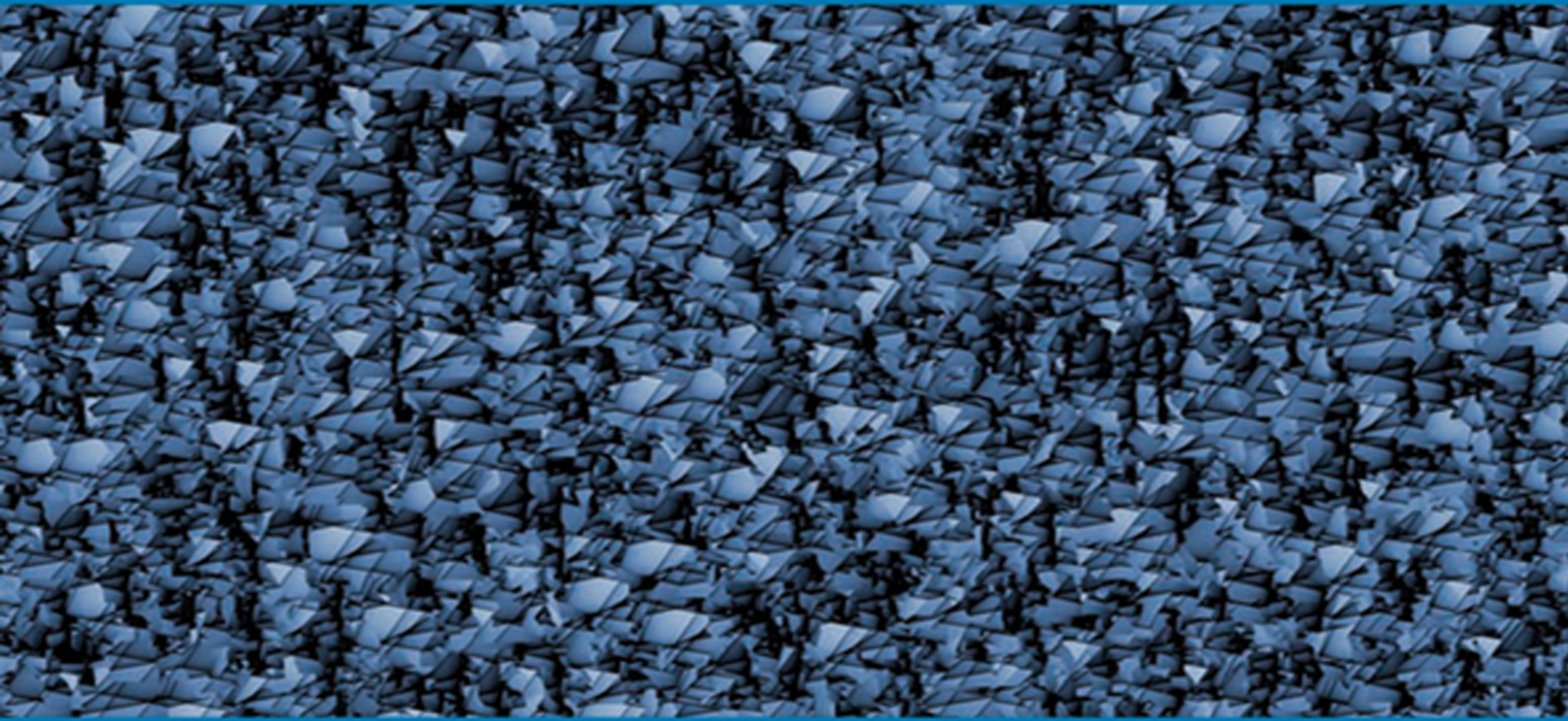

Rockfall Engineering

Edited by
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Table of Contents

Foreword

Rockfall engineering is a practical field which is currently evolving very rapidly for at least three reasons:

– the first one is linked to the experimental revolution in the measurement and monitoring means, used to quantify the displacements fields in situ in a very accurate manner (global positioning systems, photogrammetry, etc.) and to characterize the kinematic discontinuities existing at various scales in all rock bodies (laser scanning, InSAR techniques, novel geophysical methods, etc.);

– the second reason corresponds to the unexpected power of the new numerical methods to catch and describe quantitatively the main continuous and discrete aspects in the deformation of a rock cliff, in its failure and finally in the flow of the resulting blocks;

– both the first reasons have induced the current considerable enlargement of the available techniques to preserve constructions and infrastructures subjected to rockfalls, by considering not only various types of embankments or rigid structures but also flexible ones with net barriers.

These three questions are successively treated in a logical way in this book, each time with the most advanced methods, tools or technical designs. Thus, new measurement techniques are considered in Chapters 1 and 2, more recent numerical methods in Chapters 3, 4, 5 and 6, and the applications to advanced mapping and to modern rockfall protection systems in Chapters 7 to 12.

By walking in mountainous regions everybody can in fact observe the continuous nature of the rock matrix and, on the other hand, the discrete aspects of rock blocks. By considering the first aspect as predominant, that has led us to analyze rock slope stability by the methods of limit equilibrium then generalized into the methods of limit analysis (Chapter 3). These methods generally consider the rock body as a rigid-perfectly plastic material along some *a priori* given failure surfaces, ignoring the influence of the strain history on the failure limit state. By essentially preserving the continuity assumption, the finite element method has allowed us to develop stress-strain analyses and to no longer assume some *a priori* failure surfaces.

However rock failure is generally discontinuous and to take this aspect into account properly some numerical methods stemming from molecular dynamics are now available. One of them is particularly adapted to rock mechanics; this is the so-called "discrete element method", where (as generally in molecular dynamics) the rock blocks are considered as geometrically isolated individuals in interaction with each other. This kind of analysis allows us, in a very natural manner, to develop trajectory analysis tools, which are currently able to describe the propagation of a rockfall (see Chapters 5, 6 and 7) in a more quantitative way following the basic advances in rebound mechanics (Chapter 6). The kinematic discontinuities in a rock slope are usually called "rock joints", which are generally infilled by some natural geomaterials mainly coming from the aging, degradation and damage of the rock matrix.

In rock geomechanics, it is usually assumed that the stress-strain macroscopic behavior of the rock slope is essentially due to the behavior of the rock joints (Chapters 3 and 4), which thus constitutes the critical point of any failure modeling of a rock body. From a rheological point of view, an infilled rock joint is a visco-elastoplastic material, whose behavior depends strongly on climate conditions through the hydro-mechanical coupling with the interstitial water and the influence of frost/thaw cycles. These last aspects can be considered as still open questions on an international level. Coming back to the visco-elastoplastic behavior of a rock joint and considering only the fast catastrophic collapse modes, it is usual today to restrict the analysis to elastoplastic rock joints.

Having mentioned above the dual nature of a rock body (continuous and discrete), two scales appear in the analysis, the macroscopic one (i.e. the rock slope), which can be considered basically as continuous at this scale, and the mesoscopic one (i.e. the rock blocks), essentially discrete. The microscopic scale (the rock matrix constituting the blocks) must sometimes be considered to describe the block breakage for example. Thus, another question plays a fundamental role in any rock slope modern stability analysis: how can we upscale from the mesoscopic scale to the macroscopic one? With a discrete element method the upscaling is performed numerically in a direct way (Chapters 3 and 4), on the other hand, some analytical homogenization techniques are also now being considered with some success.

Finally, this book provides an up-to-date state of the art, by reviewing in situ measurement techniques, numerical and analytical tools for rock slope and protective system simulations for one of the most important gravity-driven natural hazards and risks: rockfall. Taking into account the continuously increasing number of constructions and infrastructures subjected to this risk, this book is especially welcome! Besides its rich scientific and technical content, its international opening and its pluridisciplinary character makes its subject particularly attractive. We hope you enjoy reading it!

Félix DARVE
July 2011

Introduction

This treatise aims to propose a synthesis that is devoted to rock instabilities, based on contributions from worldwide academics who are actively involved and well recognized in this domain. It is intended for engineers, students and researchers in the domain of civil engineering, transportation, risk management, protection structures and rock engineering.

This treatise considers the three main stages of the phenomenon, namely the triggering of rockfalls, the propagation of falling rocks, and the interaction of rocks with protective structures. The primary scientific breakthroughs achieved recently will be presented in a pedagogical way, with a strong connection to the potential applications expected in both expertise and engineering fields.

Rock instabilities continue as a major menace for mountainous areas, and, more broadly, for any territory with abrupt rocky cliffs. Managing this risk, for a given site, requires that the hazard be properly analyzed, by accounting for likely evolution due to weathering effects during a global climate change. This risk management also involves the development of efficient design tools, which can be adapted to the specific protective structures that can be set up.

Over recent years, significant advances have been made in both in-field experimental investigation (giving rise to a better characterization of rock scarps, along with the associated instability mechanisms), and the numerical techniques with powerful computational capacities. New methods and tools have been developed for practitioners, followed by significant improvement in the risk management domain.

Hence, the purpose of this treatise is to synthesize the existing knowledge and the available tools, by maintaining a balance between a pedagogical style adapted for most of the practitioners, and the scientific rigor expected to present the advanced methods developed.

The treatise is organized around 12 chapters, and is arranged to abide by the chronology of the phenomenon. The first 4 chapters address the rockfall risk, by describing tools and methods for the cliff description and monitoring and, investigating the mechanisms leading to rupture. Then, methods used for estimating run-out zones and rebound models are presented and discussed. On this basis, mapping and risk management are considered in 2 chapters. Finally, the last 4 chapters investigate the mechanical behavior of protective structures in order to propose new, robust methods to design such specific structures.

The content of the treatise is given thereafter, including a short description of each chapter.

Chapter 1: Geophysical Detection and Characterization of Discontinuities in Rock Slopes

The stability of a potentially unstable rock mass strongly depends on the discontinuity pattern and the face topography. Basic geological analysis could provide useful structural information, but suffers from the lack of information on discontinuities at depth. Of major importance is the persistence of discontinuities inside the rock mass. Several geophysical methods (seismic, electric and electromagnetic) are available to address this problem. These methods differ in sensitivity, resolution and depth penetration.

The purpose of the chapter is to present the common geophysical methods used for characterizing the rock mass. Section 2 is dedicated to a review of the principal geophysical parameters and methods, as well as their possibilities and limitations for discontinuity detection and characterization. In section 3, applications of the aforementioned methods are shown for three limestone cliff sites located around Grenoble (French Alps), exhibiting different geometrical and geotechnical features.

Chapter 2: Remote Sensing and Monitoring Techniques for the Characterization of Rock Mass Deformation and Change Detection

Hazard assessment, as well as monitoring, requires understanding the mechanism of rock instabilities and the quantification of deformation velocities. For several decades, classical field investigations as well as displacement measurement devices have been used, and they are still considered the basic approaches for such purposes.

Recent technologies such as remote sensing have profoundly changed the approaches of surveying and monitoring. The terrestrial and airborne laser scanners and photogrammetry provide 3D terrain representations which permit us to conduct structural analysis and deformation monitoring. The InSAR techniques have shown that most of the slopes in mountainous areas are moving down, indicating that the slope processes are not as well understood as we could expect. In addition, the increasing power of computers makes some data treatment fast enough, such as image comparison, which could soon be used in the daily routine. The current challenges involve fully using these new techniques to improve monitoring and characterization of rock masses.

Chapter 3: Mechanical Stability Analyses of Fractured Rock Slopes

In this chapter we will examine the mechanical behavior of a fractured rock mass which is considered as a block assembly separated by joints. We will focus our attention on joint behavior, and consider, by simplification, that failure occurs predominantly in pre-existing discontinuities and not in the rock matrix.

In order to comment on rock slope stability, the complete behavior of a joint under different solicitations is considered. This behavior is broadly studied in the laboratory and is only briefly described here. Since in most of the cases we are concerned about the gross stability of a block rather than internal deformation and failure of the blocks, failure computation of rigid blocks is initially considered. By failure computation we mean that we have considered that rockfalls occur when a failure criterion in joints is reached.

The methods that deal with deformability by taking into account displacements occurring along rock joints and possibly rock mass deformability are presented in this chapter. An example of such stress-strain analysis, with deformable rock joints but with blocks still rigid, is presented here. Emphasis is laid on describing, as well as possible, the mechanical behavior of rock joints. The used constitutive relation links for example tangential and normal behaviors of the joints (e.g. dilatancy). In addition, an appropriate failure criterion is considered so that all kind of failures can be predicted. This leads finally to a comprehensive stability analysis of an existing rock slope.

Chapter 4: Assessment of Constitutive Behaviors in Jointed Rock Masses from a DEM Perspective

Failure mechanisms in a rock mass are due to the combination of intact rock failure and discontinuity failure. Rock slope stability analysis therefore requires the assessment of constitutive behaviors at different levels, intact rock, rock discontinuities and the rock mass itself. The mechanical behaviors of intact rock and discontinuities are usually characterized through a series of laboratory tests performed on small scale specimens. However, it is not possible to test full discontinuities or the rock mass to characterize their behavior in the field. Various empirical schemes have therefore been developed. This chapter describes new developments for assessing the constitutive behaviors of discontinuities and rock masses. Combining a discrete representation of the rock with a specific contact model for the representation of discontinuities (namely the smooth joint contact model) we can generate a synthetic rock mass or rock joint. These virtual specimens only require easily measurable data and are representative of the field situation. They are then numerically tested under various loading conditions (e.g. direct shear tests for the synthetic rock joints, unconfined compression test for rock mass specimens). Complex behaviors such as anisotropy and scale dependency can be quantified without requiring any arbitrary empirical relationship which can be later on, incorporated in conventional slope stability analysis.

Chapter 5: Methods for Predicting Rockfall Trajectories and Run-out Zones

A further application of a rockfall trajectory simulation model will not suffice for performing rockfall trajectory analysis. In addition, in the 21st Century, rockfall trajectography without the use of rockfall trajectory and run-out zone models is unthinkable. A typical serious workflow of a rockfall trajectory study at the scale of a community or a single slope can be divided into 6 phases: A) preparation phase; B) definition of the release scenarios; C) rockfall modeling and simulation; D) plausibility check/validation of the model results; E) fixation of the model results; F) transformation into readable rockfall process maps. This chapter is structured according to the presented workflow. By doing so, we will systematically go through all the phases which are required for completing a rockfall trajectory study. As such, it will provide us with an overview of available rockfall models and present existing solutions for the integration of protective measures, either being technical structures or existing forest cover, in rockfall trajectory and run-out zone models. In the end, this chapter will provide an outlook toward potential future improvements in methods for predicting rockfall trajectories and run-out zones.

Chapter 6: Rockfall Dynamics: A Critical Review of Collision and Rebound Models

Rockfall propagation is classically described with 4 different types of motion (free flight, sliding, rolling, rebound), although most of the rockfall simulation codes consider rockfall as a succession of free flight and collision/rebound phases. Due to the complexity and variability of the interaction of a falling fragment with the soil or rock surface that forms the slope, several approaches for modeling the rebound have been developed by focusing on different aspects of this process. In this chapter, the physical processes relevant to the collision and rebound are initially detailed and illustrated. Second, the different types of rebound models are described. In this presentation, existing models are separated into approaches by considering the rock as a material point or as a solid with a specific shape and dimensions. The different approaches used to account for rebound variability are also discussed. For each model type, the advantages and limitations of the approach are highlighted.

Chapter 7: Rockfall Hazard Zoning for Land Use Planning

This chapter deals with guidelines and methodologies for assessing and zoning rockfall hazards for urban development planning. Depending on the purpose of the study, scale, as well as on the availability and quality of data, several methods are available. Each method is based on specific approaches and assumptions. An overview of currently available guidelines and zoning methodologies at the regional scale is initially provided. Then, since a detailed hazard zoning is required at the local scale for the purpose of planning urban areas, particular attention is paid to methodologies whose degree of detail and amount of information are suitable for this implementation. Precisely, methodologies based on trajectory modeling and, according to the definition of hazard, on the characterization of rockfall intensity and frequency, fulfill these requirements. Several methods are presented and their differences are highlighted. It is pointed out that it is not easy to pass from trajectory simulation results to hazard zoning. The last but one section presents further uncertainties and problems, which emerge in the elaboration of hazard maps. They are related to both departure zone characteristics and trajectory modeling results. Finally, the last part emphasizes how national guidelines have conditioned the development of zoning methodologies, which allows us to understand some of the reasons/sources of non-homogeneity in the currently used worldwide approaches. These considerations underline how social and political criteria (i.e. risk acceptance and risk management) will have to be carefully considered when comparing methodologies used in different countries and/or when transferring knowledge or approaches for hazard zoning from one country to another.

Chapter 8: Rockfall Quantitative Risk Assessment

In this chapter, the current practices that are used for the quantification of the risk due to rockfalls and their involved aspects are reviewed. The concepts and usefulness of the rockfall risk assessment are discussed, with emphasis on the quantitative approaches which yield results in probabilistic terms. The descriptors that serve for measuring the risk are summarized, for example the number of events per km per year for the hazard, and the annual probability of loss of life or the loss in €/year for the risk. The QRA (quantitative risk assessment) goals are presented as a determining factor for the selection of work-scale and methodology. Depending on the objectives of the risk assessment, the analysis might vary from the area (where an entire area is involved for considering the susceptibility of the rockfall sources, the spatial block propagation and the relative location of all the exposed elements to the rockfall run-out), to line (the phenomenon is analyzed and data are collected only across a reference section, i.e. for a road) and then to a specific location (where the phenomenon is analyzed and data are collected only at a specific point, i.e. a building). Risk components and some important aspects for their assessment are presented and relate to the source of data, the rockfall occurrence, the rockfall run-out and the exposure and vulnerability. Vulnerability is calculated based on the expected damage. Existing practices which are followed for assessing the risk based on the aforementioned risk components are presented in this chapter, along with the scenario-based calculation of the risk by aggregation of the partial risks for different rockfall magnitudes. At the end, some of the examples are used for the description of rockfall risk assessment methodologies.

Chapter 9: Multi-scale Analysis of an Innovative Flexible Rockfall Barrier

To protect traffic and more generally infrastructures against this natural hazard, many types of protective measures can be used, depending on the kinetic energy of the falling block. Flexible net barriers are commonly used as mitigation structures. In recent years, different types of wire-nets have been developed. An innovative concept was proposed by the GTS company. This cable-net system consists of pear-shalled cells, which confer an orthotropic behavior to the rockfall net. These cells are connected with rigid or fuse clamps. In this contribution, an extensive experimental campaign is conducted. A multiscale approach is adopted in order to qualify the behavior and quantify the bearing capacity of each individual component of the GTS rockfall barrier. Finally, full scale tests are conducted on the entire structure and at the same time, numerical models are used to explore and better understand the mechanical response of the structure. In order to enhance the capacity of the structure (maximum allowable load for a minimum cost), parametric studies have been carried out to identify the influence of parameters that are related to the structure resistance.

Chapter 10: A New Design Method for Rockfall Shelters Covered by Granular Layers

This chapter concerns the definition and discussion of an uncoupled approach for the design of rockfall protection tunnels. More precisely, this approach concerns tunnels covered by granular soil strata, and it derives from the interpretation of real scale experimental tests on a real structure.

This approach is based on the hypothesis of interpreting the mechanical response of the system by starting from the evaluation of the impact force acting at the boulder-soil interface, and by describing the propagation of stresses through the soil stratum. The experimental basis of the proposed method, and the modeling tools which are employed to analyze the mentioned sub-phenomena, are described in dedicated sections. Engineering considerations about the dynamic excitation of the reinforced concrete structure (the sheltering tunnel) are also suggested on the basis of the behavior observed during experiments. Finally, a section is devoted to an application of the method.

Chapter 11: Design Procedure for a Three-Layer Absorbing System for Rockfall Protection Galleries

In order to absorb and disperse the impact force resulting from falling rocks, a three-layer absorbing system has been developed, which comprises sand cushion (top), reinforced concrete (RC) core slab, and Expanded Polystyrene (EPS) block (bottom). The applicability of this system was confirmed by conducting many prototype impact tests by means of falling-weight impact tests.

This chapter has focused on an example that relates to the case of setting sand cushion analysis. This example is used to explain the prediction equation of the maximum impact force due to a falling weight. This equation was derived on the basis of Hertz's contact theory. In addition, absorbing performances of a sand cushion and three-layer absorbing system were compared based on the experimental results. After that, the practical design procedure on main parameters of the system: thicknesses of RC core slab and EPS block, and transmitted impact force, was developed, so that the procedure can be easily applied in actual rockfall protection galleries. The design values obtained from the procedure were compared with the experimental results. It is seen that the proposed procedure can be applied in design practice.

Chapter 12: Ground Reinforced Embankments for Rockfall Protection: From Real Scale Tests to Numerical Modeling

Despite the large number of constructed rockfall protection embankments, a design procedure has not been completely defined so far, due to the non-linear stress-strain behavior of the soil, the large deformations that occur during an impact, the uncertainties regarding the dynamic behavior of the soil, and the soil-reinforcement interaction. In order to understand the behavior of ground reinforced embankments during impact, a few full-scale tests have been carried out by various authors in various countries. These experiments were indeed operationally complex and costly. In fact, the complexity relates to the experiments. A limited number of tests were performed because of their complexity and cost. For this reason, numerical models were developed for studying ground reinforced embankments, along with back-analysis of the results of full-scale tests. The results of the full-scale tests carried out on prototypes of reinforced ground embankments are summarized and discussed to provide a basis for the understanding of the behavior of these structures. Then the results of numerical model computations are described. These models have been validated based on the back analysis of previous real scale experiments, as well impact due to real events.

Chapter 1

Geophysical Detection and Characterization of Discontinuities in Rock Slopes

1.1. Introduction

Rockfalls pose critical problems to risk management in mountain areas. Rockfalls are difficult to predict due to phenomenon suddenness, lack of identified reliable precursors, poor information on the internal structure of the rock mass and the multiplicity of triggering factors (freeze thaw cycles, earthquakes, human activities, water infiltration) [FRA 06]. Rock mass stability assessment requires detailed investigations of the discontinuity pattern and the 3D geometry of the potential unstable block [HOE 81].

In the context of rock cliffs, three types of investigations can be performed for predicting rockfalls:

1. geological and structural observations of the cliff face and the plateau, including in open rock fractures on cliff or rocks where they are accessible;

2. remote sensing measurements (mainly photogrammetry and laser scan), which would enable us to obtain a digital surface model of the cliff;

3. geophysical experiments conducted on the plateau and/or on the cliff face.

The remote sensing techniques and their applications for monitoring rock slopes are described in Chapter 2 of this book and will not be discussed here. This chapter

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will focus on the description of geophysical methods which are useful in this context, since they allow us to delineate the mass fracture pattern from measurements on the plateau and/or on the cliff face. A review of the different geophysical methods and their sensitivity has been provided initially. In the second part, case studies performed on various cliffs around Grenoble have been discussed.

1.2. Geophysical parameters and methods

1.2.1. *Introduction*

Geophysical methods have been increasingly used for slope investigation (for a review see [JON 07]). They are based on physical measurements conducted in the field from which physical parameters can be deduced, generally through an inversion or imagery process. The measured data and corresponding parameters have been summarized in Table 1.1 for the main geophysical techniques (seismic, electrical, gravimetry, magnetism, electromagnetism, radar). It is beyond the scope of this chapter to detail the methods that are described in general books [TEL 90, REY 97, SHA 97, KEA 02]. Geophysical techniques offer many advantages, as compared to geotechnical techniques. Geophysical techniques are fast, non-invasive and deployable on slopes. In addition, they allow us to investigate large volumes of material and provide 2D or 3D images of the subsurface [JON 07]. On the other hand, contrary to geotechnical techniques, they suffer the following drawbacks: i) when measurements are made at the surface, their resolution decreases with depth; ii) the solution is generally non-unique for a given data set, except for reflection-based methods, and iii) they provide physical parameters instead of geological or geotechnical properties. These characteristics outline the complementarities between the two families of investigation techniques.

Method	**Measurement**	**Physical parameter**
Seismic	Propagation time	Wave velocity
Electrical	Electrical potential	Electrical resistivity
Gravimetry	Gravitational acceleration	Density
Magnetism	Magnetic field	Magnetic susceptibility
Electromagnetism	Electromagnetic field	Electrical resistivity
Radar	Propagation time	Dielectric constant

Table 1.1. *Major geophysical techniques, corresponding data and derived parameters*

Selection of the geophysical methods is based on the problem to be solved. [MCC 90] has identified 4 factors which have to be considered while designing a geophysical survey: the existence of a geophysical contrast corresponding to the campaign target (e.g. the limit of the sliding mass), the penetration depth and the resolution (ability of the method to detect a body of a given size or thickness at the desired depth), the quality of the geophysical signal (noise perturbations) and the necessity to calibrate the geophysical results by geotechnical and geological data. This often requires that preliminary tests be conducted before designing a geophysical survey.

In the context of rock stability assessment, the two principal objectives of geophysical experiments are usually to characterize the fracturing pattern inside the rock mass and to delineate the prone-to-fall block geometry. In the context of a cliff or high slope geometry, measurements can be performed on the top (plateau) or on the cliff face (Figure 1.1). Geophysical investigation of the plateau may provide valuable information about the continuity of out-cropping structures (fractures, faults) or the rock quality [DUS 03, BUS 06, HEI 06]. However, the investigation depth could be low, when compared to the cliff height, and the method resolution method generally decreases with depth. Whenever possible, the use of GPR (ground-penetrating radar) on the cliff face has been found to be the most valuable tool, in terms of resolution for investigating a rock mass [DUS 03, ROC 06, JEA 06, DEP 07, DEP 08]. However, the use of GPR for cliff investigation can be limited due to safety requirements for abseiling (climbing down the front of a large rock while holding on to the rope) and by the penetration depth which can be reduced due to low electrical resistivity values of the rock.

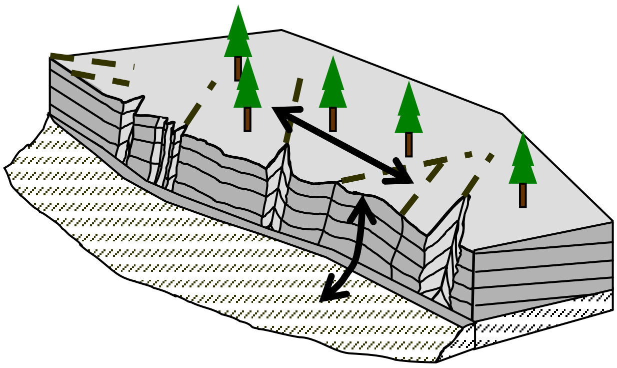

Figure 1.1. *Cliff geometry showing bedded limestone overlying a marl layer, along with the location of potential geophysical profiles (double arrows) on the plateau or on the cliff face. Fracturing is highlighted with bold dotted lines*

In the following subsections (2.2 to 2.5) the main physical parameters and the associated methods applicable to rockfall investigation have been described. The first three geophysical parameters (seismic velocity, electrical resistivity and dielectric permittivity) are common properties, which are used in many engineering and environmental geology applications [REY 97]. On the contrary, the resonance frequency, which is derived from seismic noise tests records, is a mechanical parameter which is frequently used for seismic site effect assessment [BON 06], but, is rarely applied to rockfall hazard assessment.

1.2.2. *Seismic velocity*

1.2.2.1. *Background*

When a local stress on a material (with a seismic source for example) is applied, an elastic strain energy would be propagated as seismic waves. Depending on the seismic source considered, two types of volume waves are generated, i.e. compression-dilatation waves (P waves) and shear waves (S waves). As P waves generate a volume change without any rotation of the material particles, particle displacements would occur in the direction of propagation. For S waves, particle movement is located in a plane that is perpendicular to the wave propagation direction. In any seismic survey, the main parameter which may be easily quantified is the seismic velocity distribution. It may be assessed with a certain resolution, which depends on the seismic method used (reflection, refraction, tomography), on the seismic source (frequency content), and the source-receiver configuration. Considering an elastic material, P and S wave velocities can be expressed as a function of elastic parameters, by assuming that the considered material in the absence of interstitial water is isotropic: (subsurface water contained in pore spaces between the grains of rock).

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad \textit{and} \qquad V_s = \sqrt{\frac{\mu}{\rho}} \tag{1.1}$$

where λ and μ are the Lamé (coefficients describing the relation between stress and deformation in linear elastic) and ρ is the density of the material. It is clear from this relation that P wave velocity (Vp) is always greater than S wave velocity (Vs).

Presence of fractures or faults within the rock mass reduces the wave velocities. The decrease of wave velocities depends on the size, density and properties (filling, aperture) of fracture. Air-filled fractures can induce a stronger velocity reduction, than a filling with water (Vp = 1,500 m/s compared to 300 m/s). Velocity sensitivity to fractures and the resulting anisotropy have been increasingly analyzed by oil companies for reservoir purposes, but have been seldom quantitatively analyzed in rock engineering applications [MAV 95]. 2D and 3D seismic tomography can