Chapter 1

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INTRODUCTION

This Special Report is organized into five major sections with 25 chapters. Although considerable efforts were expended to eliminate repetition of material in different chapters, some reiteration was necessary to provide continuity of thought and to allow adequate explanation of specific topics. Such repetition was judged more acceptable than excessive referral within the text to other sections and chapters.

In accordance with the evolution of this series of reports, the new title, *Landslides: Investigation and Mitigation*, was selected to reflect the increased knowledge of landslide processes, the procedures for landslide investigation that are now available, and the much more complex regulatory and economic climate under which landslide investigations and corrective actions must be undertaken. In fact, the titles of these reports since the first in 1958 mirror changes in societal values at least as much as evolution in scientific knowledge and engineering technologies. The 1958 report reflected engineering practice in resolving landslide instabilities along transportation facilities; the report published in 1978 reflected the evolving strategies for analysis and control of landslides.

In the years since the last volume was published in 1978, there have been many advances in the way landslide investigation and mitigation are conducted. Chief among these advances are the advent of the personal computer, the availability of new geotextile products, and new understandings of the behavior of earth materials. Personal computers have allowed numerical stability analysis methods to become commonplace; the use of geotextiles presents options for better and more economical mitigation procedures; and the improved methods for field investigations coupled with new understanding of landslide processes supply better data and concepts to the landslide analysis process.

However, landslide investigation and mitigation have been even more greatly affected by the imposition of environmental regulations and economic considerations. Throughout the world there has evolved a much greater appreciation of the impact of human activities on the natural environment. Consequently, the investigation of slope instabilities has been increasingly integrated with broader land use planning and land development activities. New transportation facilities, and the renovation or improvement of existing facilities, are frequently required to incorporate design elements that reflect natural landscape conditions and minimize visual impacts. In many hilly or mountainous terrains, such requirements translate into sophisticated landslide investigation and mitigation actions.

1. INTENDED AUDIENCE

Although slope stability problems related to transportation facilities are stressed, most of the discussions and examples in this report apply equally well to all cases of slope instability. As noted by Eckel in his introduction to the first TRB report on landslides:

> The factors of geology, topography, and climate that interact to cause landslides are the same regardless of the use to which man puts a given piece of land. The methods for examination of landslides are equally applicable to problems in all kinds of natural or human environment. And the known methods for prevention or correction of landslides are, within economic limits, independent of the use to which the land is put. It is hoped, therefore, that despite the narrow range of much of its exemplary material, this volume will be found useful to any engineer whose practice leads him to deal with landslides. (Eckel 1958, 2-3)

Those statements are still true. The contents of this volume include several aspects that were not addressed in the earlier editions, and the text has been written and organized to appeal to a diverse audience, including

- Transportation engineers responsible for landslide investigations throughout the world,
- Students in geoscience and geotechnical fields with an interest in landslides, and
- Researchers needing a definitive source for landslide investigation and mitigation procedures.

Each of these groups has different needs, and this report attempts to address them while maintaining a balance and some brevity in the presentation.

For example, the report contains comprehensive, practical discussions of field investigations, laboratory testing, and stability analysis procedures and technologies. These topics are important to both practicing engineers and students of landslides. It was assumed that many engineers would require a reasonably complete single source of much of the information concerning both investigation and mitigation activities. This volume addresses that need.

In addition, it was expected that many students and researchers would desire comprehensive references to the literature and discussions of case studies, state-of-the-art techniques, and research directions. Accordingly, considerable effort was expended in identifying suitable literature citations and in providing some discussion of recent developments. References to specialized and hard-to-obtain sources were avoided as much as possible; most of the cited references will be readily available through university and special libraries.

2. DEFINITIONS AND RESTRICTIONS

In this report the term *landslide* is used to denote "the movement of a mass of rock, debris or earth down a slope" (Cruden 1991). As it is now used in North America, the term has a much more extensive meaning than its component parts suggest because the phenomena described as landslides are not limited either to the land or to sliding (Cruden 1991). In accordance with the practice in previous reports, ground subsidence and collapse are excluded, and snow avalanches and ice falls are not discussed.

In the period since 1978, the Commission on Landslides and Other Mass Movements of the International Association of Engineering Geology (IAEG) has continued its work on terminology. The declaration by the United Nations of the International Decade for Natural Disaster Reduction (1990–2000) prompted the Commission's Suggested Nomenclature for Landslides (IAEG 1990) and the creation of the International Geotechnical Societies' UNESCO Working Party on the World Landslide Inventory (WP/WLI). The Working Party has prepared the *Multilingual Landslide Glossary* to encourage use of standard terminology in describing landslides (WP/WLI and Canadian Geotechnical Society 1993). The terminology used in this report and defined at some length in Chapter 3 is consistent with the suggested methods and the glossary of the UNESCO Working Party (WP/WLI 1990, 1991, 1993; WP/WLI and Canadian Geotechnical Society 1993).

3. HISTORICAL INFORMATION CONCERNING LANDSLIDES

3.1 Importance

Throughout the world, valleys in mountainous regions have experienced accelerated economic development in response to general population growth and associated demands for increased mining, forestry, and agricultural activities. In some areas, such as parts of North America and Europe, the growth of skiing and other recreational activities has spurred development in mountain regions. This economic growth has demanded expansion of transportation and communication facilities. The short history of extensive human development in many of these areas makes the evaluation of potential landslide hazards and appropriate countermeasures very difficult. A large body of documented evidence concerning landsliding events in long-inhabited mountain regions, notably the Alps of Europe, does exist. In a study conducted by the Geological Survey of Canada, 137 landslide case histories in the Alps were collected and used to formulate the appropriate roles of various active or passive mitigation measures, monitoring, and risk acceptance to guide development in the mountains of western Canada (Eisbacher and Clague 1984). Such studies have not been widely emulated, but it appears that major landslide disasters in mountain regions can be avoided if historical experience is evaluated and used wisely.

In many regions large landslides are infrequent events. In comparison with the length of human lifetimes, their occurrence is so low as to lull many into a false sense of security concerning landslide hazards, especially in areas of lower topographic relief. An appreciation of historical experiences with landslides is a frequently neglected but important component of landslide investigation and mitigation studies.

Historical descriptions of landslides often provide insight into other aspects of the development of scientific and engineering knowledge. Few useful descriptions of landslides predate the Industrial Revolution. There was neither an economic incentive nor a scientific basis to support such studies until the late 1700s and early 1800s. The development and construction of canals, and subsequently railways, placed new importance on slope instability.

3.2 Early Historical Studies

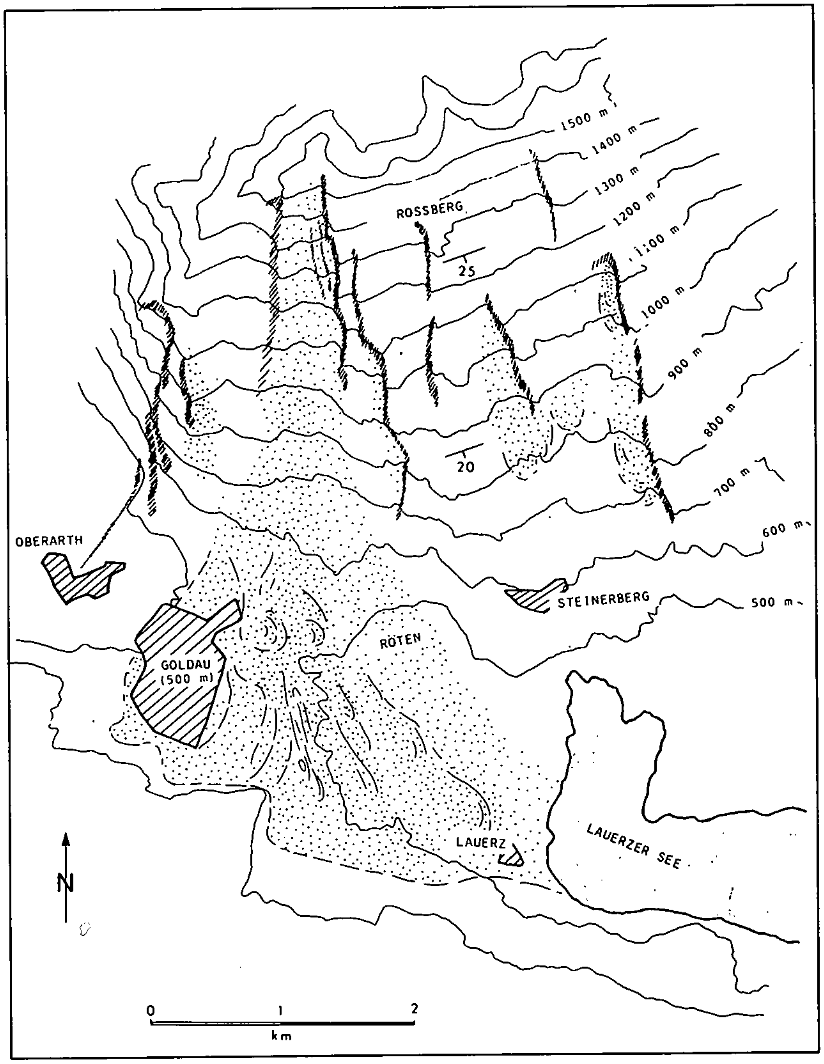
It is beyond the scope of this report to present a detailed historical review of landslide investigations. Several reviews of historical landslides have been published (Voight 1978; Eisbacher and Clague 1984).

However, four examples of early studies from the 1800s are briefly presented to provide the reader with some concept of the insights that these historical documents may provide. All happen to be European examples; they were chosen because they illustrate the evolution of concepts concerning landslide processes. Three examples refer to large and spectacular natural landslides that were subjects of great popular interest and debate. The fourth example concerns what appears to have been the earliest application of soil mechanics methods to slope stability analysis.

3.2.1 Rossberg Landslide of 1806

On September 2, 1806, a very large, extremely rapid rock fall–rock slide, or *sturzstrom*, occurred in central Switzerland. As described by Eisbacher and Clague (1984), a large section of the Rossberg Massif, estimated to involve 10×10^6 to 20×10^6 m^3 of rock, rapidly moved down and away from the mountain and buried much of the small town of Goldau, destroying about 300 houses and killing 457 people (Figure 1-1). Part of the material filled about one-seventh the volume of the Lauerzer See, producing a wave 20 m high that surged over some lakeside villages. Zay (1807)

FIGURE 1-1
Sketch map of the Rossberg landslide of 1806 near Goldau, Switzerland (Eisbacher and Clague 1984).



wrote an extremely important, early technical monograph. The landslide was subsequently studied by many others [e.g., Heim (1932)].

This catastrophe attracted wide attention throughout Europe, and the site of the disaster was visited by many notable persons, including artists such as the landscape painter Turner and writers such as Lord Byron. Its cause was debated by many scientists. Evidence pointed to groundwater conditions as the major cause. The winter of 1805–1806 was exceptionally snowy in central Switzerland, and the heavy snowpack was retained by a cold spring. The delayed but rapid snowmelt was augmented by heavy rains in July and August (Eisbacher and Clague 1984). It was thus logical to suggest that exceptional saturation of the rocks was the primary cause. Conybeare et al. (1840) explicitly referred to the Rossberg landslide as "far too well known to require any detail. . . . It occurred in the summer of 1806 after a season of excessive wetness, and is universally ascribed to the undermining agency of land-springs."

3.2.2 Bindon Landslide of 1839

On Christmas Day 1839, a very different type of landslide occurred along the south coast of England. Although there was no loss of life and only minor property damage, the date of the landslide's occurrence provoked wide public attention and heated debate concerning possible causes and religious significance. As a consequence of this interest, the "Bindon landslip" is among the most documented of all landslides to have occurred in Britain.

The landslide was subjected to extensive scientific investigation by several of the most eminent geologists of the period. Reports based on eyewitness accounts and geological observations at the site were quickly published by Conybeare et al. (1840), Roberts (1840), and many others. These reports included numerous engraved illustrations (Figure 1-2) that gained wide distribution. Conybeare et al. (1840) opened their account as follows:

> The following memoir has been undertaken in order to lay before the reader a distinct account of the most remarkable example ever recorded to have occurred within this island of that class of disturbances affecting the configuration of portions of the earth's surface which results from the undermining agency of water. (Conybeare et al. 1840, 1)

The landslide attracted enormous crowds of curious visitors during the following years, and the local farmers levied a charge of sixpence on visitors wishing to pass through their lands to view it. It has been reported that it was accorded the sin-

FIGURE 1-2
Contemporary view of the Bindon landslide of 1839 in England. View is to east along zone of subsidence that marks landward extent of landslide. Area to right of this valley moved laterally toward the sea (Roberts 1840).
COURTESY OF GRAHAM McKENNA, CHIEF LIBRARIAN, BRITISH GEOLOGICAL SURVEY

gular honor of having a popular musical score, "The Landslip Quadrille," written to celebrate it.

The Bindon landslide also materially affected the evolving science of geology. The early reports (Conybeare et al. 1840; Roberts 1840) were the first to explain the significance of climate and groundwater conditions in promoting slope instability. The clear intent of most investigators was to demonstrate that water could cause such slope instabilities and that such landslides were not related to volcanism or earthquakes. Roberts (1840) stated that "the summer, autumn, and winter of 1839 will long be remembered as the wettest that has almost been known" and quoted the engineer of the Southampton Railway as saying that "so large a quantity of rain has not fallen within the memory of any living person."

Roberts (1840) suggested that these same landslide processes had potential for disrupting roads and that there was a real danger in not understanding them. He provided an example to support his claims:

> It is surprising, often almost incredible how soon and how completely all recollection of natural phenomena, storms, slips, etc., unless attended by unusual features is erased. When the deep cutting . . . was about to commence in 1825, an elderly gentleman, Mr. John Warren, told his brother commissioners of turnpike, that the whole of that highly elevated valley had subsided forty years before; and prognosticated that a road would not long remain without accident. . . [M]any disbelieved the statement. The road was accordingly made, and soon slipped down from twenty feet at one end, to eight feet at the other, towards the sea. (Roberts 1840)

Conybeare et al. (1840) also provided analyses of the mechanisms of the failure, including calculations of the weights of the failed masses and the effects of hydrostatic pressures in promoting instability. These reports and concepts had a major impact on those responsible for constructing earthworks for the rapidly expanding railway system.

3.2.3 Elm Landslide of 1881

The catastrophe at Elm, Switzerland, in 1881 became famous because the events leading up to and accompanying the failure were carefully documented in German by Buss and Heim (1881) and Heim (1882, 1932). An excellent modern review of these historical reports was provided in English by Hsu (1978), and Heim's 1932 report was translated into English by Skermer (1989). The original reports (Buss and Heim 1881; Heim 1882) included interviews with eyewitnesses as well as geological observations. One of the eyewitnesses used a stopwatch to time the initial failure (Eisbacher and Clague 1984).

The failure was a very large and extremely rapid rock fall–rock slide, or *sturzstrom*, similar to but somewhat smaller than the Rossberg landslide of 1806. In this case the failure of the slope was precipitated partly by natural causes and partly by the extraction of slate from the Plattenberg quarry located at the foot of the cliff. This quarry was developed by local farmers with no mining experience (Hsu 1978). The quarrying undermined a large mass of rock on the mountainside above the quarry. The sudden failure of the mountain slope caused a mass of rock, estimated to have been 10 × 10^6 m^3, to fall onto the Plattenberg quarry platform. From there the rock mass was expelled horizontally at velocities estimated to have exceeded 80 m/sec (Heim 1932) across the valley and toward the town of Elm, claiming the lives of 115 people (Figures 1-3 and 1-4).

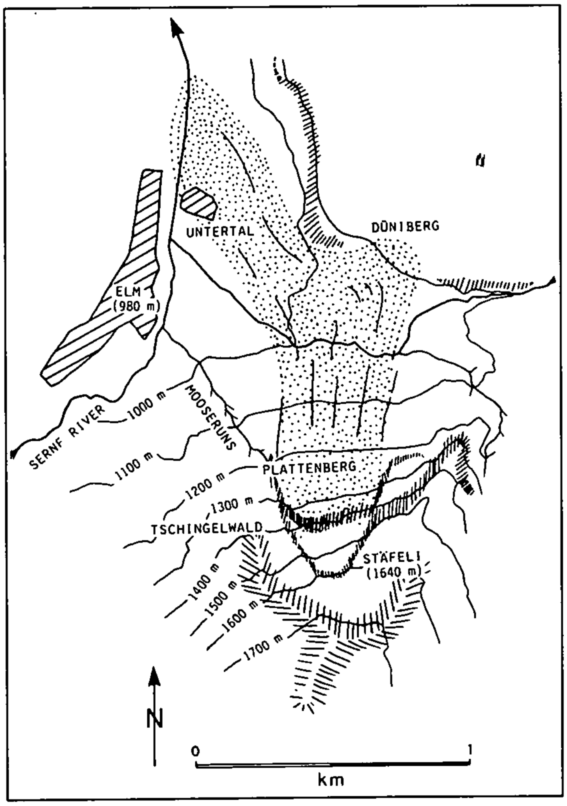


FIGURE 1-3 Sketch map of Elm landslide of 1881 in Switzerland (Eisbacher and Clague 1984).

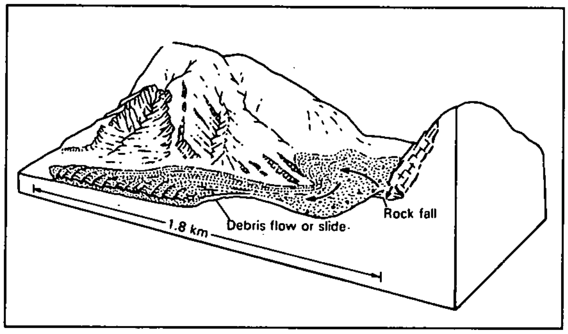


FIGURE 1-4
Isometric view of Elm landslide of 1881 (Schuster and Krizek 1978).

The initial reports (Buss and Heim 1881; Heim 1882) emphasized the unexpected ways in which these sturzstroms move. For example, Heim (1882) reported that several people lost their lives when they ran uphill toward the hamlet of Düniberg (see Figure 1-3) and were overwhelmed by material that surged up the opposite valley slope to a height of about 100 m (Hsu 1978). Heim also reported the observations of several survivors in Elm, in particular their impressions of the flowing nature of the rock mass and the suddenness with which it stopped moving. Heim's detailed observations led to conclusions concerning the hazards resulting from these sturzstroms, especially the large horizontal distances over which they move (Eisbacher and Clague 1984). In his later work, Heim (1932) included calculations concerning the kinematic behavior of the Elm sturzstrom (Hsu 1978). Hsu stated that Heim's interpretations of the mechanisms of sturzstrom movement did not get the recognition they deserved, perhaps because Heim's work was not translated into English until more than 50 years later (Skermer 1989).

3.2.4 Studies of Slope Stability Along French Canals

In 1846, Alexandre Collin, a French engineer with extensive experience in the construction of canals, published his treatise on the stability of clay slopes (Collin 1846). Unfortunately, perhaps because it was not translated into English until more than a century later (Schriever 1956), Collin's report did not become widely known to civil engineers.

The instability of clay slopes was a relatively new problem to engineers in the mid-1800s. Early canals in both England and France did not involve deep cuts and high fills; such heavy earthworks were not associated with canals until the 1820s. Slope failures resulted, and subsequently railway engineers also encountered widespread slope failures in clay materials forming both cuts and fills. They clearly recognized the deep rotational type of movement and adopted gravel-filled trenches passing through the slip surfaces as their chief remedial measure.

Collin's report presented valuable field data, including surveys of the slip surface for about 15 failures (Figure 1-5). He concluded that the cause of failure was inadequate shear strength. Because he was working with materials that today would be classified either as stiff-fissured clay (in the cut slopes) or as poorly compacted clay (in the fills), he noted that in many cases failure occurred some years after initial construction. He attributed this failure to a process causing progressive softening of the clay and suggested water saturation as the most common cause. To reduce the probability of failures, he recommended drainage and establishment of grass cover on slopes, methods that today are recognized as appropriate for cut slopes in stiff-fissured clays.

Collin conducted the first documented shear tests on clays, which demonstrated the importance of water content and what are now referred to as the rheological properties of clays. He advocated the inductive approach: working from observation to theory. In this he was at odds with many of his contemporaries, who favored the deductive approach: the derivation of theoretical conclusions from oversimplified assumptions without reference to field observations. Using the inductive approach, Collin outlined an approximate method for analyzing the stability of clay slopes based on the shape of the slip surface and the strength of the clay.

Skempton (1946) presented a review of the historical significance of Collin's work and provided a list of references to Collin's report that he had found. The list is very short; there are only four references by English-speaking scientists and engineers to Collin's work in the century following the publication of Collin's report. It is unfortunate that Collin's observations and recommendations concerning the stability of clay slopes did not receive much wider exposure.

However, the investigators of the disastrous Panama Canal landslides, which are discussed further in Chapter 2, apparently were aware of Collin's report because they referred to it (Reid 1924). Just before World War II, this same reference came to

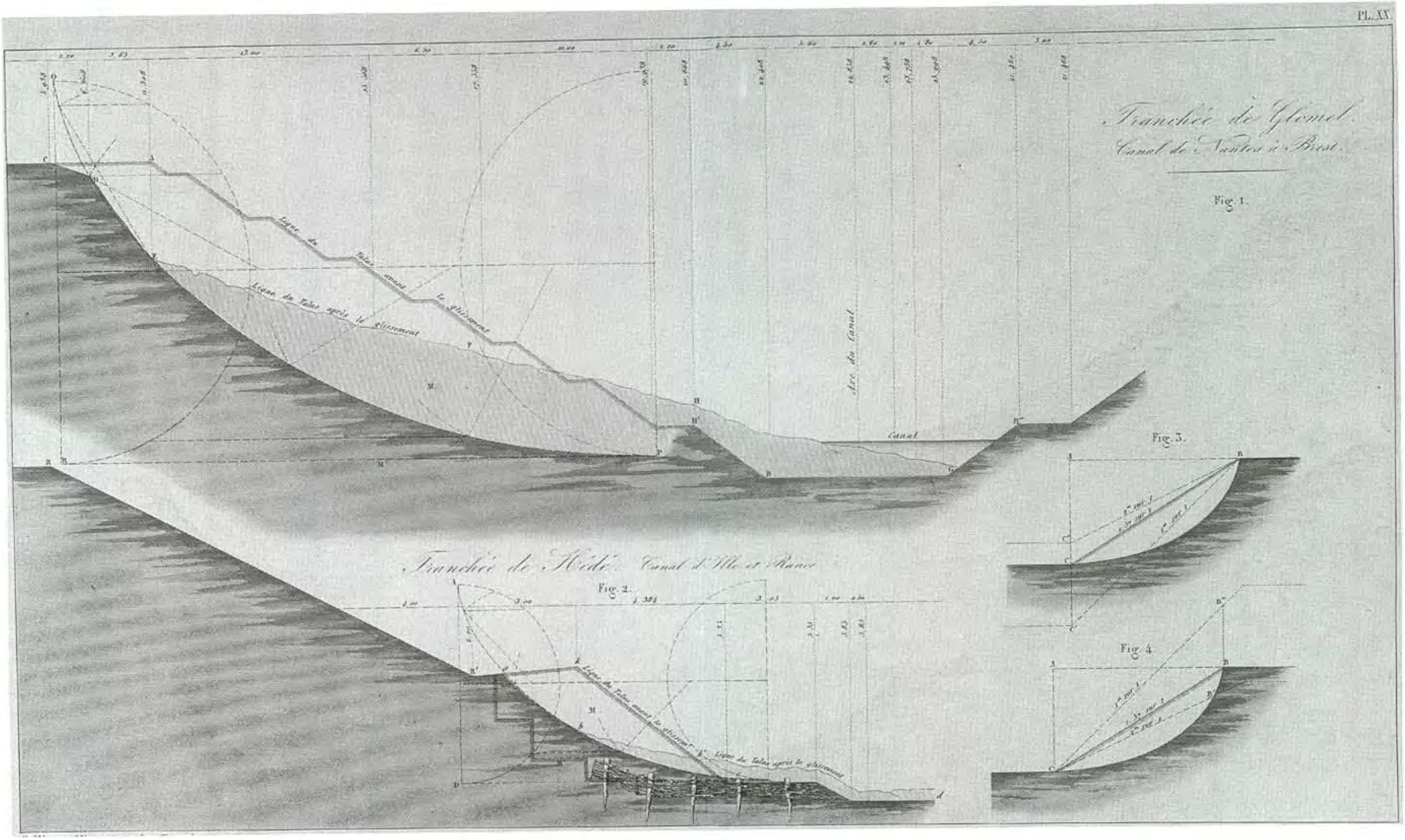


FIGURE 1-5
Two landslides in clay slopes along French canals. Upper drawing shows Gomel cut failure of May 1838 on canal from Nantes to Brest. Lower drawing shows 1838 failure of Hédé cut on Ille-et-Rance canal (Collin 1846, Plate XX).

COURTESY OF DAVID W. CORSON, DIRECTOR, OLIN • KROCH • URIS LIBRARIES, CORNELL UNIVERSITY the attention of Robert F. Leggett, Director of the Division of Building Research of the Canadian National Research Council in Ottawa. With some difficulty, Leggett obtained a copy of the Collin report. Although his war duties intervened, Leggett initially assisted with the report's translation into English and ultimately encouraged and supported others in completing such a translation, which was finally published after about a decade of part-time efforts (Schriever 1956). The translation also contains a memoir concerning Collin written by Skempton (1956), which is an updated version of his earlier review (Skempton 1946).

4. OVERVIEW OF REPORT

The 25 chapters forming this report are organized into Parts 1 through 5. This arrangement was adopted to group chapters according to related landslide investigation and mitigation topics. It is hoped that this grouping will assist readers in identifying those chapters most likely to address their immediate needs.

Part 1, Principles, Definitions, and Assessment, contains six chapters. In addition to this introductory chapter, topics covered are the socioeconomic significance of landslides, landslide types and processes, landslide triggering mechanisms, principles of landslide hazard reduction, and the application of hazard and risk assessment and decision making under uncertainty to landslide management.

Many of these topics are either new to this report or greatly expanded compared with the discussions contained in previous reports. The socioeconomic significance of landslides is emphasized because landslide losses continue to grow as human development expands into unstable hillside areas under the pressures of increasing populations. A significant proportion of world landslide losses involves transportation facilities: highways, railways, canals, and pipelines. The nation most severely affected by landslides is Japan, which suffers estimated total (direct plus indirect) landslide losses of $4 billion annually. In the United States, Italy, and India, total annual economic losses due to landslides have been estimated to range from $1 billion to $2 billion. Many other countries have lesser, but major, annual landslide losses.

Chapter 3 includes further development of the landslide classification principles introduced in previous reports, introduces current international standards proposed for the terminology and description of landslides, and links these standards to the landslide classification. In a similar fashion, the chapters on landslide triggering mechanisms, principles of landslide hazard reduction, and landslide hazard and risk assessment methods represent considerable expansions of earlier presentations.

Part 2, Investigation, includes five chapters that collectively review, in some detail, the entire landslide investigation process. This section begins with the organization of the investigation process and the importance of providing adequate field investigation. Subsequent chapters focus on various aspects of an ideal landslide investigation:

- Initial reconnaissance methods, including aerial photography, remote sensing, and geographic information systems;
- Surface observation and geologic mapping, including the use of surveying methods for identifying and monitoring landslide movements;
- Subsurface investigation, including geophysical explorations, field tests, sample collection methods, and groundwater monitoring; and
- Specialized field instrumentation to monitor landslide movements.

Four chapters form Part 3, Strength and Stability Analysis. The principles of soil and rock mechanics are presented in separate chapters, and stability analysis methods for both soil and rock slopes are presented in two other chapters. A considerable effort has been made to explain and contrast the most appropriate methods for both soil and rock materials.

Part 4 comprises three chapters on landslide mitigation issues. Chapter 16 introduces this section with a review of important considerations and constraints that affect the slope design process. Design methods for the stabilization of soil slopes are provided in Chapter 17, and rock slope stabilization and protection measures are discussed in Chapter 18. In this report an attempt has been made to treat soil and rock slopes on a more equal basis and to compare the best mitigation procedures for each class of slopes.

Part 5, Special Cases and Materials, represents a major addition to the coverage in previous reports: the issues and concerns of landslide investigations in specific environmental or geotechnical conditions. Such special aspects include tropical and residual soils, colluvium and talus, shales and other degradable materials, hydraulic tailings, loess, soft sensitive clays, and permafrost.

REFERENCES

ABBREVIATIONS

HRB	Highway Research Board (now Transportation Research Board)
IAEG	International Association of Engineering Geology
UNESCO	United Nations Educational, Scientific, and Cultural Organization
WP/WLI	Working Party on the World Landslide Inventory (International Geotechnical Societies and UNESCO)

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