rocscience

RocFall2

Rigid Body Analysis

Verification Manual

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1. *RocFall2* Collision Analysis Verification

This document presents several Rigid Body rockfall examples, which have been used as verification problems for *RocFall2*. *RocFall2* is a 2D statistical analysis program designed to assist with assessment of slopes at risk for rockfalls.

The results produced by *RocFall2* agree very well with the documented examples and confirm the reliability of *RocFall2* results.

1.1. *RocFall2* Verification Problem #1 – Comparison between Lump Mass and Rigid Body Formulations

[*RocFall2 Build 8.009*]

1.1.1. Problem Description

In this exercise, the output using Lump Mass or Rigid Body formulations are compared against each other. *RocFall2 4.0* uses the Lump Mass formulation, which assumes rocks as point masses. Since *RocFall2 5.0*, an additional engine using Rigid Body mechanics, that incorporates shape into impact calculations, has been added. In this study, a very small radius is used for a spherical rock to eliminate any shape effects when comparing results.

1.1.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and the Lump Mass and Rigid Body material parameters for all slope segments are presented in the following tables:

Table 1-1: Slope Geometry

	X-Coordinate	Y-Coordinate
Vertex 1	0	0
Vertex 2	3.05	-12.19
Vertex 3	6.71	-12.19
Vertex 4	9.75	-24.38
Vertex 5	13.41	-24.99
Vertex 6	20	-24.99
Vertex 7	22	-24.99
Vertex 8	22.199	-24.99

Lump Mass

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Lump Mass model, ensure that **Consider rotational velocity** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

A friction angle of 0.1° is used in the Lump Mass model because the internal computation of rock paths is more stable with a small friction angle rather than zero friction angle.

Table 1-2: Lump Mass Slope Material Parameters

Normal Restitution R_N	**Tangential Restitution** R_T	**Friction Angle** ϕ **(deg)**	**Slope Roughness (deg)**
0.7	1	0.1	0

Rigid Body

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Rigid Body model, ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

CRSP assumes rocks bounce and roll, so frictional sliding is not accounted for.

Table 1-3: Rigid Body Slope Material Parameters

Normal Restitution R_N	**Dynamic Friction**	**Rolling Friction**
0.7	0	0

Initial Conditions

The rock starts at location X_0 = 0 m, Y_0 = 0 m (which coincides with the first slope vertex). The rock was given an initial velocity of V_{X0} = 3.5 m/s, V_{Y0} = 0 m/s. The rock has a mass of 10 kg and density of 2.1x10^6 kg/m^3.

Enter the seeder and slope geometry values from Table 1-1 into *RocFall2* for both the Lumped Mass and Rigid Body analyses models.

The *RocFall2* model looks like this:

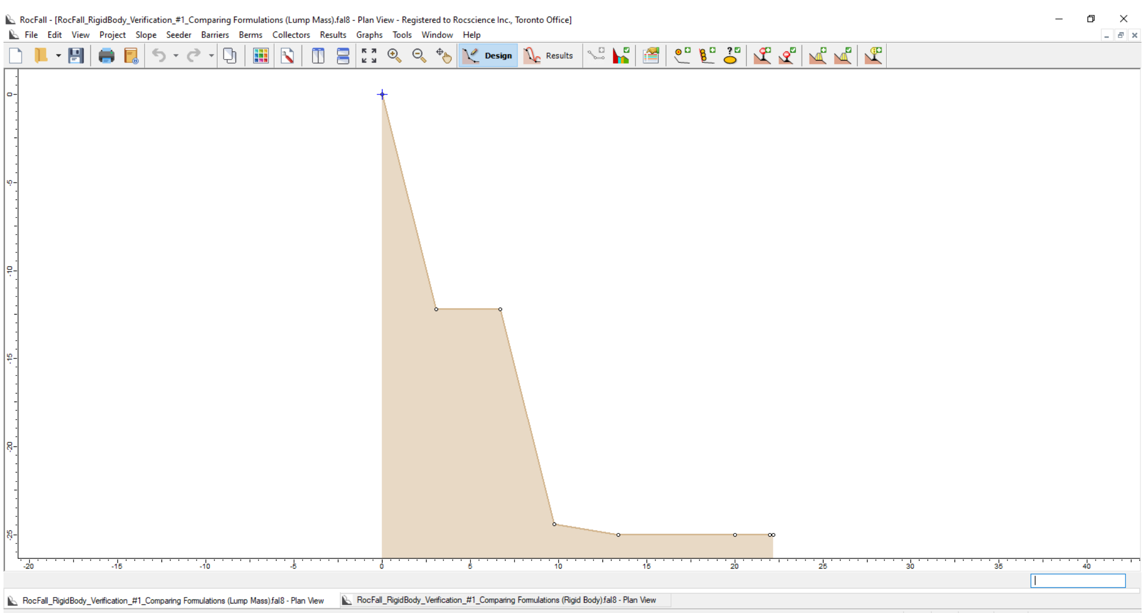

Figure 1-1: *RocFall2* Model Geometry

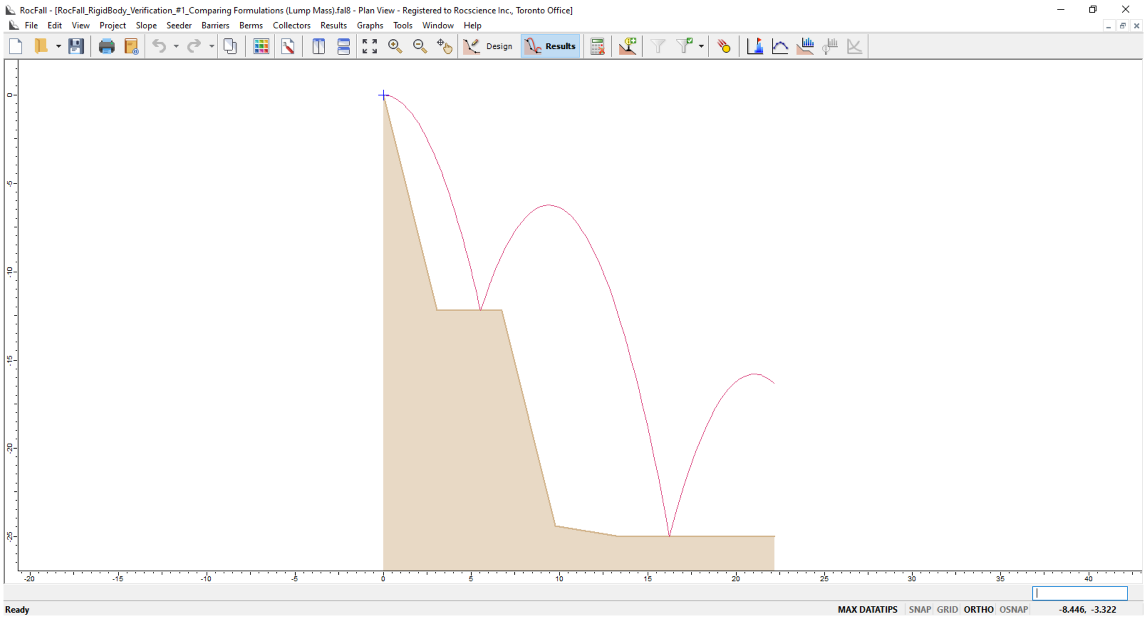

Figure 1-2: *RocFall2* Rock Trajectory Model Results (Lump Mass)

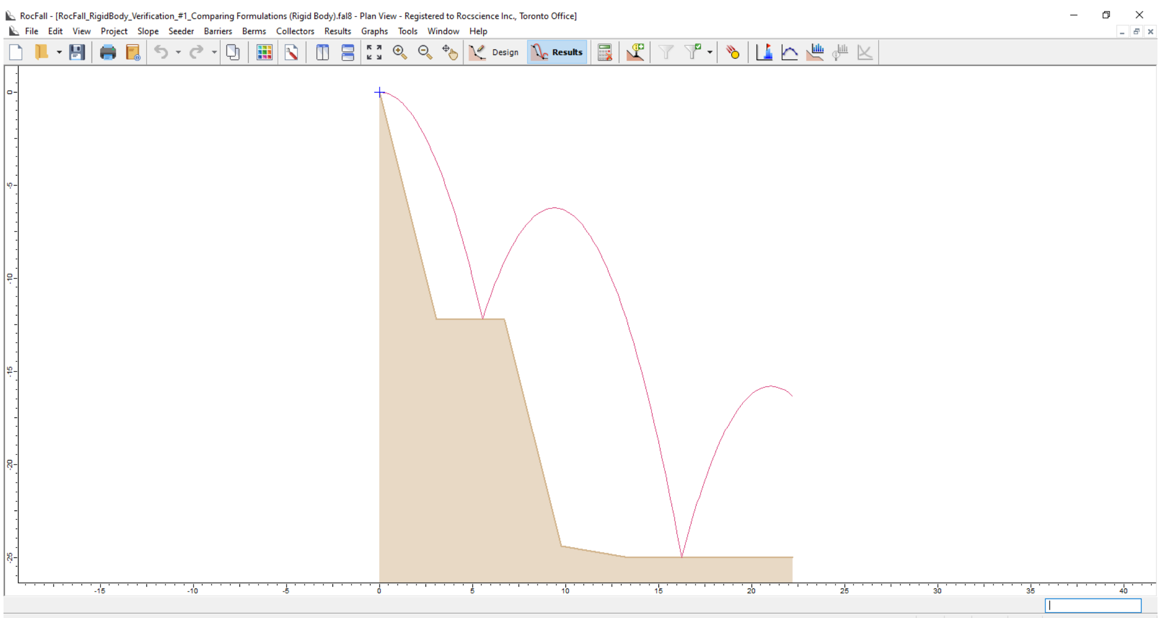

Figure 1-3: *RocFall2* Rock Trajectory Model Results (Rigid Body)

1.1.3. Results

Figure 1-4 and Figure 1-5 are the bounce height graphs, and Figure 1-6 and Figure 1-7 are the total kinetic energy graphs for the Lump Mass and Rigid Body cases.

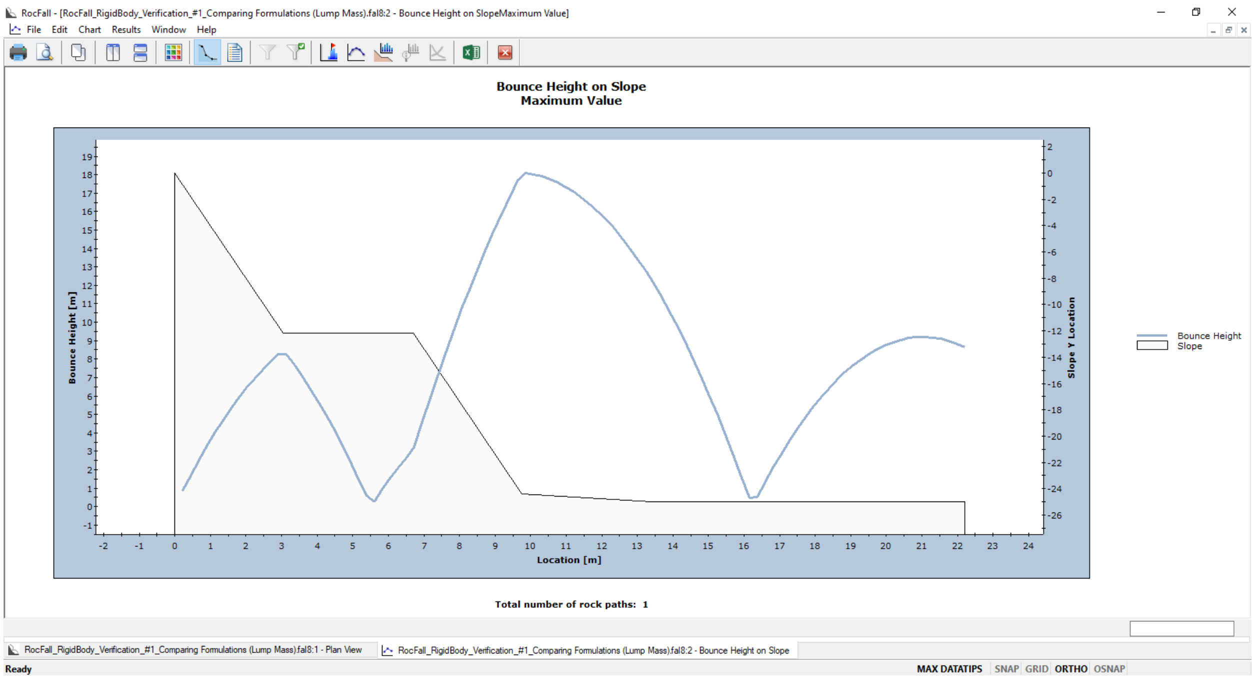

Figure 1-4: *RocFall2* Bounce Height Graph (Lump Mass)

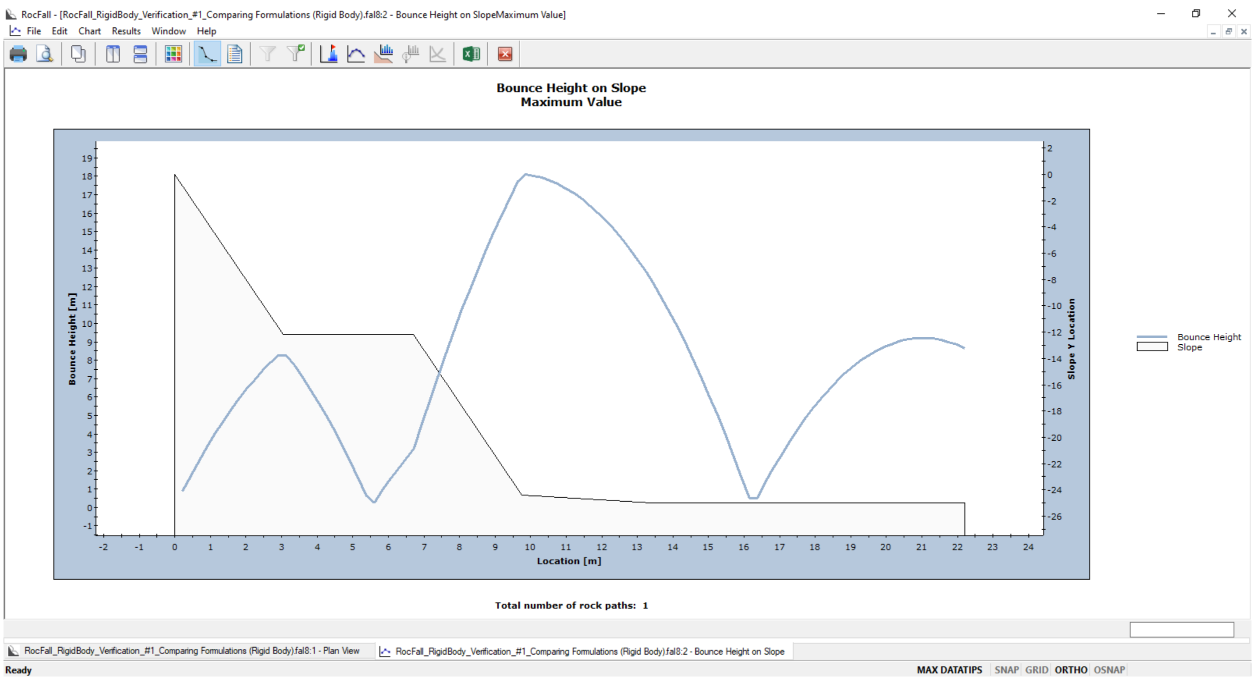

Figure 1-5: *RocFall2* Bounce Height Graph (Rigid Body)

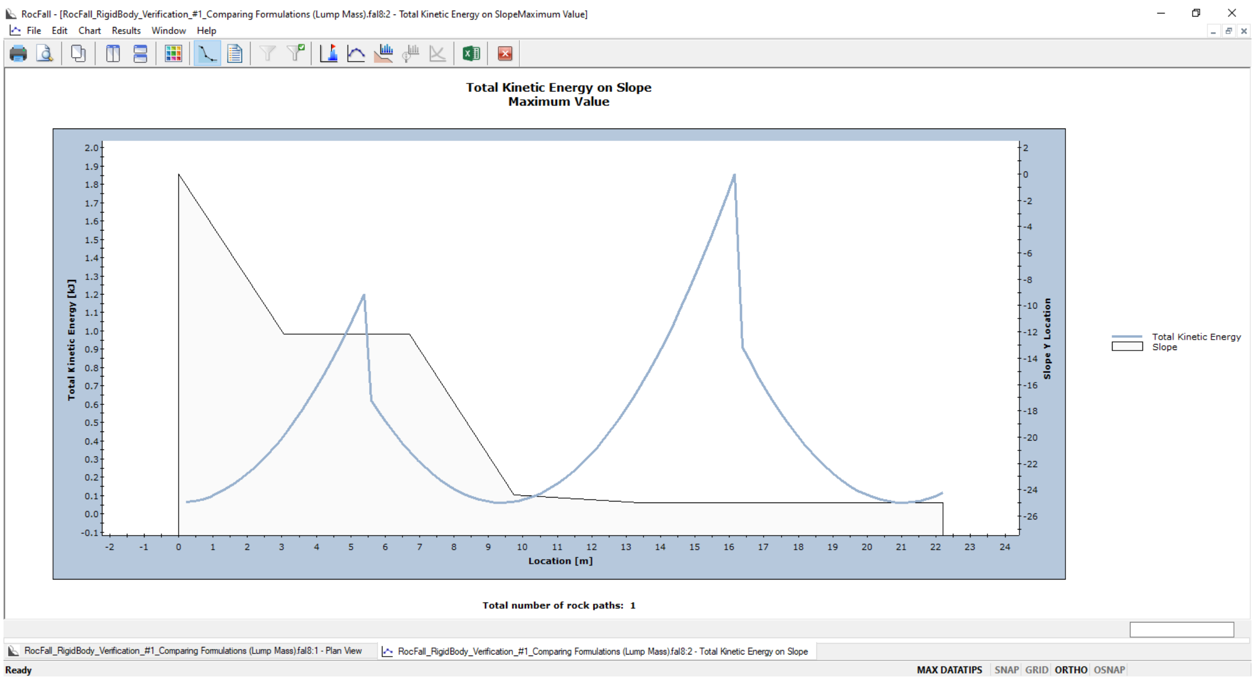

Figure 1-6: *RocFall2* Total Kinetic Energy Graph (Lump Mass)

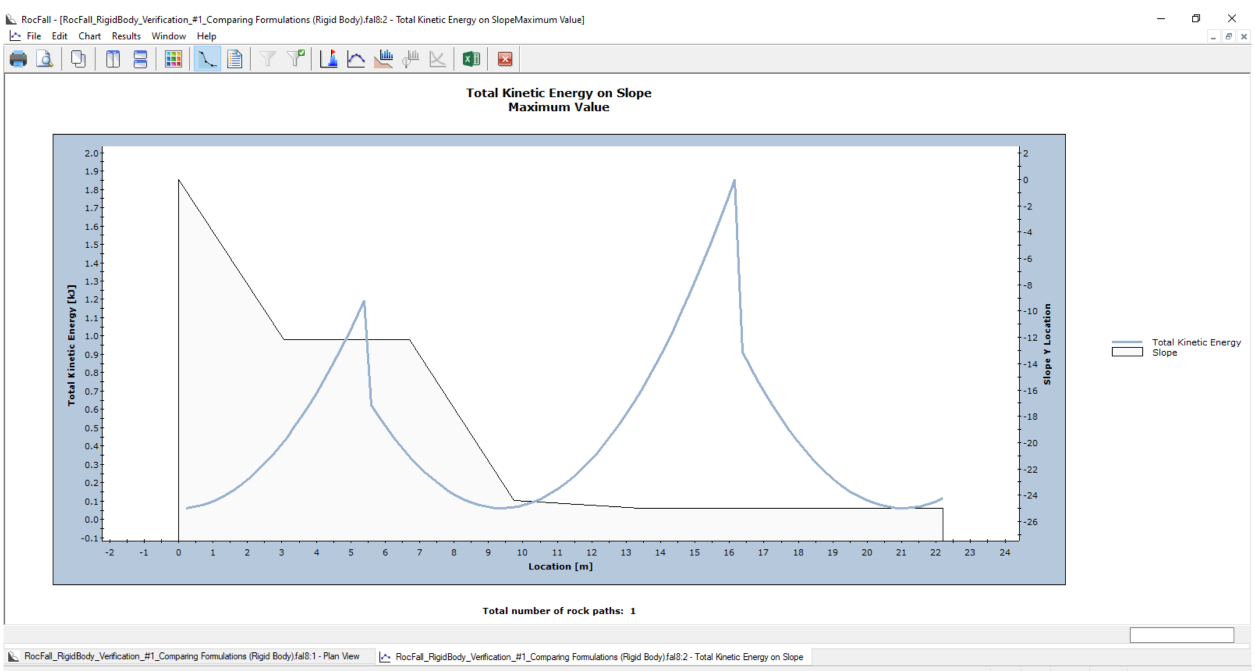

Figure 1-7: *RocFall2* Total Kinetic Energy Graph (Rigid Body)

The results using the Lump Mass formulation compare well with the Rigid Body formulation; they are almost identical.

This is one of three examples of this type (see *RocFall2* Verification Problem #2 – Comparison between Lump Mass and Rigid Body Formulations and *RocFall2* Verification Problem #3 – Comparison between Lump Mass and Rigid Body Formulations).

1.1.4. Input Files

RocFall_RigidBody_Verification_#1_Comparing Formulations (Lump Mass).fal8

RocFall_RigidBody_Verification_#1_Comparing Formulations (Rigid Body).fal8

1.2. *RocFall2* Verification Problem #2 – Comparison between Lump Mass and Rigid Body Formulations

[***RocFall2 Build 8.009***]

1.2.1. Problem Description

In this exercise, the output using Lump Mass or Rigid Body formulations are compared against each other. *RocFall2 4.0* uses the Lump Mass formulation, which assumes rocks as point masses. Since *RocFall2 5.0*, an additional engine using Rigid Body mechanics, that incorporates shape into impact calculations, has been added. In this study, a very small radius is used for a spherical rock to eliminate any shape effects when comparing results.

1.2.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and the Lump Mass and Rigid Body material parameters for all slope segments are presented in the following tables:

Table 2-1: Slope Geometry

	X-Coordinate	Y-Coordinate
Vertex 1	0	0
Vertex 2	25	0

Lump Mass

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Lump Mass model, ensure that **Consider rotational velocity** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

A friction angle of 0.1° is used in the Lump Mass model because the internal computation of rock paths is more stable with a small friction angle rather than zero friction angle.

Table 2-2: Lump Mass Slope Material Parameters

Normal Restitution R_N	Tangential Restitution R_T	Friction Angle ϕ (deg)	Slope Roughness (deg)
0.7	1	0.1	0

Rigid Body

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Rigid Body model, ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

CRSP assumes rocks bounce and roll, so frictional sliding is not accounted for.

Table 2-3: Rigid Body Slope Material Parameters

Normal Restitution R_N	Dynamic Friction	Rolling Friction
0.7	0	0

Initial Conditions

The rock starts at location X_0 = 0 m, Y_0 = 10 m. The rock was given an initial velocity of V_{X0} = 2 m/s, V_{Y0} = 0 m/s. The rock has a mass of 10 kg and density of 2.1x10^6 kg/m^3.

Enter the seeder and slope geometry values from Table 2-1 into *RocFall2* for both the Lumped Mass and Rigid Body analyses models.

The *RocFall2* model looks like this:

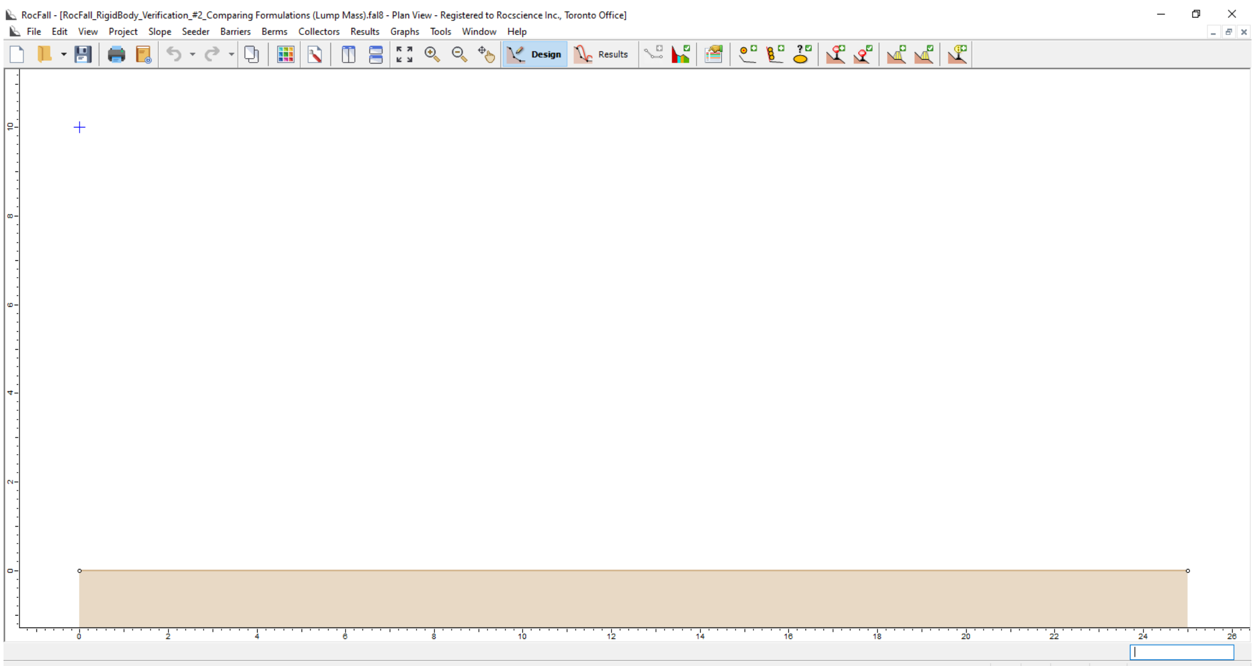

Figure 2-1: *RocFall2* Model Geometry

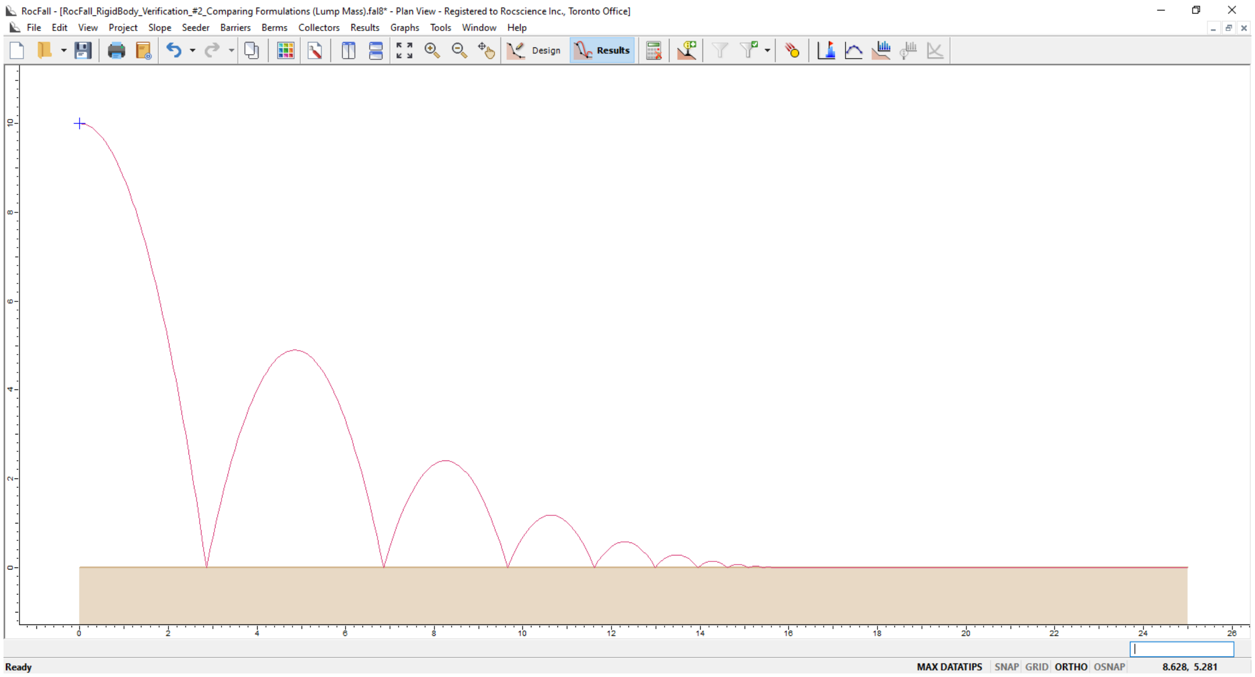

Figure 2-2: *RocFall2* Rock Trajectory Model Results (Lump Mass)

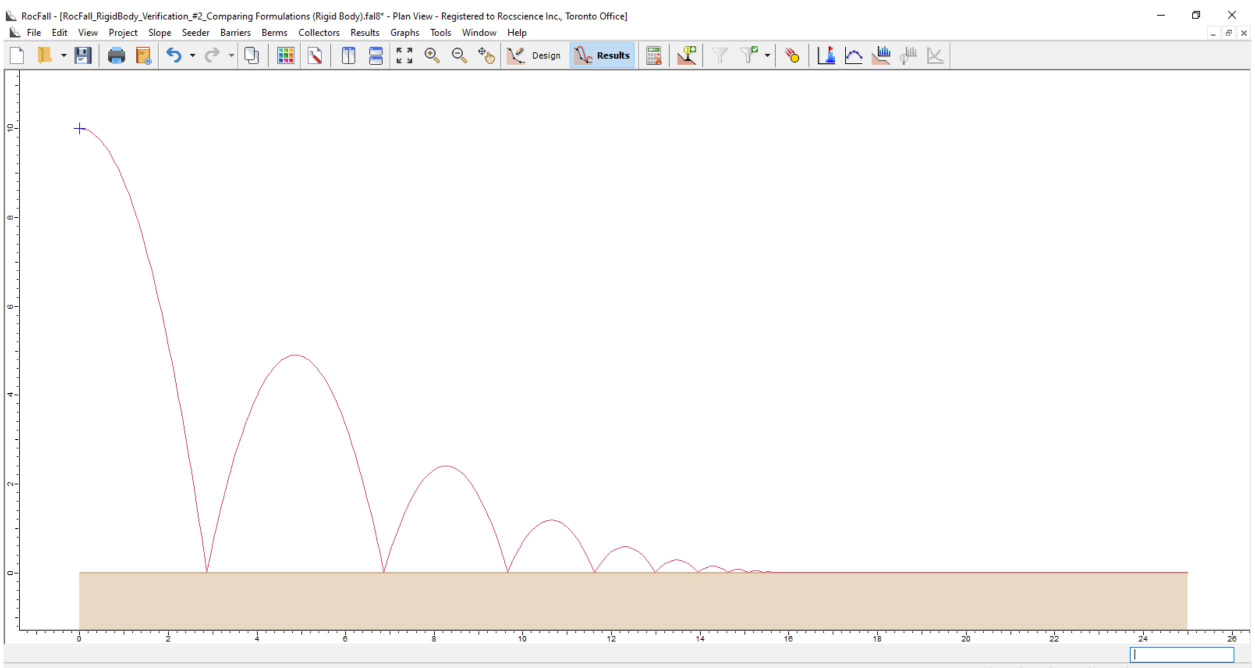

Figure 2-3: *RocFall2* Rock Trajectory Model Results (Rigid Body)

1.2.3. Results

Figure 2-4 and Figure 2-5 are the bounce height graphs, and Figure 2-6 and Figure 2-7 are the total kinetic energy graphs for the Lump Mass and Rigid Body cases.

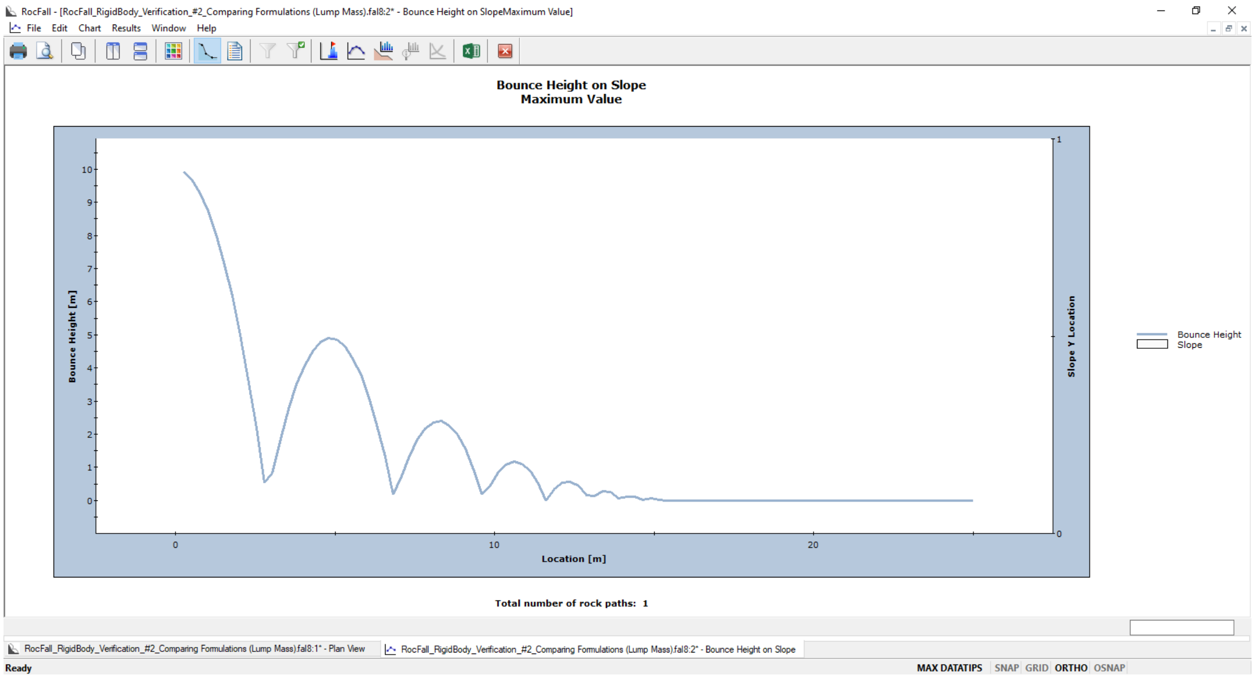

Figure 2-4: *RocFall2* Bounce Height Graph (Lump Mass)

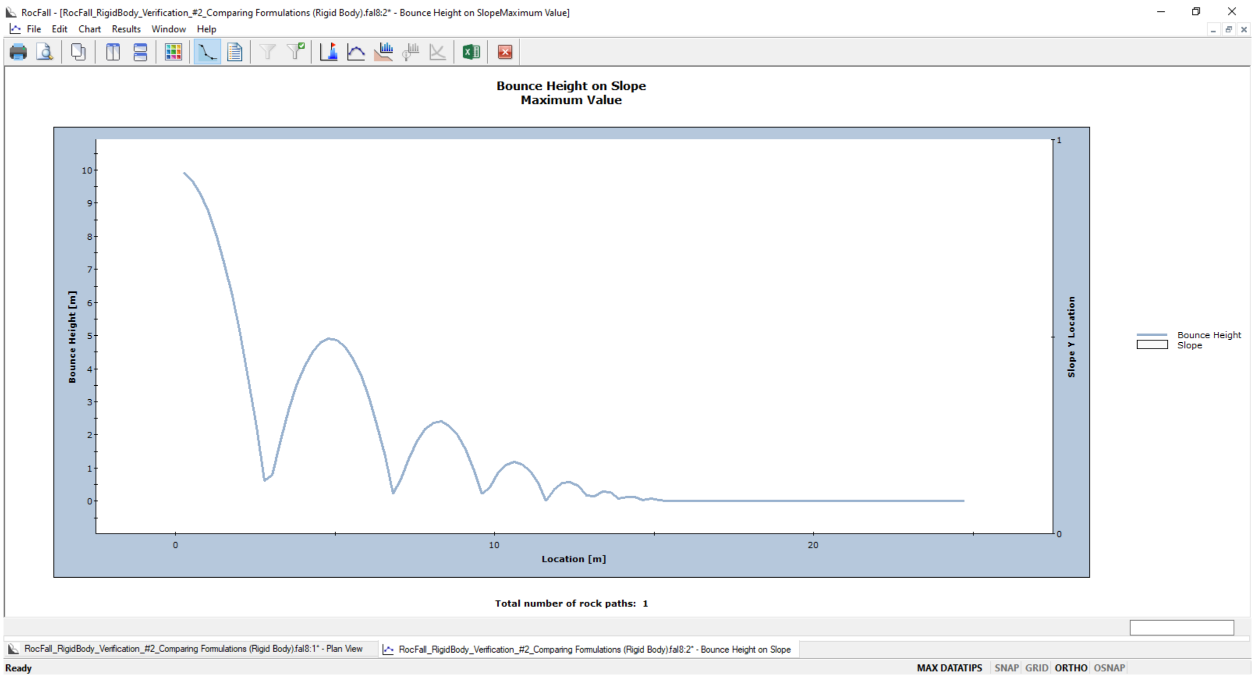

Figure 2-5: *RocFall2* Bounce Height Graph (Rigid Body)

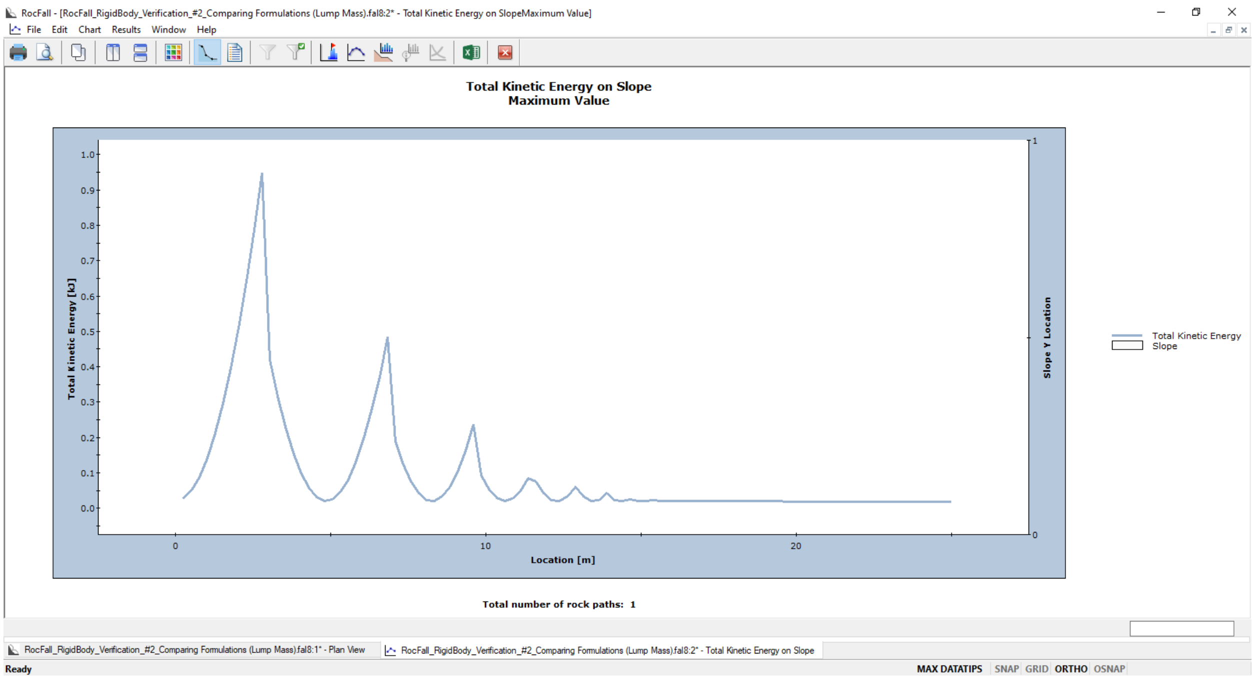

Figure 2-6: *RocFall2* Total Kinetic Energy Graph (Lump Mass)

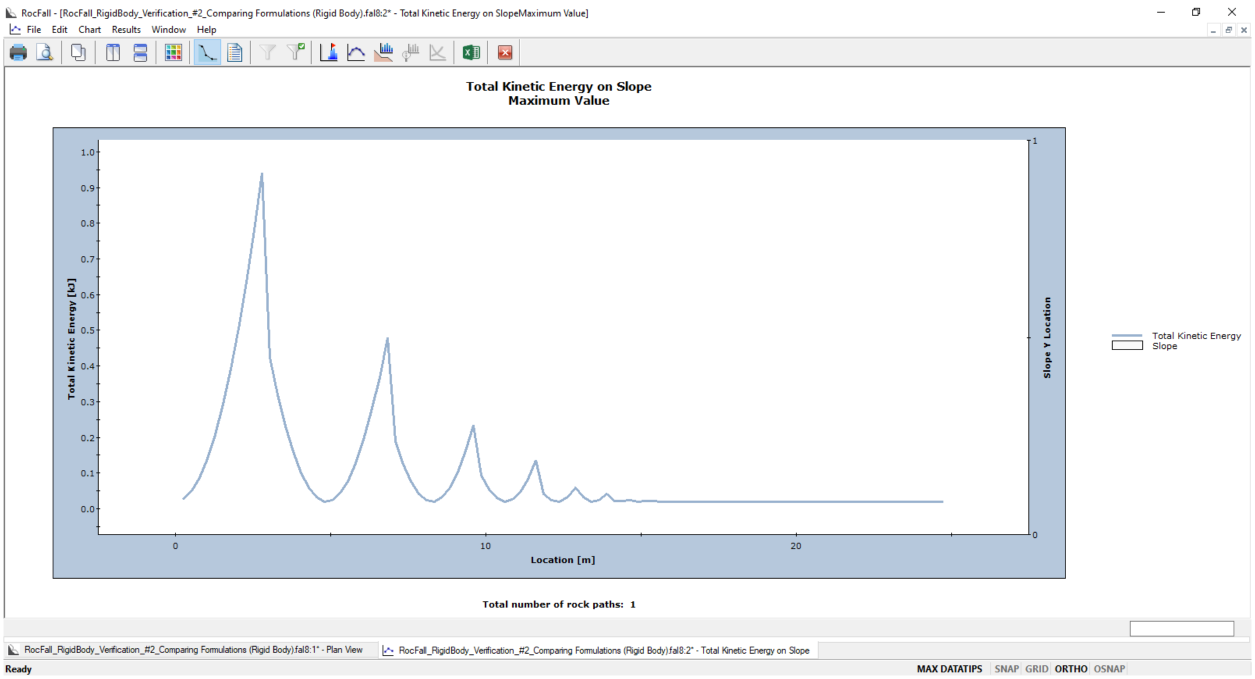

Figure 2-7: *RocFall2* Total Kinetic Energy Graph (Rigid Body)

The results using the Lump Mass formulation compare well with the Rigid Body formulation; they are almost identical.

1.2.4. Input Files

RocFall_RigidBody_Verification_#2_Comparing Formulations (Lump Mass).fal8

RocFall_RigidBody_Verification_#2_Comparing Formulations (Rigid Body).fal8

1.3. *RocFall2* Verification Problem #3 – Comparison between Lump Mass and Rigid Body Formulations

[*RocFall2 Build 8.009*]

1.3.1. Problem Description

In this exercise, the output using Lump Mass or Rigid Body formulations are compared against each other. *RocFall2 4.0* uses the Lump Mass formulation, which assumes rocks as point masses. Since *RocFall2 5.0*, an additional engine using Rigid Body mechanics, that incorporates shape into impact calculations, has been added. In this study, a very small radius is used for a spherical rock to eliminate any shape effects when comparing results.

1.3.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and the Lump Mass and Rigid Body material parameters for all slope segments are presented in the following tables:

Table 3-1: Slope Geometry

	X-Coordinate	Y-Coordinate
Vertex 1	0	0
Vertex 2	10	0
Vertex 3	20	-2.68
Vertex 4	32	-2.68

Lump Mass

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Lump Mass model, ensure that **Consider rotational velocity** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

A friction angle of 0.1° is used in the Lump Mass model because the internal computation of rock paths is more stable with a small friction angle rather than zero friction angle.

Table 3-2: Lump Mass Slope Material Parameters

Normal Restitution R_N	Tangential Restitution R_T	Friction Angle ϕ (deg)	Slope Roughness (deg)
0.7	1	0.1	0

Rigid Body

Angular velocity and coefficient of normal restitution (R_n) scaling are not considered in this analysis.

> Note: In the Rigid Body model, ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

CRSP assumes rocks bounce and roll, so frictional sliding is not accounted for.

Table 3-3: Rigid Body Slope Material Parameters

Normal Restitution R_N	Dynamic Friction	Rolling Friction
0.7	0	0

Initial Conditions

The rock starts at location X_0 = 0 m, Y_0 = 5 m. The rock was given an initial velocity of V_{X0} = 6 m/s, V_{Y0} = 0 m/s. The rock has a mass of 10 kg and density of 2.1x10^6 kg/m^3.

Enter the seeder and slope geometry values from Table 3-1 into *RocFall2* for both the Lumped Mass and Rigid Body analyses models.

The *RocFall2* model looks like this:

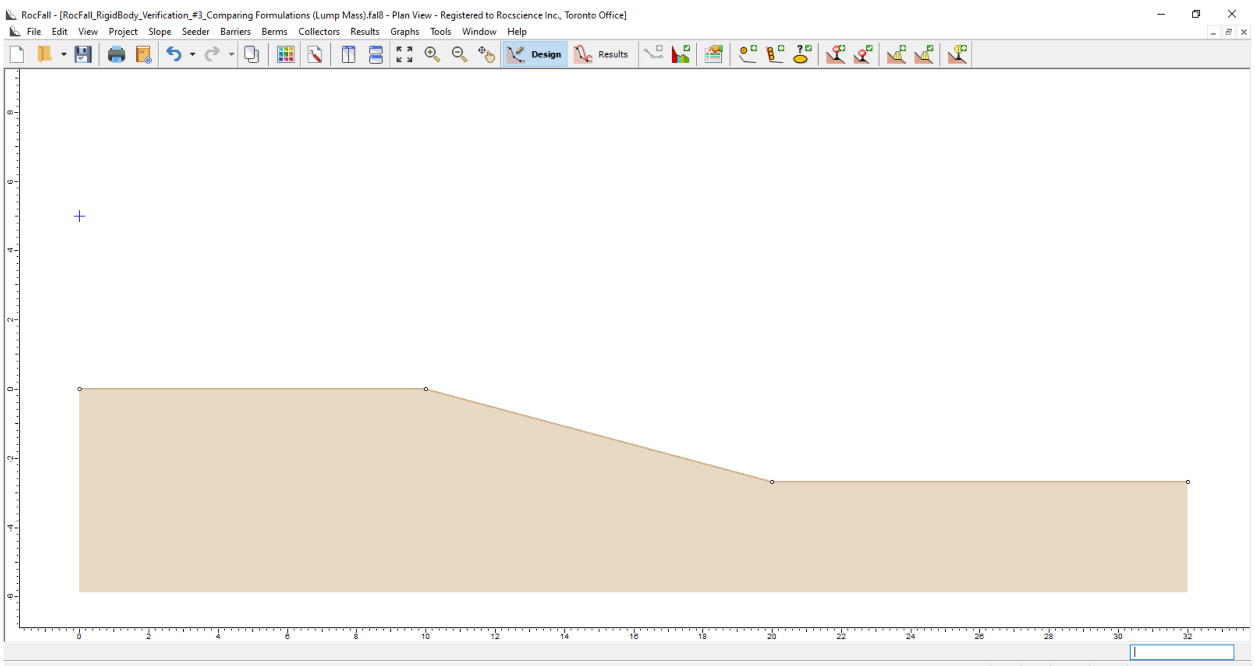

Figure 3-1: *RocFall2* Model Geometry

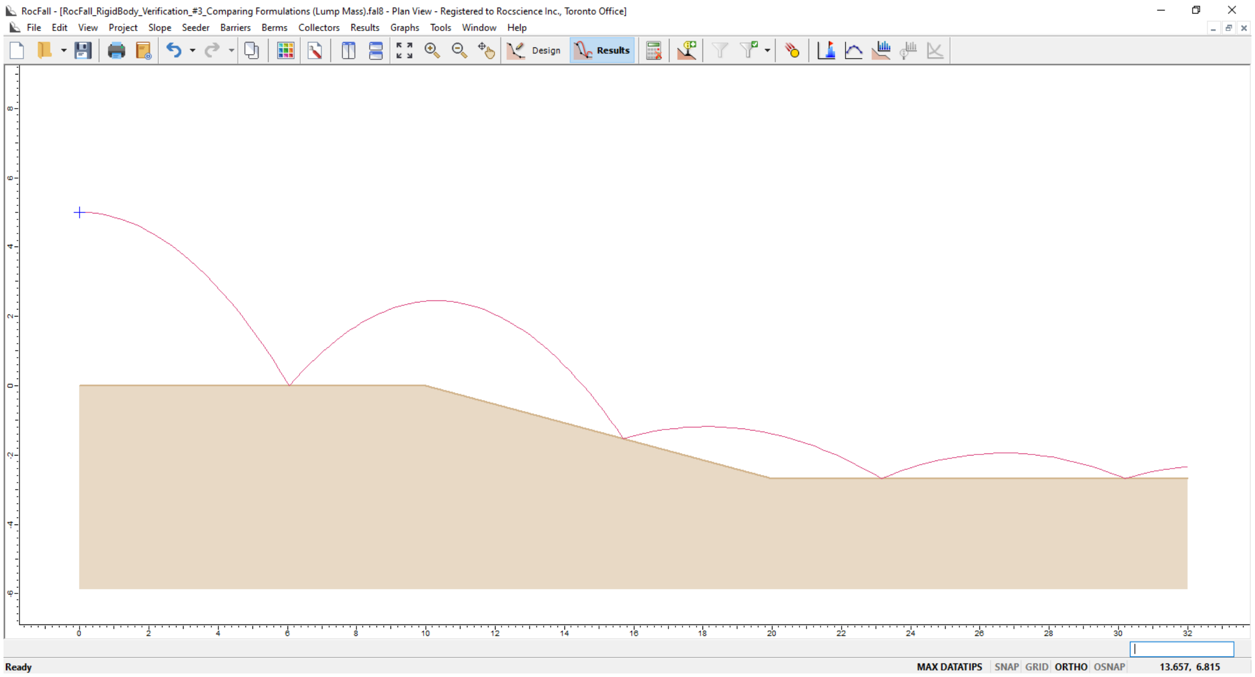

Figure 3-2: *RocFall2* Rock Trajectory Model Results (Lump Mass)

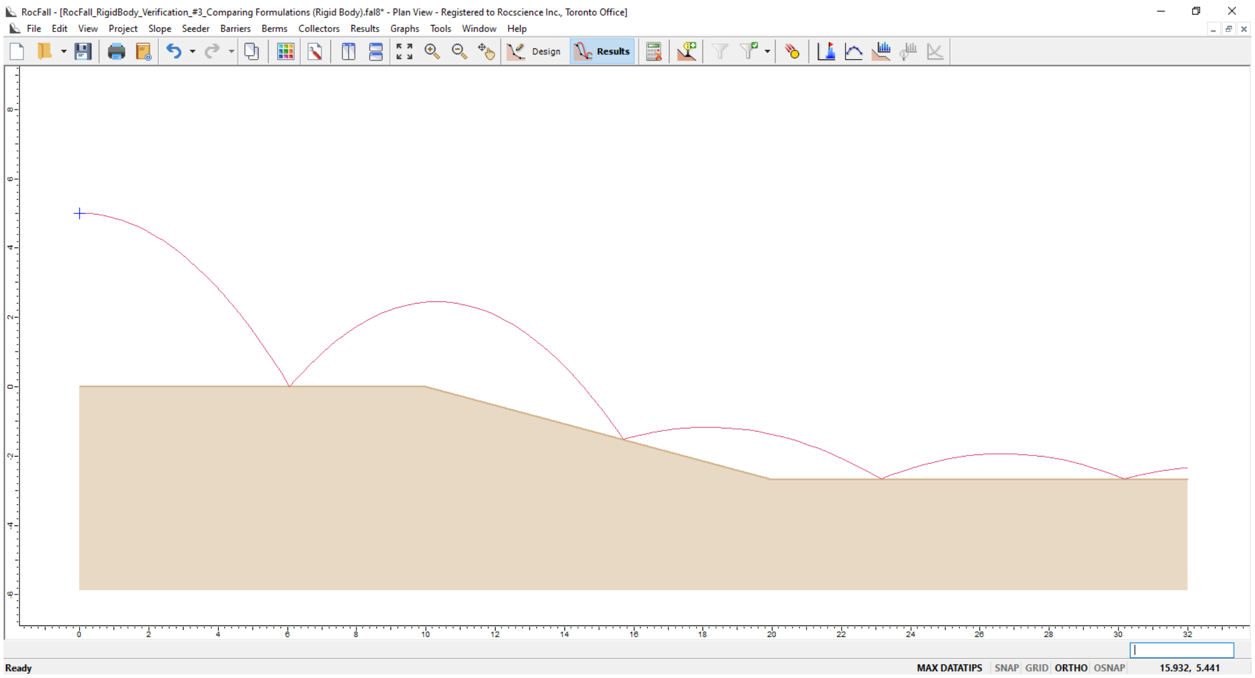

Figure 3-3: *RocFall2* Rock Trajectory Model Results (Rigid Body)

1.3.3. Results

Figure 3-4 and Figure 3-5 are the bounce height graphs, and Figure 3-6 and Figure 3-7 are the total kinetic energy graphs for the Lump Mass and Rigid Body cases.

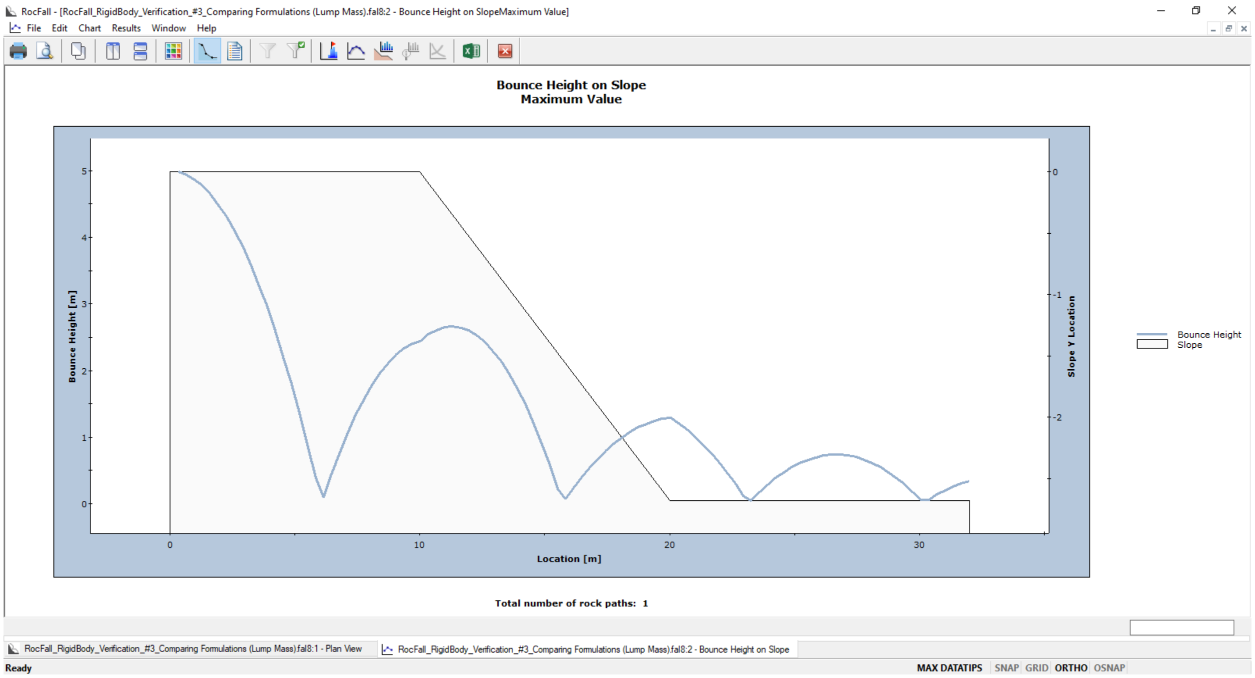

Figure 3-4: *RocFall2* Bounce Height Graph (Lump Mass)

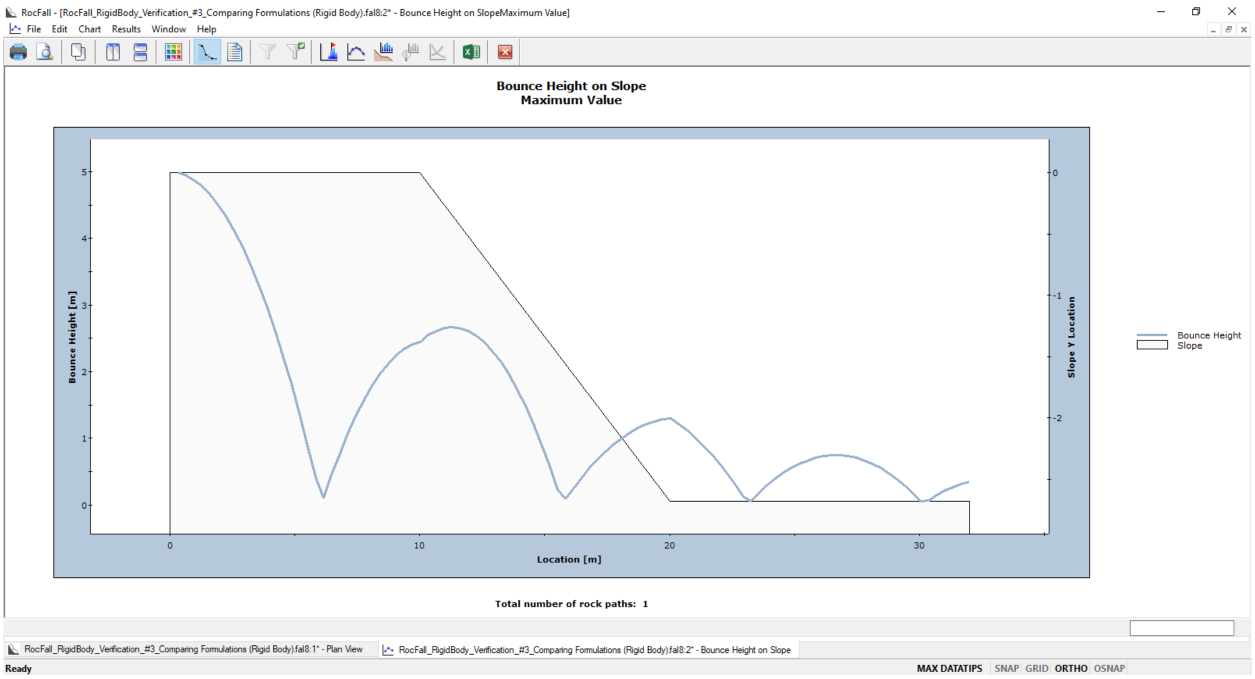

Figure 3-5: *RocFall2* Bounce Height Graph (Rigid Body)

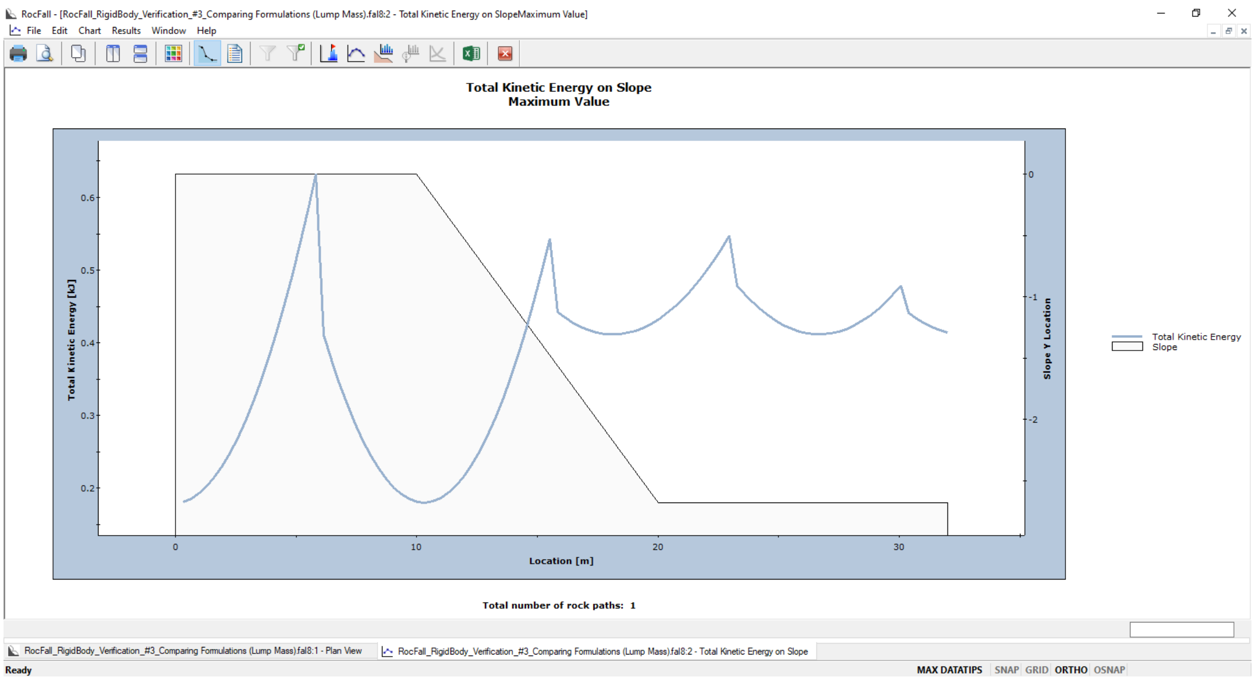

Figure 3-6: *RocFall2* Total Kinetic Energy Graph (Lump Mass)

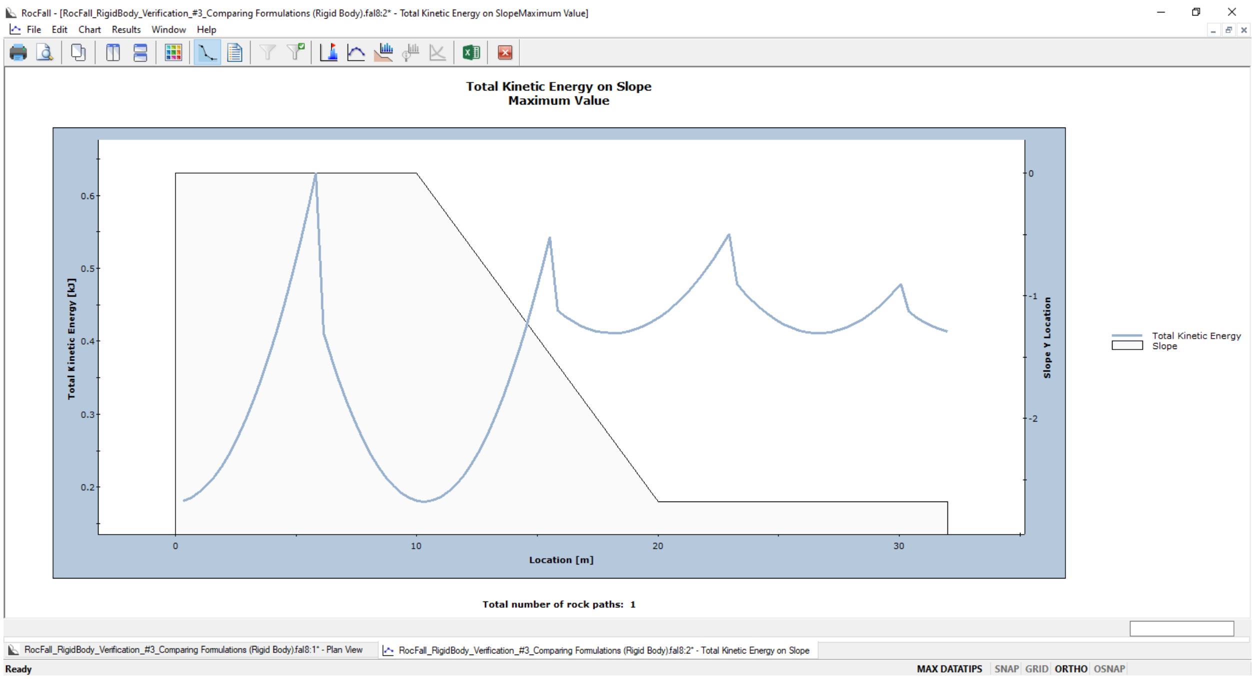

Figure 3-7: *RocFall2* Total Kinetic Energy Graph (Rigid Body)

The results using the Lump Mass formulation compare well with the Rigid Body formulation; they are almost identical.

1.3.4. Input Files

RocFall_RigidBody_Verification_#3_Comparing Formulations (Lump Mass).fal8
RocFall_RigidBody_Verification_#3_Comparing Formulations (Rigid Body).fal8

2. *RocFall2* Sliding Verification

The purpose of this verification is to confirm that the sliding and scarring mechanism used by *RocFall2* is working correctly. The sliding and scarring mechanism calculates the motion of the rocks while they are sliding on a slope. Friction contributes to majority of tangential damping in the rigid body method. Therefore, it is essential that sliding and scarring work correctly.

2.1. *RocFall2* Sliding Theory

2.1.1. Background

The scarring model is built on the theory developed by Leine et. al. [1]. It is theorized that ground can deform under contact. As the rock ploughs into the slope, softer ground materials can accumulate in front of the rock in its path; hence increasing ground friction. The coefficient of friction is dependent on the total accumulated sliding distance. The coefficient of friction is as follows:

$$\mu_d(s) = \mu_{d_{min}} + \frac{2}{\pi}\left(\mu_{d_{max}} - \mu_{d_{min}}\right)\operatorname{atan}(\kappa s)$$

Where:

$\mu_{d_{min}}$ is the minimum dynamic coefficient of friction that can be achieved

$\mu_{d_{max}}$ is the maximum dynamic coefficient of friction that can be achieved

κ is a parameter that controls the rate of increase of the coefficient of friction depending on the materials

s is the accumulated scarring distance in meters

The *RAMMS::ROCKFALL User Manual* [2] provides recommended values for these ground parameters for different terrain types. An abbreviated copy of the values is transcribed below:

Table 4-1: Recommended Ground Parameter Values [2]

Terrain Type	Min. Dynamic Friction Coeff. $\mu_{d_{min}}$	Max. Dynamic Friction Coeff. $\mu_{d_{max}}$	κ	β	Ground Drag Coeff.
Extra Soft	0.2	2.0	1	50	0.9
Soft	0.25	2.0	1.25	100	0.8
Medium Soft	0.3	2.0	1.5	125	0.7
Medium	0.35	2.0	2	150	0.6
Medium Hard	0.4	2.0	2.5	175	0.5
Hard	0.55	2.0	3	185	0.4
Extra Hard	0.8	2.0	4	200	0.3
Snow	0.1	0.35	2	150	0.7

We plot the dynamic coefficient of friction over slip distance with 3 different materials to show the effect of κ on the rate of increase.

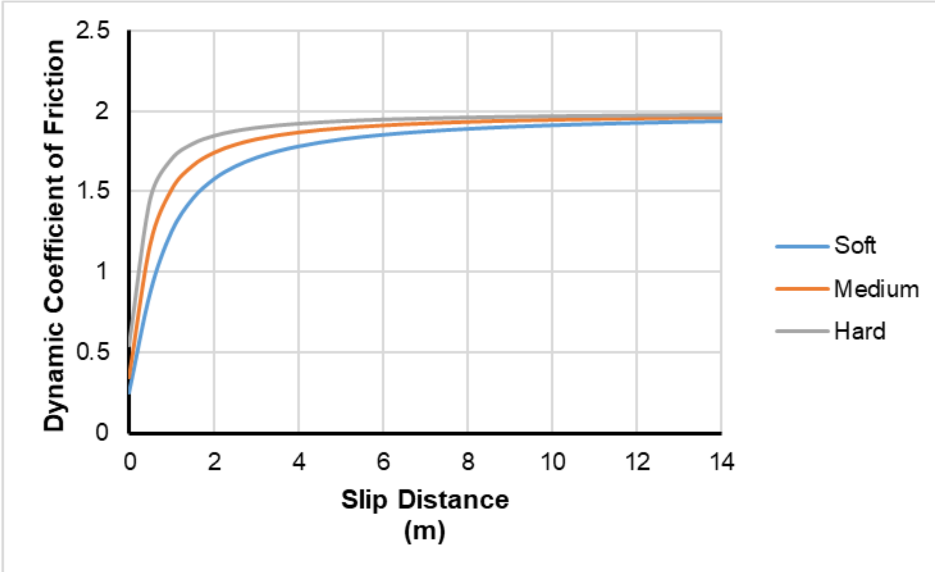

Figure 4-1: Dynamic Coefficient of Friction (μ_d) vs. Slip Distance (s)

The slip distance (s) does not reset back to 0 m immediately after the rock takes off from the ground. The effect of increased dynamic coefficient of friction is not immediately removed. It decreases at a rate of $-\beta$ over time. This can be expressed as:

$$\frac{\mathrm{d}s}{\mathrm{d}t} = -\beta s$$

Solving the ordinary differential equation gives:

$$s = s_0 e^{-\beta t}$$

Where:

s_0 is the accumulated slip distance as the rock takes off from the ground

The slip distance decreases exponentially with time and the rate of decrease is controlled by the parameter β. We plot the drop in slip distance against time with 3 different materials. An accumulated initial slip distance of 100 m is assumed to generate the plot. The initial accumulated slip distance of 100 m was chosen to exaggerate the effect of β for presentation. The slip distance does not necessarily reflect typical distances that are used in rockfall analyses.

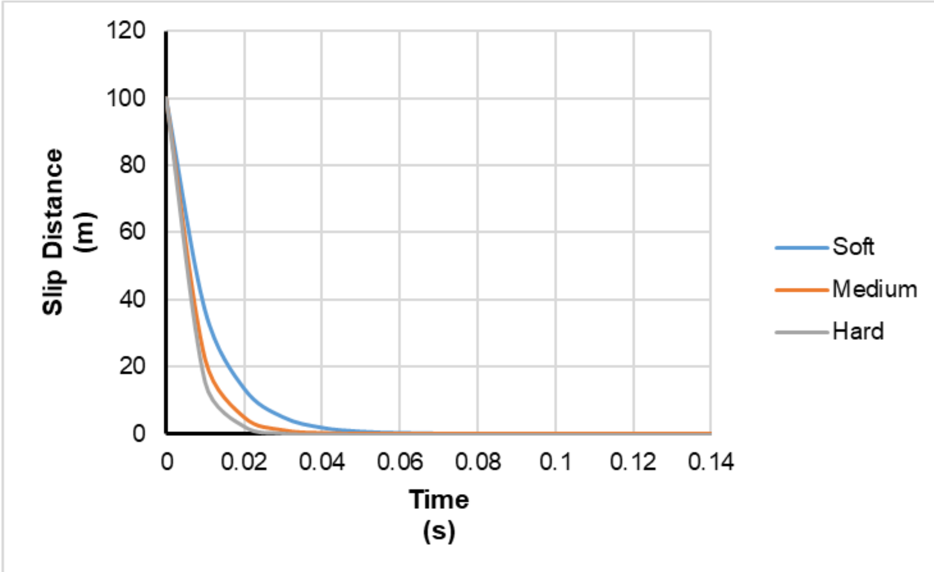

Figure 4-2: Slip Distance Decay Over Time

The viscoplastic ground drag is also based on the theory developed by *RAMMS::ROCKFALL* [2]. It is to account for any possible energy dissipation from "the viscoplastic deformation that occurs in soils under rock impact" [2]. It is only applied when the rock is in contact with the slope. The drag force (F_v) is:

$$\bar{F_v} = -\frac{m}{2} C_v \bar{v}$$

Where:

C_v is the drag coefficient ranging between 0.0/m and 1.0/m

$\bar{v}$ is the translational velocity vector consisting of v_x and v_y

Recommended C_v values dependent on terrain types are listed in Table 4-1. $\bar{F_v}$ can be expanded into:

$$F_{vx} = -\frac{m}{2} C_v v_x$$

$$F_{vy} = -\frac{m}{2} C_v v_y$$

2.2. *RocFall2* Verification Problem #1 – Sliding on Hard Terrain

[*RocFall2 Build 8.009*]

2.2.1. Problem Description

A model is created to observe the effect of scarring as the rock traverses on the ground. This verification problem examines pure sliding on flat ground without the effect of scarring nor viscoplastic ground drag. "Hard terrain" with μ_d = 0.55 is used. This is to serve as the baseline, to confirm that sliding is working properly.

To verify the scarring algorithm, we are comparing the trajectory profile to that modeled using *RAMMS::ROCKFALL*, and also hand calculations.

2.2.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and material parameters for all slope segments are presented in the following tables:

Table 5-1: Slope Geometry and Material Properties

	X-Coordinate	Y-Coordinate	Normal Restitution	Dynamic Friction	Rolling Friction
Vertex 1	11	0			
Segment 1			0	0.55	0
Vertex 2	31	0			

Initial Conditions

The rock starts at location X_0 = 12 m, Y_0 = 0.25 m. The rock was given an initial velocity of V_{X0} = 5 m/s, V_{Y0} = 0 m/s and a mass of 337.5 kg (0.5 m cube with 2700 kg/m^3 density).

There is only one slope segment in the model.

Create a custom polygon using as below:

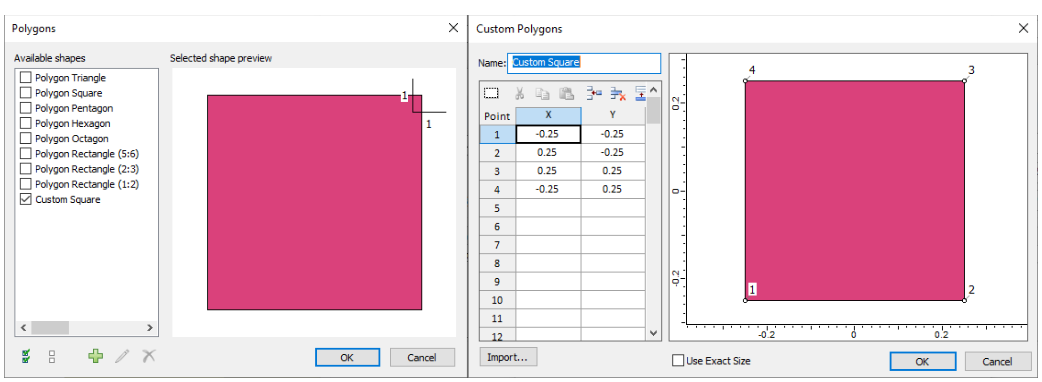

Figure 5-1: *RocFall2* Rock Shape

Enter the seeder and slope geometry values from Table 5-1 into *RocFall2*.

> Note: Ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

The *RocFall2* model looks like this:

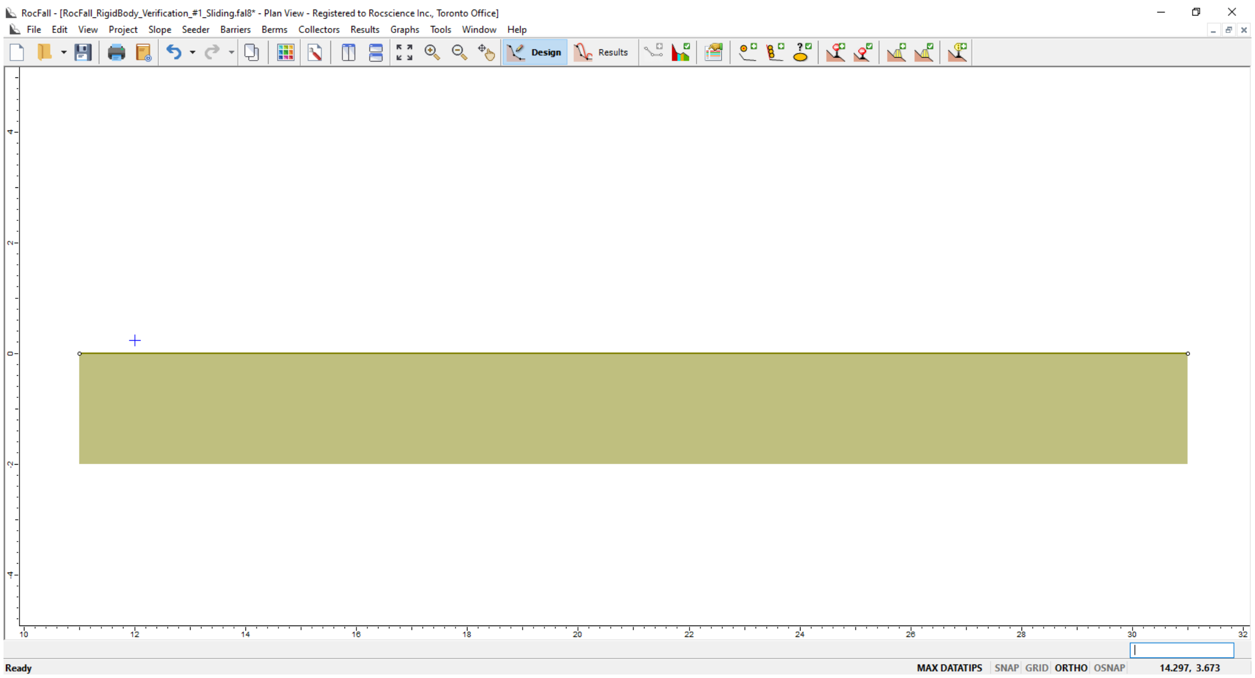

Figure 5-2: *RocFall2* Model Geometry

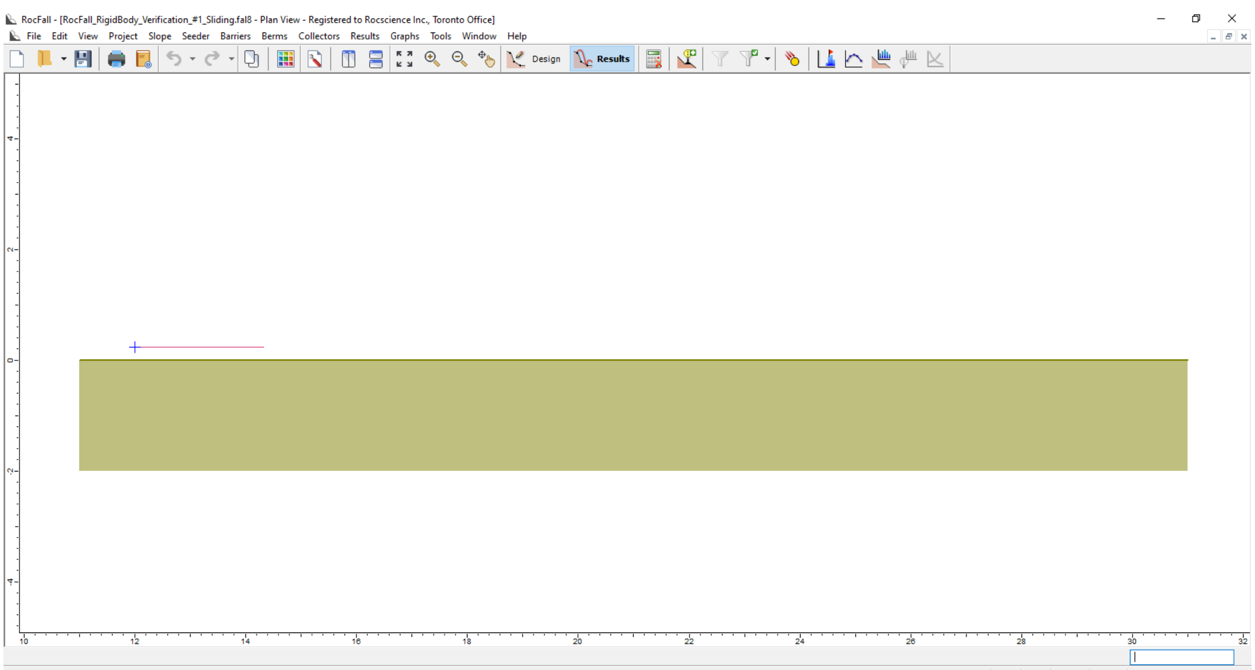

Figure 5-3: *RocFall2* Rock Trajectory Model Results

2.2.3. Analytical Solution

The friction force is computed as:

$$F_f = \mu_d N = \mu_d mg = (0.55)(337.5\ \text{kg})\left(9.81\,\frac{\text{m}}{\text{s}^2}\right) = 1821\ \text{N}$$

The acceleration (i.e., deceleration due to friction of sliding) is computed as:

$$a = -\frac{F_f}{m} = -\frac{1821\ \text{N}}{337.5\ \text{kg}} = -5.396\,\frac{\text{m}}{\text{s}^2}$$

The time for sliding to stop (i.e., V_{x_0} to reach 0 m/s) is computed as:

$$t = \frac{\Delta V_x}{a} = \frac{0\,\frac{\text{m}}{\text{s}} - 5\,\frac{\text{m}}{\text{s}}}{-5.396\,\frac{\text{m}}{\text{s}^2}} = 0.9266\ \text{s}$$

The distance travelled is computed as:

$$\Delta x = V_{x_0}t + \frac{1}{2}at^2 = \left(5\,\frac{\text{m}}{\text{s}}\right)(0.9266\ \text{s}) + \frac{1}{2}\left(-5.396\,\frac{\text{m}}{\text{s}^2}\right)(0.9266\ \text{s})^2 = 2.317\ \text{m}$$

Where:

F_f	is the frictional force
μ_d	is the dynamic coefficient of friction
N	is the normal force
m	is the mass of the rock
g	is acceleration due to gravity
a	is acceleration in the direction of sliding
V_x	is horizontal velocity
t	is time

2.2.4. Results

Output from *RocFall2*:

The rock slid 2.326 m before coming to a stop (see Figure 5-3) in 0.9263 sec.

Output from *RAMMS*:

The rock slid 2.317 m before coming to a stop in 0.93 sec.

Hand Calculations:

The rock slid 2.317 m before coming to a stop in 0.9266 sec.

The 3 sets of results are very similar. Error between *RocFall2* to that of hand calculation is only 0.39% in total sliding distances and 0.032% in total sliding time.

$$\frac{|2.326\ \text{m} - 2.317\ \text{m}|}{2.317\ \text{m}} = 0.0039$$

$$\frac{|0.9263\ \text{s} - 0.9266\ \text{s}|}{0.9266\ \text{s}} = 0.00032$$

The differences are very minor, much less than the confidence level with the material properties. They may have arisen from contact point determinations and difference in analysis method. *RocFall2* simulates the sliding behavior while constantly checking for potential impacts. Physically the behavior approximates that of pure sliding. Mathematically the model is not that smooth. Also, *RocFall2* models all events with a single contact point. The resulting behavior may be more discrete rather than continuous than that of the common physics sliding model. Keeping the differences in assumptions in mind, *RocFall2* simulates sliding behavior properly.

2.2.5. Input Files

RocFall_RigidBody_Verification_#1_Sliding.fal8

2.3. RocFall2 Verification Problem #2 – Sliding on Soft Terrain with Scarring

[***RocFall2 Build 8.009***]

2.3.1. Problem Description

A model is created to observe the effect of scarring as the rock traverses on the ground. This verification problem examines sliding with scarring enabled on a 30° slope with default settings for "soft terrain".

To verify the scarring algorithm, we are comparing the trajectory profile to that modeled using *RAMMS::ROCKFALL*, and also hand calculations.

2.3.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and material parameters for all slope segments are presented in the following tables:

Table 6-1: Slope Geometry and Material Properties

	X	Y	Normal Restitution	Advanced Friction				Rolling Friction
				Dynamic Friction	Max. Dynamic Friction	β	κ	
Vertex 1	3	5.7735						
Segment 1			0	0.25	2	100	1.25	0
Vertex 2	5	5.7735						
Segment 2			0	0.25	2	100	1.25	0
Vertex 3	15	0						
Segment 3			0	0.25	2	100	1.25	0
Vertex 4	20	0						

These **Advanced Friction Parameters** are the default recommended scarring parameters for "Soft" terrain in *RocFall2*.

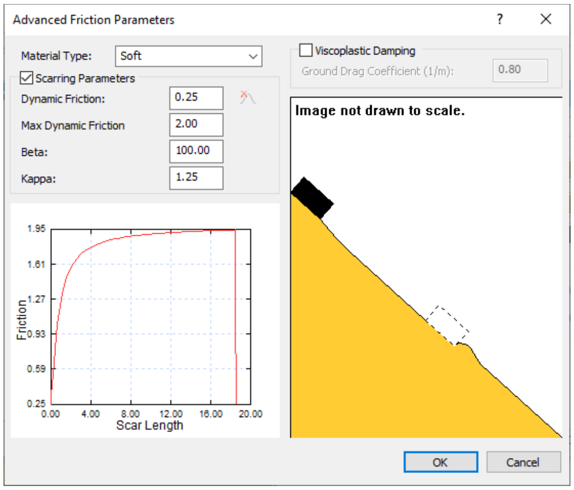

Figure 6-1: *RocFall2* Advanced Friction Parameters

Initial Conditions

The rock starts at location X_0 = 5.25 m, Y_0 = 6.0235 m. The rock was given an initial velocity of V_{X0} = 0 m/s, V_{Y0} = 0 m/s and a mass of 337.5 kg (0.5 m cube with 2700 kg/m^3 density). We are using the same cubic rock from *RocFall2* Verification Problem #1 – Sliding.

Enter the seeder and slope geometry values from Table 6-1 into *RocFall2*.

> Note: Ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

The *RocFall2* model looks like this:

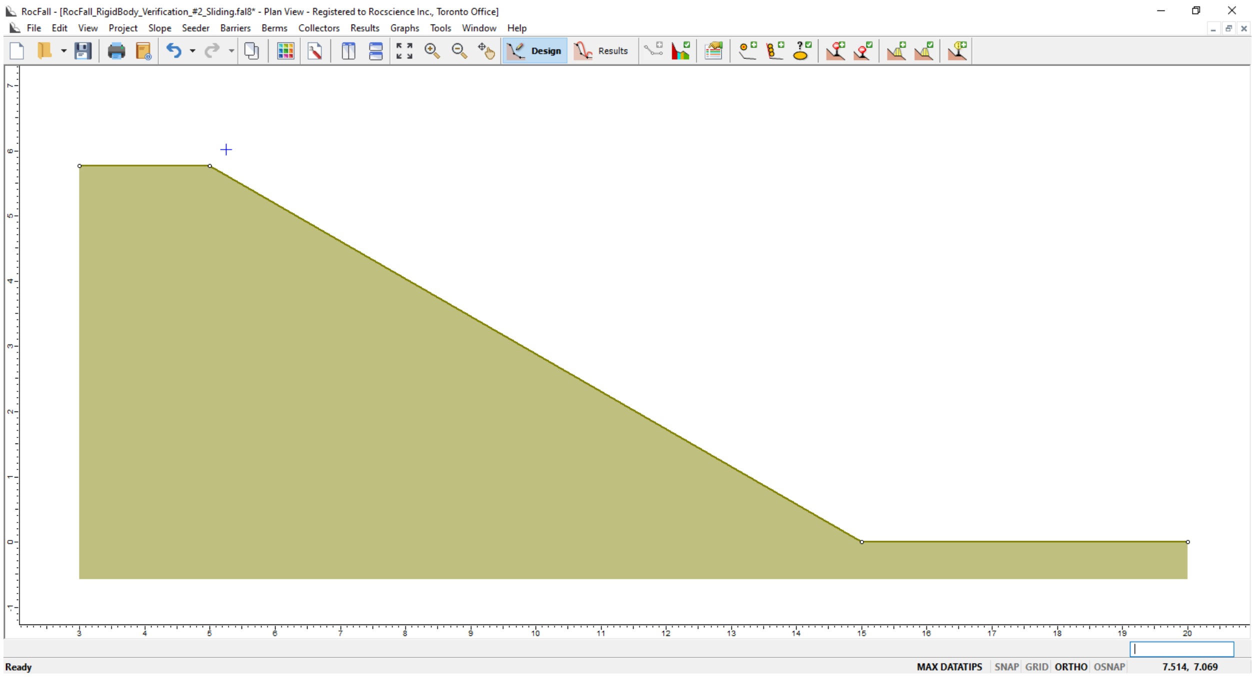

Figure 6-2: *RocFall2* Model Geometry

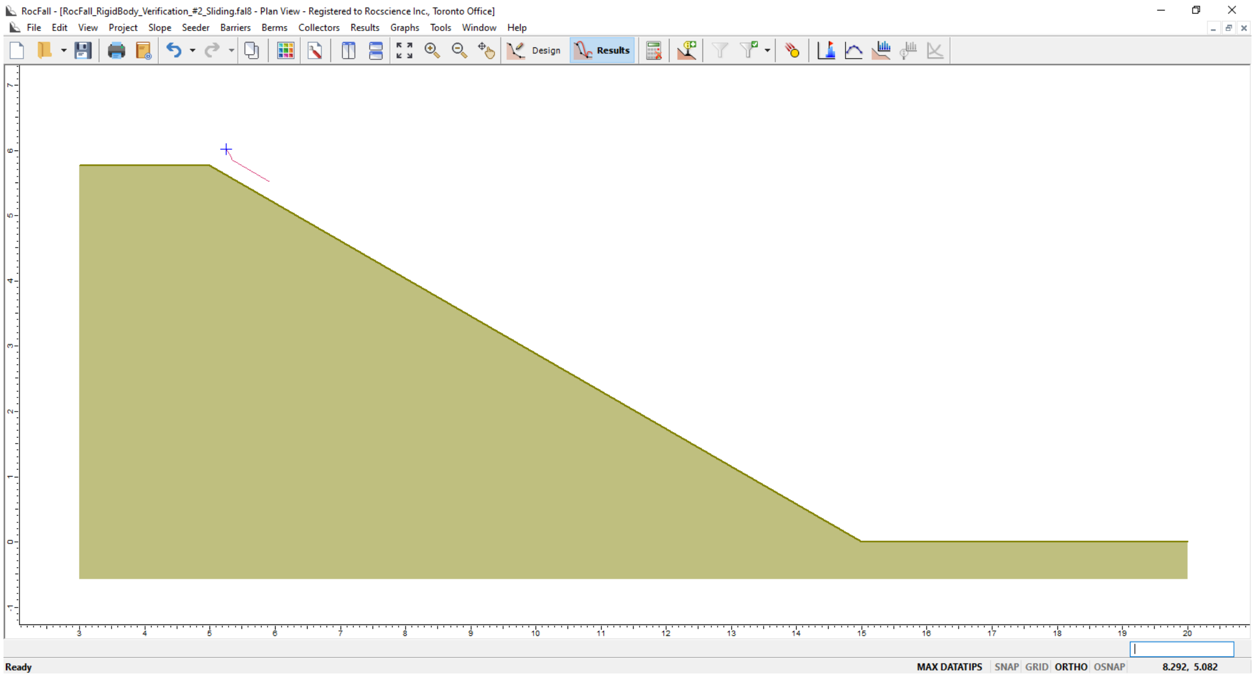

Figure 6-3: *RocFall2* Rock Trajectory Model Results

2.3.3. Analytical Solution

After the initial short drop, the rocks from *RocFall2* and *RAMMS* started sliding at roughly the same point. *RAMMS*' block started sliding at (5.3550, 5.8525) and *RocFall2*'s started sliding at (5.3473, 5.8503). The difference is only 0.00801 m, which is negligible. For the purpose of the verification, we will only calculate the sliding trajectory. We will take the after-impact velocities and sliding start coordinates from *RocFall2* at time of 0.2645 s for the hand calculations.

Table 6-2: Rock Locations and Velocities at Start of Sliding

Analysis	Sliding Start Point (m, m)	Initial Sliding Velocity (m/s)	Initial Tangential Velocity (m/s)
RocFall2	(5.3473, 5.8503)	(0.8377, -0.5647)	1.0103
RAMMS	(5.355, 5.8525	(0.848, -0.489)	0.9789
Hand Calculation	(5.3473, 5.8503)	(0.8377, -0.5647)	1.0103

The hand calculations are done using the timestepping method. A timestep size of 0.01 s is selected. We will show the calculation of the first and second steps here. The steps were repeated in a spreadsheet until the tangential velocity reached 0 m/s, meaning the rock stopped.

The normal force is computed as follows (337.5 kg block on a 30° slope):

$$N = mg\cos 30 = (337.5\text{ kg})\left(9.81\frac{\text{m}}{\text{s}^2}\right) = 2867.302\text{ N}$$

The tangential acceleration from gravity is computed as:

$$a_g = \frac{N}{m}\sin 30 = \frac{mg}{m}\sin 30 = g\sin 30 = \left(9.81\frac{\text{m}}{\text{s}^2}\right)\sin 30 = 4.905\frac{\text{m}}{\text{s}^2}$$

Where:

m is mass of the rock

g is acceleration due to gravity

Step 1:

$t = 0$ s to $t = 0.01$ s

$V_0 = 1.0103\frac{\text{m}}{\text{s}}$

Accumulated slip distance, $s = 0$ m

The dynamic coefficient of friction is computed as:

$$\mu_d = \mu_{d_{min}} + \frac{2}{\pi}\left(\mu_{d_{max}} - \mu_{d_{min}}\right)\operatorname{atan}(\kappa s) = 0.25 + \frac{2}{\pi}(2 - 0.25)\operatorname{atan}[(1.25)(0)] = 0.25$$

The friction force is computed as:

$$F_f = \mu_d N = 0.25(2867.302\text{ N}) = 716.826\text{ N}$$

The frictional acceleration is computed as:

$$a_f = -\frac{F_f}{m} = -\frac{716.826\text{ N}}{337.5\text{ kg}} = -2.124\frac{\text{m}^2}{\text{s}}$$

At the end of the time step, the velocity is computed as:

$$V = V_0 + \left(a_g + a_f\right)\Delta t = 1.0103\frac{\text{m}}{\text{s}} + \left(4.905\frac{\text{m}}{\text{s}^2} - 2.124\frac{m^2}{s}\right)(0.01\text{ s}) = 1.0381\frac{\text{m}}{\text{s}}$$

The distance travelled is computed as:

$$\Delta d = V_0\Delta t + \frac{1}{2}\left(a_g + a_f\right)(\Delta t)^2 = \left(1.0103\frac{\text{m}}{\text{s}}\right)(0.01\text{ s}) + \left(4.905\frac{\text{m}}{\text{s}^2} - 2.124\frac{m^2}{s}\right)(0.01\text{ s})^2 = 0.0104\text{ m}$$

Step 2:

$t = 0.01$ s to $t = 0.02$ s

$V_0 = 1.0381\frac{\text{m}}{\text{s}}$

The total accumulated slip distance is now:

$$s = 0.0104\text{ m}$$

The dynamic coefficient of friction is computed as:

$$\mu_d = \mu_{d_{min}} + \frac{2}{\pi}\left(\mu_{d_{max}} - \mu_{d_{min}}\right)\operatorname{atan}(\kappa s) = 0.25 + \frac{2}{\pi}(2 - 0.25)\operatorname{atan}[(1.25)(0.0104)] = 0.2645$$

The friction force is computed as:

$$F_f = \mu_d N = 0.2645(2867.302 \text{ N}) = 758.275 \text{ N}$$

The frictional acceleration is computed as:

$$a_f = -\frac{F_f}{m} = -\frac{758.275 \text{ N}}{337.5 \text{ kg}} = -2.247 \frac{\text{m}^2}{\text{s}}$$

At the end of the time step, the velocity is computed as:

$$V = V_0 + (a_g + a_f)\Delta t = 1.0381 \frac{\text{m}}{\text{s}} + \left(4.905 \frac{\text{m}}{\text{s}^2} - 2.247 \frac{\text{m}^2}{\text{s}}\right)(0.01 \text{ s}) = 1.0647 \frac{\text{m}}{\text{s}}$$

The distance travelled is computed as:

$$\Delta d = V_0 \Delta t + \frac{1}{2}(a_g + a_f)(\Delta t)^2 = \left(1.0381 \frac{\text{m}}{\text{s}}\right)(0.01 \text{ s}) + \left(4.905 \frac{\text{m}}{\text{s}^2} - 2.247 \frac{\text{m}^2}{\text{s}}\right)(0.01 \text{ s})^2 = 0.0106 \text{ m}$$

The total accumulated slip distance is now:

$$s = 0.0104 \text{ m} + 0.0106 \text{ m} = 0.021 \text{ m}$$

We keep repeating the steps until tangential velocity reaches 0 m/s. In the first 2 steps, frictional force was not enough to slow down the rock. As the slip distance accumulates, eventually the rock slows down and stops eventually.

Table 6-3: Timestep Calculations

Time	V_0 (m/s)	Δd (m)	s (m)	μ_d	F_f (N)	a_f (m/s²)	V
0	1.010	0.000	0.000	0.250	716.825	-2.124	1.038
0.01	1.038	0.010	0.010	0.264	758.275	-2.247	1.065
0.02	1.065	0.011	0.021	0.279	800.772	-2.373	1.090
0.03	1.090	0.011	0.032	0.294	844.248	-2.501	1.114
0.04	1.114	0.011	0.043	0.310	888.634	-2.633	1.137
0.05	1.137	0.011	0.054	0.326	933.857	-2.767	1.158
0.06	1.158	0.012	0.066	0.342	979.841	-2.903	1.178
0.07	1.178	0.012	0.078	0.358	1026.507	-3.042	1.197
0.08	1.197	0.012	0.090	0.374	1073.777	-3.182	1.214
0.09	1.214	0.012	0.102	0.391	1121.567	-3.323	1.230
0.1	1.230	0.012	0.114	0.408	1169.795	-3.466	1.244
0.11	1.244	0.012	0.127	0.425	1218.376	-3.610	1.257
0.12	1.257	0.013	0.139	0.442	1267.226	-3.755	1.269
0.13	1.269	0.013	0.152	0.459	1316.261	-3.900	1.279
0.14	1.279	0.013	0.165	0.476	1365.397	-4.046	1.287
0.15	1.287	0.013	0.178	0.493	1414.551	-4.191	1.294
0.16	1.294	0.013	0.191	0.510	1463.641	-4.337	1.300
0.17	1.300	0.013	0.204	0.528	1512.587	-4.482	1.304
0.18	1.304	0.013	0.217	0.545	1561.313	-4.626	1.307
0.19	1.307	0.013	0.230	0.561	1609.742	-4.770	1.309
0.2	1.309	0.013	0.243	0.578	1657.803	-4.912	1.308
0.21	1.308	0.013	0.256	0.595	1705.426	-5.053	1.307
0.22	1.307	0.013	0.269	0.611	1752.547	-5.193	1.304
0.23	1.304	0.013	0.282	0.627	1799.103	-5.331	1.300

0.24	1.300	0.013	0.295	0.643	1845.036	-5.467	1.294
0.25	1.294	0.013	0.308	0.659	1890.292	-5.601	1.287
0.26	1.287	0.013	0.321	0.675	1934.820	-5.733	1.279
0.27	1.279	0.013	0.334	0.690	1978.574	-5.862	1.269
0.28	1.269	0.013	0.346	0.705	2021.513	-5.990	1.259
0.29	1.259	0.013	0.359	0.720	2063.597	-6.114	1.246
…	…	…	…	…	…	…	…
0.66	0.230	0.002	0.658	1.017	2916.643	-8.642	0.193
0.67	0.193	0.002	0.660	1.019	2921.232	-8.656	0.156
0.68	0.156	0.002	0.662	1.020	2924.921	-8.666	0.118
0.69	0.118	0.001	0.663	1.021	2927.713	-8.675	0.080
0.7	0.080	0.001	0.664	1.022	2929.611	-8.680	0.042
0.71	0.042	0.000	0.664	1.022	2930.614	-8.683	0.005
0.72	0.005	0.000	0.664	1.022	2930.724	-8.684	-0.033

The rock slid to full stop at time = $0.2645\ \mathrm{s} + 0.7211\ \mathrm{s} = 0.99\ \mathrm{s}$

Total sliding distance = $0.6643\ \mathrm{m}$

End coordinate = $(5.3473 + 0.6643\cos 30\,,\ 5.8503 - 0.6643\sin 30) = (5.923, 5.518)$

2.3.4. Results

Output from *RocFall2*:

The rock slid to full stop at (5.921, 5.519) (see Figure 6-3).

Output from *RAMMS*:

The rock slid to full stop at (5.848, 5.5685).

Hand Calculations:

The rock slid to full stop at (5.923, 5.518).

The three sets of results are very similar. The results and error range are listed below in Table 6-4.

Table 6-4: Summary of Sliding with Scarring Results

Analysis	End Point (m, m)	Total Sliding Distance (m)	% Difference Total Sliding Distance vs. *RocFall2*
RocFall2	(5.921, 5.519)	0.6625	-
RAMMS	(5.848, 5.569)	0.5690	14.1%
Hand Calculation	(5.923, 5.518)	0.6643	1.9%

The differences between *RocFall2* and that from hand calculations are minor, less than the confidence level with the material properties. They may have arisen from contact point determinations and difference in analysis method (discussed in detail in *RocFall2* Verification Problem #1 – Sliding). The difference between *RocFall2* and *RAMMS* is larger. Aside from the two reasons above, *RAMMS*' initial sliding speed at the start of sliding was also 5% slower. We venture a guess that the block in *RAMMS* lost slightly more energy during the impacts from the initial drop. In a perfect world, the rocks would be sliding perfectly on the slope without the short drop. However, due to technical difficulties the drop is required to maintain the same starting rock conditions. Keeping the differences in assumptions in mind, *RocFall2* performs well and simulates sliding with scarring behavior properly. Its sliding distance is between that of *RAMMS* and hand calculations.

2.3.5. Input Files

RocFall_RigidBody_Verification_#2_Sliding.fal8

2.4. *RocFall2* Verification Problem #3 – Sliding on Soft Terrain with Scarring and Viscoplastic Ground Drag

[*RocFall2 Build 8.009*]

2.4.1. Problem Description

A model is created to observe the effect of scarring as the rock traverses on the ground. This verification problem examines sliding with both scarring and viscoplastic ground drag enabled on a 20° with default settings for “soft terrain”.

To verify the scarring algorithm, we are comparing the trajectory profile to that modeled using *RAMMS::ROCKFALL*, and also hand calculations.

2.4.2. *RocFall2* Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and material parameters for all slope segments are presented in the following tables:

Table 7-1: Slope Geometry and Material Properties

	X	Y	Normal Restitution	Advanced Friction					Rolling Friction
				Dynamic Friction	Max. Dynamic Friction	β	κ	Ground Drag	
Vertex 1	3	3.6397							
Segment 1			0	0.25	2	100	1.25	0.8	0
Vertex 2	5	3.6397							
Segment 2			0	0.25	2	100	1.25	0.8	0
Vertex 3	15	0							
Segment 3			0	0.25	2	100	1.25	0.8	0
Vertex 4	20	0							

These **Advanced Friction Parameters** are the default recommended scarring parameters for “Soft” terrain in *RocFall2*.

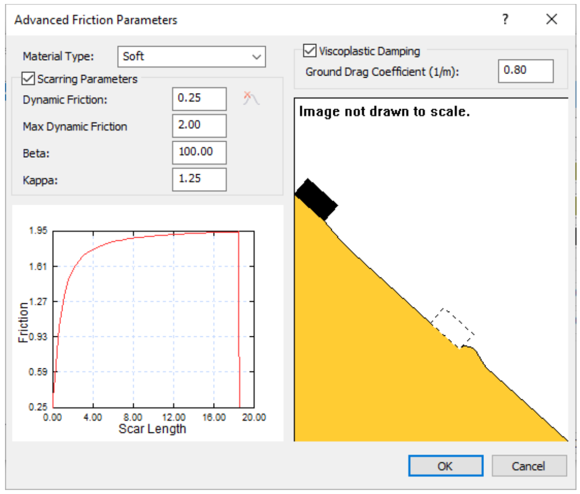

Figure 7-1: *RocFall2* Advanced Friction Parameters

Initial Conditions

The rock starts at location X_0 = 5.25 m, Y_0 = 3.8897 m. The rock was given an initial velocity of V_{X0} = 5 m/s, V_{Y0} = 0 m/s and a mass of 337.5 kg (0.5 m cube with 2700 kg/m^3 density). We are using the same cubic rock from *RocFall2* Verification Problem #1 – Sliding.

Enter the seeder and slope geometry values from Table 7-1 into *RocFall2*.

Note: Ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

The *RocFall2* model looks like this:

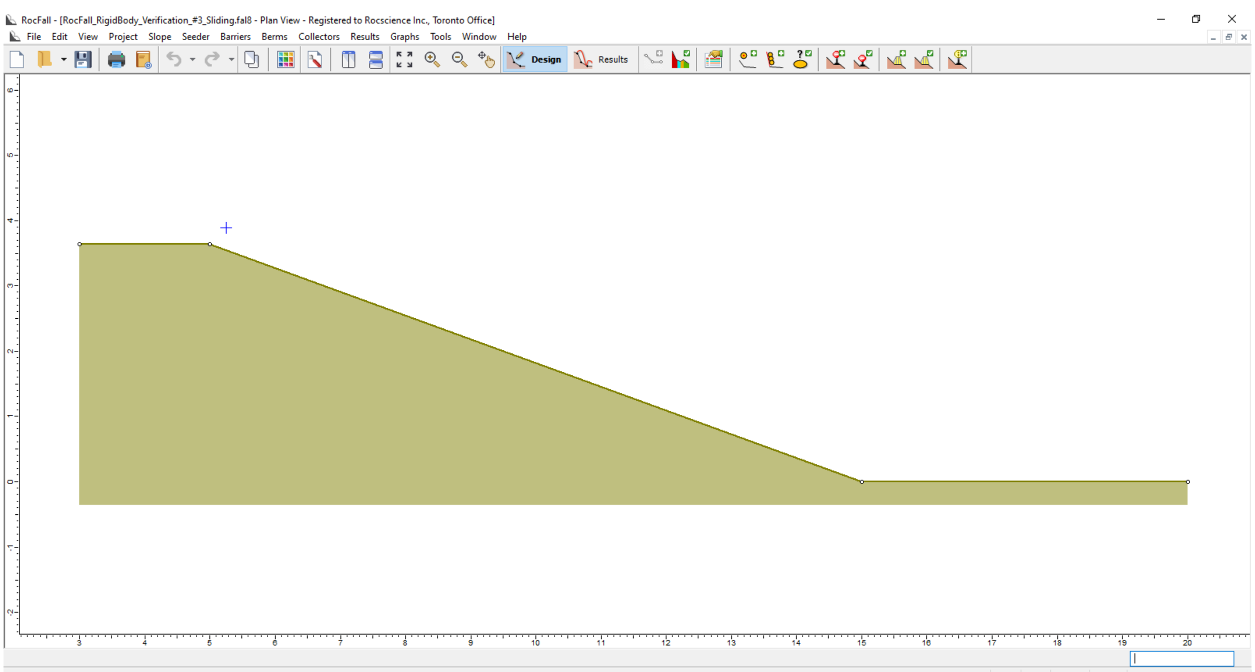

Figure 7-2: *RocFall2* Model Geometry

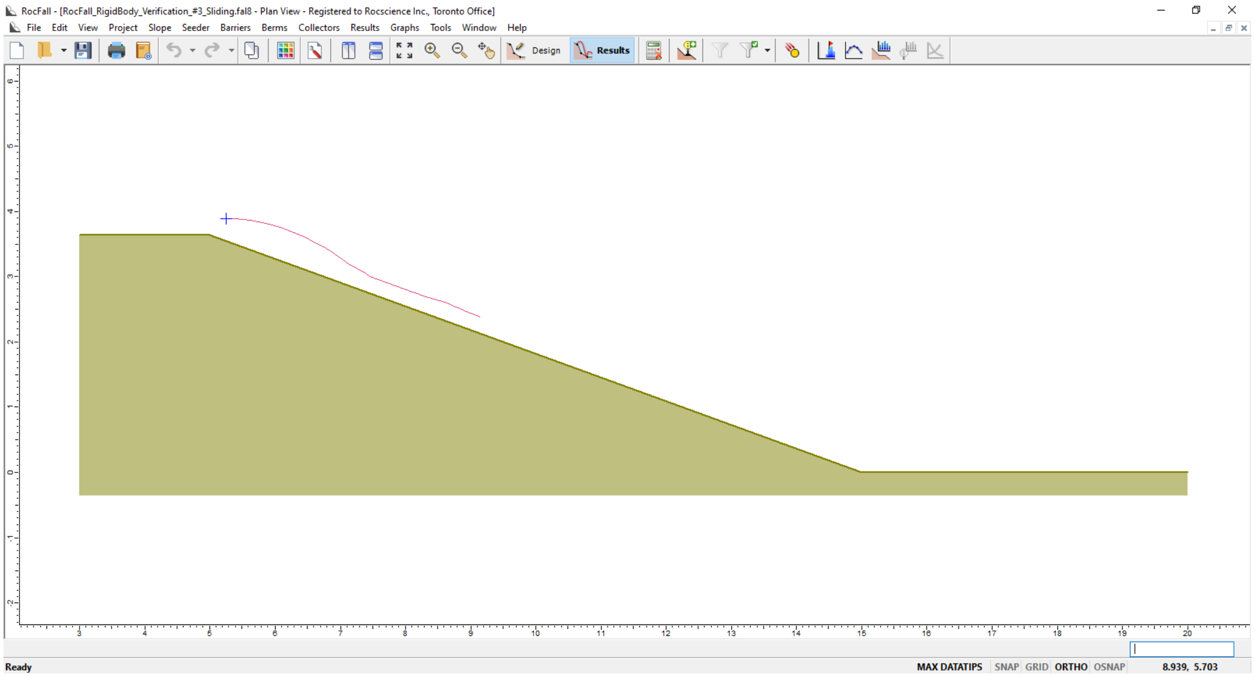

Figure 7-3: *RocFall2* Rock Trajectory Model Results

2.4.3. Building a Compatible RAMMS Model

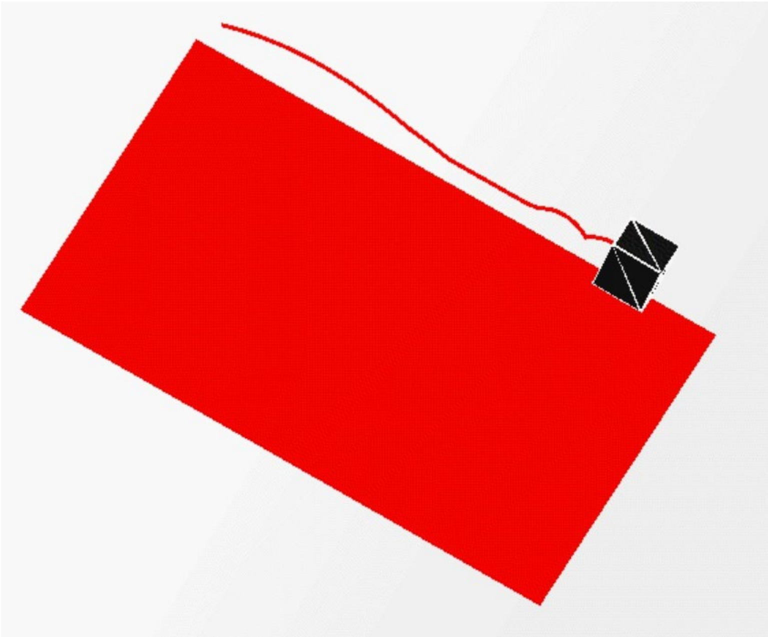

Figure 7-4: *RAMMS* Rock Trajectory Model Results

2.4.4. Results

Output from *RocFall2*:

The rock slid to full stop at (9.151, 2.385) (see Figure 7-3).

Output from *RAMMS*:

The rock slid to full stop at (9.214, 2.3967) (see Figure 7-4).

The two sets of results are very similar. The results and error range are listed below in Table 7-2.

Table 7-2: Summary of Sliding with Scarring Results

Analysis	End Point (m, m)	Total Sliding Distance (m)	% Difference Total Sliding Distance vs. *RocFall2*
RocFall2	(9.151, 2.385)	1.8097	-
RAMMS	(9.214,2.3967)	1.8906	4.47%

The differences are very minor, much less than the confidence level with the material properties. They may have arisen from contact point determinations and difference in analysis method. *RocFall2* is event-based and *RAMMS::Rockfall* employs a timestepping mechanism. Also, we cannot determine if *RAMMS* uses the same contact point determination method as *RocFall2*. Different contact points can have significant effects on the rock behavior. Keeping the differences in assumptions in mind, *RocFall2* performs well and simulates sliding with scarring and viscoplastic ground drag properly.

2.4.5. Input Files

RocFall_RigidBody_Verification_#3_Sliding.fal8

2.5. References

Leine, R., Schweizer, A., Christen, M., Glover, J., Bartelt, P. & Gerber, W. (2013). Simulation of rockfall trajectories with consideration of rock shape. *Multibody System Dynamics*, 1-31.

Bartelt, P., Bieler, C., Buhler, Y., Christen, M., Dreier, L., Gerber, W., Glover, J. & Schneider, M. (2016). *RAMMS::ROCKFALL User Manual*. http://ramms.slf.ch/ramms/downloads/RAMMS_ROCK_Manual.pdf.

3. *RocFall2* Forest Damping Verification

The purpose of this verification is to confirm that the forest damping algorithm used by the program is working correctly. The forest damping algorithm calculates the motion of the rocks while they are travelling through a forest, bouncing from one point on the slope to another. The vast majority of the simulation time in *RocFall2* takes place in the projectile algorithm. Any errors in the projectile algorithm would surely produce incorrect results. Therefore, it is essential that the projectile algorithm work correctly.

3.1. *RocFall2* Verification Problem #1 – Forest Damping

[*RocFall2 Build 8.009*]

3.1.1. Problem Description

This verification example consists of a horizontal and fully elastic (1.0 normal coefficient of restitution) frictionless slope and a single spherical rock that was dropped at 20 m height with an initial tangential velocity of 2 m/s. A medium dense forest of a height of 4.5 m was chosen. Without forest damping, the rock would just keep on bouncing forever since no kinetic energy is being lost. With forest damping, the rock's velocity is damped as it traverses through the forest layer. It bounces a number of times before coming to rest. The initial tangential velocity for the rock is chosen so we can observe the effects of damping in the tangential direction and also so that the rock will follow a distinct path (clearly separated from previous path). This velocity does not necessarily reflect typical initial velocities that are used in rockfall analyses.

The fully elastic frictionless slope is created to exclude any other means of energy loss except for forest damping, so we can observe the effects of forest damping alone. The geometry does not necessarily reflect typical slopes that are used in rockfall analyses. No statistics are incorporated into this verification (i.e., only mean values were used; all standard deviations are set to 0).

To verify the projectile algorithm with forest damping, we are comparing the trajectory profile to that modeled using discrete element method and also hand calculations.

3.1.2. RocFall2 Analysis

Slope Geometry and Material Properties

The location of the slope vertices, and material parameters for all slope segments are presented in the following tables:

Table 9-1: Slope Geometry and Material Properties

	X	Y	Normal Restitution	Tangential Restitution	Dynamic Friction	Rolling Friction	Forest/Vegetation Damping	
							Effective Height (m)	Drag Coeff. (500 kg/s)
Vertex 1	0	0						
Segment 1			1	0	0	0	4.5	500
Vertex 2	20	0						

Initial Conditions

The rock starts at location X_0 = 1 m, Y_0 = 20 m. The rock was given an initial velocity of V_{X0} = 2 m/s, V_{Y0} = 0 m/s. The rock has a mass of 1,000 kg (approximately 0.446 m radius sphere with 2700 kg/m^3 density).

Enter the seeder and slope geometry values from Table 9-1 into *RocFall2*. A forest height of 4.5 m is used, and a medium dense forest is selected with a damping coefficient of 500 kg/s. The three default damping coefficients can be selected based on the effective forest density (i.e., Open Forest, Medium Forest, Dense Forest), which is defined based on the basal area. These are suggested default values provided by *RAMMS::ROCFALL2 User Manual* [4]. The user can enter any number between 100 kg/s to 999 kg/s.

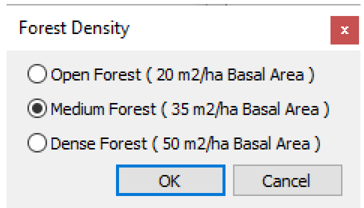

Figure 9-1: *RocFall2* Forest Density

Note: Ensure that **Use Tangential CRSP Damping** and both **Scale Rn by Velocity** and **Scale Rn by Mass** are unchecked under **Project Settings**.

The *RocFall2* model looks like this:

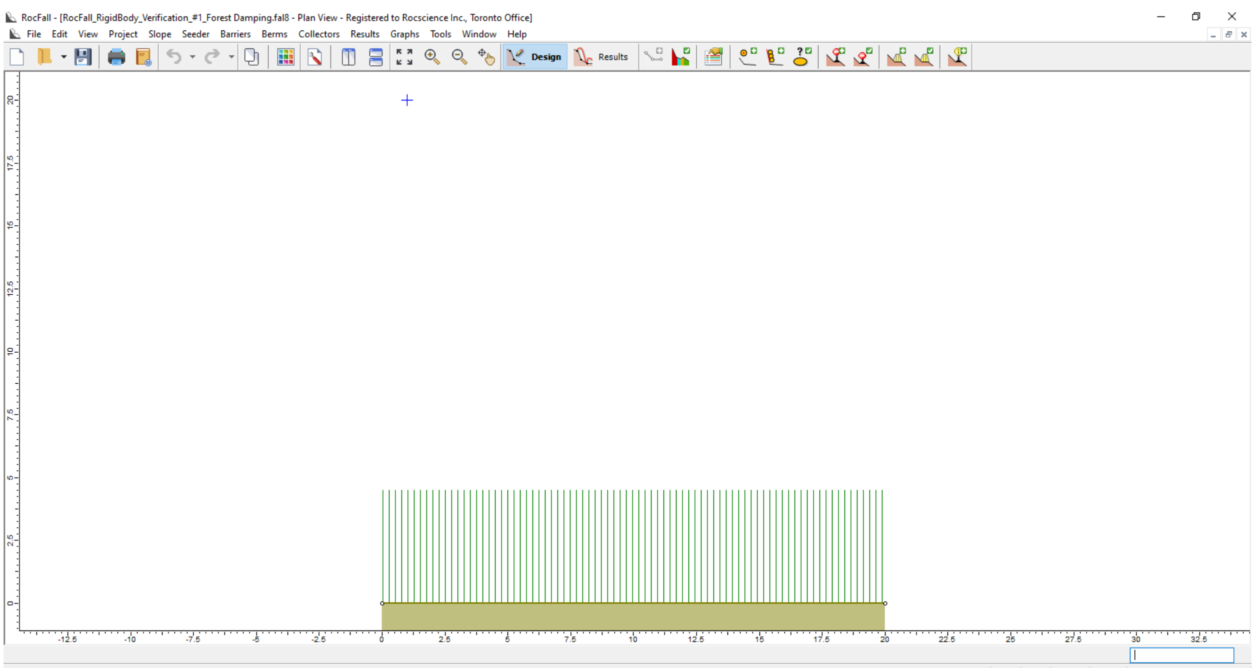

Figure 9-2: *RocFall2* Model Geometry (Forest Area is Represented by Green Vertical Hatch)

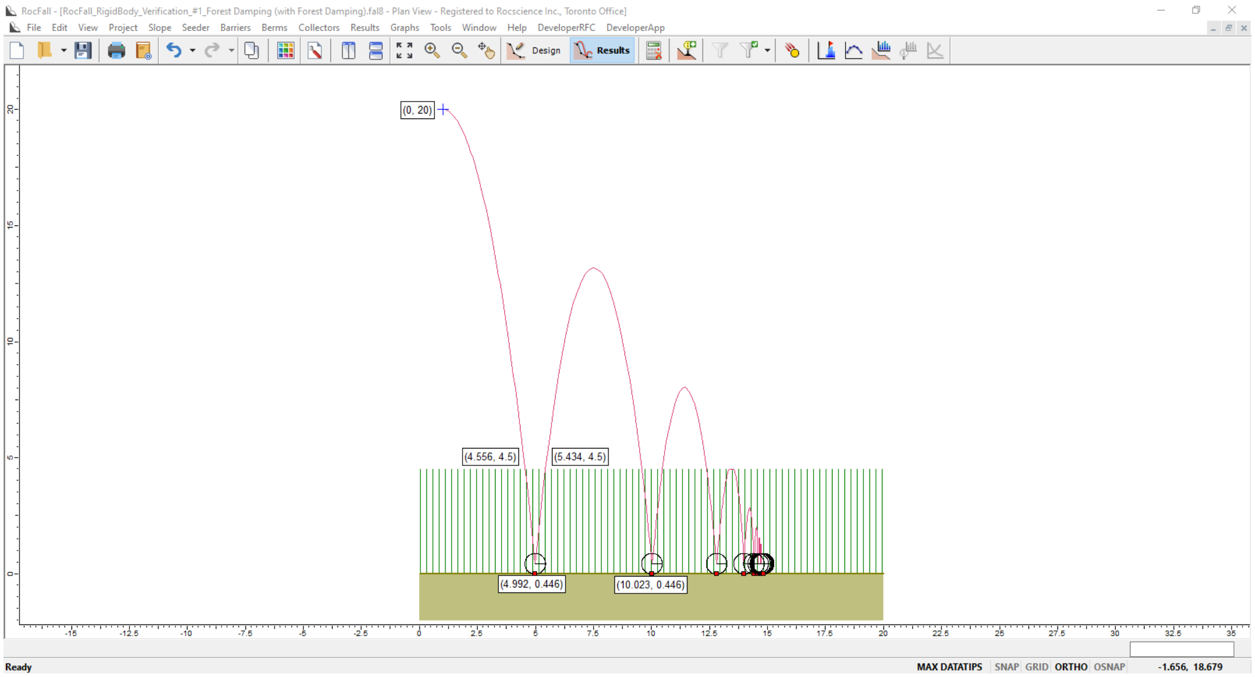

Figure 9-3: *RocFall2* Rock Trajectory Model Results (with Forest Damping)

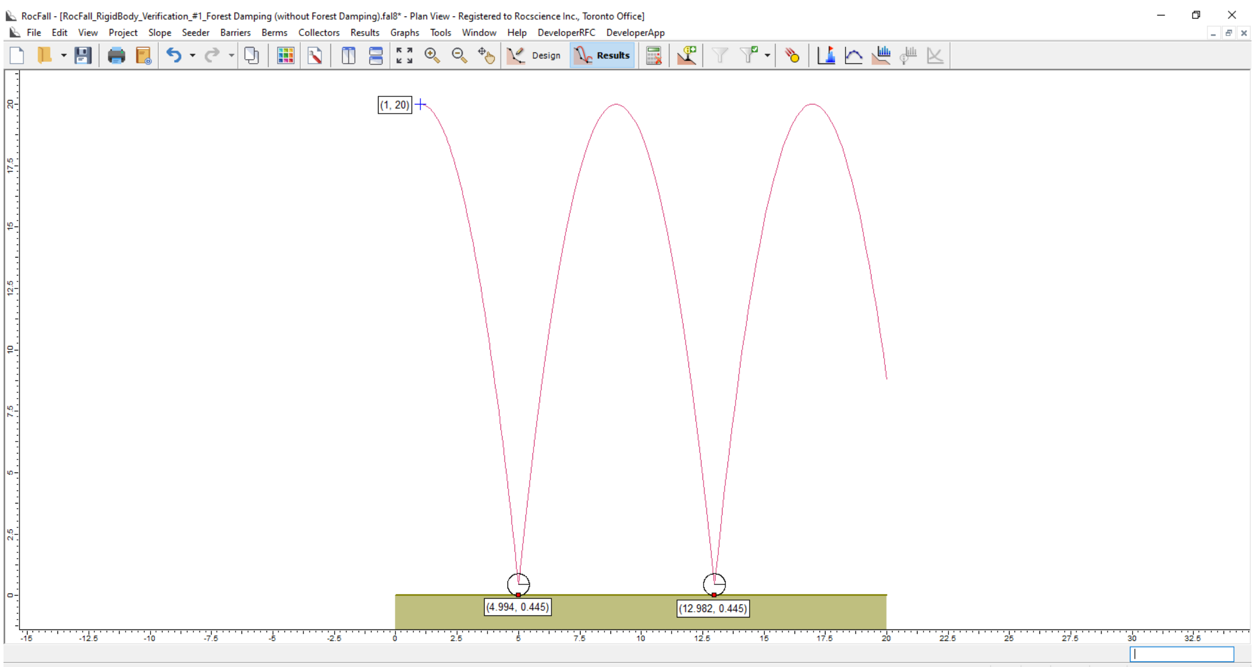

Figure 9-4: *RocFall2* Rock Trajectory Model Results (without Forest Damping)

3.1.3. Building a Compatible Discrete Element Method (DEM) Model

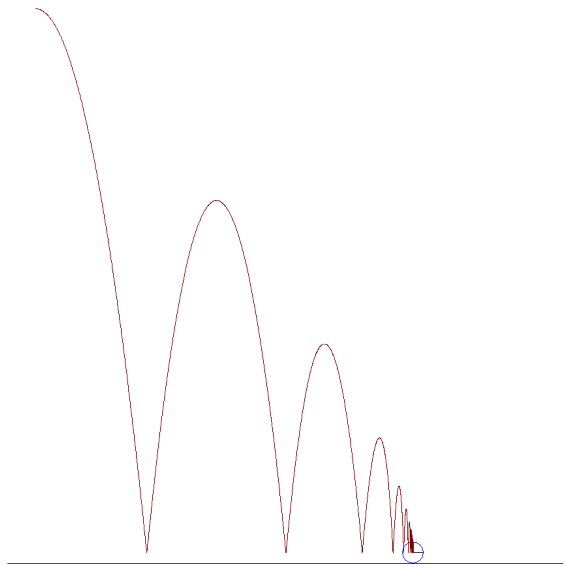

Figure 9-5: Discrete Element Method (DEM) Rock Trajectory Model Results (with Forest Damping)

3.1.4. Analytical Solution

The projectile algorithm consists, mainly, of the process of determining the intersection between a parabola (the path the rock follows while it is in the air) and a line segment (one of the slope segments). The location of the parabola-line intersection are determined by the roots of the quadratic equation, when there is no damping:

$$\left[\frac{1}{2}g\right]t^2 + [V_{Y0} - qV_{X0}]t + [Y_0 - Y_1 + q(X_1 - X_0)] = 0 \tag{1}$$

Where:

q is the slope of the segment

$$q = \frac{Y_2 - Y_1}{X_2 - X_1}$$

The forest damping model is built on the theory developed by Leine et. al. [3]. When there is damping, the forest drag force is defined as:

$$F_d = -C_f\mathbf{V} \tag{2}$$

Where:

C_f is the damping coefficient (as discussed earlier)

$\mathbf{V}$ is the rock velocity vector, which consists of 2 components: velocities in the x and y directions (V_X and V_Y)

Note that the velocity is not constant; it changes as the rock traverses through air. The velocities at the specific moment of time need to be computed to find the correct drag forces. This can be achieved by either time stepping (advancing time at small increments and updating rock status at each step) or solving the ordinary differential equation explicitly. Since *RocFall2* is event driven, we will use the later method to reduce numerical errors. The comparing DEM model employs the time stepping method.

Equation (2) gives us the force acting on the rock at its center of mass. We know that acceleration multiplied by mass equals force. From Equation (2) we get:

$$\mathbf{a_f} = -\frac{C_f \mathbf{V}}{m} \tag{3}$$

Acceleration is essentially change in velocity over time ($a = \frac{\mathrm{d}v}{\mathrm{d}t}$). Equation (3) becomes:

$$\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = -\frac{C_f \mathbf{V}}{m} \tag{4}$$

Separate Equation **(4)** into x and y components and add in gravitational acceleration, we get:

$$\frac{\mathrm{d}V_X}{\mathrm{d}t} = -\frac{C_f V_X}{m} \tag{5}$$

$$\frac{\mathrm{d}V_Y}{\mathrm{d}t} = -g - \frac{C_f V_Y}{m} \tag{6}$$

Where:

$g = 9.81 \frac{\mathrm{m}}{\mathrm{s}^2}$

The above two ordinary differential equations can be solved, and we get:

$$V_X = V_{X0} e^{-\frac{C_f}{m}t} \tag{7}$$

$$V_Y = -g\frac{m}{C_f} + \left(V_{Y0} + g\frac{m}{C_f}\right) e^{-\frac{C_f}{m}t} \tag{8}$$

Where:

V_{X0} and V_{Y0} are x and y velocities at $t = 0\ \mathrm{s}$

Integrating velocity over time gives the distance travelled:

$$d_X = V_{X0}\frac{m}{C_f}\left(1 - e^{-\frac{C_f}{m}t}\right) \tag{9}$$

$$d_Y = \frac{m}{C_f}\left[-gt + \left(V_{Y0} + g\frac{m}{C_f}\right)\left(1 - e^{-\frac{C_f}{m}t}\right)\right] \tag{10}$$

Each step consists of determining the necessary parameters and solving the quadratic equation or the ordinary differential equation to find the intersection point. Once the intersection point is found, the impact is calculated. If the rock has enough velocity after the impact, as determined by a comparison to the minimum velocity (V_{min}), another step is initiated.

In the interest of brevity, we will only show calculations for the 4 points shown in Figure 9-3.

<u>Step 1:</u>

Finding the intersection from the rock's initial location at (1, 20) with the top of forest line (y = 4.5 m). Slope of the segment is 0, Equation (1) simplifies to

$$\frac{1}{2}gt^2 + V_{Y0}t = Y_0 - Y_1$$

$$\frac{1}{2}gt^2 = 20 \text{ m} - 4.5 \text{ m} = 15.5 \text{ m}$$

Solving for t we get $t = 1.778$ s.

At t = 1.778 s, the change in x is:

$$\mathrm{d}x = \left(2\frac{\mathrm{m}}{\mathrm{s}}\right)(1.778 \text{ s}) - 3.556 \text{ m}$$

And the rock's location is (4.556 m, 4.5 m). It matches the rock's first entry point into the forest layer.

<u>Step 2:</u>

Now we need to find when and where the rock hits the ground. The radius of a 1,000 kg rock with a density of 2700 kg/m^3 is 0.4455 m. Therefore, we need to find when and where the rock reaches y = 0.4455 m.

$$\mathrm{d}y = 0.4455 \text{ m} - 4.5 \text{ m} = -4.0545 \text{ m}$$

From Equation (10), we iterate using Newton Raphson's method to find t = 0.2309 s.

Plug the time into equation (9) we get:

$$\mathrm{d}x = 0.4361 \text{ m}$$

$$x = 4.556 \text{ m} + 0.436 \text{ m} = 4.992 \text{ m}.$$

The rock's location at t = 1.778 + 0.231 = 2.009 s is (4.992 m, 0.446 m), which matches that in Figure 9-3.

Step 3:

We then need to find when and where the rock exits the forest. We first determine if the rock has enough momentum to leave the forest by finding when the V_Y reaches 0. That is done by solving Equation (8) by setting V_Y = 0 m/s. We know that the outgoing V_{X0} and V_{Y0} equal to that before impact with V_{Y0} in the opposite direction because coefficient of restitution is 1 and coefficient of friction is 0.

Starting with V_{X0} = 1.782 m/s and V_{Y0} = 17.673 m/s: V_Y reaches 0 m/s when t = 1.285 s, $\mathrm{d}y$ = 10.144 m > 4.0545 m. The rock will exit the forest layer.

We set $\mathrm{d}y$ = 4.0545 m and solve Equation (10) for when the rock will reach y = 4.5 m, and t = 0.2648 s.

From Equation (10) with t = 0.2648 s and V_{X0} = 1.782 m/s, we get:

$$\mathrm{d}x = 0.442 \text{ m.}$$

The rock exits the forest at:

$$x = 4.99 \ + 0.442 = 5.434 \text{ m}$$

$$y = 4.5 \text{ m.}$$

This matches that in Figure 9-3. V_X and V_y at this time (2.2738 s) are 1.561 m/s and 13.049 m/s, respectively, using Equations (7) and (8).

The rock is still going up. It will fall back down to y = 4.5 m following Equation (1). V_y will reach 0 m/s at t = 1.33 s.

The rock will re-enter the forest at:

$$t = 2(1.33 \text{ s}) = 2.66 \text{ s}$$

The rock's x location is:

$$x = \left(1.561 \frac{\text{m}}{\text{s}}\right)(2.66 \text{ s}) + 5.434 \text{ m} = 9.587 \text{ m}$$

The rock's x and y velocities are 1.561 m/s and -13.049 m/s, respectively.

Step 4:

We can then find the second impact location. $\mathrm{d}y$ is still -4.0545 m. Following the same procedure as in Step 2, we find that the rock will impact the ground the second time at (10.023 m, 0.4455 m), which matches that in Figure 9-3.

3.1.5. Results

The same geometry and parameters were input into *RocFall2* and a simulation was performed. The results from *RocFall2* were compared to the hand calculations and that using the DEM. Figure 7 below plots the results from *RocFall2* and DEM together. The results from the three separate methods were identical for all practical purposes. The impact locations calculated by hand agreed with the program results up to the third decimal place in all cases (i.e., less than 0.5 mm difference, everywhere). Therefore, the projectile algorithm is working correctly. The comparison of the results produced by these two programs does not prove the validity of the equations; however, it does provide greater confidence that the equations were properly coded into the programs.

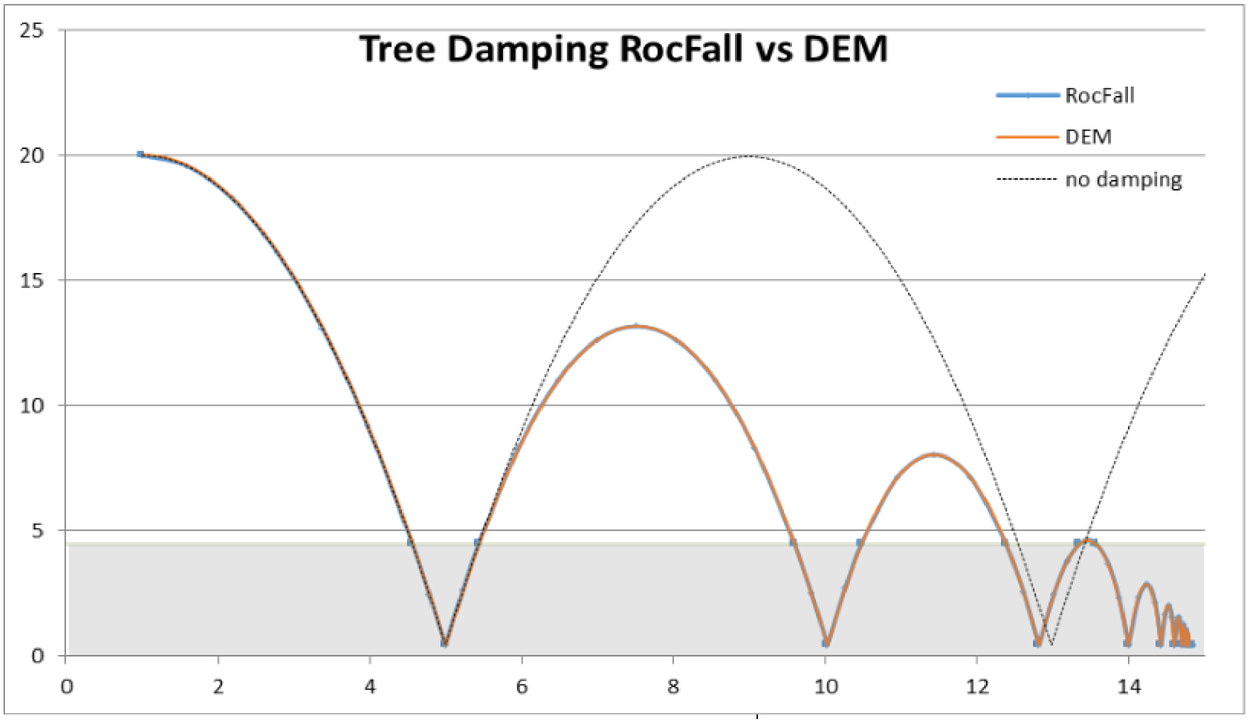

Figure 9-6: Comparison of Tree Damping Trajectories using *RocFall2* and DEM

3.1.6. Input Files

RocFall_RigidBody_Verification_#1_Forest Damping (with Forest Damping).fal8
RocFall_RigidBody_Verification_#1_Forest Damping (without Forest Damping).fal8

3.2. References

https://en.wikipedia.org/wiki/Basal_area

http://www.firewords.net/UnitCoversions/BasalAreaUnits.htm

Leine, R.; Schweizer, A.; Christen, M.; Glover, J.; Bartelt, P. & Gerber, W. 2013. Simulation of rockfall trajectories with consideration of rock shape. Multibody System Dynamics, 1-31.

Bartelt, P.; Bieler, C.; Buhler, Y.; Christen, M.; Dreier, L.; Gerber, W.; Glover, J. & Schneider, M. 2016. RAMMS::ROCKFALL User Manual. http://ramms.slf.ch/ramms/downloads/RAMMS_ROCK_Manual.pdf.