Application of a Rockfall Simulation Program in an Alpine Valley in Slovenia

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Abstract

Two rockfalls in the Trenta valley in NW Slovenia (Upper Soča River) were analyzed using a commercially available computer program for rockfall simulation (Rockfall version 6.1, forest module RockTree). The program was calibrated in the Osojnik rockfall in two longitudinal profiles. The starting values of relevant model parameters were taken from the literature and different combinations were tried out. The computer runs were performed using different number of blocks (0.2–6.0 m). The model was successfully calibrated using silent witnesses (more than 20 rockfall blocks with 1–340 m^3, having shadow angles 28°–32°). Rockfall run-out was mostly determined by terrain configuration (roughness) and vegetation (surface) properties. Large blocks had high total kinetic energy and large bounce height but not larger run-out than small blocks. The forest could effectively stop blocks smaller than 0.2 m, and had no effect on 6-m blocks. The calibrated model was then applied on the Berebica rockfall in two longitudinal profiles: with and without the rockfall gallery made of reinforced concrete in 2001. The program performance was tested using silent witnesses (over 10 rockfall blocks with 1–220 m^3, having shadow angle of 28°–30.5°). The simulation results (total kinetic energy, bounce height) confirmed the correctness of the decision to build a 276-m long rockfall gallery that was questioned by some experts. The study confirmed that the calibrated 2-D simulation models of rockfalls may be useful engineering tools when used carefully.

Keywords: rockfalls, computer models, model calibration, the European Alps, hazard assessment

Introduction

All over the Earth, the mountainous environment is subjected to many natural hazards. In the last decades, due to the rapid development in these areas, including the Alps and particularly the Slovenian Alps as a part of the alpine arch, an intensification of the conflicts between natural processes and human usage of natural resources as well as human presence in this occasionally very harsh environment has been observed. In Slovenia (20,273 km^2), in 2001 over 63 % were wooded areas. The high annual precipitation and terrain of low permeability produce a dense hydrographic network of running waters (26,989 km of stream channels, average density of 1.33 km/km^2, in some areas over 2 km/km^2). On the other hand, a rather dense network of over 20,000 km roads has been built. Some of them run through the Alps and are of vital importance for regional traffic in the area (Petje, 2005). For such roads, threatened by rockfalls, snow avalanches and torrential floods, a sound combination of preventive measures and technical countermeasures must be achieved.

As an example of an alpine valley with an important road connection under threat (Petje et al., 2005), we have chosen the Trenta Valley in the Triglav National Park in NW Slovenia. Through this idyllic alpine valley of glacial origin a regional road connects Bovec (480 m asl) in the Soča River Valley (the Meditteranean Sea basin) with Kranjska gora (810 m asl) in the Upper Sava River Valley (the Black Sea basin), running across the Vršič Pass (1611 m asl). The Trenta Valley is largely threatened by earthquake-induced rockfalls and snow avalanches (Mikoš and Fazarinc, 2000) and less by torrential floods.

Here we present how a commercially available two-dimensional rockfall computer program was calibrated on one rockfall and then applied to another one, both being active in the Trenta Valley and threatening the regional road through it. After a short description of the computer simulation program, a short description of the two rockfalls will be introduced. Furthermore, the results of the model sensitivity analysis and the model calibration on the first rockfall using silent witnesses will be given. The calibrated model was then validated on the second rockfall in order to show the effectiveness of a 276-m long rockfall gallery built of reinforced concrete in 2001 in order to protect a reach of the regional road. Finally, conclusions about the applicability of the computer simulation model as an engineering tool will be drawn.

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Table 1. Main model parameters in the computer program Rockfall 6.1.

Module	Model parameters
Slope geometry	longitudinal profile (X & Y co-ordinate (m))
Slope surface properties	dynamic friction angle R_g; normal damping D_n (°); tangential damping D_t (°); rolling resistance R_w (°); amplitude of surface roughness O_a; frequency of surface roughness O_f
Properties of the rockfall mass	shape (sphere or cylinder), radius R (m), the length of cylinder (m), density (t/m³)
Initial parameters	position (X & Y co-ordinate (m)); type of initial movement (free fall, sliding, rolling); number of rocks in one computation run
Control parameters	time step (s); normal and tangential minimum velocities (m/s); interval of the envelope curve (m) for the representation of the kinetic energy and the computed bounce heights

Photo. 1. The Osojnik rockfall in the Trenta Valley (left: the Plajer farmhouse is indicated by a circle; right: the rockfall source area).

Photo. 2. The Berebica rockfall in the Trenta Valley (left: 1 day after the event; the road was damaged and closed; right: the upper part).

Rockfall modeling

For rockfall modeling in the Trenta Valley we applied a commercially available 2-D computer program Rockfall 6.1 with a forest module RockTree (Spang, 2003). The main model parameters are given in Table 1. The parameter values were determined from the literature and on the basis of the field inspection. For example, the value for dynamic friction angle R_g can be determined from an empirical equation (Statham, 1976): $\tan\Phi_{ud} = \tan\Phi_0 + kd/2R$, where $R_g = \arctan\ \Phi_{ud}, \Phi_0$ is slope gradient, d is mean block size on the slope talus (m), R is the diameter of a falling block (m), and k is a form coefficient with values between 0.17 and 0.26. For example, if we use values $k = 0.2$, slope gradient $\Phi_0 = 30.7°, d = 0.6$–1.0 m and $R = 1$–6 m, we get values for R_g between 31° and 35°.

The Osojnik rockfall

The Plajer farmhouse was built in the late 19$^{\text{th}}$ century in the Trenta Valley at the toe of a large rockfall (called the Osojnik rockfall; Photo 1) that was dormant and covered with vegetation at the time. On June 28, 1989, the first signs of re-activation were noticed. This new rockfall with dimensions around 400 ×


Photo. 3. The Berebica rockfall in the Trenta valley and the 276 m long gallery on the regional road Bovec-Vršič pass (1611 m).

Photo. 4. The Osojnik rockfall in the Trenta Valley.

300 m was initiated within the old one. At the toe, its debris was around 20 m thick (Orožen Adamič, 1990). The final analysis confirmed that about 300,000 to 400,000 m^3 of rock were released.

The rockfall was released as a wedge rockslide in a system of fractures along a fault zone that travels in the NW to SE direction across the Osojnik slope. The main rupture surface developed on the slightly undulating fracture, parallel to the slope and perpendicular to the fault. On the other rupture surfaces many fractures developed transversal to perpendicular to the main rupture surface. The rock block that fell crushed into smaller blocks. Single rock blocks were larger than 10 m^3.

In the narrow alpine valleys with steep slopes, cut by glaciers, the so-called twin rockfalls (Orožen Adamič, 1990), which nearly face each other from two opposite valley slopes can be observed frequently. This is also the case in the Trenta valley, where on the opposite slope of the Plajer farmhouse and the Osojnik rockfall another rockfall developed, called the Berebica rockfall.

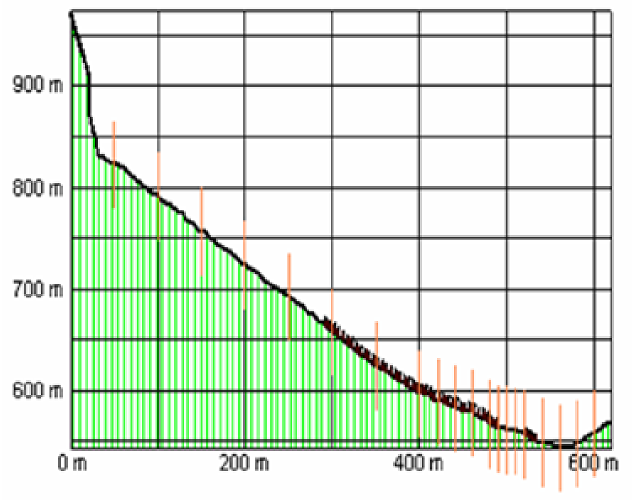

Fig. 1. The longitudinal profile “Osojnik desno”.

Photo. 5. Two boulders in the longitudinal profile “Osojnik desno” a day after their release in 1989.

The Berebica rockfall

The last major Berebica rockfall event was registered on December 19, 1993 (Pavšek, 1994; Photo 2). Above the Fačer farmhouse large rock mass with dimensions of 30 × 50 × 5 m was released from the rock face, which then disintegrated when it hit the slope and spread over the slope talus. Single blocks were between 0.5 to 100 m^3; some of them stopped on the regional road Bovec-Vršič pass (1611 m), and some of them reached the Soča riverbank. One of the blocks even bounced to the other riverbank. The majority of the mass of a volume of 7,500 m^3 remained on the slope talus below the rock face (Photo 2). Rock blocks damaged the road at a length of 150 m, and in a short distance it was fully covered with tree trunks and rockfall debris including large boulders.

After the 1993 rockfall, three large rock blocks remained partially released in the rock face. Two of them released and fell in 1998. Hence, in the rock face only one large rock block with dimensions of 70×20×25 m still remained to fall (Zorn, 2001). Because of the rockfall hazard, an alarm system was erected, and in 2001 a 276-m long rockfall gallery was built of reinforced concrete (Photo 3).

Calibration of the rockfall model Rockfall 6.1

The computer model Rockfall 6.1 was calibrated in two longitudinal profiles of the Osojnik rockfall (Photo 4). The profile “Osojnik desno” (Fig. 1) was put in the middle of the talus, nearby of two large boulders (Photo 5).

Table 2. Low/high parameter values used in calibration of the model — using the Rockfall 6.1.

Surface properties	D_n	D_t	O_a	O_f
Blocks	0.40/0.45	0.88/0.95	0.2/0.3	1/2
Scree – large blocks	0.30/0.40	0.82/0.88	0.3/1.0	8/10
Scree – covered with bushes	0.30/0.30	0.80/0.85	0.3/1.5	6/10
Scree – covered with trees	0.28/0.28	0.80/0.85	0.5/2.0	6/10
Meadow	0.20/0.30	0.25/0.80	0.2/0.4	8/10
Trees	0.28/0.28	0.75/0.79	0.2/0.5	6/8
Channel	0.28/0.35	0.75/0.86	0.3/0.3	3/5

Table 3. Number of the released blocks traveling over given distance L (m), computed for high and low roughness D_n and D_t as defined in Table 2.

	$R = 0.8$ m, $R_g = 20°$, $R_h = 40°$ High roughness (case c) in Fig. 2)						$R = 0.8$ m, $R_g = 31°$, $R_h = 40°$ Low roughness (case d) in Fig. 2)					
L (m)	**10**	**%**	**500**	**%**	**10000**	**%**	**10**	**%**	**500**	**%**	**10000**	**%**
50	10	100	500	100	9993	99.9	10	100	500	100	10000	100
300	10	100	500	100	9993	99.9	10	100	500	100	10000	100
400	10	100	490	98	9993	99.9	10	100	500	100	10000	100
420	9	90	417	83.4	5452	54.5	10	100	500	100	10000	100
450	9	90	415	83	5427	54.3	10	100	500	100	3647	36.5
470	9	90	415	83	5414	54.1	10	100	500	100	3647	36.5
490	9	90	415	83	5319	53.2	10	100	500	100	3647	36.5
500	8	80	415	83	5296	53.0	0	0	0	0	0	0
510	8	80	404	80.8	5274	52.7						
530	8	80	404	80.8	5268	52.7						
550	7	70	394	78.8	5160	51.6						
570	7	70	245	49	4987	49.9						
600	0	0	8	1.6	1250	12.5						

The longitudinal profile "Osojnik desno"

Computations using Rockfall 6.1 in the computerized longitudinal profile "Osojnik desno" (Fig. 1) were performed using combinations of model parameters: number of blocks (10, 500, 10000), block size R (0.4 m, 0.8 m, 2.0 m, 6.0 m), fall height (930 ± 40 m), dynamic friction angle R_g (20°, 31°, 33°), static friction angle R_h (40°), rolling resistance R_w (0.3), trees (yes, no), model parameter variation (0 %, 20 %). The low and high values for surface roughness O_a and O_f, and normal damping D_n and tangential damping D_t are given in Table 2.

The sensitivity analysis was performed to evaluate the influence of slope roughness (O_a and O_f) on run-out distance (Table 3, Fig. 2). Furthermore, the sensitivity of the model on the forest presence with a different tree diameter was tested: trees with selected diameters were added to describe the field conditions (Tables 4 & 5).

Using field data on silent witnesses (such as shown on Photos 5 & 6) the computer model Rockfall 6.1 was then calibrated using computations with block size 5 m ± 50 % and 8.0 m ± 40 %, and using the RockTree module to evaluate the influence of trees (trees $d_1 = 0.3$ m (293 m to 490 m) and trees $d_2 = 0.15$ m (522 m to 533 m) damping coefficient wood/rock = 0.2); the model parameter variation was set to 2 %. The calibrated model yielded the model parameters given in Table 6. The modeled run-out distances are given in Table 7.

From the calibration of the model the following main conclusions can be drawn:

- The number of the released blocks influences the run-out distance; especially with high slope surface roughness one should be careful and use a rather large number of released blocks (compare results for 10,000 versus 500 blocks as shown in Table 3) to cover also extreme cases if necessary — computer time is no real restriction, even though with 10,000 blocks the program might abort and abruptly terminate the simulation. This is even more true if a large model parameter variation (> 20 %) is set.
- Slope surface roughness has a major influence on the run-out. With higher roughness the run-out distance increases (left hand part of Table 3) — it seems as if surface irregularities force the blocks to jump further as being on ski jumps (compare cases a) and c) with high roughness and cases b) and d) with low roughness in Fig. 2). The number of rebounds, bounce height, total kinetic energy and variation

Table 4. The influence of trees on runout distance: D_n and D_t are high — see Table 2; in the longitudinal profile trees $d_1 = 0.15$ m are placed within stationing $L = 293$ m–490 m and trees $d_2 = 0.10$ m are placed within $L = 522$ m–533 m; block size $R = 0.8$ m; $R_h = 40°$; the damping coefficient between wood and rock was set to 0.1.

	500 released blocks				500 released blocks				10,000 released blocks				500 released blocks			
	R_g=20° high roughness				R_g=31° high roughness				R_g=31° high roughness				R_g=31° low roughness			
L (m)	Without trees		Trees		Without trees		Trees		Without trees		Trees		Without trees		Trees	
	1.	2.	1.	2.	1.	2.	1.	2.	1.	2.	1.	2.	1.	2.	1.	2.
50	500	500	500	500	499	500	500	500	9982	9998	1000	2000	500	500	500	500
200	500	500	500	500	499	500	500	500	9982	9998	1000	2000	500	500	500	500
300	500	500	500	500	499	500	500	500	9973	9998	1000	2000	500	500	500	500
400	490	500	499	500	448	498	478	298	9914	9998	981	1962	500	500	500	500
450	415	221	463	416	251	494	478	298	9707	4233	981	1950	500	402	455	500
470	415	221	463	414	251	493	478	298	9702	4232	981	1950	500	402	455	500
490	415	215	463	411	251	493	477	298	9702	4224	981	1950	500	402	455	500
500	415	213	463	410	249	489	475	289	9675	4148	978	1934	0	0	0	0
510	404	212	455	409	230	487	474	288	9623	3993	977	1900				
530	404	212	455	409	227	487	474	288	9622	3993	977	1898				
550	394	199	452	392	226	484	473	288	9508	3869	967	1877				
570	245	184	443	355	118	478	467	276	9354	3620	967	1853				
600	8	0	80	72	0	188	184	4	2958	48	258	606				

Table 5. The influence of tree diameter and block size on runout distance: number or released blocks: 500; $R_g = 31°$; $R_h = 40°$; D_n and D_t are high — see Table 2; surface roughness is high; in the longitudinal profile trees d_1 are 6 m high, 4 m apart and placed within $L = 293$ m–490 m and trees d_2 are 4 m high, 2 m apart and placed within $L = 522$ m–533 m; damping coefficient wood/rock = 0.3 for larger trees and 0.2 for smaller trees, respectively.

cases #1, #4, #7 and #10: without trees cases #2, #5, #8 and #11: trees d_1=0.3 m ± 10 %, d_2=0.2 m ± 10 % cases #3, #6, #9 and #12: trees d_1=0.5 m ± 10 %, d_2=0.3 m ± 10 %												
L (m)	R=0.2 m			R=1 m			R=2 m			R=6 m		
	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
50	500	500	500	500	500	500	500	500	500	500	500	500
200	500	500	500	500	500	500	500	500	500	500	500	500
300	500	499	500	500	500	499	499	500	500	500	500	500
400	488	470	125	497	489	498	499	499	500	499	500	481
420	469	364	73	308	315	353	473	481	490	493	491	481
450	469	335	33	302	314	346	473	481	490	493	490	480
470	469	323	27	302	314	346	473	481	489	493	489	480
490	469	322	15	302	314	343	473	480	489	493	489	480
500	467	299	13	301	308	343	473	480	487	493	489	480
510	458	273	7	293	297	342	472	479	482	493	487	479
530	458	272	7	293	297	342	472	478	482	493	486	479
550	436	249	5	287	280	329	285	468	477	486	481	248
570	430	216	3	276	260	303	282	458	466	480	476	247
600	157	49	0	161	130	153	140	114	92	141	129	68

Table 6. Calibrated values of the model parameters in the longitudinal profile "Osojnik desno" — using Rockfall 6.1 and $R_g = 33°$, $R_h = 40°$, $R_w = 0.3$.

Slope surface properties	D_n	D_t	O_a	O_f
Rock	0.45	0.93	0.3	1
Scree – large blocks	0.40	0.85	1.0	8
Scree – covered with bushes	0.30	0.82	1.0	8
Scree – covered with trees	0.28	0.79	1.0	8
Meadow	0.28	0.40	0.3	8
Trees on a lower river terrace	0.25	0.80	0.5	8
River channel	0.30	0.86	0.3	3

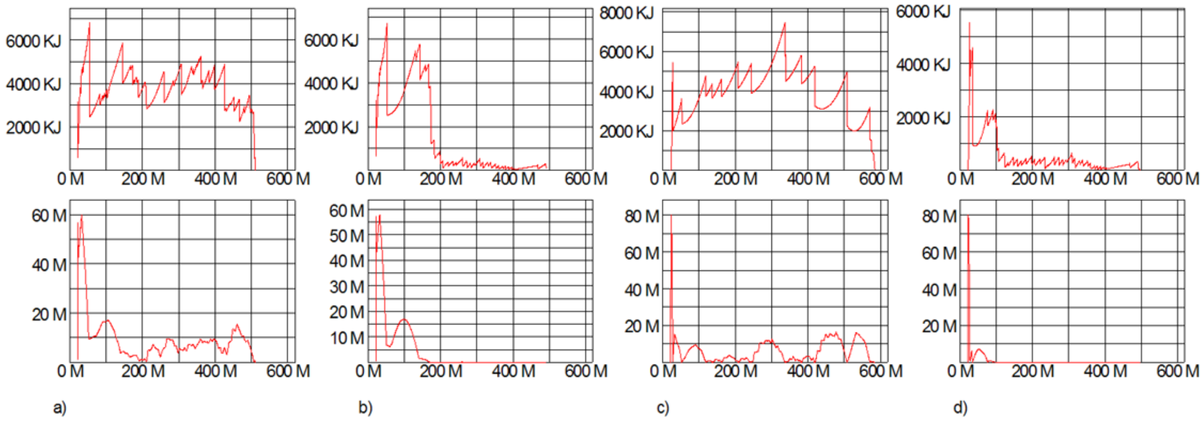

Fig. 2. The comparison of kinetic energy (first row) and bounce heights (second row) for different surface roughness (other model parameters: $R = 0.8$ m, $R_g = 31°$, $R_h = 40°$). For cases a) and c) the surface roughness was high, for cases b) and d) it was low. For cases a) and b), D_n and D_t were low, for cases c) and d) they were high.

Photo. 6. Silent witness in the longitudinal profile "Osojnik desno".

of run-out increase when compared to slope surface with low roughness when practically all blocks stop at the same run-out (at the toe of the talus with $L = 500$ m as shown in Table 4).

It is therefore essential that a rockfall model should be calibrated before used under similar field conditions elsewhere. It is not wise to use easily available commercial rockfall simulation programs and use model parameter values suggested in the literature without taking into account any field data to calibrate the model.

– The rock size influences primarily the total kinetic energy (i.e. first row in Fig. 2) and to a large extent also the maximal bounce height (i.e. second row in Fig. 2), but not the maximal run-out, which is at high slope surface roughness high for all rock sizes (Table 5).

  It is therefore practically obligatory to involve into simulating rockfalls an engineering geologist who should estimate block sizes in rockfalls under consideration using field evidences such as rock joints, microfracturing, bedding and average rock layer thickness. Any relict (released) blocks under active rockfalls may help as well.

– The program Rockfall 6.1 defines two rock shapes: sphere and cylinder. If planar slides are involved in a rockfall under consideration, then many released blocks rather have the shape of a plate (discus) than a sphere. If such a block rolls like a wheel it can out-run a spherical block, and if it slides, its run-out will be small due to large friction angle. In such a case large model variability should be taken into account

Table 7. Modeled run-out distances for block size 5 m ± 50 % in the longitudinal profile “Osojnik desno” using Rockfall 6.1.

	Without trees				Trees			
Number $R = 5.0$ m	1500	1500	1500	10,000	1500	1500	1500	1500
L (m)	1.	2.	3.	4.	5.	6.	7.	8.
50	1500	1498	1500	9976	1499	1496	1500	1500
100	1500	1498	1500	9976	1499	1496	1499	1500
400	1500	1498	1500	9976	1499	1496	1499	1500
420	991	1498	1500	817	913	255	252	297
440	19	20	15	186	14	20	44	119
460	17	17	14	175	14	19	6	56
480	17	17	14	175	14	19	6	55
490	17	17	14	175	14	19	6	55
500	5	3	12	8	13	19	0	37
510	2	1	7	0	11	5		25
520	2	0	5		11	2		10
540	0		0		2	0		0
560					0			

Table 8. Calibrated values of model parameters in the longitudinal profile “Osojnik levo” — using Rockfall 6.1 and $R_g = 33°$, $R_h = 40°$, $R_w = 0.3$.

Slope surface properties	D_n	D_t	O_a	O_f
Rock	0.45	0.95	0.3	1
Scree – large blocks	0.40	0.90	0.8	8
Scree – small blocks	0.32	0.88	0.5	8
Meadow	0.30	0.78	0.3	8

Table 9. Computed run-out distances for the longitudinal profile “Osojnik levo” for different cases (parameter variation v = 20 %; meadow was added in case #9 starting at stationing 483 m with $D_n = 0.28$ and $D_t = 0.40$).

Case #	1	2	3	4	5	6	7	8	9
L (m)	$R = 4.5$ m				$R = 0.2$ m		$R = 6.0$ m		$R = 4.5$ m
50	4994	4979	5000	4966	4955	4999	4977	4973	4998
460	4994	4979	5000	4966	4955	4999	4977	4973	4998
480	3343	816	1760	1531	288	353	2180	2435	3579
500	359	0	144	168	84	21	4	729	0
520	34		45	9	69	19	4	585	
540	33		7	5	36	18	3	106	
560	0		6	5	36	18	1	106	
580			3	2	13	7	0	39	
600			0	0	10	1		1	
620					1	0		0	

to deal with the case of wheel-like blocks. The block shape is not adequately covered in Rockfall 6.1 and also many other mathematical rockfall models.

– The Rockfall 6.1 has a forest module called RockTree that allows for assessment of the influence of a forest stand on rockfall dynamics, especially the run-out. An open forest stand with trees of diameters of some 10 cm (up to 50 cm) being approximately 10 times their diameter apart from each other can only stop blocks of comparable diameter. Larger trees with the diameter 0.5 m and 0.3 m (case #3 in Table 5) effectively stop nearly all the blocks of the size of 0.2 m which is not the case with smaller trees with the diameter 0.3 m and 0.2 m (case #2 in Table 5). Blocks much larger than the trees are much less effectively stopped as the trees are not that easily hit by the blocks (see Table 5 and results for block sizes $R = 0.2$ m and $R = 1$ m). For very large blocks of size comparable to the spacing between trees, the efficiency of trees to reduce kinetic energy of blocks, if not to fully stop them, rises again (see Table

Photo. 7. The longitudinal profile “Osojnik left” on the Osojnik rockfall in the Trenta Valley.

5 and results for block sizes $R = 2$ m and $R = 6$ m). For more precise interpretation one may release more than 500 blocks for each computational case, as was the case in Table 7; the improvement is not very dramatic when compared to the influence of the variability of other model parameters, especially the previously mentioned slope surface properties.

– The initial block velocity (when released) should have, according to results of Bozzolo (1987), an important influence on the block run-out but this was not supported by the results obtained in this case study.

– For this specific field case study on the Osojnik rockfall both friction angles (R_g and R_h), which are important when sliding is the major mechanism, do not have large influence since the sliding does not prevail over bouncing and rolling.

– Large blocks and boulders as silent witnesses are a good sign of the rockfall run-out — often defined by the so-called shadow angle. Evans and Hungr (1993) defined the minimal shadow angle to be 27.5°; Meissel (1998) gave values of only 26°. Shadow angles determined for the Osojnik rockfall, using field data on released boulders, are $> 28°$. Only for extremely large blocks (> 6 m) one may expect that these would reach the Soča riverbed (stationing $L > 550$ m in the longitudinal profile “Osojnik desno”) and in such case the shadow angle would be $< 28°$.

The longitudinal profile “Osojnik levo”

Because the sensitivity analysis of the model was already performed in the longitudinal profile “Osojnik desno”, the model parameters for the profile “Osojnik levo” (Photo 7; Fig. 3) were determined (Table 8) using experiences from the profile “Osojnik desno”. The calibrated values of the model parameters in the longitudinal profiles “Osojnik desno” (Table 6) and “Osojnik levo” (Table 8) are quite similar.

Next, the run-out was computed for selected blocks sizes using 5,000 released blocks for each computational case (Table 9). Small blocks (Table 9, cases #5 & #6 with $R = 0.2$ m) had run-outs quite comparable to very large blocks (Table 9, cases #1 through #4 with $R = 4.5$ m).

Much larger influence on the computed run-out was detected for slope surface properties describing block impacts — normal and tangential damping. The influence of the meadow in case #9 (Table 9) when compared with other cases is an example of this: small blocks roll across the meadow without high kinetic energy losses when compared to large blocks that impact the meadow and lose kinetic energy. This example again stresses the importance of the slope surface properties on rockfall dynamics where block size and block shape are closely related to each other.

Validation of the rockfall model on the Berebica rockfall

Finally, the calibrated model Rockfall 6.1 was applied to the Berebica rockfall (Photo 8 & Fig. 4) using the adopted model parameters (Table 10).

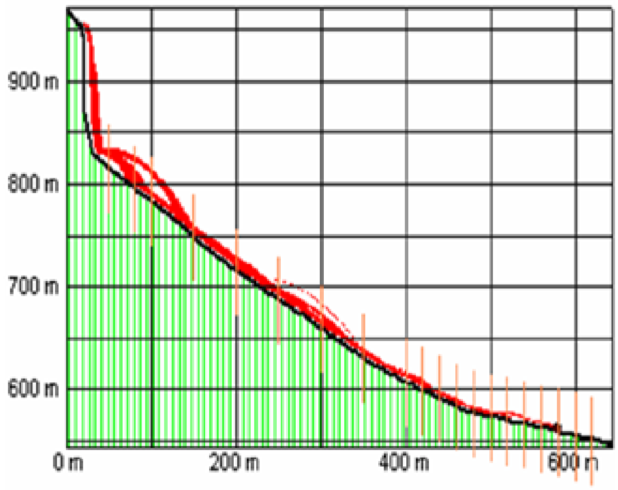

Fig. 3. The longitudinal profile “Osojnik levo”.

Table 10. Calibrated values of model parameters for the “Berebica” rockfall — using Rockfall 6.1 and $R_g = 33°$, $R_h = 40°$, $R_w = 0.3$, parameter variation = 20 %.

Slope surface properties	D_n	D_t	O_a	O_f
Rock	0.45	0.93	0.3	1
Upper part of the scree	0.30	0.85	0.8	5
Lower part of the scree	0.40	0.88	0.5	8
Lower part: rocks & grass	0.28	0.60 (0.40)	0.15	8

Table 11. Block size influence on rockfall run-out in the case of the Berebica rockfall (parameter variance = 50 %; initial velocity = 0 m/s) — using the Rockfall 6.1.

	without gallery – 5000 blocks			with gallery – 5000 blocks		
Case #	1	2	3	4	5	6
L (m)	R=0.5 m	R=2.5 m	R=5 m	R=0.5 m	R=2.5 m	R=5 m
50	4816	4982	4997	4985	4998	4993
70	4816	4982	4997	4985	4997	4992
90	4816	4982	4996	4985	4997	4991
200	4816	4982	4996	4985	4997	4991
210	919	1043	4992	3485	3997	4355
220	918	941	748	416	1063	826
230	913	927	734	286	837	720
235	876	910	707	16	93	86
240	839	892	681			
250	781	873	672			
260	619	721	654			
270	389	714	654			
280	301	707	652			

The run-out was computed for different block sizes (Table 11) for the case without and with the gallery, respectively. For the situation before the construction of the gallery the computed run-out corresponded to the run-out of the blocks that reached the Soča riverbed during the 1998 rockfall, as witnessed by large blocks. Also the Berebica rockfall exhibits the minimum shadow angle of 28°, comparable to the value obtained for the Osojnik rockfall.

The computed total kinetic energy (in kJ) for block sizes 0.5 m ± 50 % and the slope situation before the gallery was constructed (Fig. 5) showed that the total kinetic energy of released blocks in the cross section

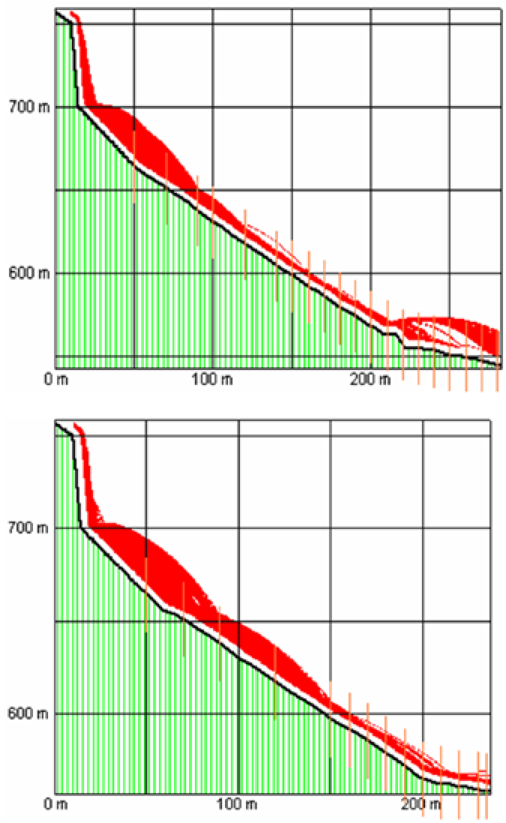

Fig. 4. The longitudinal profile "Berebica" (left: without the rockfall gallery; right: with the gallery).

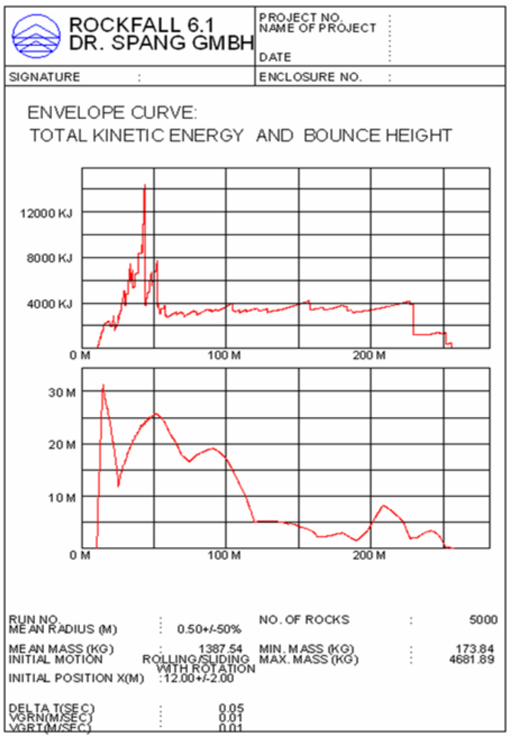

Fig. 5. An envelope curve for the total kinetic energy and bounce heights in case of the Berebica rockfall before the gallery was constructed (case #1 in Table 11).

Photo. 8. The Berebica rockfall in the Trenta valley with two longitudinal profiles.

of the regional road (stationing 210 m in the longitudinal profile on Fig. 5) was of the order of 4000 kJ. This value is the upper limit where dynamic barriers can still be effectively used. Since much larger blocks than 0.5 m may still be released from the rock face of the Berebica rockfall, the decision to plan and build a rockfall gallery made out of reinforced concrete was the appropriate technical solution on this important regional road.

Conclusions

Using a 2-D rockfall mathematical model (e.g. Rockfall 6.1), the first problem was the choice of the appropriate longitudinal profile. In the case of an active rockfall, we should use silent witnesses (released blocks, tree damage, damaged forest under-storey, block "imprints" in soils), otherwise we should evaluate several profiles. Even precise surveying cannot show all local irregularities. In Rockfall 6.1 these irregularities are described by two model parameters: the amplitude of the surface roughness O_a and the roughness frequency O_f. The model results are very much a function of these two model parameters.

Another problem is the choice of the release point of the rockfall. To be on the safe side, one should take into computation the upper scar in the rock face. With active (fresh) rockfalls the color of the rock face indicates the release points (surfaces) and the choice is easier.

Also the released mass of blocks should be varied and determined from local geotechnical and geological inspection of the rock face, if possible. Silent witnesses may help to some extent.

Different values of friction and rebound coefficients can be chosen along the longitudinal profile, but even in doing so, not all variability in slope surface properties can be taken into account. After the free fall and the first hit with the slope surface, large energy losses can be detected and frequently the falling mass disintegrates. If these energy losses are taken to be too high, the run-out distance is underestimated.

It is essential that a rockfall model should be calibrated before it will be used under similar field conditions elsewhere. It is not wise to use easily available commercial rockfall simulation programs and use model parameter values suggested in the literature without taking into account field data to calibrate the model.

In the last decade or so, 3-D rockfall models have been developed and tested. The existing 3-D mathematical models solve some of the problems mentioned above, however, they introduce new ones. Any existing 2-D rockfall model should be used in engineering practice with much care and with full understanding of the processes involved in a rockfall. We believe that model applications, such as the one described in this paper, using different but real field data are essential for further development of rockfall models.

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