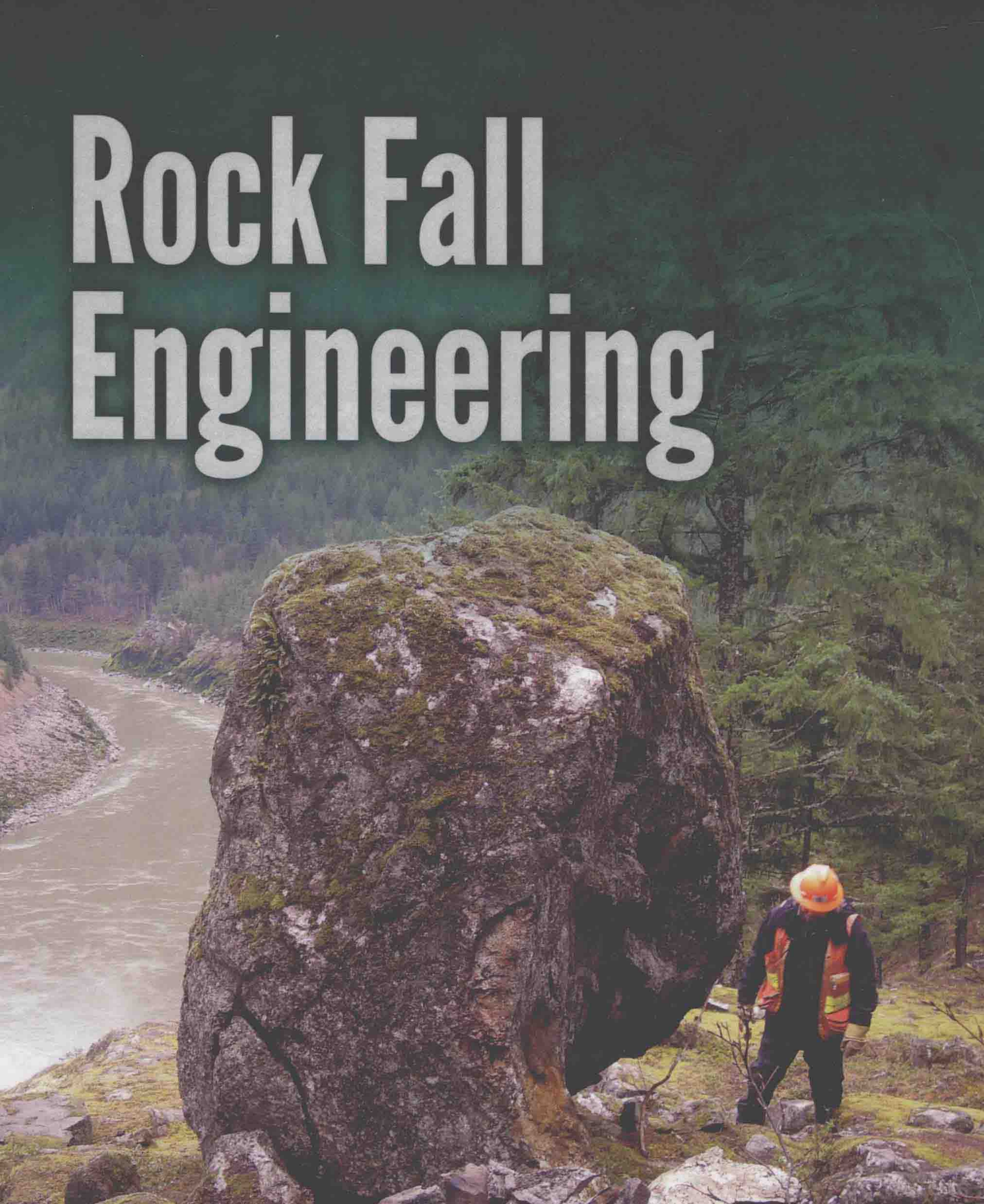
Rock Fall Engineering



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DUNCAN C. WYLLIE

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About the Author

Duncan C. Wyllie earned a physics degree from the University of London, and engineering degrees from the University the New South Wales, Australia, the University of California, Berkeley, and the University of British Columbia. He is presently a principal with Wyllie & Norrish Rock Engineers in Vancouver, Canada, a specialist engineering company working in the fields of rock slopes, landslides, tunnels, foundations, and blasting, and is a registered Professional Engineer in British Columbia, Canada.

Duncan has been working in the field of applied rock mechanics since the mid-1960s, for both civil and mining projects. These projects have been undertaken mainly in North America but also in overseas countries from Australia to Turkey. Typical assignments have included the design and construction of slopes and tunnels, foundations of bridges and dams, and the study of landslides. He carried out the initial development of a widely used hazard rating system for highways in mountainous terrain. He has also worked in the mining industry in the design of open-pit slopes, underground support, and tailings dams.

Duncan has lectured widely for 30 years, conducting training courses in rock slope engineering to state and federal highway engineers across the United States and fourth-year courses in engineering geology at the University of British Columbia. He has also authored and coauthored a number of textbooks on applied rock mechanics: *Foundations on Rock* (1st and 2nd editions in 1989 and 2001), *Rock Slope Engineering* (4th edition, 2002), both also published by Taylor & Francis, and *Landslides, Investigation and Mitigation* published by the Transportation Research Board in 2004.

Since 2009, he has been conducting research in rock falls, with particular emphasis on the application of impact mechanics to rock fall behavior, and how this can be used to model rock falls and design protection structures. The results of this research, together with nearly 40 years of experience on projects involving rock falls, are the subject of this book.

Introduction

This book on rock fall engineering has arisen from an initial passing interest in the subject as the result of extensive project work on transportation projects in the mountainous area of North America. This interest developed into a mission to fully understand all aspects of rock fall behavior and the application of this behavior to the design and construction of protection structures. Lately, this mission has evolved into an obsession to help develop improved methods of modeling rock falls and the design of more efficient and cost-effective protection structures.

As with my other two books, *Foundations on Rock* and *Rock Slope Engineering*, the intention of this book is to provide both the theory, and the application of the theory to design. In this book, this approach involves describing five case studies where the impacts are well defined, and then showing how trajectory calculations and impact mechanics can be applied to these actual rock fall conditions. It is hoped that the field data will be useful for calibration of computer rock fall simulation programs.

In addition, a wide range of well-proven rock fall protection measures are discussed. These discussions describe both design methods, and practical construction experience based on many projects in which the author has been involved. It is intended that users of this book will be both researchers working on the development of rock fall simulation, and practitioners working in the field of rock fall mitigation design and construction.

My work on rock falls has benefited from my association over many years with practitioners involved with the design and construction of mitigation structures. These people include Dale Harrison, Chuck Brawner, and British Columbia Ministry of Transport personnel in Canada; John Duffy in California; Bob Barrett, Rick Andrew, Randy Jibson (USGS); and Ty Ortiz (CDOT) in Colorado. In Japan, I have worked closely with Toshimitsu Nomura and his colleagues at Protec Engineering, as well as Dr. Masuya at Kanazawa University and Dr. Hiroshi Yoshida. Dr. Bill Stronge of Cambridge University has also been most helpful in furthering my understanding of impact mechanics as well as Dr. Giacomini at Newcastle University in Australia.

I also acknowledge my long association with the Canadian Pacific Railway and their rock mechanics engineer Tony Morris. Many of the concepts discussed in this book have developed from a wide variety of rock fall protection projects that the railway has undertaken.

The research on rock falls and the preparation of this book have involved the collection of field data and analysis of the results. I have received much valuable assistance in this work from Thierry Lavoie, Phillip Lesueur, and Tom Beingessner while they were attending the University of British Columbia. In addition, Tom Reynolds conducted the model tests of attenuator nets and canopies, Jan Meyers has spent long hours compiling references and research documents, and Rhona Karbusicky found many vital and sometimes obscure references. Most important, Cheng-Wen Tina Chen has provided invaluable assistance in data analysis and preparing drawings and in overall organization and preparation of the manuscript.

Some early funding for this work was provided by the National Research Council of Canada, and the Railway Ground Hazards Research Group in Alberta, Canada, for which I am appreciative.

I would also like to acknowledge the support of my family during yet another long period of dedication to book writing.

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North Vancouver, Canada

Foreword

After having published two highly appreciated books on geological engineering for rock slopes, then for rock foundations, Duncan Wyllie now presents a fine instructive volume on geological engineering for protecting rock cuts and engineering works potentially threatened by rock falls. This richly illustrated treatise improves the practical tools available for evaluating and remediating potential rock fall hazards that can threaten highways and developments with high-velocity rock mass impacts. This work is not intended to be a survey of various geologies and methodologies, but rather functions as a practical tutor for geologists and engineers evaluating rock fall hazards and engineering safeguards.

The book is clearly written and concise, and contains ideas refining and focusing the analytical treatment of rock fall paths, and energies, including an introduction to the fundamentals of impact mechanics. There follows a discussion of the kinematics and energy balances of bouncing trajectories affecting a rock fall's path and velocity as well as a detailed discussion of coefficients of restitution. The attention given to these important facets of rock fall engineering, which may be new to some readers, gives special value to this book.

The importance of accurately accounting for energy gains and losses during rock fall descent is very much in my mind as I recall an experience observing a series of rock fall tests at an abandoned quarry being considered for home construction. Large blocks of rock were trucked to the quarry top and released. Each block path was filmed up to its final landing. Observing from below at "a very safe distance," I witnessed some surprising block trajectories in which a large block bouncing from a rock shelf would explosively release a host of smaller block fragments on entirely new paths. After I left the site, the experiment continued and several large block pieces over-flew my previous "safe" station.

The issue of rock fall protection is well presented, with chapters on selection and design of rock fall protection ditches, barriers, nets, fences, and rock sheds. Very importantly, the application of popular computational systems for rock fall modeling is evaluated in the light of five instructive case histories.

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Nomenclature

0 Subscript for velocities at the start of trajectory ($t = 0$)
A Width of MSE barrier at impact height (m)
A Constant used in [time–force] relationship for flexible nets; acceleration
B Base width of MSE barrier (m)
B Constant used in [time–force] relationship for stiff nets
C Coefficient related to mode of failure of rock sheds; crest width of MSE barrier (m)
D Diameter of falling rock (m)
d_h Drill hole diameter (mm)
e_N Normal coefficient of restitution
e_T Tangential coefficient of restitution
E_c Energy absorbed during compression phase of impact (J)
E_e Energy efficiency for fence design
$(E_f - E_c)$ Energy recovered during restitution phase of impact (J)
E_i, E_f Impact (i) and restitution (final, f) energies for impact with protection structures (J)
F Force (N)
f Subscript for velocities and energies at the completion of impact ($t = f$)
g Gravitational acceleration ($m \cdot s^{-2}$)
H Rock fall height (m)
h Trajectory height—vertical (m)
h' Trajectory height—normal to slope (m)
I Moment of inertia ($kg \cdot m^2$)
I' Tensor defining components of moments of inertia
i Subscript for velocities at the moment of impact ($t = i$); inclination of asperities (degrees)
k Radius of gyration (m)
L Side length of cubic block; length of trajectory between impacts; bond length of rock bolts; sliding length of rock falls (m)
M Average mass of rock falls related to Gumbel extreme value theory
m Mass of rock fall (kg)
$m_{(n)}$ Mass of rock fall at impact point n (kg)
$m_{(0)}$ Mass of rock fall at source (kg)
N Subscript for the component of velocity normal to the slope
n Impact number; gradient of line for [time–force] relationship for rigid structures
P Equivalent static force in roof of rock sheds (kN)
p Probability
p_N Normal impulse ($kg \cdot m \cdot s^{-1}$)
p_T Tangential impulse ($kg \cdot m \cdot s^{-1}$)
R Frictional resistance at impact point
r Radius of rock fall body (m)

S Sliding distance (m); standard deviation of mass of rock falls related to Gumbel extreme value theory
s Dimension defining slope roughness (m)
T Subscript for the component of velocity tangential to the slope; thickness of sand cushion on rock fall sheds (m)
t Time (s)
v Relative velocity at contact point ($m \cdot s^{-1}$)
v_N Normal component of relative velocity at contact point ($m \cdot s^{-1}$)
v_T Tangential component of relative velocity at contact point ($m \cdot s^{-1}$)
V_i Velocity of centre of mass at impact time $t = 0$ ($m \cdot s^{-1}$)
V_f Velocity of centre of mass, final or restitution at time $t = f$ ($m \cdot s^{-1}$)
V_{iN} Normal component of impact velocity of centre of mass ($m \cdot s^{-1}$)
V_{iT} Tangential component of impact velocity of centre of mass ($m \cdot s^{-1}$)
V_{fN} Normal component of final velocity of centre of mass ($m \cdot s^{-1}$)
V_{fT} Tangential component of final velocity of centre of mass ($m \cdot s^{-1}$)
W Weight of sliding block (N)
x Horizontal coordinate (m); exponent in time–force power relationship
z Vertical coordinate (m)
α Angle of velocity vector relative to positive x-axis (degrees); location parameter (Gumbel extreme value distribution)
$\beta_1, \beta_2, \beta_3$ Inertial coefficients related to rotation of block during impact; scale parameter (Gumbel extreme value distribution); cushion layer thickness/rock fall diameter ratio
γ Factor of safety, fence design; density ($kN \cdot m^{-3}$)
δ Deformation or displacement or compression (mm)
δ_m, δ_v Displacement of mountain (*m*) and valley (*v*) sides of MSE banner
ε Angle defining slope roughness (m)
η Slope resistance factor used in velocity calculations
θ_i Impact angle relative to slope surface (degrees)
θ_f Final or restitution angle relative to slope surface (degrees)
K Slope gradient, trajectory calculations
λ Reduction coefficient related to loss of mass during rock falls (m^{-1}); Lamé parameter for sand cushion ($kN \cdot m^{-2}$)
μ Friction coefficient at impact point
μ' Effective friction coefficient of slope surface
$\sigma_{u(r)}$ Uniaxial compressive strength of rock (MPa)
τ_{all} Allowable rock-grout bond strength (kPa)
φ Friction angle (degrees)
ψ Dip angle–slope (s), face (f), plane (p), (degrees)
Ω Volume of rock fall (m^3)
Ω_0 Volume of rock fall at source (m^3)
ω Angular velocity ($rad \cdot s^{-1}$)

Contents

Chapter 1

Rock Falls—Causes and Consequences

In mountainous terrain, infrastructure such as highways, railways, and power generation facilities, as well as houses and apartment buildings, may be subject to rock fall hazards. These hazards can result in economic losses due to service interruptions, equipment damage, and loss of life. Rock fall hazards are particularly severe in areas with heavy precipitation, frequent freeze-thaw cycles, and seismic events (TRB, 1996). These climatic conditions exist, for example, in the Alps, on the West Coast of North America, and in Japan. In contrast, in Hong Kong, where temperatures are more mild but intense rainfall events occur, rock fall risks can also be severe because of the high population density (Chau et al., 2003).

Protection against rock fall hazards can be provided by a variety of structures that are now well proven as the result of extensive testing by the manufacturers of these systems and their use in a wide variety of conditions, as discussed in Chapters 10 and 11. These protection structures include ditches that can be designed to reasonably well-defined criteria, and will be more effective if they incorporate barriers with steep faces such as gabions or MSE walls constructed from locally available materials. In addition, proprietary fence systems have been developed that use various configurations of high-strength steel cables and wires. In some high-hazard locations, it may be appropriate to construct reinforced concrete rock sheds that incorporate energy-absorbing features such as flexible hinges and a cushioning layer of sand or Styrofoam on the roof (Japan Road Assoc., 2000; Yoshida et al., 2007).

Design of protection measures requires data for two basic parameters of rock falls—impact energy and trajectory. That is, information is required on the mass and velocity of falls to determine the required energy capacity, and on impact locations and trajectory paths to determine the optimum location and dimensions of the barrier or fence. Development of these design parameters requires the collection of relevant site data, followed by analysis of energies and trajectories and then selection and design of the appropriate protection measure.

The design process for protection structures comprises the following steps as described in this book:

- **Topography and geology**—The location of potential rock falls requires mapping to identify source areas, and the gullies in which the falls may concentrate. Geological studies will provide information on the likely size and shape of falls based on rock strength and on discontinuity persistence and spacing (Chapter 1).
- **Calibration of rock fall models**—Because of the complexity of rock fall behavior, it is useful to have data on actual rock falls with which to calibrate mathematical models. Falls on slopes comprising rock, talus, colluvium, asphalt, and concrete have been documented to provide this calibration data (Chapter 2).
- **Trajectory analysis**—The trajectory that the rock fall follows between impacts is a parabolic path defined by gravitational acceleration, resulting in translational energy

gain during the trajectory phase of the fall. Trajectories define the required height of protection structures (Chapter 3).

- **Impact mechanics**—The impact process between a rock fall and the slope can be defined by the theory of impact mechanics. Application of this theory to rock falls enables calculation of changes in tangential, normal, and rotational velocities that occur during impact, and the corresponding changes in kinetic and rotational energy (Chapter 4).
- **Coefficients of restitution**—The basic parameters defining the changes in tangential and normal velocities during impact are the corresponding coefficients of restitution. These parameters are related, respectively, to friction on the contact surface and the angle at which the body impacts the slope (Chapter 5).
- **Energy losses during impact**—The result of velocity changes during impact are corresponding changes to the translational and rotational energies of the body. The energy changes are the result of the frictional resistance to slipping/rolling in the tangential direction, and plastic deformation of the body and slope in the normal direction (Chapter 6).
- **Rock fall modeling**—Computer programs have been developed (by others) to model rock fall behavior and provide ranges of energies and trajectories for use in design. The principles of modeling are discussed, and the case studies described in Chapter 2 have been simulated in a widely used commercial rock fall modeling program to determine the parameters required to reproduce these actual events (Chapter 7).
- **Selection of protection structures**—Selection of the appropriate protection structure for a site involves first having a rational means, such as decision analysis, of selecting the required level of protection. Selection of rock mass values to use in design may involve statistical methods to extrapolate limited field data on rock fall dimensions. This analysis calculates the frequency of occurrence of design blocks with masses larger than those observed in the field (Chapter 8).
- **Design principles of protection structures**—Optimizing the absorption of impact energy by fences is related to attenuation in which the rock fall is deflected by the net, and the energy is absorbed uniformly over the time of impact. These attributes will limit impact forces generated in the structure (Chapter 9).
- **Protection structures**—Methods of protecting against rock falls include ditches, barriers, fence, nets, and rock sheds. Each structure has a specific range of impact energy capacity and suitability to the topography at the site, such as ditches, barriers, fences (Chapter 10), and rock sheds (Chapter 11).

1.1 SOURCE ZONES AND TOPOGRAPHY

Identification of rock fall source zones usually requires careful field investigations, possibly involving examination of air photographs, helicopter inspections, and climbing the slopes. Evidence of recent rock falls may include open tension cracks and fresh exposures on the rock faces, impact marks on trees along the fall path, and accumulations of falls on the lower part of the slope. It is also found that falls tend to collect in gullies, in the same way that water flows down valleys. That is, falls from a large area of the slope will accumulate at the base of gullies, a condition that can allow protection structures to be located only at these topographic features.

Other factors influencing rock fall behavior are the slope angle and the slope material. Figure 1.1 shows a typical slope configuration and the corresponding rock fall behavior on four zones of the slope as follows:

- **Rock slope**—On steep, irregular rock slopes, falls will have widely spaced impacts, high-speed translational and rotational velocities, and high-angle trajectories.
- **Colluvium slope**—On slopes that are just steeper than the angle of repose (i.e., if greater than 37 degrees for loose rock fragments), closely spaced impacts and shallow trajectories will occur, but falls will not accumulate on the slope.
- **Talus slope**—Falls accumulating on talus slopes form at the angle of repose ranging from about 37 degrees in the upper portion to 32 degrees near the base. Rock falls undergo a natural sorting when they reach the talus with smaller fragments accumulating near the top and larger ones reaching the base, such that the talus deposit enlarges uniformly forming a cone-shaped deposit.
- **Run-out zone**—A few of the larger, higher energy blocks may move beyond the base of the talus and on to a slope that is flatter than the talus. It has been found that the maximum run-out distance for these blocks is defined by a line inclined at about 27.5 degrees from the base of the steep rock slope; this angle represents the rolling friction coefficient of rock falls (Hungr and Evans, 1988). Within the run-out zone, rock falls move in a series of closely spaced impacts or rolling action, which means rocks can be readily stopped in this zone with shallow ditches or low fences.

The run-out zone as defined in Figure 1.1 has important implications for identifying hazards zones below rock slopes, and the need to install protection measures and/or establish development exclusion zones. Objects at risk that may be found within run-out zones include roads with low traffic volumes or golf courses that require little or no protection, to houses with full-time occupants that require high-reliability protection measures such as fences or barriers.

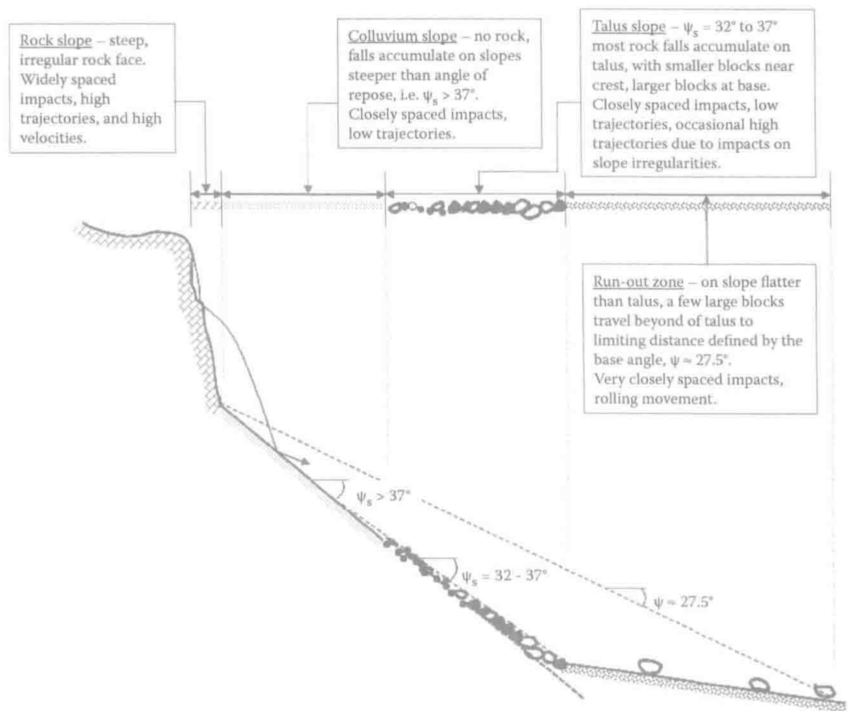

Figure 1.1 Typical slope configuration showing the relationship between slope angle and rock fall behavior.