ARMA 12-267

Rigid body dynamics for rock fall trajectory simulation

Basson, F. R. P.

Newmont Asia Pacific, Perth, Western Australia, Australia

This paper was prepared for presentation at the 46th US Rock Mechanics / Geomechanics Symposium held in Chicago, IL, USA, 24-27 June 2012.

ABSTRACT: Rock falls are difficult to model accurately, partly because the readily available simulation packages simplify problems to either two dimensions and ignore the fall body geometries with particle models. Lumped-mass models concentrate the fall body mass into a single point, ignore the fall body shape and can only simulate sliding movement. Rotation is mimicked by assigning a zero friction angle to the interaction between the fall body and slope. In reality, falling rocks often free fall, bounce, slide, and roll during a single trajectory, and the falling body shape and size, and the three dimensional topography largely determine the trajectory path and associated energy.

The author developed a rock fall simulation package, Trajec3D, using existing technologies. The resulting software is a three dimensional rigid body rock fall analysis program that can simulate the trajectory of volumetric bodies during free fall, bouncing, sliding and rolling. The physical interaction between materials is a function of the combined properties of the fall body and the impact surface, with only three input parameters required; the coefficient of restitution, and the static and dynamic friction angles.

1. ROCK FALL MOTION TYPES

A falling rock can experience four types of motion along its path; free fall, rolling, bouncing and sliding. A typical rock fall consists of more than one of these motions during a single event. No interaction takes place between the fall body and slope during free fall, but interaction does take place for all other types of motion during which the rock may also fracture into smaller pieces.

Fig. 1. Types of motion during a rock fall [1].

During interaction of the fall body with the slope surface (rolling, bouncing and sliding), the behavior is largely governed by the geometries and mechanical characteristics of the slope surface and fall body. As will be discussed in this paper, the two dimensional particle models mostly used today are too simplistic and ignore important aspects of the rock fall problem. However, these simplified models are used due to a lack of better available tools - an astonishing thought given the fact that most modern computer games implement real-time physics engines.

2. SIMULATION OF ROCK FALLS

A computer simulation, a computer model, or a computational model is a computer program, or network of computers, that attempts to simulate an abstract model of a particular system. Simulation is nowadays successfully used in many applications as diverse as weather forecasting, traffic engineering, and training pilots with flight simulators.

Although computer simulations are used for many reasons, the most relevant to rock falls (in the author's opinion) are:

- **(i)** Visualise potential rock fall patterns.
- **(ii)** Quantify potential outcomes - for example 1 in 5 rocks from a specific bench face will end up on a ramp.

- **(iii)** Comparative and sensitivity studies with different variables.
- **(iv)** Exposing surprise events overlooked by visual inspection.
- **(v)** Educational tool (toy) that opens the imagination to potential outcomes.

If the above could be achieved with rock fall modelling, why is rock fall modelling done so infrequently in open pit environments? After spending some time with many rock fall software packages and having discussions with open pit engineers, the author concluded that results from the available software solutions often contradict common sense and engineers thus have low confidence in the software predictions.

Discrete element method (DEM) codes can accurately model rock-slope interactions and even simulate breakup [2], but:

- **(i)** Are time consuming to set up.
- **(ii)** Require many input parameters with some not observable and difficult to estimate.
- **(iii)** Require an expert user as the software is not user friendly.
- **(iv)** Are reasonably expensive.
- **(v)** Could require high-end hardware.
- **(vi)** Have slow computational speeds due to the extremely small time steps required.

A less sophisticated approach that captures the essence of fall body behavior is rigid body mechanics. This approach uses the equations of motion and kinematics, assumes an instantaneous period of contact, and the contact region between colliding bodies are very small [2]. This method is fast enough for real time simulation of multiple fall bodies and even for probabilistic analysis.

The input parameters for rigid body mechanics are few, measureable and intuitive. In addition to shape, mass and velocity, Trajec3D only requires the static and dynamic friction angles and elasticity of the contacting surfaces. The elasticity or "bounciness" is defined by the coefficient of restitution, a fractional value representing the ratio of speeds after and before impact, taken along the line of impact.

A coefficient of restitution of 1 indicates a perfectly elastic collision with no loss in velocity and thus no loss in energy. A value of 0 implies a perfectly plastic collision where all the velocity along the line of impact is absorbed. If a fall body impact a surface at an angle, the fall body will not be brought to rest, but the velocity component along the line of impact will be absorbed.

The velocity coefficient of restitution for an object bouncing from a stationary object is defined as shown in Equation 1 [3].

$$C_R = \frac{v}{V} \tag{1}$$

Where v is the scalar velocity of the fall body after impact and V is the scalar velocity of the fall body before impact.

From Newton's equations of motion for constant acceleration, velocity can be calculated as indicated below.

$$v^2 = u^2 + 2as$$

If the body starts from rest, then u = 0.

$$v^2 = 0^2 + 2as$$

$$v = \sqrt{2as}$$

If the acceleration is due to gravity, then a = g.

$$v = \sqrt{2gs}$$

If the relevant distance is height h, then s = h.

$$v = \sqrt{2gh} \tag{2}$$

Where v is velocity, u is starting velocity, a is acceleration, and s is distance.

Substituting Equation 2 into Equation 1 gives the equation below.

$$C_R = \frac{\sqrt{2gh}}{\sqrt{2gH}}$$

$$C_R = \sqrt{\frac{h}{H}} \tag{3}$$

Where h is the bounce height and H the drop height.

Equation 3 is an easy way to determine the coefficient of restitution; drop rocks from a known height onto a horizontal slope surface and determine the average distance of vertical rebounds.

3. ROCK FALL MODELLING APPROACHES

Rock fall trajectory codes can be classified as two- or three-dimensional and use rigorous or particle models [4]. The analysis with the selected model can then be done deterministically or probabilistically. Each type of model has profound implications, and the limitations should be well understood by the users.

3.1. Two vs. three dimensional models

For two-dimensional models, the ground profile is typically selected along the line of steepest slope, but the geometries of slopes vary considerably from one cross-section to another. Also, two-dimensional models assume that the rock fall occurs in a linear plane, and the rock trajectory is unaffected by the plane surfaces of the slope or fall body (see Figure 2).

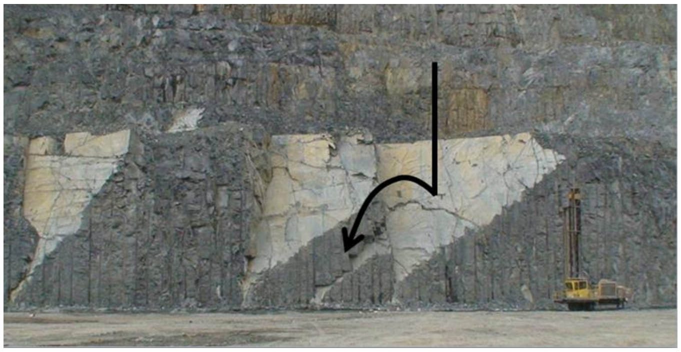


Fig. 2. Potential for out-of-plane bouncing.

Three-dimensional models take account of the full topography of a slope to determine the anticipated path (see Figure 3).

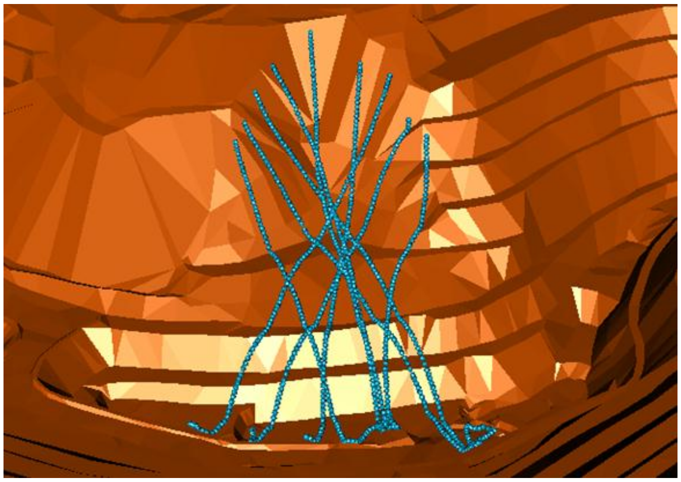


Fig. 3. Slope geometry affecting the fall body trajectory.

3.2. *Lumped-mass vs. rigorous models*

Lumped-mass or stereo-mechanical models represent falling bodies as point masses. Lumped-mass models thus ignore the fall object shape and size, and the fall body mass does not affect the overall fall body trajectory, but is only used to compute energies. Lumped-mass models can only represent sliding motion and mimics rotation with a zero friction angle.

Two fictitious input parameters, the normal and tangential coefficients of restitution, are required for lumped-mass models to compensate for the lack of physics captured in the simplified models. These two parameters depend on factors such as the incident angle, frictional characteristics of the fall body and slope contact, and the collision point on a fall body shape with non-spherical shape [2].

Rigorous models consider the fall body shape and volume and can solve for all the types of motion, including rotation. Figure 4 shows a reconstructed fall body path [5] and Figure 5 a similar trajectory in a rigid body dynamics simulation with the body rotation captured along the trajectory.

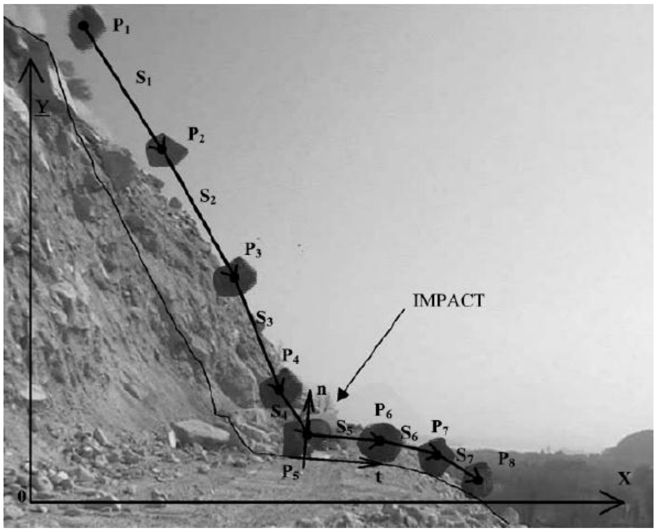


Fig. 4. Reconstructed fall body positions [5].

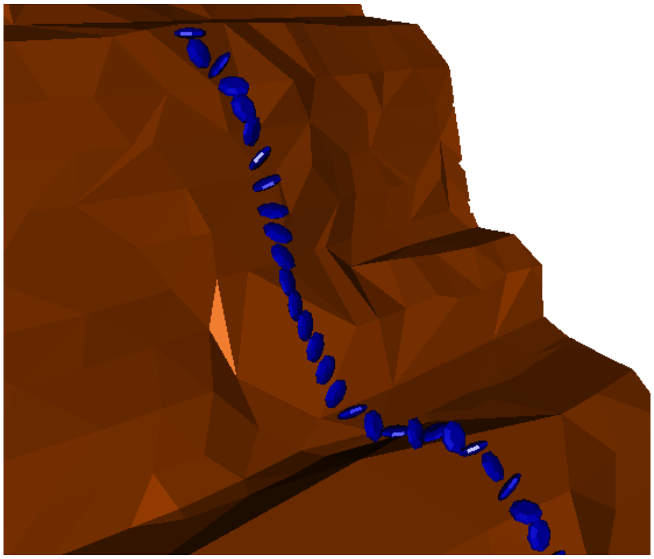


Fig. 5. Fall body rotation along the trajectory path

4. TRAJEC3D

4.1. *Origins*

The requirements the author set before starting development of Trajec3D [6] were based on the weaknesses of the evaluated rock fall software packages:

(i) Stand-alone software, for example no GIS or CAD-software dependence.
(ii) Intuitive mouse control of the scene, similar to mining software packages.
(iii) Physics engine that can solve for three dimensions.
(iv) Rigorous model that takes account of shapes and rotational movements.
(v) Easy DXF-format topography import with no pre-processing or transformations required.
(vi) Quick simulations with visual feedback of the simulation paths.

- **(vii)** Graphing of the velocities and energies for individual fall paths.
- **(viii)** Low hardware requirements.

The requirements resulted in the development of Trajec3D, a three dimensional rigid body rock fall analysis program that can simulate the trajectory of volumetric shapes during free fall, bouncing, sliding and rolling. It is a modelling tool that enables the quick assessment of scenarios to better understand potential paths dislodged rocks could follow, the time it should take to reach areas of interest, and an estimate of the energy stored along the trajectory.

Trajec3D was developed by making use of a game graphics engine [7] and a physics engine [8] which are used in commercial applications and games. The physics engine implements a deterministic solver that makes it suitable for real-time physics simulations.

The physics interaction between materials is a function of the combined properties of the fall body and the impact surface and only three parameters are required; coefficient of restitution, static and dynamic friction angles.

4.2. Limitations

As in all modelling tools, Trajec3D is a simplification of reality with the aim to investigate different possibilities. The results from Trajec3D should be considered an aid towards decision making, and not an absolute design criterion.

A common problem with rigid body dynamic physics engines are sharp corners that could result in spurious bounces. This problem occurs more frequently when using fall bodies with few vertices and sharp corners, or when the fall bodies are large in relation to the polygons of the stationary slope geometry.

Figure 6 shows an example where spherical shapes are released from a fixed height onto a very detailed topography with small triangulations in relation to the fall bodies. Most fall bodies behave correctly and the spurious bounces are quite obvious. The fall bodies come to rest at the boundaries of the defined physics volume.

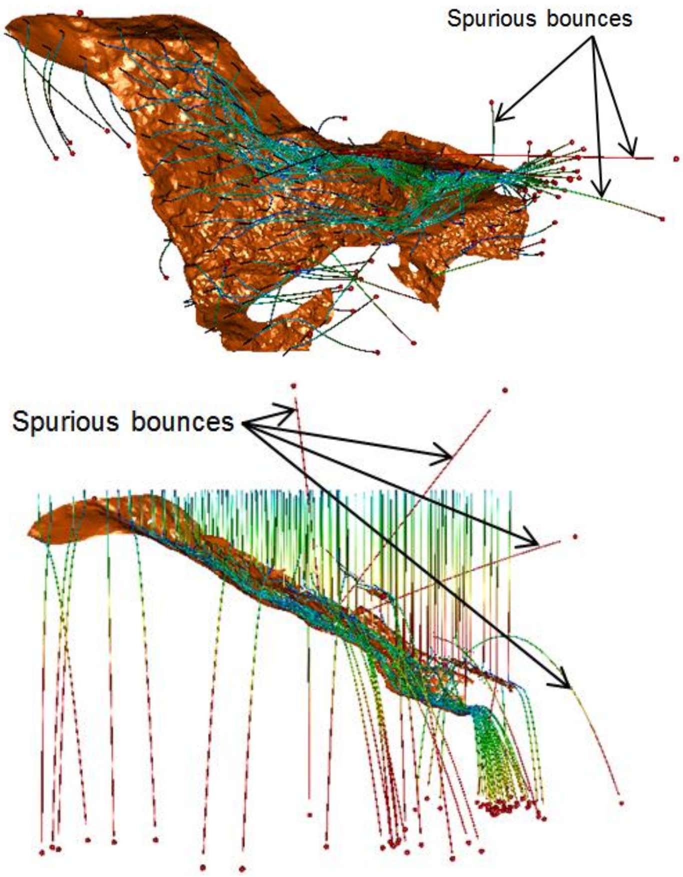


Fig. 6. Plan and side view of spurious bounces due to a small topology triangulation compared to the fall body dimensions.

4.3. Verification

Results from Trajec3D are not yet verified against field observations. The author is collaborating with the Australian Centre for Geomechanics and the University of Newcastle to verify the code against recorded rock fall events in the near future.

5. PRACTICAL APPLICATIONS

This section discusses three-dimensional rigorous modelling results of scenarios that would be impossible to model with two-dimensional particle models.

5.1. Importance of fall body size

Figure 7 shows the modeled trajectory paths of fall bodies with different masses, and thus different volumes. As expected, the larger blocks are not as easily caught by the berms as the smaller blocks. The larger blocks thus tend to fall further, and are less affected by the catch benches, resulting in greater maximum velocities than the smaller blocks as indicated in Table 1.

Table 1. Maximum velocity of different fall body masses

Mass (tons)	Maximum velocity (m/s)
1	9.1
10	12.8
100	15.4
1000	16.1

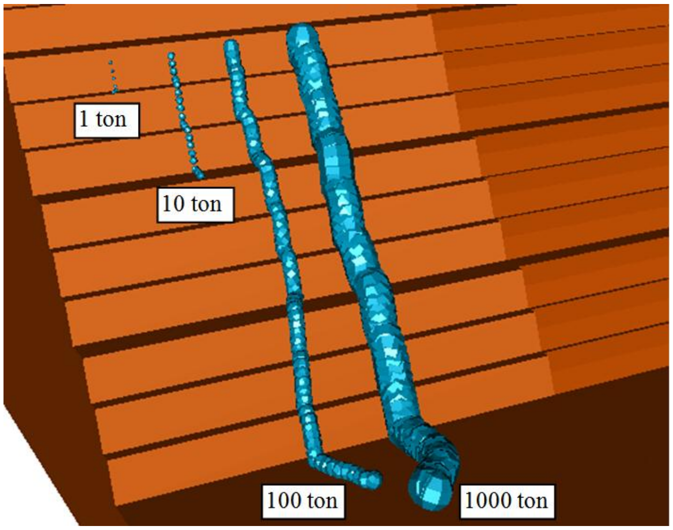


Fig. 7. Fall bodies with different dimensions.

5.2. *Importance of fall body shape*

Figure 8 shows the modeled trajectories of blocks with the same mass but different shapes. The red fall body to the left is mathematically a perfect sphere, and the other shapes are all angular.

The rounded shapes falls furthest down the slope followed by the square shape. Flat fall bodies are typically the easiest to arrest by catch benches as they tend to slide and do not easily roll.

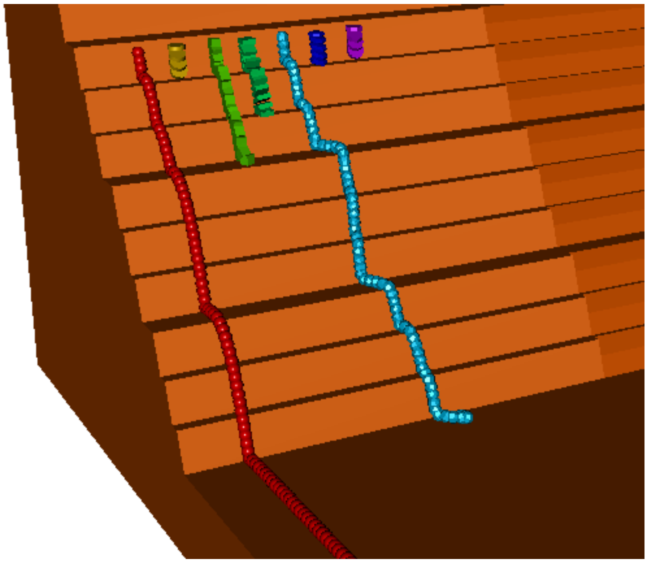


Fig. 8. Fall bodies with different shapes.

5.3. *Slope geometry*

The three dimensional slope geometry plays an important role in the fall body trajectory as illustrated in Figures 3 and 6.

5.4. *Friction angle influence on motion*

In many instances, the friction angles between the fall object and slope determine the type of motion of rounded shapes. When the friction angle is lower than the slope gradient, sliding motion typically occur. When the friction angle is higher than the slope gradient, rotational motion typically occur with rounded shapes on steep slopes.

Figure 9 shows the movement of flat cylinders (yellow), square boxes (green) and angular flattened spheres (blue) with different friction angles down a plane. All the objects slide down the slope when their friction angles are less than the slope gradient. When the friction angles exceed the slope gradient, the flat cylinder stops shortly after release, but the rounded shapes roll down the slope.

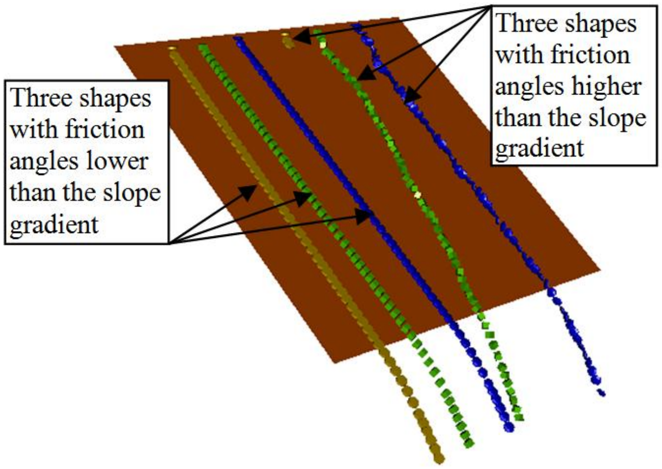


Fig. 9. Friction angle impact on motion.

5.5. *Rotational energy*

A rounded shape that rolls down a slope has translational as well as rotational energy as shown in Figure 10. The rotational energy of a rounded shape could contribute substantially to the total energy.

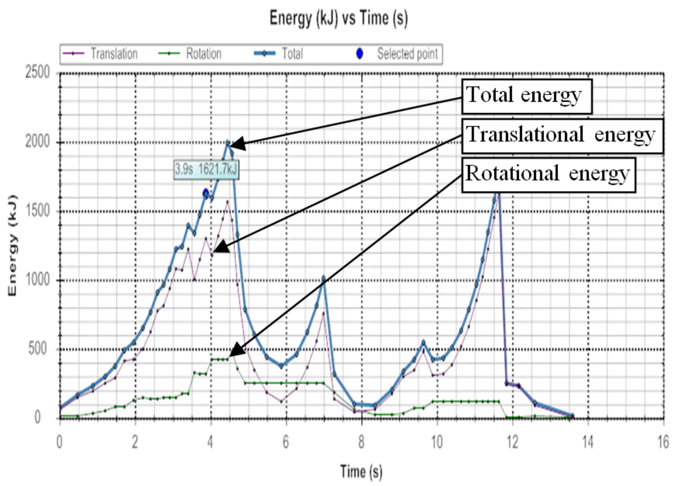
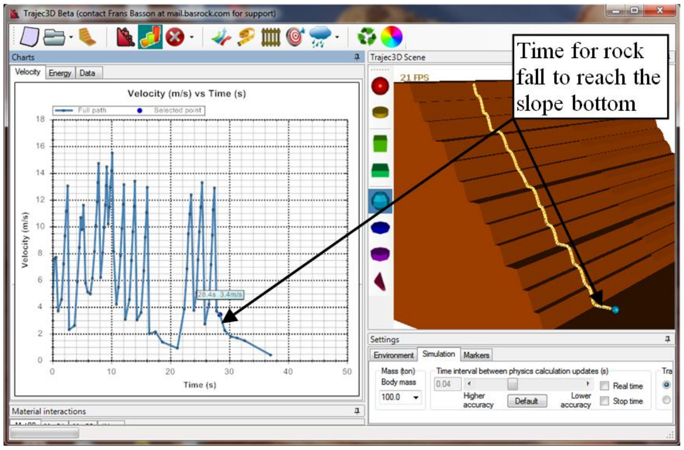


Fig. 10. Total Energy = (Translational + Rotational) Energy

5.6. *Travel times for rock falls*

The time a rock fall takes from a potentially unstable area to the slope bottom is important. Many open pit mines rely on “spotters” to warn other workers when a rock fall starts. This practice is only effective when enough time is available for the workers to evacuate before the rock fall could impact them.

Trajec3D gives the time of a fall body along the path, and also have a “Real time” option that displays the fall body motion in actual time. Figure 11 shows the fall body path and a graph with the velocity and time along the path.



Mass (ton) Body mass: 100.0
Time interval between physics calculation updates (s): 0.04
Higher accuracy — Default — Lower accuracy
☐ Real time
☐ Stop time

Fig. 11. Velocity and time for a fall body at a selected point

5.7. *Crest loss impact on rock falls*

Figure 12 shows results for rock falls from a perfect design (left half of slope) and the adverse impact from crest loss (right half of slope) on rock fall trajectories. Crest loss impacts rock falls markedly, but is often not accounted for during the design stage.

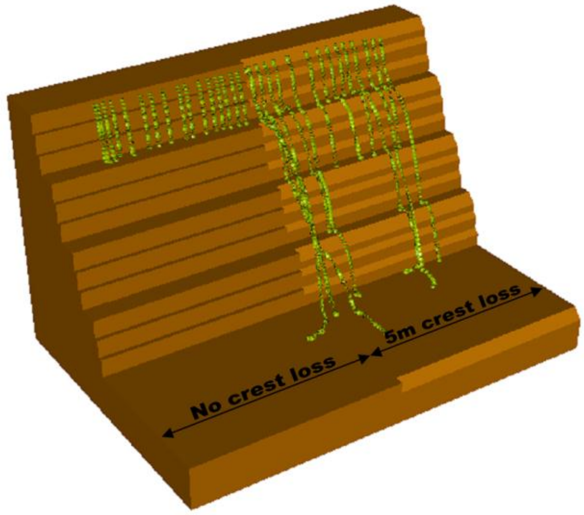


Fig. 12. Crest loss impact on rock fall trajectories.

6. CONCLUSIONS

Three dimensional rigid body analyses capture the expected behavior of fall bodies well and successfully simulate all types of motion, requiring only three measureable and intuitive input parameters. The method is fast enough for real time simulation of multiple fall bodies and even for probabilistic analysis.

The author developed a rock fall simulation package, Trajec3D [6], using existing technologies. The software is not yet verified against recorded rock falls, but many important lessons can already be learned from the results that would have been impossible with particle models.

7. ACKNOWLEDGEMENTS

The author gratefully acknowledges the permission given by Newmont Asia Pacific to publish this paper.

REFERENCES

1. Lo C.M., M.L. Lin and W.C. Lee. 2008. Talus Deposition Pattern of Rockfall through Mechanical Model and Remote Sensing technology (Presentation). *Geophysical Research Abstracts* Vol. 10, 5th EGU General Assembly.

2. Curran J.H. and R.E. Hammah. 2006. Keynote Lecture: Seven Lessons of Geomechanics Software Development. *ARMA/USRMS Golden Rocks 2006, 41st U.S. Symposium on Rock Mechanics (USRMS), 50 Years of Rock Mechanics – Landmarks and Future Challenges.*

3. Richards L.R., B. Peng, and D.H. Bell. 2001. Laboratory and Field Evaluation of the Normal Coefficient of Restitution for Rocks. *Rock Mechanics: A Challenge for Society – Proceedings of ISRM Regional Symposium Eurorock 2001.* 149-155. June 2001.

4. Labiouse V. 2007. Prediction of Rockfall Trajectories (Presentation). Available for download from *http://w3.unicaen.fr/mountainrisks/spip/IMG/pdf/11_Mountain-Risks_Labiouse_Trajectography.pdf.* Mountain Risk Workshop Reference to a journal article.
5. Giani G.P., A. Giacomini, M. Migliazza and A. Segalini. 2004. Experimental and Theoretical Studies to Improve Rock Fall Analysis and Protection Work Design. *Rock Mech. Rock Engng*. (2004) 37 (5), 369-389. March 2004.
6. BasRock Trajec3D. 2012. *Available from http://www.basrock.com/page13.htm - the beta is available as a free download*.
7. TrueVision3D. *Available from http://www.truevision3d.com/*.
8. Newton Game Dynamics. *Available from http://newtondynamics.com/forum/newton.php*.