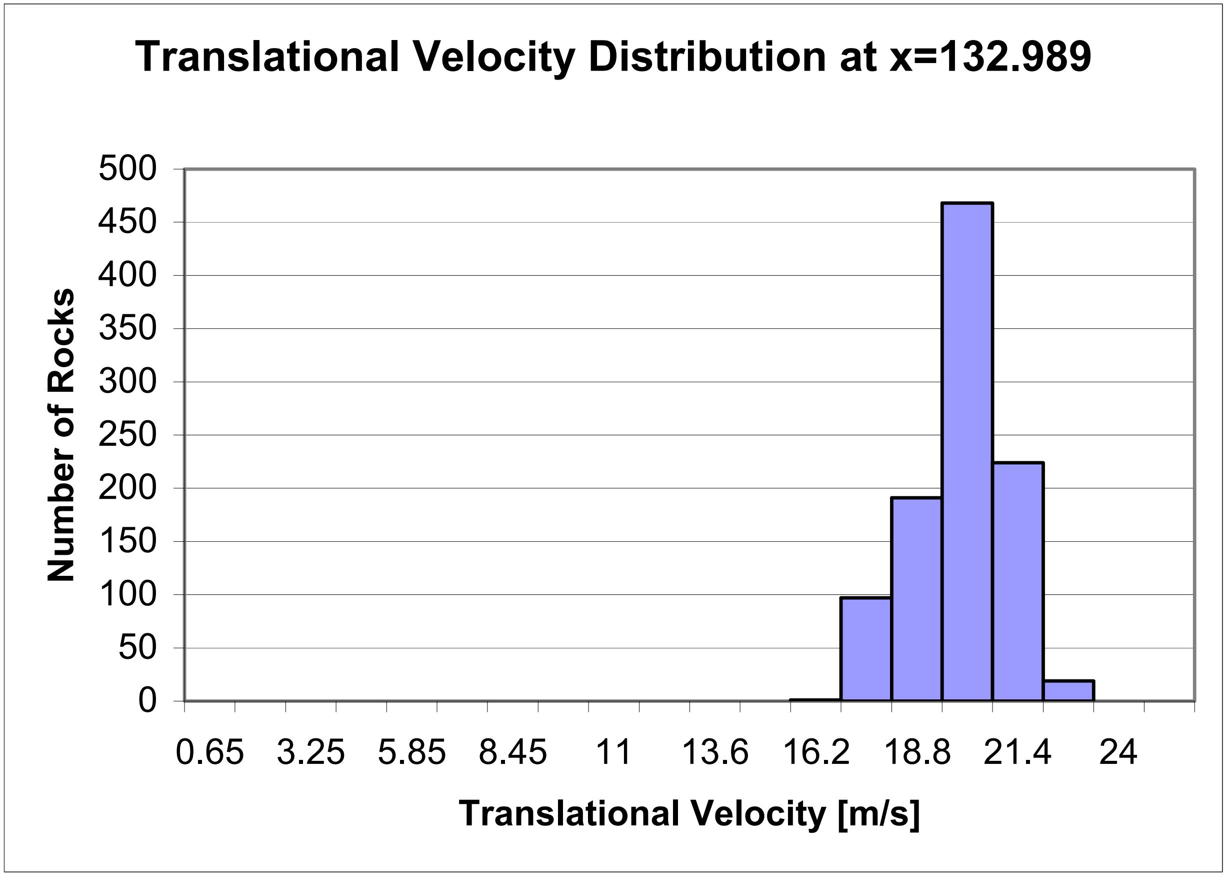
Number of data points:	1000
Minimum:	-0.0012
Maximum:	4.5714
Mean:	0.496102
Standard deviation:	0.755185
Range:	4.5726
Median:	0.1718
Variance:	0.570304
Height at 95% percentile	2.32

Velocity


Translational Velocity Distribution at x=132.989
Number of Rocks
500
450
400
350
300
250
200
150
100
50
0
0.65
3.25
5.85
8.45
11
13.6
16.2
18.8
21.4
24
Translational Velocity [m/s]

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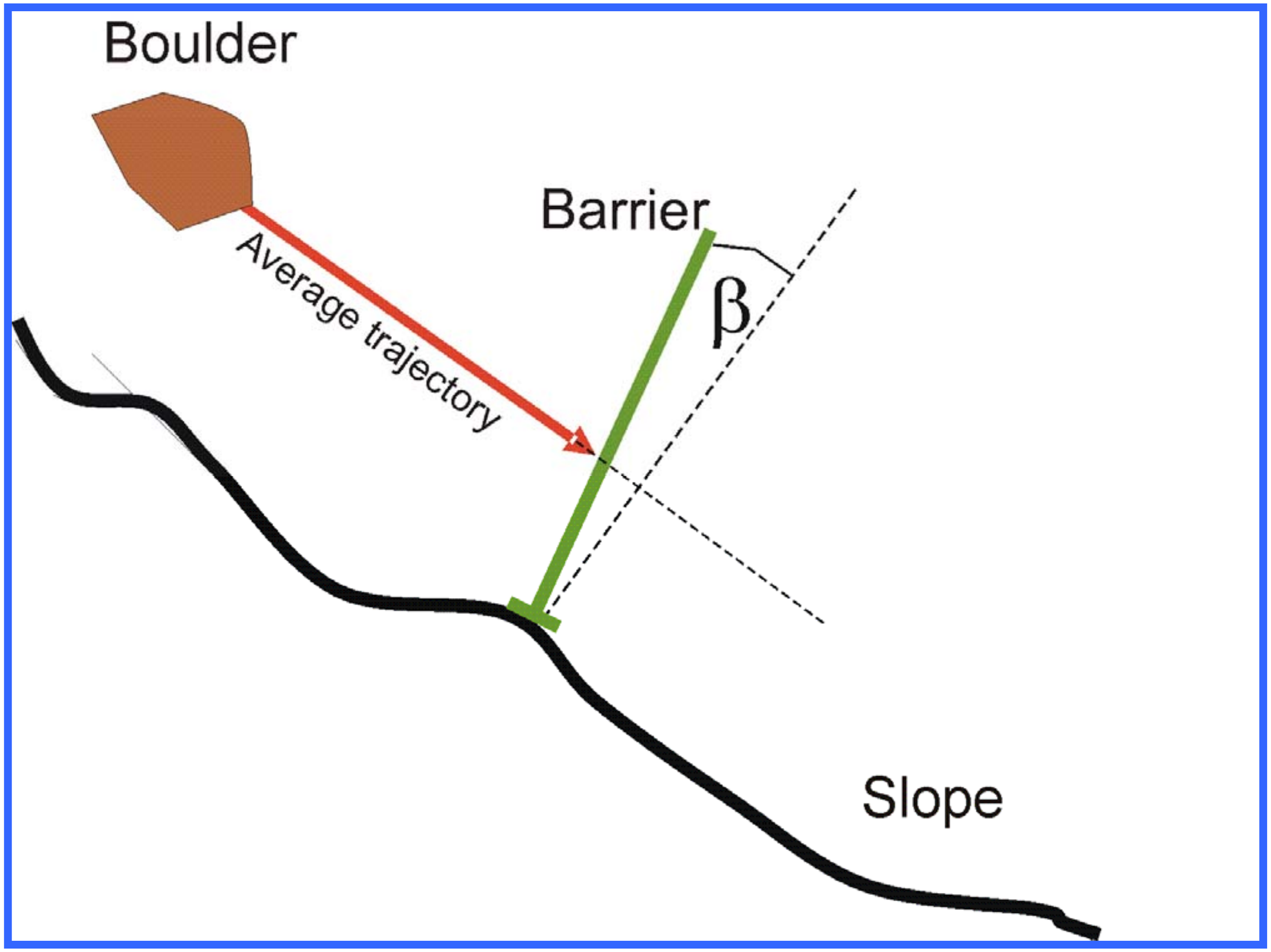
Velocity

Velocity - Statistics of Raw Data at x =	132.989
Number of data points:	1000
Minimum:	16.6928
Maximum:	23.1255
Mean:	20.013
Standard deviation:	1.13327
Range:	6.4327
Median:	20.41
Variance:	1.2843
Velocity at 95% percentile	21.31

Simulation Result

Data analysis			
Simulation developed with		1000	trajectories
Confidence limit: statistical approach on the		95%	of the population
Average inclination of the trajectoies	[α]	30.00	[°]
Tollerance for the barrier inclination	[β]	20.00	[°]
Trajectory height on the vertical for the 95% of the cases	[Hv]	2.32	[m]
Traj. height on the barrier plane [cos (a -b) * Hv]	[Ht]	2.28	[m]
Minimum distance between barrier and infrastructure	[Di]	6.00	[m]
Velocity (translational) - confidence limit 95%	[Vt]	21.31	[m/s]
Size	[St]	0.85	[m3]
Density of the rock	[W]	2500.00	[kg/m3]


Boulder
Barrier
β
Average trajectory
Slope

Barrier Design - No Safety Factors

Design trajectory			
Design trajectory velocity [Vt * γtt * γtr]	[Vd]	21.31	[m/s]
Design trajectory mass [St *γtg * W * γtw]	[Md]	2146.25	[kg]
Design trajectory height [Ht * γtt * γtr + Boulder radius]	[Hd]	2.28	[m]
Design trajectory energy [0.5 * Md * Vd ^2]	[Ed]	517.20	[kJ]

Barrier Design - No Safety Factors

Design performance of the barrier			
Design Energy [E_{BTE} / (γ_{EN} *i)]	**[E]**	**521.00**	**[kJ]**
Design elongation [Db * γ_{DB}]	**[D]**	**2.95**	**[m]**
Design height barrier [Hb - Fb]	**[H]**	**2.5**	**[m]**
Proof Barrier			
Energy proof [(Ed - E) ≤ 0]		**-3.8**	**Fullfilled**
Elongation proof [(D - Di) ≤ 0]		**-3.1**	**Fullfilled**
Height barrier [(Hd - H) ≤ 0]		**-0.2**	**Fulfilled**

Barrier Design - With Safety Factors

Data analysis			
Simulation developed with		1000	trajectories
Confidence limit: statistical approach on the		95%	of the population
Average inclination of the trajectoies	[α]	30.00	[°]
Tollerance for the barrier inclination	[β]	20.00	[°]
Trajectory height on the vertical for the 95% of the cases	[Hv]	2.32	[m]
Traj. height on the barrier plane [cos (a -b) * Hv]	[Ht]	2.28	[m]
Minimum distance between barrier and infrastructure	[Di]	6.00	[m]
Velocity (translational) - confidence limit 95%	[Vt]	21.31	[m/s]
Size	[St]	0.85	[m3]
Density of the rock	[W]	2500.00	[kg/m3]

Barrier Design - With Safety Factors

Partial Safety coefficient			
Quality of Topographic survey	[γtt]	1.07	
Quality of Geomechanical survey - size	[γtg]	1.10	
Quality of Geomechanical survey - density	[γtw]	1.05	
Quality of rock fall simulation	[γtr]	1.07	
Design trajectory			
Design trajectory velocity [Vt * γtt * γtr]	[Vd]	24.40	[m/s]
Design trajectory mass [St *γtg * W * γtw]	[Md]	2454.38	[kg]
Design trajectory height [Ht * γtt * γtr + Boulder radius]	[Hd]	2.97	[m]
Design trajectory energy [0.5 * Md * Vd ^2]	[Ed]	730.49	[kJ]

Barrier Design - With Safety Factors

MACCAFERRI barrier features			
Maximum energy according to ETAG 27	[MEL]	1076.00	[kJ]
Service energy level according to ETAG 27	[SEL]	358.67	[kJ]
Maximum dynamic elongation MEL	[Db]	3.50	[m]
Standard Height of the barrier 3.5 m and 4 m			
Nominal height of the barrier	[Hb]	4.0	[m]
Upper free border for the design boulder	[Fb]	0.7	[m]

Barrier Design - With Safety Factors

Design Method		
Design procedure aimed to (MEL or SEL)		MEL
Maximum Energy Level - using energy	[E_{BTE}]	1076.00
Amplification factor which considers the risk of places having		
(1)_low_economical_value,_and_can_be_easily_repaired	[i]	1.00
Safety coefficient for reduction of the barrier energy	[γ_{EN}]	1.2
Safety coefficient for the deformation	[γ_{DB}]	1.3

Barrier Design - With Safety Factors

Design performance of the barrier			
Design Energy [E_{BTE} / (γ_{EN} *i)]	[E]	896.67	[kJ]
Design elongation [Db * γ_{DB}]	[D]	4.55	[m]
Design height barrier [Hb - Fb]	[H]	3.3	[m]
Proof Barrier			
Energy proof [(Ed - E) ≤ 0]		-166.2	Fullfilled
Elongation proof [(D - Di) ≤ 0]		-1.5	Fullfilled
Height barrier [(Hd - H) ≤ 0]		-0.3	Fulfilled

Final factor of global safety of the barrier	1.87

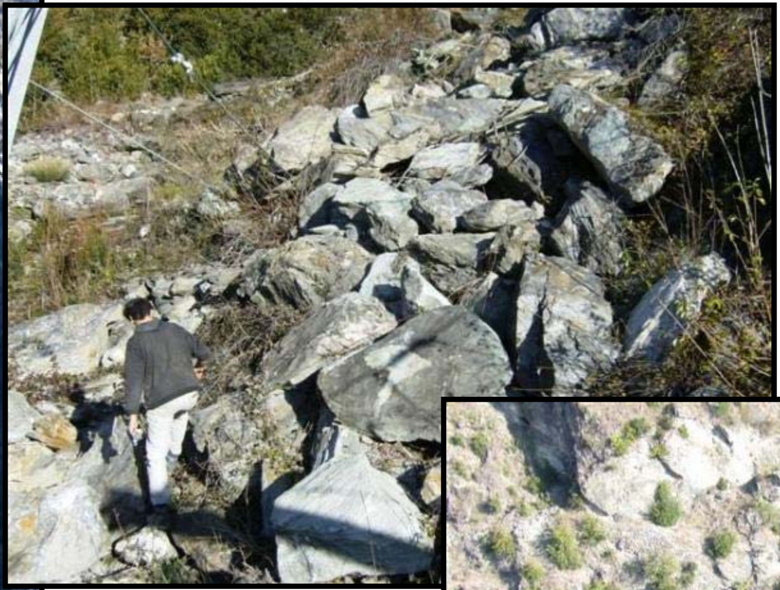
Design Example at MEL without safety factors

500 kJ barrier with a high of 2.5 m

Design Example at MEL with safety factors **1.87**

1000 kJ barrier with a high of 4 m

The area



The rockfall

The impacted barrier, Aosta, Oct.. 2009

Arnod – Aosta (Italy) - Barrier OM CTR 30/04/A - 3.000 kJ

The rock block: 12 m3

The performance of the under – estimated barrier

Multiple impact of dozens of blocks, the largest with an energy level of 4000 kJ

(33% more than the nominal capacity of the barrier!)

The impacted barrier, Aosta, Oct.. 2009 -Maccaferri-