ROCKFALL

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Chapter 9

A. KEITH TURNER AND
JOHN D. DUFFY

MODELING AND PREDICTION OF ROCKFALL

1. INTRODUCTION

Rockfalls are a concern in mountainous areas. They can threaten lives, settlements, equipment, facilities, and transportation corridors. They pose hazards along engineered slopes, even in regions of modest relief. Despite their typically limited volumes, rockfalls are characterized by high velocity and mobility, which makes them a potential cause of fatalities; hence, they pose a significant hazard and risk (Chapter 5). Rockfalls can be triggered by earthquakes (Kobayashi et al. 1990), by rainfall (Krautblatter and Moser 2009), by freeze–thaw cycles (Matsuoka and Sakai 1999), or by the progressive weathering of rock material, especially along discontinuities, under suitable climatic conditions (Nicholson 2004).

Chapters 1 and 2 have addressed the appropriate definition of rockfall. The convention adopted throughout this book is that rockfall involves significant velocities and some measure of free flight, but there is no universal upper limit on the volume or kinetic energy of rockfall. Movement may involve any combination of free-falling, bouncing, rolling, or sliding. Rockfall may involve more than one rock but typically does not include large volumes of rock such as rock avalanches or landslides that may include rock. There is a continuum between slope movements that may be called rockslides and rockfalls, and many of the rock mass properties and geological processes that contribute to a rockfall consisting of one or a few rock blocks may also contribute to the instability of a large portion of a slope. Rochet (1987) classified rockfall phenomena into four categories:

- *Single block falls*, which typically involve volumes ranging between 0.01 and 100 m^3 (0.35 and 3,500 ft^3);
- *Mass falls*, which typically involve volumes ranging between 100 and 100,000 m^3 (3,500 and 3.5 million ft^3);
- *Very large mass falls*, which typically involve volumes ranging between 100,000 and 10 million m^3 (3.5 million and 350 million ft^3); and
- *Mass displacements*, which typically involve volumes greater than 10 million m^3 (350 million ft^3).

Hungr and Evans (1988) defined rockfalls that involved relatively small volumes of material as *fragmental rockfalls*. They were characterized by more or less independent movements of the individual fragments, as opposed to the sliding or mass flow of coherent or broken rock typical of much larger rock mass failures. These large failures invariably disintegrate and are transformed into a rapid movement of unsorted fragments, termed a *stürzstrom* (Heim 1932), a *rock avalanche* (McConnell and Brock 1904), or a *rockfall avalanche* (Varnes 1978), where inclusion of the term *rockfall* implies an episode of free fall during the event.

Table 9-6

3-D Rockfall Simulation Programs That Incorporate Assessments of Terrain Variations Within the Rockfall Zone

INITIAL RELEASE[a]	PROGRAM NAME	KINEMATIC PRINCIPLE[b]	SIMULATION METHOD[c]	3-D TOPOGRAPHY REPRESENTATION[d]	SOURCE	COMMENTS
1987	No name	Rigid body	Deterministic	Finite element mesh	Descoeudres and Zimmermann 1987	First 3-D rockfall simulation model; entirely deterministic.
1991	ROTOMAP	Lumped mass	Probabilistic	DEM raster supported by ISOMAP	Scioldo 1991; Castelli and Scavia 2008; Geo and Soft 2009; Nocilla et al. 2009; Longo and Oreste 2010	Self-contained modeling approach provides basic GIS tools and probabilistic rockfall analysis when combined with ISOMAP.
2001	EBOULEMENT	Rigid body	Probabilistic	DEM raster based on finite element mesh	Dudt and Heidenreich 2001	Revised and improved version of Descoeudres and Zimmermann model; probabilistic analysis evaluates uncertainty.
2002	STONE	Lumped mass	Probabilistic	DEM raster internally converted to triangulated regular network	Guzzetti et al. 2002; Agliardi and Crosta 2002, 2003	Extensively used 3-D program. Inputs and results designed to interface with commercial GIS programs.
2007	RockFall Analyst	Lumped mass	Probabilistic	DEM raster	Lan et al. 2007, 2010	Programmed as an extension to ArcGIS with two major components: 3-D rockfall trajectory simulation and geostatics-based raster spatial modeling of rockfall hazard.
2008	PiR3D	Lumped mass	Probabilistic	TIN	Cottaz and Faure 2008; Cottaz et al. 2010a, 2010b	Designed for use by engineering consultants. Uses TIN to define topography and links to CAD systems.
2008	HY-STONE	Lumped mass and hybrid	Probabilistic	DEM raster—internally converted to triangulated regular network	Frattini et al. 2008; Agliardi et al. 2009	Improved version of STONE with some enhanced algorithms. Retains links to GIS programs.

(*continued on next page*)

Table 9-6 (*continued*)

3-D Rockfall Simulation Programs That Incorporate Assessments of Terrain Variations Within the Rockfall Zone

Initial Release[a]	Program Name	Kinematic Principle[b]	Simulation Method[c]	3-D Topography Representation[d]	Source	Comments
2010	Rockyfor3D Version 3.0	Lumped mass	Probabilistic	DEM raster	Dorren 2010	10 to 15 raster files define simulation parameters. Models impacts of rocks with trees. Sophisticated methods for evaluating surface roughness, rebound from soft soils, and deviations on impact.
2011	CRSP-3D	Discrete element	Probabilistic	DEM raster	Documentation currently under review by the Technology Development Program of the Central Federal Lands Highway Division of the Federal Highway Administration. On approval, will be at http://www.cflhd.gov/programs/techDevelopment/.	Uses an entirely new algorithm based on discrete element concepts. May be used in either 2-D or 3-D modes.

[a] Initial release dates are estimated on the basis of the earliest published descriptions of the program.

[b] Kinematic principles refer to methods used to analyze the rockfall block motions. *Rigid body* refers to motion analysis that takes into account the size and shape of the body; it allows for analysis of translational and rotational velocities and energies. *Lumped mass* refers to motion analysis that ignores the body shape and size; only translational velocities and energies are evaluated. *Hybrid* refers to a combination of lumped-mass and rigid-body methods; usually lumped-mass methods are used for free-fall portions of the rockfall trajectory while rigid-body methods are used to evaluate bouncing and rolling motions. *Discrete element* refers to use of discrete element methods discussed in Section 2.1 that permit block fragmentation.

[c] Simulation methods are either deterministic or probabilistic. Under deterministic methods, rockfall trajectories are entirely defined by fixed properties and Newtonian mechanical principles. Under probabilistic methods, rockfall trajectories are defined by parameters that vary from simulation to simulation on the basis of predefined ranges of values and probability distributions; this introduces a range of uncertainty in rockfall trajectories.

[d] The following are methods of representing the local topographic conditions within the rockfall zone:

- DEM raster—a series of equally spaced grid cells (usually square) of specified size (see Section 4.1);
- Triangulated regular network—a series of triangles developed from a DEM raster (see Section 4.4.4);
- TIN—a series of triangles of varying dimensions define the terrain, with small triangles in rough (irregular) areas and large triangles in smooth areas; and
- Finite element mesh—an irregularly sized mesh of quadrilaterals defined by irregularly spaced elevation observations (it is similar to a TIN, but the elements may be shapes other than triangles).

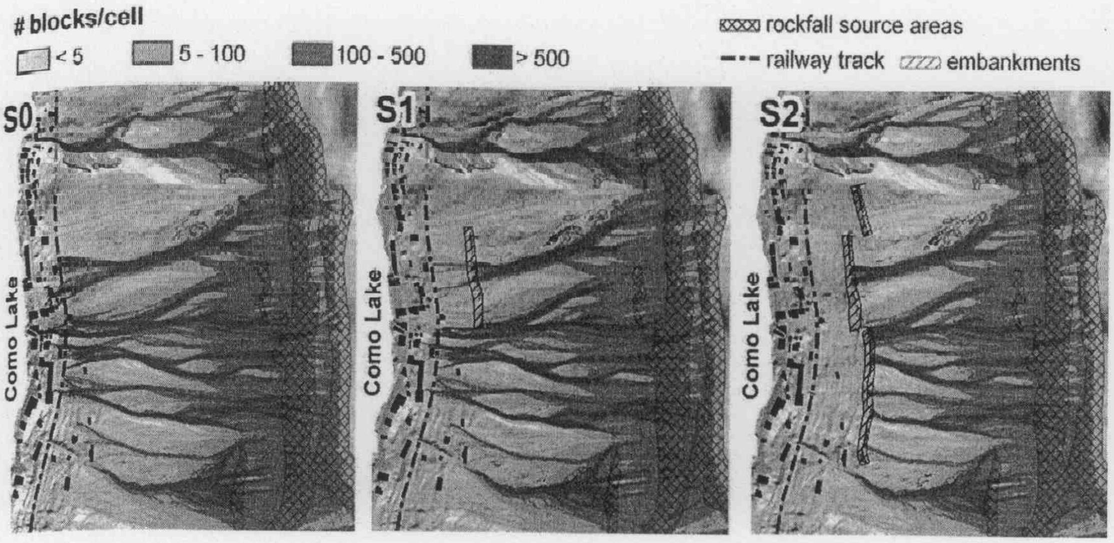

FIGURE 9-63 HY-STONE raster display showing analysis of alternative mitigation measures at village of Fiumelatte, Lake Como, Italy (adapted from Agliardi et al. 2009). (See accompanying DVD for image in color.)

rockfall in November 2004 resulted in two casualties, destruction of several buildings, and damage to transportation corridors. The HY-STONE model evaluated interactions between rockfall blocks and proposed countermeasures or structures by assessing their geometries and energy absorption capacities. An elasto-viscoplastic model (Di Prisco and Vecchiotti 2006) was used to model block impact on soft ground, whereas rockfall impacts against vegetation and fragmentation phenomena were simulated as stochastic processes (Crosta et al. 2006). The HY-STONE simulations were calibrated by backanalysis of the 2004 event, and then predictions were made for the whole area at risk by considering scenarios without protection (S0), with a provisional embankment (S1), and with a series of long-term protection embankments (S2), as shown in Figure 9-63.

6.5 RockFall Analyst

RockFall Analyst differs from the other described 3-D rockfall simulation programs in that it is not a stand-alone program but is an extension of ArcGIS (Lan et al. 2007, 2010). This linkage provides it with powerful analytical capabilities and an attractive user interface but also requires access to the commercial ArcGIS software. RockFall Analyst has two major components: 3-D rockfall trajectory simulation (Component 1) and geostatistics-based raster spatial modeling of rockfall hazard (Component 2). Figure 9-64 summarizes the typical sequence of steps used in assessing rockfall hazards with the two components of RockFall Analyst.

Component 1 of RockFall Analyst performs 3-D rockfall trajectory simulation by using a lumped-mass approach to the evaluation of rock block motions. Thus, block rotations are ignored, and the analysis is concerned with free fall (including airborne rebound trajectories) and combined rolling and sliding motions and with impact dynamics. RockFall

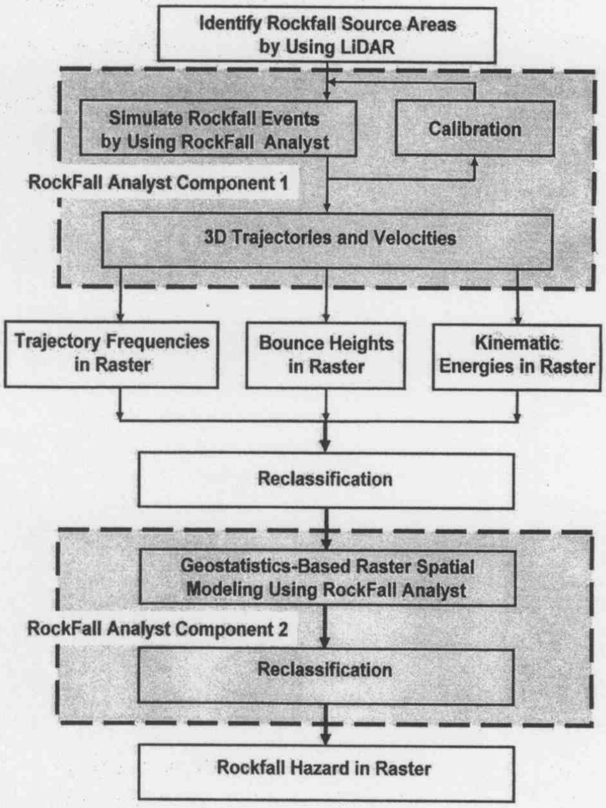

FIGURE 9-64
Rockfall hazard assessment workflow using RockFall Analyst (adapted from Lan et al. 2010).

Analyst relies on ArcGIS tools to compute slope and aspect relationships for each grid cell within a DEM. These GIS functions are described in Section 4.1.3. RockFall Analyst uses the orientation of the DEM cell at the point of impact to compute arrival and rebound trajectory angles. The values of the normal and tangential coefficients of restitution are allowed to vary within predefined limits, which provides a probabilistic character to the RockFall Analyst assessments. Lan et al. (2007) provided a detailed description of the computational algorithms used by RockFall Analyst to determine impact responses and to compute rolling and sliding block motions.

RockFall Analyst uses DEM data to describe the topographic conditions within the rockfall zone. Lan et al. (2010) emphasized the importance of a high-resolution DEM in defining these topographic conditions and recommended the use of LiDAR technology to obtain suitable DEM data. They compared the results produced by RockFall Analyst when DEM data sets with 1- and 5-m resolutions were used. They discovered the accuracy of the trajectory paths to be considerably less when 5-m grid cells were used, because many terrain irregularities were not identified. Consequently, lower-resolution DEM data produce trajectories with much less lateral dispersion.

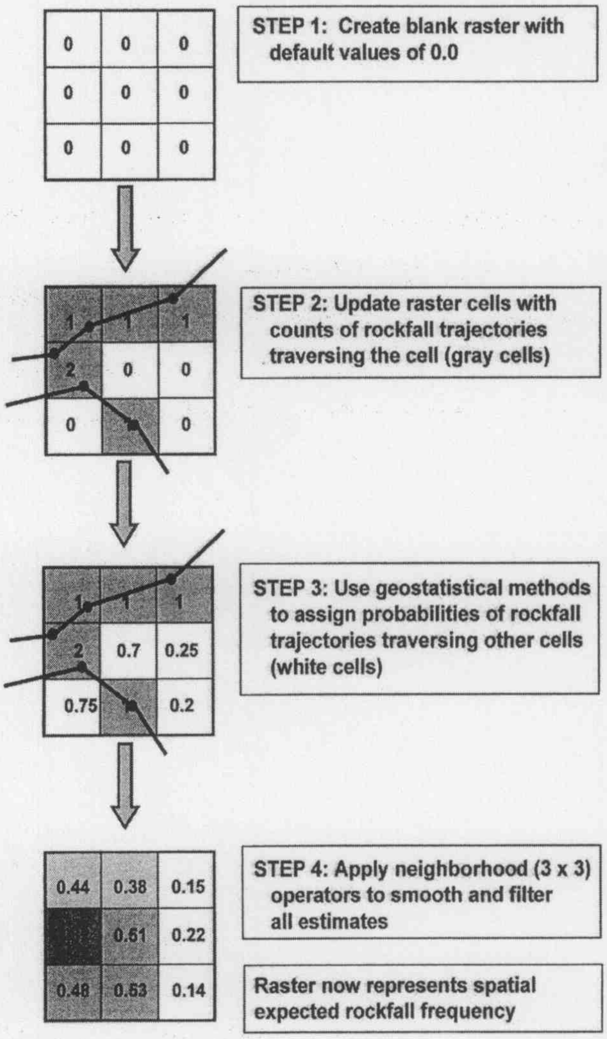

FIGURE 9-65
Four-step process used to compute spatial raster of frequency of rockfall trajectories (adapted from Lan et al. 2007).

As shown in Figure 9-64, RockFall Analyst Component 1 produces information describing a series of 3-D rockfall trajectories and translational velocities of blocks along these trajectories. Since the assumed mass of each block is also known, the velocities are readily converted to kinetic energies. RockFall Analyst evaluates this information by first summarizing the spatial distributions of the predicted rockfall trajectories by using raster GIS functions. Figure 9-65 illustrates the four-step process for converting the Component 1 trajectory information produced in vector form related to each trajectory path to a raster form required by RockFall Analyst Component 2. As shown in Figure 9-65, the process first identifies raster cells traversed by one or more trajectories. However, cells that have not been traversed by any rockfall block but that are close to cells that have been traversed have significant probabilities of being subjected to rockfall. Geostatistical spatial interpolation procedures and neighborhood filtering and smoothing functions, which are both available as ArcGIS tools, allow for the computation of these probabilities. Figure 9-65 illustrates the process for identifying the frequencies of rockfall trajectories. The same process is used to compute the probabilities for bounce heights (related to rockfall potential energies) and kinetic energies. Lan et al. (2007) provided further details of these analyses.

As shown in the middle portion of Figure 9-64, three raster products, representing the spatially distributed probabilities of the frequency of rockfall trajectories, maximum bounce heights, and kinetic energies of rockfall blocks, are used by RockFall Analyst Component 2 to undertake a probabilistic assessment of the spatial distribution of rockfall hazard. The process involves a series of reclassifications of the three input rasters, their spatial combination, and reclassification of the result. Lan et al. (2007) described this process. Figure 9-66

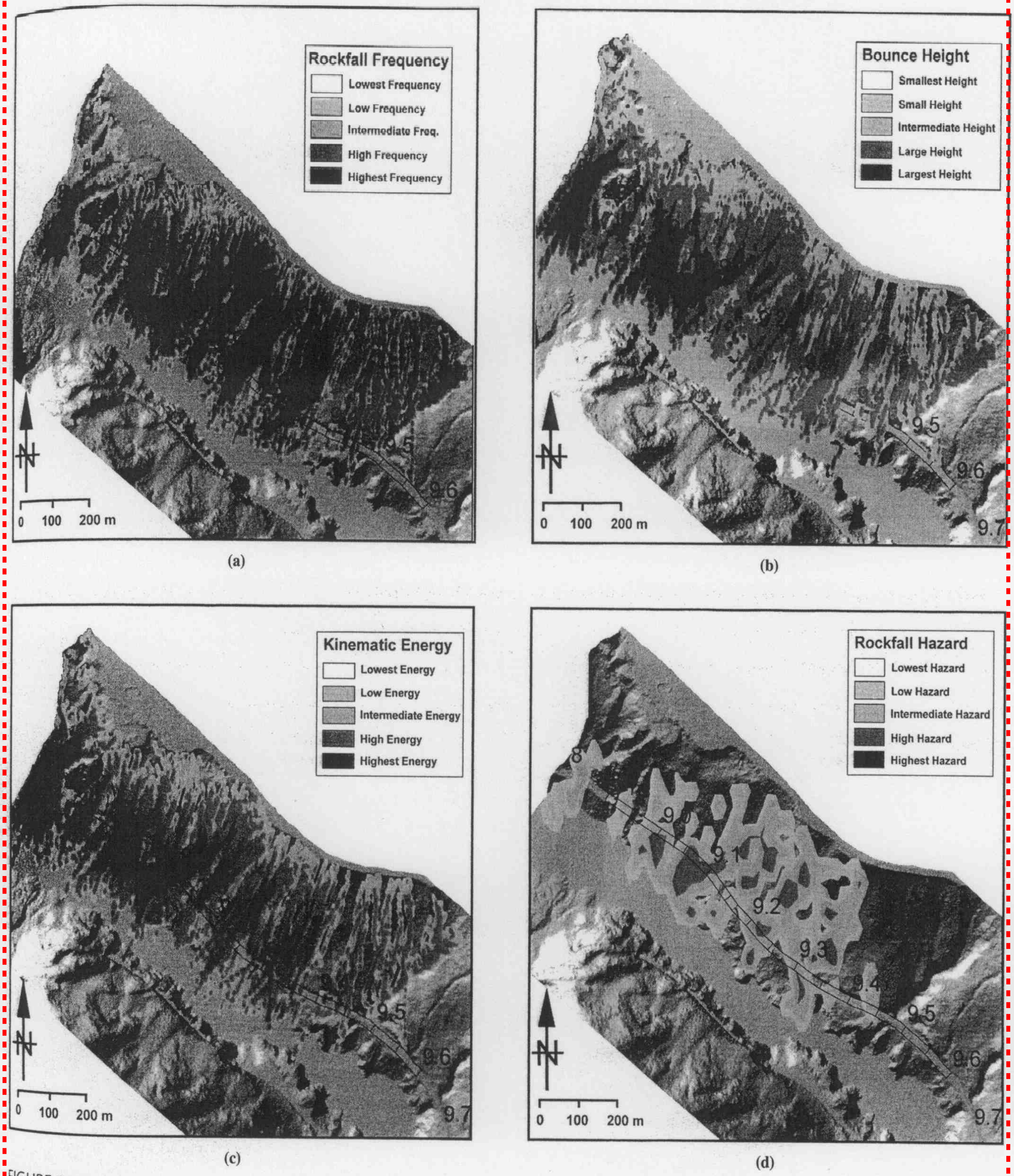

FIGURE 9-66
RockFall Analyst Component 2 probabilistic spatial analysis of rockfall hazard along Canadian National Railway in southern British Columbia: (*a*) frequency of rockfall trajectories, (*b*) maximum bounce heights, (*c*) kinetic energies, and (*d*) rockfall hazard assessment produced by combining Images *a* through *c* (adapted from Lan et al. 2010).

illustrates the RockFall Analyst Component 2 assessment of rockfall hazard for a location along the Canadian National Railway in southern British Columbia, described in detail by Lan et al. (2010).

6.6 PiR3D Program

In 2008, an experimental program was completely redeveloped to produce a new 3-D rockfall simulation program that could be easily used by engineering consultants (Cottaz and Faure 2008). The program, named PiR3D, was developed to provide a fully integrated solution that supported all the numerical evaluation aspects of a rockfall hazard investigation. Its design thus reflects the computational tools and expectations of rockfall practitioners.

Reflecting its connections to the engineering community, PiR3D has links to commercial CAD programs rather than links to commercial GIS programs, which are features of several other 3-D rockfall programs. A major difference is its use of a triangulated irregular network (TIN) to define the topographic conditions within the rockfall zone. The TIN method of representing topographic variations uses varying sizes of triangles to connect irregularly spaced elevation values. Small triangles allow for the accurate representation of highly dissected (rough) areas, while large triangles are used to represent relatively uniform (smooth) areas (Figure 9-67). TIN representations are widely used by CAD software, although most GIS programs can also use them.

PiR3D uses a simple lumped-mass approach for evaluating rockfall block motions. Thus, it only considers free fall, a combination of rolling and sliding, and impact mechanics, since it does not assess block rotations. PiR3D applies a probabilistic approach in evaluating block trajectories. It uses a combination of uniform and Gaussian probability distributions to vary values of parameters within specified limits during sequences of block motions defining a trajectory. Probabilistically selected values are assigned to the normal and tangential coefficients of restitution, a measure of dynamic friction, and perturbations of the horizontal and vertical trajectory orientations after an impact. Greater parameter uncertainties, and thus larger variations in these parameters, are allowed during lower block velocities. At high velocities, the parameters assume nearly constant assigned values. After each impact, PiR3D decides whether the trajectory continues as a free fall (a ballistic bounce) or as a rolling–sliding motion along the ground surface. If the rebound trajectory rises above the local topographic surface at an angle greater than a predefined limiting angle, the block is considered to be in a bouncing mode and the trajectory is computed as a free-fall event.

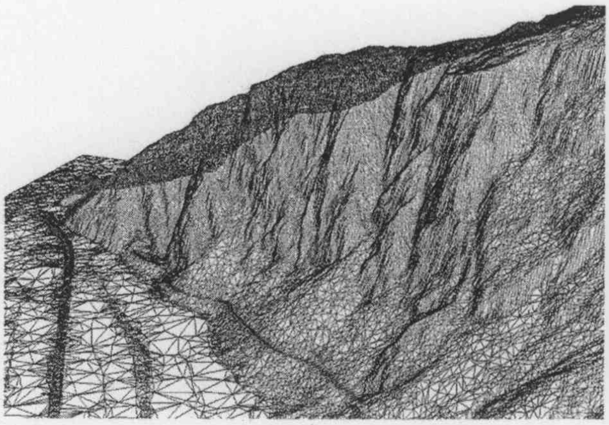

FIGURE 9-67
PiR3D uses TIN to represent topographic conditions within rockfall zone (adapted from Cottaz et al. 2010b).

Results of a PiR3D evaluation include a number of 2-D and 3-D visualizations (Figure 9-68). In addition to a variety of 3-D visualizations of the rockfall trajectories, PiR3D produces several graphical summaries of rockfall impacts at selected locations. For example, if a rockfall fence is proposed, PiR3D can provide a graph showing the energy distribution of rockfall impacts on the fence (Figure 9-68*a*) or a representation of the locations of impacts and their energies along the fence (Figure 9-68*b*). Several other analytical displays may be produced by PiR3D (Cottaz et al. 2010a).

6.7 Rockyfor3D Version 3.0

Rockyfor3D Version 3.0 combines physically based, deterministic algorithms with stochastic approaches; thus it is appropriately classified as a probabilistic process-based 3-D rockfall trajectory model. Rockyfor3D Version 3.0 has evolved from research on 2-D, and subsequently 3-D, models since 1998. The evolution of Rockyfor3D has been recorded under different names (including Rocky3 and RockyFor) in a series of scientific articles (Dorren and Seijmonsbergen 2003; Dorren and Heuvelink 2004; Dorren et al. 2004, 2006; Stoffel et al. 2006). Dorren (2010) documented Rockyfor3D Version 3.0.