rocscience

RocFall3

3D Rigid Body

Verification Manual

Table of Contents

Introduction

The rigid body analysis in RocFall3 is calculated using non-smooth dynamics and considers multi-contact. The following user inputs are the basic required parameters used for modelling energy dissipation on slope-rock contact:

- Normal coefficient of restitution (R_n)
- Dynamic friction coefficient (μ)
- Frictional dissipation method in impacts
- And whether the normal and tangential impulses are to be solved simultaneously

R_n is applied at contact points and is used to find the relative normal velocities before and after an impact.

μ is applied at contact points and is used in frictional impacts and sliding. RocFall3 uses a linearized friction cone constraint.

The latter two inputs primarily influence frictional impacts and are user inputs available from the Advanced Rigid Body Options dialog in Project Settings. The default settings for RocFall3 rigid body analysis use the simultaneous calculation of normal and tangential impulses as well as the maximum dissipation of friction. This combination of default settings is recommended because it provides comparable behaviour among the different impact theories adopted in RocFall3, RocFall2, and RAMMS, as illustrated in the following validation examples.

1. Unit Test Set 1 – R_n and Impacts Normal to Contacts

The coefficient of normal restitution (R_n) is applied at contact points in RocFall3. The R_n ranges from 0 to 1 and serves to dampen the contact incoming normal velocity ($v'_{n,\,in}$) to result in a smaller contact outgoing normal velocity ($v'_{n,\,out}$):

$$R_n = \frac{v'_{n,out}}{v'_{n,in}} \quad (1.1)$$

In a collinear impact, the normal velocity at the rock center-of-mass is the same as the normal velocity at the contact point.

A series of freefall unit tests with collinear impacts were conducted, with rock center-of-mass results tabulated below. Results show that R_n is correctly applied in RocFall3 for various contact types, and the computed rebound heights (h_1 followed by h_2) compare well to the analytical solution:

$$R_n = \sqrt{\frac{h_2}{h_1}} \quad (1.2)$$

Table 1.1: Freefall of a cube (1 m^3, 2700 kg) from z = 10 m and over a drop distance of 9.5 m; R_n = 0.5; face-face contact.

	Analytical	**RocFall3**	**RAMMS**
Rebound 1 z (m)	2.88	2.87	2.86
Rebound 2 z (m)	1.09	1.09	1.06

Table 1.2. Freefall of rocks with different shapes and contact types; 1 m^3, 2700 kg.

	Octahedron R_n = 0.3 Drop distance = 9.09 m Vertex-face contact		**Dodecahedron R_n = 0.8 Drop distance = 9.34 m Edge-face contact**	
	Analytical	**RocFall3**	**Analytical**	**RocFall3**
Rebound 1 z (m)	1.73	1.73	6.64	6.63
Rebound 2 z (m)	0.98	0.98	4.49	4.48

Table 1.3. Freefall of an octahedron (1 m^3, 2700 kg) from z = 10 m for Rn = 1 and Rn = 0.

	$R_n = 1$		$R_n = 0$	
	Analytical	**RocFall3**	**Analytical**	**RocFall3**
Rebound 1 z (m)	10	10.00	0	0.00
Rebound 2 z (m)	10	10.00	-	-
Rebound 3 z (m)	10	10.00	-	-

2. Unit Test Set 2 – *μ* and Sliding

The dissipation of rock energy during sliding occurs through friction at the contacts. In RocFall3, the dynamic friction coefficient (μ) is applied at contact points and acts in the directions opposite to the incoming tangential impulses.

In sliding, the work done by friction is equal to the initial translational kinetic energy of the rock. Thus, an analytical solution is available for calculating the sliding distance of a rock with an initial translational velocity.

A series of sliding unit tests were conducted, with results at the rock center-of-mass tabulated below. The results show that μ is applied correctly in rock sliding for various contact types, and the computed sliding distances compare well to the analytical solution.

Table 2.1. Sliding distance of a cube (1 m^3, 2700 kg) with an initial translational velocity of 5 m/s in the direction <1, 0, 0>; μ = 0.5; face-face contact.

	Analytical	RocFall3	RAMMS
Sliding Distance (m)	2.55	2.55	2.55

Table 2.2. Sliding distance of a tetrahedron (1 m^3, 2700 kg) with an initial translational velocity of 3 m/s in the direction <1, -1, 0>; μ = 0.1; edge-face contact.

	Analytical	RocFall3
Sliding Distance (m)	4.59	4.59

3. Unit Test Set 3 – Frictional Impacts

As both R_n and μ are used in the calculation of frictional impacts, it was important for unit testing to isolate and validate the effect of each parameter. This was done by first analyzing rotating, eccentric impacts without friction, in which calculations used just R_n, and then by analyzing frictional impacts, in which calculations used both R_n and μ.

The solution for frictional impacts is non-trivial, and no analytical solution is available. For verification, RocFall3 was compared with RAMMS and RocFall2.

3.1. Impacts without Friction

A cube (1 m^3, 2700 kg) was dropped from z = 10 m with an initial rotational velocity of 45 deg/s. The cube impacted a horizontal slope surface at z = 0 m. For the case of zero friction (μ = 0) and R_n = 0.5, the rock rebounded vertically because no friction was acting to change the translational velocity vector. However, the rotational velocity changed as a result of the eccentric impact. Table 3.1 lists the rock center-of-mass velocities following the first impact. Results show that the three software yield similar results for eccentric impacts without friction. Considering these results along with those from Set 1 unit test, we can conclude that R_n is correctly implemented in RocFall3 rigid body computations.

Table 3.1. Freefall with rotation (μ = 0, Rn = 0.5, 45 deg/s rotational velocity); velocities and total kinetic energies after first impact are reported.

	Rotational velocity vector <1,0,0> Edge-face contact				Rotational velocity vector <1,1,0> Vertex-face contact	
	2D Scenario				3D Scenario	
	RocFall2	**RocFall3**	**RAMMS (R_t = 0)**	**RAMMS (R_t = 1)**	**RocFall3**	**RAMMS (R_t = 1)**
x-velocity (m/s)	0.00	0.00	0.00	0.00	0.00	0.00
y-velocity (m/s)	-	0.00	0.00	0.00	0.00	0.00
z-velocity (m/s)	2.21	2.39	2.19	2.19	5.41	5.29
x-rotational velocity (rad/s)	20.54	20.62	20.90	20.90	8.64	9.15
y-rotational velocity (rad/s)	-	0.00	0.00	0.00	8.64	9.15
Total Kinetic Energy (kJ)	101.52	103.44	104.74	104.74	73.19	75.38

Note that the use of R_t in RAMMS appeared to insignificantly affect outcomes.

3.2. Impacts with Friction

The only piece left to validate is the behaviour of friction in impacts (non-zero μ). When a rotating rock enters a frictional impact, energy loss occurs via the parameters R_n and μ.

Table 3.2 shows the post-impact results for μ = 1, R_n = 1, using a cube (1 m^3, 2700 kg) dropped from z = 10 m with an initial rotational velocity. By using R_n = 1, energy loss occurred via friction alone and not R_n. Similar results were found for RocFall3, RocFall2, and RAMMS.

Table 3.2. Freefall with rotation (μ = 1, Rn = 1); velocities and total kinetic energies after first impact are reported.

	Rotational velocity 45 deg/s around <1,0,0> Edge-face contact				**Rotational velocity 63.6 deg/s around <1,1,0> Vertex-face contact**		
	2D Scenario				**3D Scenario**		
	RocFall2	**RocFall3**	**RAMMS (R_t = 0)**	**RAMMS (R_t = 1)**	**RocFall3**	**RAMMS (R_t = 0)**	**RAMMS (R_t = 1)**
x-velocity (m/s)	-	0.00	0.00	0.00	7.07	7.07	7.31
y-velocity (m/s)	-5.78	-5.79	-5.89	-6.06	-7.07	-7.07	-7.31
z-velocity (m/s)	11.48	11.58	11.54	11.65	6.52	6.48	6.78
x-rotational velocity (rad/s)	8.55	8.57	8.73	8.19	9.72	9.71	9.26
y-rotational velocity (rad/s)	-	0.00	0.00	0.00	9.72	9.71	9.26
Total Kinetic Energy (kJ)	239.44	239.61	243.76	247.89	234.82	234.074	244.921

The results in Table 3.3 are for a cube (1 m^3, 2700 kg) that has an initial rotational velocity of 45 deg/s around <0,1,0>, dropped from z = 10 m (slope at z = 0 m). The first impact consists of an edge-face contact. Here, energy loss was applied via parameters R_n = 0.5 and for various values of non-zero μ.

Table 3.3. Freefall with rotation (edge-face contact, Rn = 0.5, various values of non-zero μ)

	RocFall3				RAMMS (Rt = 0)			
φ (deg)	**5**	**10**	**14**	**45**	**5**	**10**	**14**	**45**
$\mu = \tan \varphi$	**0.087**	**0.176**	**0.249**	**1**	**0.087**	**0.176**	**0.249**	**1**
xy-velocity (m/s)	1.47	3.18	4.39	4.39	1.48	3.18	4.47	4.47
z-velocity (m/s)	3.38	4.52	5.33	5.33	3.18	4.33	5.20	5.20
Rotational velocity (rad/s)	15.88	10.39	6.49	6.49	16.17	10.73	6.62	6.62

The above results illustrate that RocFall3 and RAMMS compute similar behaviours for eccentric, frictional impacts, where the energy dissipation occurs via the parameters Rn and μ. The example also illustrates that the frictional effect is capped (i.e., with reference to the values above, any increase in friction angle above 14 degrees stopped influencing the frictional impact). The physical explanation is that the rock would “stick” rather than “slip” with a large enough friction. Upon reaching the threshold of sticking, post-impact behaviour would no longer be influenced by an increase in the friction angle.

4. Simple Slope Example (3 Rocks)

Three (3) cubes (1 m^3, 2700 kg) travelled down a simple slope by freefalling from 3 discrete point sources, as illustrated in Figure 4.1 below. As the rocks were dropped from different heights and with different initial rotational velocities, they had different configurations at impact and thus exited the first impact at different exit velocities and kinetic energies. RocFall3 results were compared with RocFall2 results because this is a 2D scenario. All rocks were rotating symmetrically about the axis into the page, and all rock paths were confined to the same plane as illustrated in Figure 4.1.

Table 4.1. Rock drop heights and initial rotational velocities

	Drop height above slope (m)	**Initial rotational velocity (deg/s)**
Rock 1	2	10
Rock 2	5	45
Rock 3	10	180

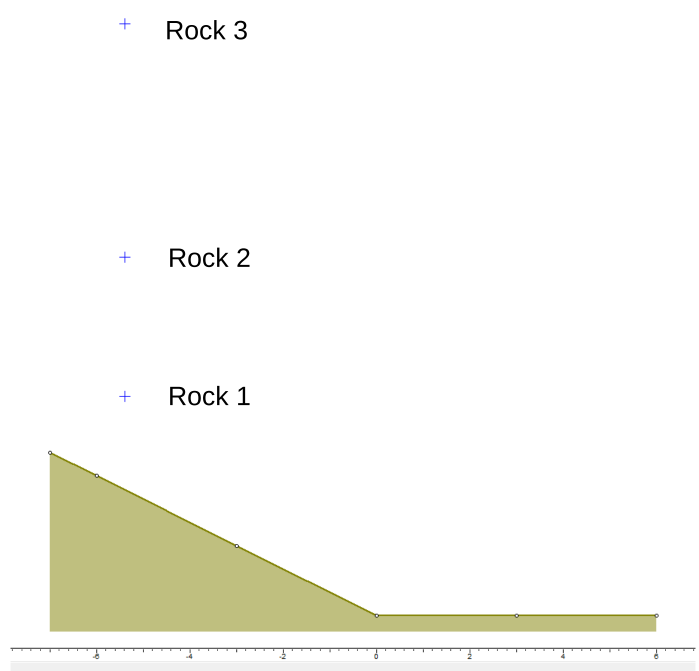

Figure 4.1. Schematic of a simple slope and rock starting location.

The following material (contact) properties were applied:

$R_n = 0.35$

$\mu = 0.6$

The following table lists the velocity and energy quantities following the first impact.

Table 4.2. Exit velocities and energies for first impact.

	Rock 1		Rock 2		Rock 3	
	RocFall2	**RocFall3**	**RocFall2**	**RocFall3**	**RocFall2**	**RocFall3**
x-velocity (m/s)	2.72	2.86	0.07	0.04	5.67	5.66
y-velocity (m/s)	-	0.00	-	0.00	-	0.00
z-velocity (m/s)	-1.49	-1.20	2.77	2.60	2.37	2.32
x-rotational velocity (rad/s)	-	0.00	-	0.00	-	0.00
y-rotational velocity (rad/s)	4.68	4.77	-2.00	-1.82	5.67	5.71
Kinetic energy entering first impact (kJ)	32.46	32.33	111.22	113.15	238.84	244.48
Kinetic energy exiting first impact (kJ)	17.92	18.08	11.23	9.86	58.23	57.84
Loss of kinetic energy in first impact (kJ)	14.54	14.26	99.99	103.29	180.60	186.64

5. Simple Slope Example (Statistical)

Five thousand (5000) cubes (all 1 m^3 and 2700 kg) free-fell from a point source 5 m above a simple slope, as illustrated in Figure 5.1. Statistical distributions were applied to R_n, μ, and the rock initial rotational velocity, thus introducing variability to the frictional impacts and resulting trajectories. RocFall3 results were compared with RocFall2 results as this is a 2D scenario, where all rock paths were confined to the plane as shown in Figure 5.1.

Seeder Name	Number of Rocks	Rock Types	Horizontal Velocity (m/s)	Vertical Velocity (m/s)	Rotational Velocity (rads/s)	Initial Rotation (deg)
Seeder 1	5000	Cube	0	0	Normal Mean: 90 Std Dev: 20 Rel. Min: 60 Rel. Max: 60	0

Material Name	Color	Normal Restitution	Dynamic Friction	Rolling Friction
Bedrock Outcrops		Normal Mean: 0.5 Std Dev: 0.1 Rel. Min: 0.3 Rel. Max: 0.3	Normal Mean: 0.5 Std Dev: 0.1 Rel. Min: 0.3 Rel. Max: 0.3	0

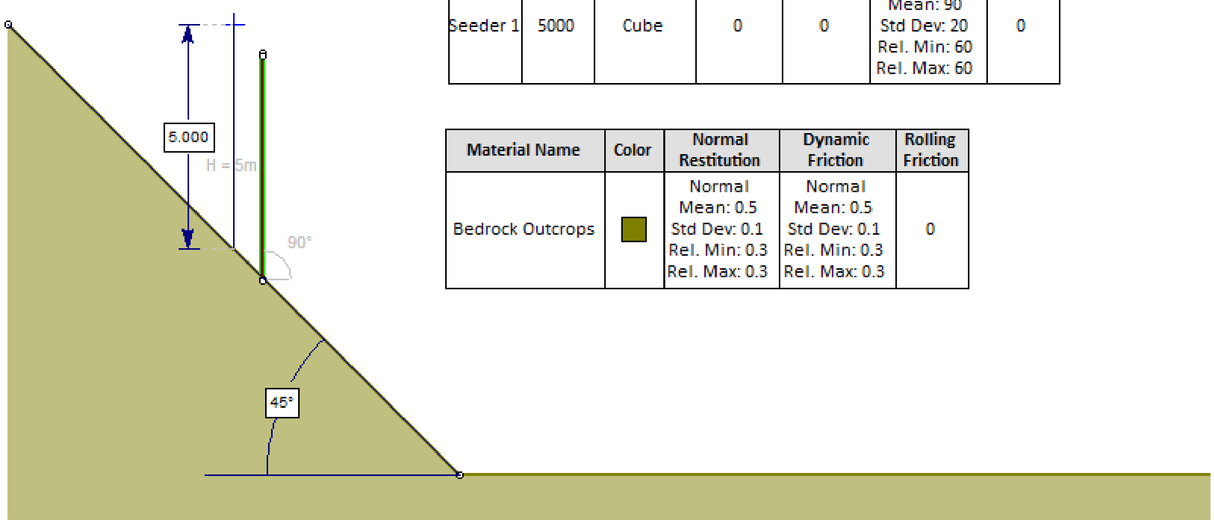

Figure 5.1. Schematic of a simple slope, with values displayed for material and seeder properties; a collector is installed immediately downhill of the point source to collect data of rocks exiting the first impact.

The following Figures 5.2 through 5.9 show the rock energy and trajectory height distributions at the collection point shown in green in Figure 5.1 (immediately after the first impact location). These results show that RocFall3 and RocFall2 rigid body analyses produce comparable statistical outcomes in terms of the mean, minimum, maximum, and the overall distribution shape.

A comparison was also made for the distribution of the total runout distance (Figures 5.10 and 5.11). Here, a similarity in the overall shape of the distribution is expected, though similarities in the minimum, maximum, or mean values, are not expected. This is because rigid body dynamics is chaotic, and any small difference found early in two trajectories can propagate, resulting in two trajectories that are very different overall. This is why RocFall3 and RocFall2 show very similar results at the collector, which is immediately after the first impact, but greater differences in the runout distribution, which accounts for the total rock paths.

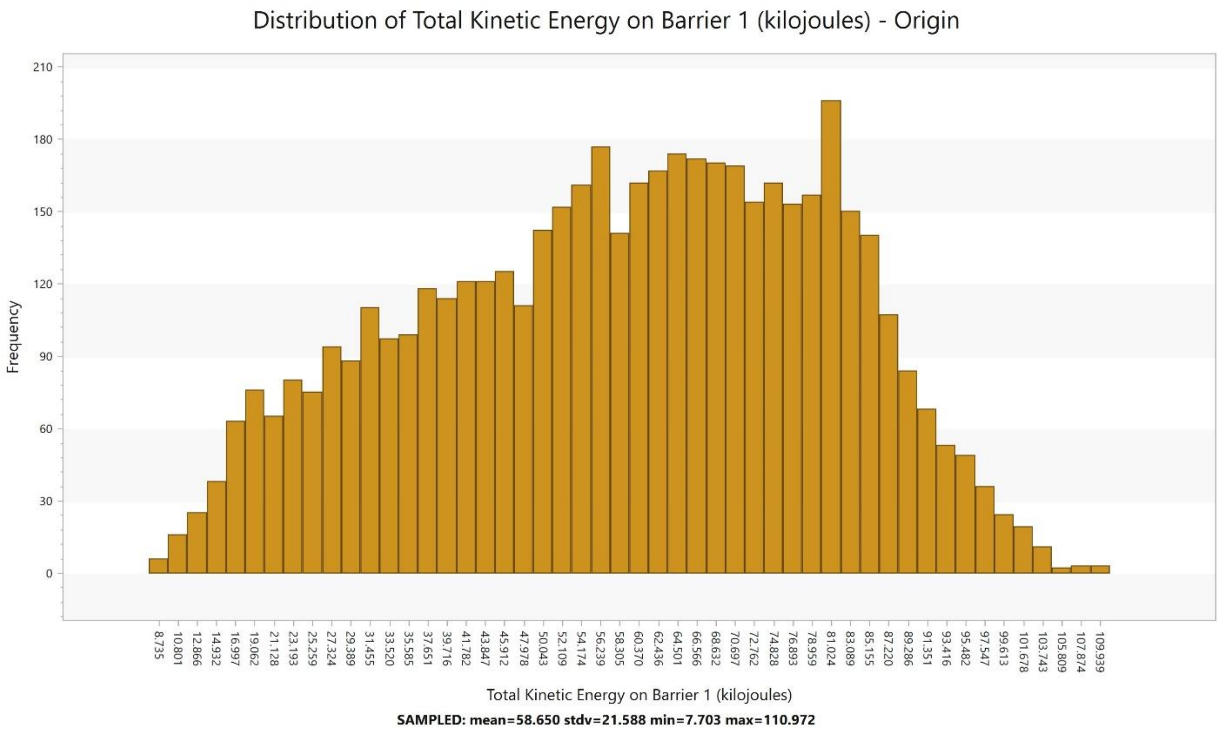

Figure 5.2. Total Kinetic Energy on Collector in RocFall3

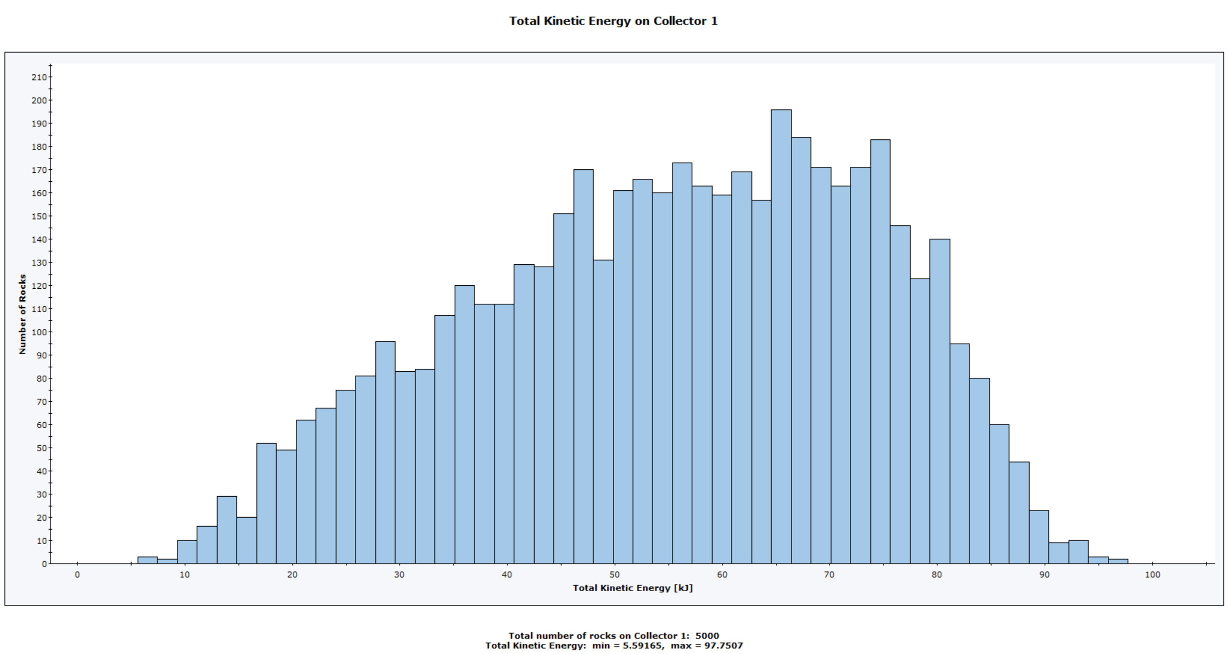

Figure 5.3. Total Kinetic Energy on Collector in RocFall2

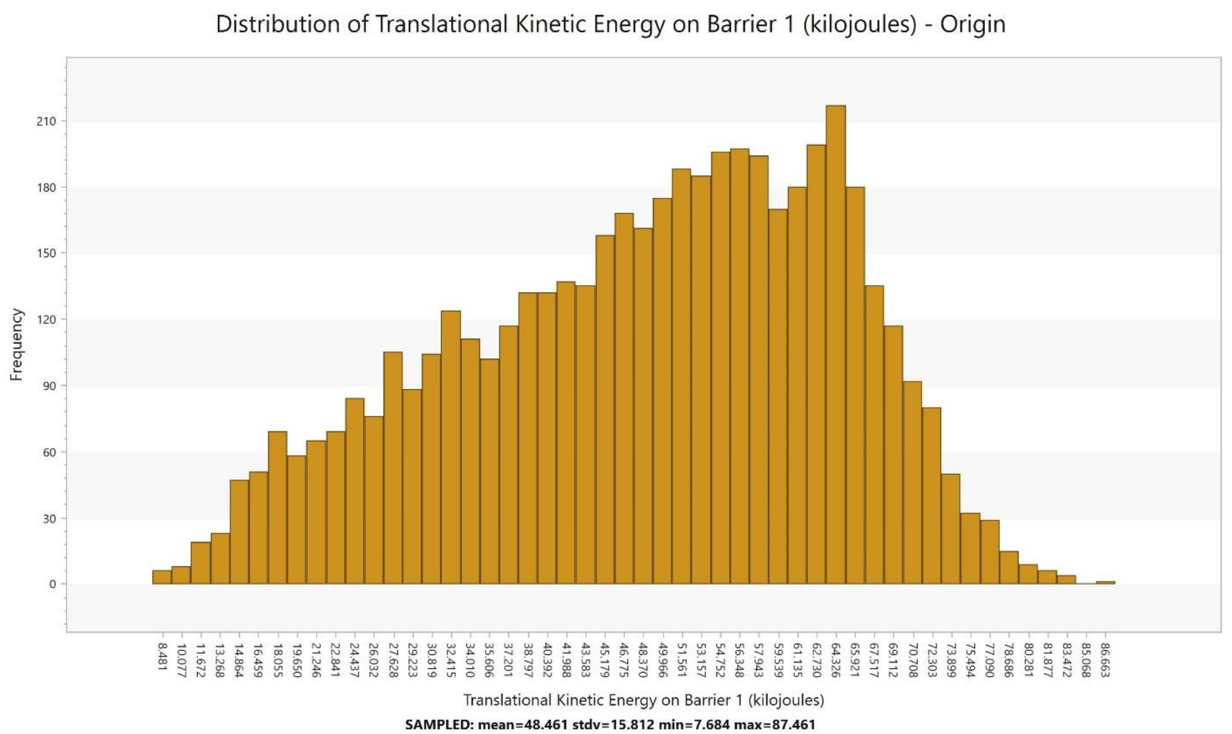

Figure 5.4. Translational Kinetic Energy on Collector in RocFall3

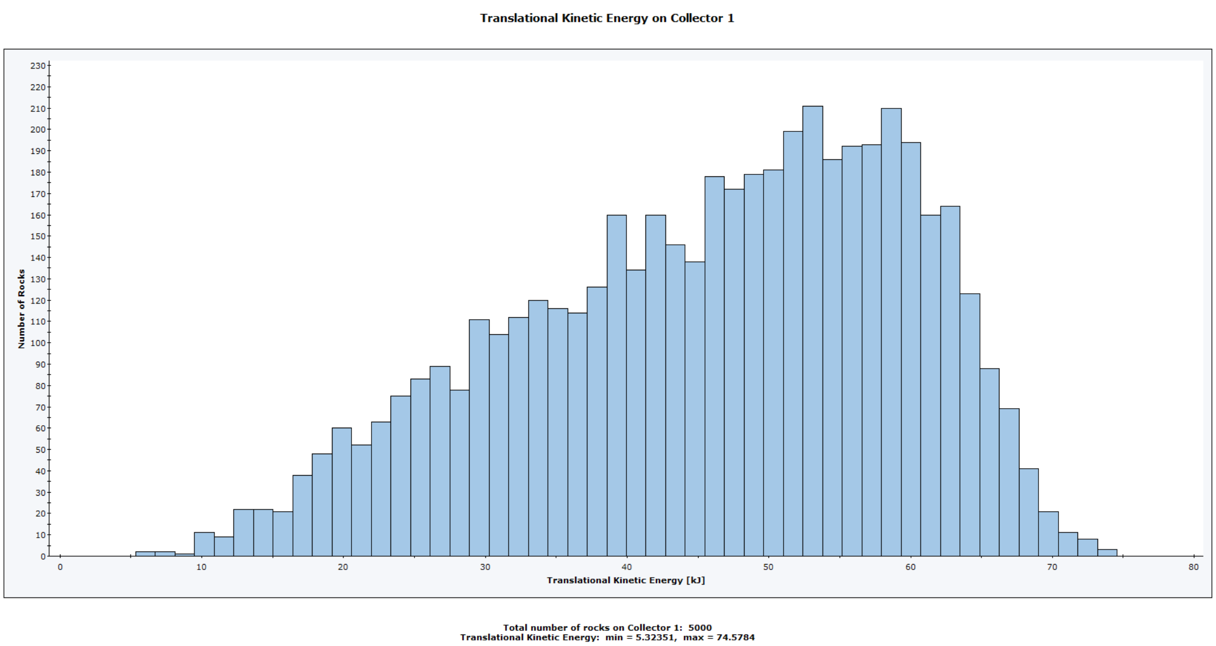

Figure 5.5. Translational Kinetic Energy on Collector in RocFall2

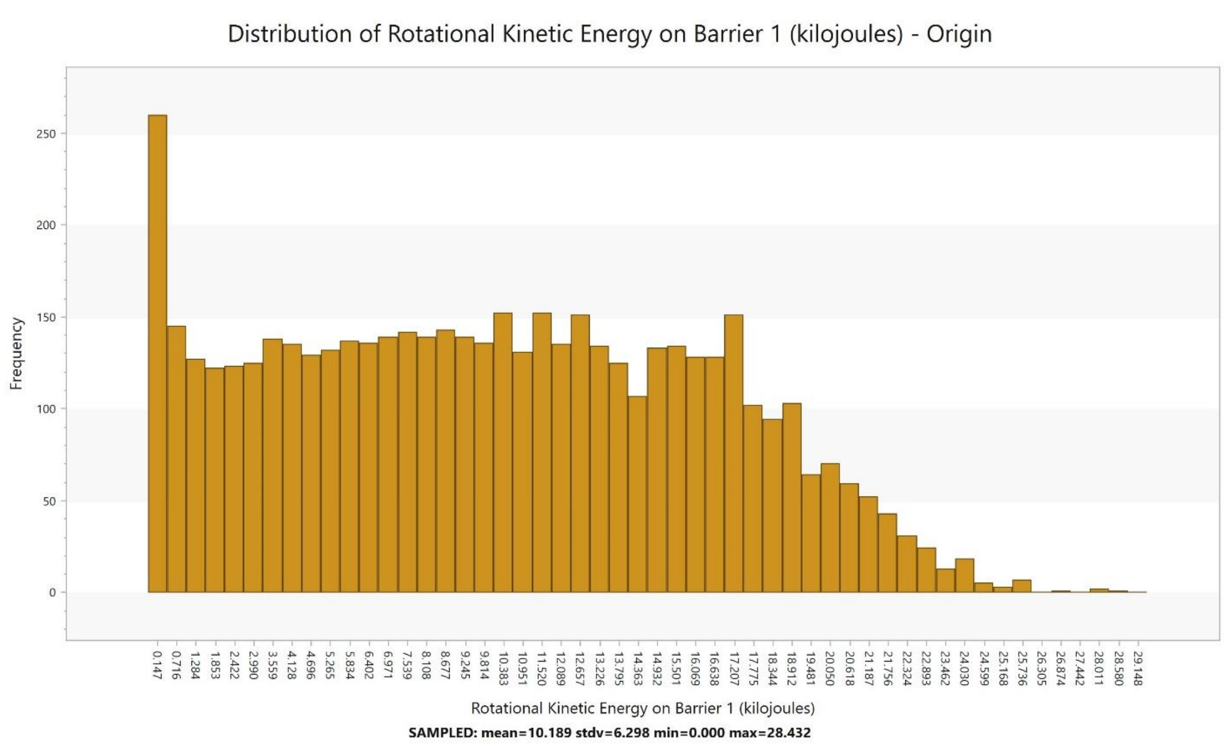

Figure 5.6. Rotational Kinetic Energy on Collector in RocFall3

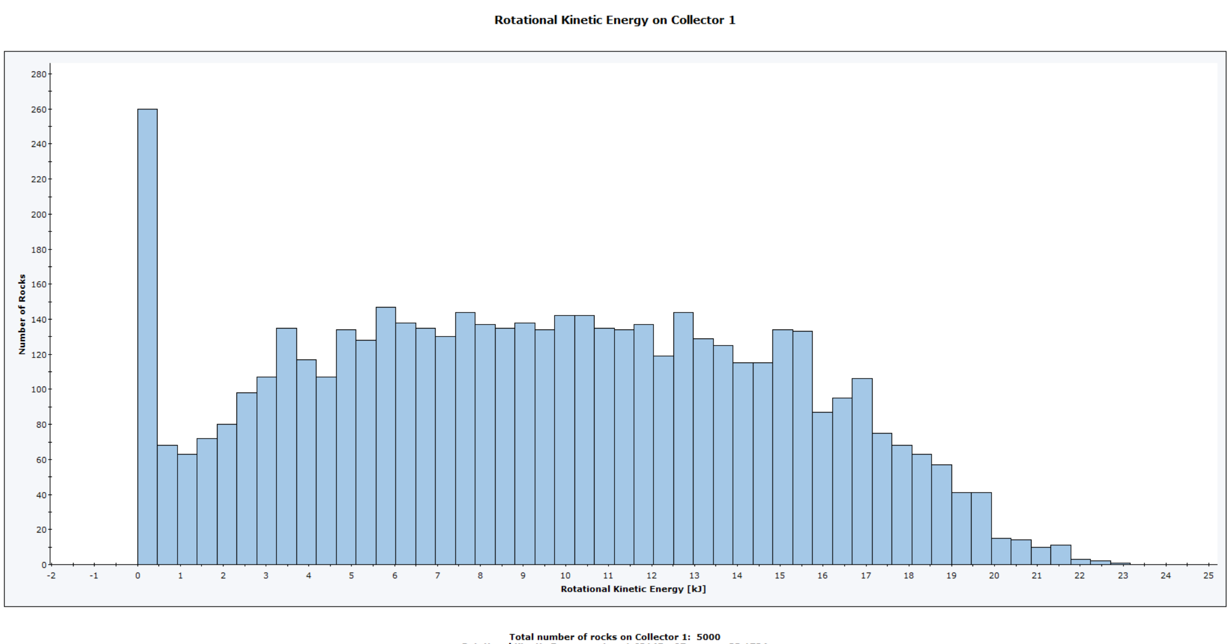

Figure 5.7. Rotational Kinetic Energy on Collector in RocFall2

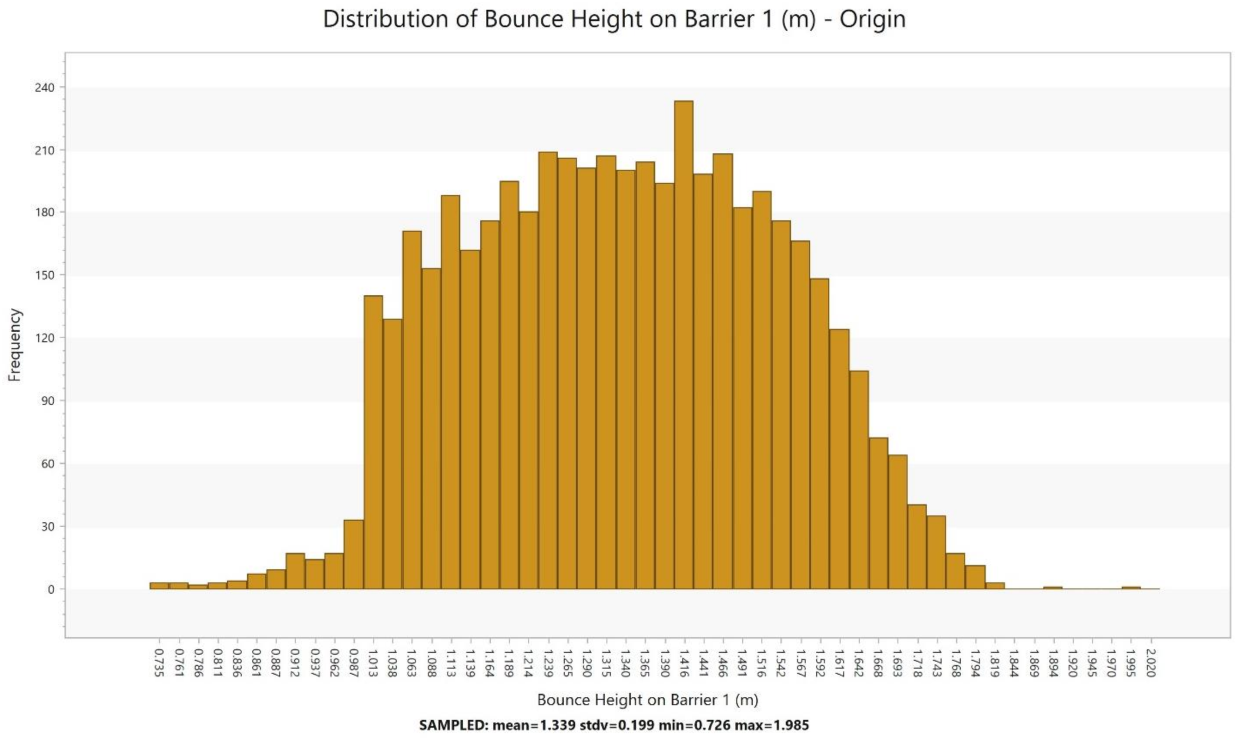

Figure 5.8. Impact Height on Collector in RocFall3

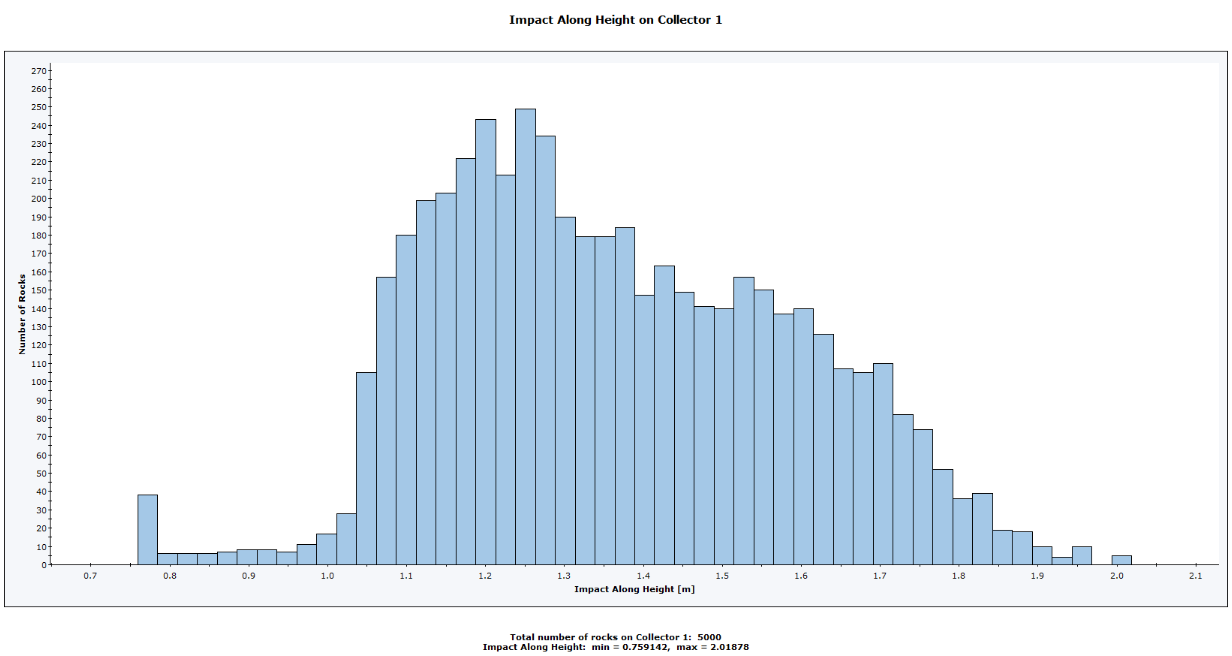

Figure 5.9. Impact Height on Collector in RocFall2

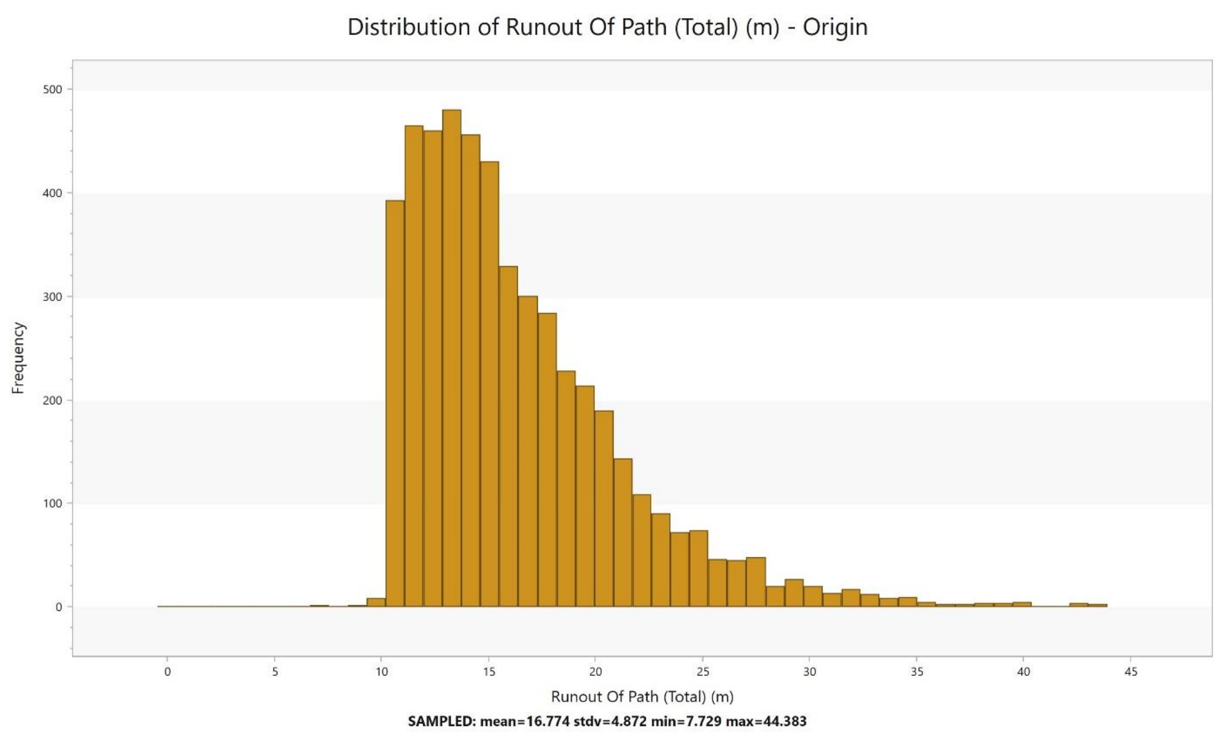

Figure 5.10. Runout distance distribution in RocFall3

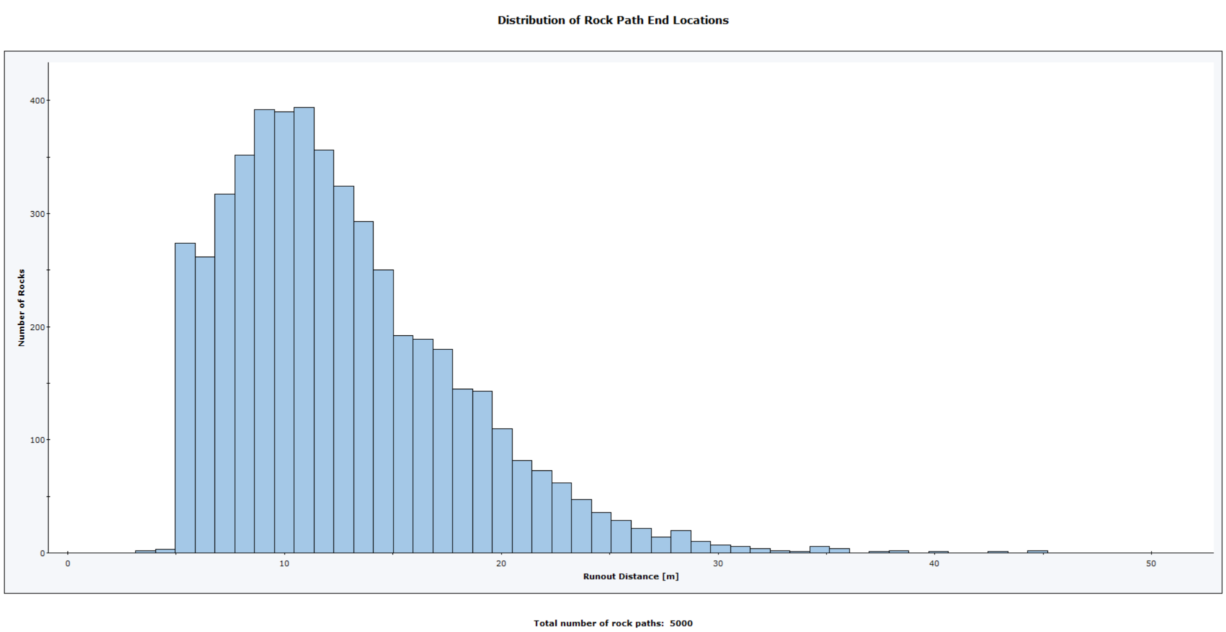

Figure 5.11. Runout distance distribution in RocFall2