PÁDOVÁ SIMULACE NA ŘEZU 4 (km 4,000)

Trajectories of falling blocks along a slope
The falling motion of a boulder along a rocky slope depends on many factors that are not easy to express numerically.
The trajectories of the boulders depend on the geometry of the slope, on the shape of the falling boulder and on its initial velocity at the moment of detachment from the slope, and also on the entity of the energy dissipated due to the impacts during the fall.
The falling boulders can slide, roll or bounce downstream depending on their shape, flattened or rounded, and on the gradient of the slope.
The energy dissipated due to impacts is generally different and varies with the characteristics of the motion and depends on the mechanical characteristics of the boulder and on the materials present along the slope (rock, soil, vegetation) that oppose in a different manner to the motion of the boulders.
In reality, however, it is practically impossible to determine precisely the contour of a slope and detect the shape of the different boulders that may detach.
In addition, the geometry of the slope and the nature of the outcropping materials undergo changes over time, sometimes sensitive, as a result of the alteration of the rock, of the accumulation of debris in the less steep areas and of the development of the vegetation.
Finally, it is practically impossible to model the motion of boulders fall in cases in which these shatter due to impacts, nor is it possible to identify the areas of the slopes where shatter occurs.
For the analysis of the falling trajectories we need to refer to very simplified models: the geotechnical design of the protection interventions must be, therefore, developed on the basis of a large numerical experimentation, making it possible to explore the different aspects of the phenomenon and recognize the main factors that affect the motion of fall in the particular situation in question.
In more complex cases it might be necessary to calibrate the model on the basis of an analysis of trajectories detected by in situ cinematography following the collapse of the boulders.

Lumped Mass computation model
The assumptions of the Lumped Mass model are:

1) plan outline, the slope profile similar to a broken line consisting of straight line segments
2) point boulder and neglectable air resistance

In this case the trajectory of the boulder can be determined using the equations of motion of a rigid body

Representation of the trajectory

with reference to a system of orthogonal Cartesian axes the equations are:

where:

v_x = horizontal component of the velocity of the boulder

v_y = vertical component of the velocity of the boulder

t = time

g = acceleration of gravity

x_0 = abscissa of the point where the boulder is detached from the slope or impacts in the falling motion

y_0 = ordinate of the point where the boulder is detached from the slope or impacts in the falling motion

Along the x-axis the motion is uniform while along the y axis the motion is uniformly accelerated.
In this way the trajectory of the boulder motion is composed of a series of parabolas drawn between the point at which the detach takes place and the point at which the boulder collides on the slope for the first time, in the initial phase of motion, and between two successive impact points on the slope, or at the foot of the slope, later, to the stop point.
The coordinates of the impact points and velocity components are determined by solving the system between the equation (1) and the equation of the straight line representing the profile of the slope.
In practice we proceed from the point where the detachment of the boulder occurs and we resolve this system of equations considering in turn the different equations of the straight lines that contain the successive segments of the broken line up to finding the coordinates of a point, impact point, that belongs to the parabola that represents the trajectory and falls within of one of the segments of the broken line and is therefore also a point of the slope.
This point is the first impact point of the boulder on the slope. The procedure is repeated from that point to determine the next arc of the trajectory and a new impact point.

Representation of the impact points, the trajectories of the boulder and the arrival and departure velocity vector at each bounce

The loss of kinetic energy due to friction and impacts can be modeled by reducing the velocity of the falling boulder whenever this impacts on the slope.
In particular, indicating with vn and vt the components (normal and tangential) of the velocity before impact, after the impact v'_n, v'_t can be calculated using the relationship:

where R_n and R_t are the restitution coefficients, variable in the range 0-1.

CRSP computation method

The *CRSP* model (*Colorado Rockfall Simulation Program*) has been developed by *Pfeiffer* and *Bowen* (1989) with the purpose of modeling the falling motion of boulders having the shape of spheres, cylinders or discs, with circular cross section in the vertical plane of the movement.

To describe the movement of the boulders the CRSP model applies the parabolic equation of motion of a body in free fall and the principle of conservation of the total energy.

The phenomenon of the impact is modeled using as additional parameters, compared to the *Lumped Mass* method, the roughness of the slope and the size of boulders.

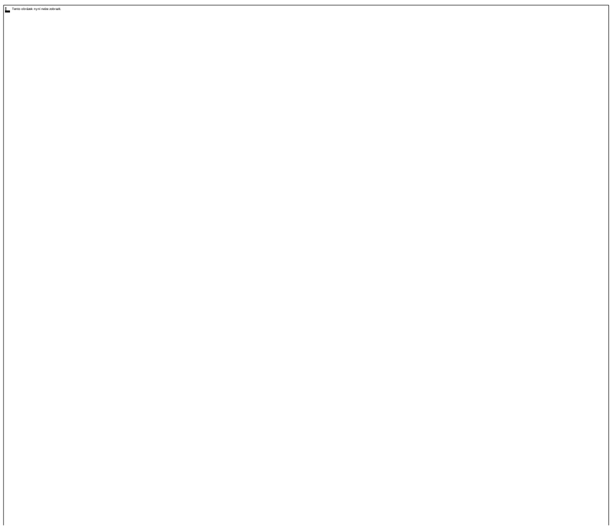
In particular, the *CRSP* model assumes that the angle formed between the direction of the boulder and the profile of the slope varies according to a statistic that must be defined for each analyzed case. The model considers statistically also the results that mainly consist in the velocities and bounce heights, as compared to the surface of the slope, during the fall path.

So the model considers the combinations of movements of free fall, of bounce, rolling and slipping, which can vary depending on the size of the boulders and the roughness of the slope.

The reliability of the model was verified by comparisons between numerical results and the results obtained from in situ tests.

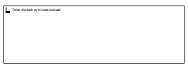
The description of the motion of free fall starts from a point in which the initial velocity is known and is decomposed into its horizontal and vertical components. The boulder is subjected to the movement of free fall until it collides with the surface of the slope.

From the intersection are obtained the coordinates of the impact point. The velocity vector of pre-impact V, forms an angle α with the slope.



Representation of the impact phase: a) the angle of impact is defined as a function of the trajectory of the boulder; q) inclination of the slope; f) variation of the slope as a function of local roughness of the slope

For each impact, the angle of the slope ϕ is varied randomly in a range of values between 0 and θ_{max}. The value of θ_{max} depends on the roughness of the slope and on the size of the boulder and is determined by in situ measurements. Being R the radius of the boulder under consideration we have:



Influence of the roughness of the slope on the path of the boulder: the ratio between the height of the asperities and the radius of the boulder

The velocity that is obtained as a result of the impact is determined by the conservation equation of the total energy expressed as follows:

where:

R = Radius of the boulder
M = Mass of the boulder
J = Moment of inertia of the boulder
w_1 = Angular velocity before impact
w_2 = Angular velocity after impact
V_{t1} = Tangential velocity before impact
V_{t2} = Tangential velocity after impact

The function of friction *f(F)* is defined:

While the scale function *SF* is defined:

Where:

R_n = *Normal restitution coefficient*
R_t = *Tangential restitution coefficients*
R = *Radius of the boulder*

The terms f(F) and SF are obtainable through empirical expressions that are used to assess the kinetic energy dissipated in collisions between the boulder and the slope because of friction and impact.
The friction is primarily concerned with the dissipation of the energy produced by the tangential velocity, while the impact the energy produced by the velocity normal to the slope.

The tangential and angular post-collision velocities are related between them by the following equation:

Tento obrázek nyní nelze zobrazit.

which assumes that the boulders leave the contact with the slope rotating, regardless of the previous angular velocity. From (1) we obtain V_{t2}, while the normal post-collision velocity is obtained by the following empirical expression:

Tento obrázek nyní nelze zobrazit.

that will to take account of the fact, also verified experimentally, that the ratio between the normal post-impact and pre-impact velocities decreases with the increase of the normal pre-impact velocity itself.

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BOULDER CHARACTERISTIC S

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Boulder form Sphere	
Density	2600,0 Kg/m3
Elasticity	50000,0 kPa
Initial velocity in x	3,0 m/s
Initial velocity in y	-3,0 m/s
Terminal limit velocity	0,01 m/s
Diameter	1,5 m

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DESIGN VELOCITY OF BLOCKS

Reliability coefficient for trajectory calculation	1
Quality coefficient of slope topography discretization	1
Velocity safety coefficient	1

DESIGN BLOCK MASS

Mass calculation coefficient	1
Survey precision coefficient	1
Survey precision coefficient	1

DESIGN STRESSING ENERGY

Energy amplifying coefficient	1

BARRIERS

Safety coefficient to apply to the energy values MEL or SEL...1

Mass	4594,579 Kg
Weight	4594,579 Kgf
Moment of inertia	1033,78 Kgxm2

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Materials li st

N	Description	Coefficient normal restitution Rn	Coefficient of restitution tangential Rt	Roughness (m)	Frequency (m)	Friction angle (°)	
1	Solid rock	0,9	0,8	0			
2	Degraded rock	0,7	0,7	0			
3	Sand	0,4	0,6	0			
4	Rock detritus	0,6	0,6	0			
5	Fine debris	0,32	0,82	0			
6	Debris with vegetation	0,29	0,8	0			
7	Debris with shrubs	0,3	0,7	0			
8	Terrain or grass	0,31	0,79	0			
9	Paved surface	0,4	0,9	0			

SLOPE DA TA

N	X (m)	Y (m)	Material
1	-17,55	72,81	Solid rock
2	-9,57	66,13	Solid rock
3	-1,91	58,49	Solid rock
4	6,33	50,74	Solid rock
5	9,06	43,19	Degraded rock
6	15,39	36,7	Degraded rock
7	22,11	29,11	Degraded rock
8	31,0	18,0	Degraded rock
9	39,0	10,0	Paved surface
10	52,11	9,66	Terrain or grass
11	72,0	0,0	Terrain or grass

IMPACT

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Throw no. 1 Xp=6,76 m Yp=51,36 m

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Ni xi (m) yi (m) vx (m/s) vy (m/s) t (s) E (kJ)

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1,0	10,048	42,178	9,574	-2,34	1,096	455,402
2,0	26,563	23,544	11,686	-9,496	1,725	952,994
3,0	33,64	13,691	0,005	0,005	1,725	952,994

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Throw no. 2 Xp=7,16 m Yp=50,63 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,363	41,854	9,368	-2,335	1,066	436,98
2,0	26,055	24,179	11,38	-9,279	1,675	910,775
3,0	33,582	14,3	0,005	0,005	1,675	910,775

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Throw no. 3 Xp=7,33 m Yp=50,16 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,447	41,768	9,17	-2,33	1,038	419,654
2,0	25,302	25,121	11,037	-9,06	1,62	955,964
3,0	33,478	15,126	0,005	0,005	1,62	955,964

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Throw no. 4 Xp=7,5 m Yp=49,69 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,528	41,685	8,966	-2,324	1,008	402,212
2,0	24,538	26,076	10,681	-8,833	1,563	900,658
3,0	32,997	16,003	11,622	-7,476	0,792	895,33
4,0	33,465	9,98	0,005	0,005	0,792	895,33

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Throw no. 5 Xp=7,67 m Yp=49,22 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,606	41,605	8,756	-2,319	0,977	384,644
2,0	23,763	27,044	10,308	-8,599	1,503	844,783
3,0	32,068	16,932	11,552	-7,215	0,806	869,712

4,0	33,584	9,981	0,005	0,005	0,806	869,712

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Throw no. 6 Xp=7,84 m Yp=48,75 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,681	41,528	8,539	-2,314	0,946	366,938
2,0	22,975	28,028	9,916	-8,355	1,44	788,243
3,0	31,084	17,916	11,464	-6,941	0,818	842,037
4,0	33,69	9,983	0,005	0,005	0,818	842,037

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Throw no. 7 Xp=8,01 m Yp=48,28 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,754	41,454	8,314	-2,308	0,913	349,079
2,0	22,172	29,032	9,501	-8,101	1,373	730,908
3,0	29,481	19,899	9,228	-8,891	0,769	769,832
4,0	32,383	16,617	8,384	-6,459	0,315	525,147
5,0	33,468	13,328	0,005	0,005	0,315	525,147

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Throw no. 8 Xp=8,18 m Yp=47,81 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,822	41,383	8,081	-2,302	0,879	331,05
2,0	21,472	29,83	9,898	-6,907	1,318	682,954
3,0	31,912	17,088	12,078	-6,928	1,055	908,986
4,0	33,64	9,968	0,005	0,005	1,055	908,986

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Throw no. 9 Xp=8,36 m Yp=47,34 m

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Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,886	41,318	7,839	-2,296	0,844	312,83
2,0	20,772	30,621	9,527	-6,691	1,261	635,399

3,0	30,598	18,502	10,017	-9,087	1,031	857,579
4,0	33,268	15,732	8,191	-7,012	0,267	545,073
5,0	33,414	13,764	0,005	0,005	0,267	545,073

Throw no. 10 Xp=8,53 m Yp=46,87 m

Ni	xi (m)	yi (m)	vx (m/s)	vy (m/s)	t (s)	E (kJ)
1,0	10,946	41,256	7,586	-2,29	0,807	294,394
2,0	20,06	31,426	9,137	-6,465	1,201	587,346
3,0	28,808	20,739	9,427	-8,674	0,957	769,467
4,0	32,763	16,237	8,953	-6,599	0,42	579,977
5,0	33,463	11,941	0,005	0,005	0,42	579,977

Defined types no.1

Descr.	**H (cm)**	**Thickness (cm)**	**Inclination (°)**	**E (kJ)**
1000kJ	400,0	12,0	60,0	1000,0

Protection works inserted no.1

Descr.	Type	xb (m)	yb (m)	E (kJ)
1000kJ	1,0	33,406	15,594	1000,0

Energy on barriers: Trajectory no.1

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,465	19,36	19,36	861,082

Energy on barriers: Trajectory no.2

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,35	19,445	19,445	868,601

Energy on barriers: Trajectory no.3

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,143	19,708	19,708	892,265

Energy on barriers: Trajectory no.4

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,116	14,037	14,037	452,622

Energy on barriers: Trajectory no.5

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,355	14,344	14,344	472,649

Energy on barriers: Trajectory no.6

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)

1000kJ	33,406	15,594	0,567	14,681	14,681	495,154

Energy on barriers: Trajectory no.7

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,122	11,402	11,402	298,671

Energy on barriers: Trajectory no.8

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,466	14,673	14,673	494,587

Energy on barriers: Trajectory no.9

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,014	10,897	10,897	272,781

Energy on barriers: Trajectory no.10

Descr.	Xb (m)	Yb (m)	Hp (m)	Vt (m/s)	Vd (m/s)	E (kJ)
1000kJ	33,406	15,594	0,113	11,594	11,594	308,793

(HpMax) Maximum height, (Vmax) Maximum velocity, (Emax) Maximum energy of the boulder upon the barrier

Descr.	Xb (m)	Yb(m)	HpMax (m)	Vmax (m/s)	Emax (kJ)
1000kJ	33,406	15,594	0,567	19,708	892,265

STATISTIC COMPUTATION S

Maximum velocity	21,511	m/s
Minimum velocity	11,32	m/s
Average velocity	16,539	m/s
Mean standard deviation	3,156	m/s
Maximum pre-impact energy	**955,964**	**kJ**
Average pre-impact energy	650,545	kJ
Energy standard deviation	236,518	kJ
Average stop abscissa	33,542	m
Maximum abscissa reached	33,69	m

% Stopped boulders

X (m)	% Stopped boulders
34,76	100
38,76	100
42,76	100
46,76	100
50,76	100
54,76	100
58,76	100
62,76	100
66,76	100
70,76	100