Chapter 7

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ORGANIZATION OF INVESTIGATION PROCESS

1. INTRODUCTION

To investigate is "to observe or inquire into in detail; examine systematically," as defined in *The American Heritage Dictionary* (New College Edition). Investigation and characterization of subsurface conditions form the core of landslide studies.

Geotechnical engineering applications incorporate naturally occurring materials characterized by highly variable physical properties. Although most engineers work with materials that have known properties and undertake designs reflecting these properties, geologists and geotechnical engineers must utilize a structured investigation process to deduce the properties of naturally occurring materials and their geometrical relationships. Successful investigations require the investigator to have sound judgment and the ability to make decisions.

2. FIELD INVESTIGATION OF LANDSLIDES

Field investigation has long been recognized as the central and decisive part of a study of landslides and landslide-prone regions (Philbrick and Cleaves 1958; Sowers and Royster 1978). Landslide investigation supports the adage that a problem is already half solved when one recognizes that a problem exists. Investigation should be directed toward both recognition of actual or potential slope movements and identification of the type and causes of the movement. Both aspects are important in identifying appropriate procedures for the prevention or correction of landslides.

Rib and Liang (1978) suggested that landslide investigations should be designed with reference to four basic guidelines that have evolved over many years of experience:

- Most landslides or potential failures can be predicted if proper investigations are performed in time;
- The cost of preventing landslides is less than the cost of correcting them, except for small landslides that can be handled by normal maintenance procedures;
- Massive landslides that may cost many times the cost of the original facility should be prevented; and
- The occurrence of initial slope movement can lead to additional unstable conditions and movements.

3. DEFINITION OF INVESTIGATION PROCESS

An appropriate investigation process cannot be defined by the rigid application of a set of procedural rules. Because the investigation process is so central to geotechnical applications, it has been discussed in numerous textbooks and papers in professional journals (Burwell and Roberts 1950; Terzaghi and Peck 1967; Kiersch 1969; Peck 1969; Dowding 1979a; Boyce 1982; Clayton et al. 1982;

Fookes et al. 1985). The American Society of Civil Engineers sponsored a specialty conference on the topic and subsequently published a book containing the principal papers and discussions (Dowding 1979a). Clayton et al. (1982) aimed at "improving the quality of site investigation by providing a relatively simple reference book." Their book relates to British conditions but includes numerous examples defining basic site investigation principles that should guide all investigators.

Investigations produce information that forms the basis for design decisions. In a few cases, subsurface conditions at a site are generally conceded to be so complicated that any ordinary and reasonable investigation will yield only a partial and incomplete evaluation. Under such rare circumstances, steps are taken to allow for changes in the facility design or the construction methods as actual conditions are revealed. This flexibility is expensive, however, and in the majority of cases, investigation is expected to yield reasonably accurate predictions of subsurface conditions.

3.1 Investigation Failures

An investigation is inadequate if it fails to reveal information concerning subsurface conditions that is needed to produce a safe and economical design or fails to determine appropriate construction methods. Yet investigations generally should not, and usually will not, remove all uncertainty. Minor unexpected conditions are often found during construction; in fact, such changed conditions are to be expected. Investigations are considered to have failed only when the revealed conditions are found to differ grossly from the predictions. Osterberg (1979) stated that geotechnologists must "take every advantage of every method, tool, and observational opportunity to communicate with personnel involved in order to avoid such failures."

Osterberg (1979) suggested that there are five general reasons for investigation failures:

- General knowledge of geologic processes was not used in planning the exploration program and in evaluating the findings of the investigation;
- The investigator had a preconceived notion of what the site evaluation should be and showed reluctance, or even refused, to consider evidence that contradicted the preconceived idea;
- Not all the available tools were used for site evaluation even though they may have been simple and obvious;
- The investigator failed to properly discuss the goals of the exploration program with all the persons involved; and
- Open and free lines of communication were not set up.

3.2 Site Characterization

A number of authors emphasize the concept of *characterization* during the investigation process. According to Dowding (1979b), characterization of the subsurface includes identification of the geometry of relatively homogeneous zones as well as the constitutive properties of the material within the zones. Constitutive properties are those parameters that allow the prediction of a material's strength, deformation, or permeability in response to changes over time due to stress or other environmental conditions.

Duncan (1979) stated that such characterization serves two distinct purposes:

- Anticipating problems and effects, and
- Quantifying site geometric characteristics or material properties.

Duncan suggested that these purposes interact, the first providing a more or less qualitative definition of the critical issues and problems and the second providing more detailed and quantitative definitions suitable for analysis and design.

3.3 Effect of Economic Factors

Few investigations have sufficient time or money to permit the collection of every pertinent fact; thus critical factors must be identified and assessed on the basis of limited data, relying on the judgment and experience of the investigator. Duncan (1979) quoted Peck (1974) as stating that "even the most experienced practitioner has to form his judgments on the basis of less than perfect data." Subsurface soil and rock conditions are notoriously variable, and reality often differs from expectation. The investigation process must be supported by a logical thought process for appropriate conclusions to be reached.

3.4 Importance of Proper Site Investigation Procedures

The importance of proper site investigation procedures has long been a topic of concern to leading engineers. For example, in reviewing the experience with soil mechanics before World War I, Terzaghi stated:

> Engineers imagined that the future science of foundations would consist of carrying out the following program: Drill a hole in the ground. Send soil samples obtained from the hole through a laboratory with standardized apparatus served by conscientious human automatons. Collect the figures, introduce them into equations, and compute the result. (Terzaghi 1936, 14)

Terzaghi then went on to lament the status of civil engineering education, which he suggested was biased toward the concept that all engineering problems should and could be resolved with a priori assumptions regarding the material properties. Peck (1969) suggested that Terzaghi's great success was due to his use of observation and also to his insistence on full personal responsibility and authority concerning all details of critical investigations.

Underwood suggested that there were two important problem areas in investigation:

> One attitude that has discouraged the writer over the past few years is the apparent hope for some new magical development that will fill in the gaps between a few poorly sampled, widely spaced and often poorly logged borings. . . . Field investigations are often hurriedly and carelessly conducted and the incomplete data is then carefully analyzed by precise (out to 8 digit accuracy) computer techniques which produce impressive but erroneous results which in turn lead to inaccurate design assumptions. (Underwood 1974)

These problems logically lead to the following conclusions about the importance of the proper investigation process:

- New and ever-more-sophisticated equipment will never substitute for a properly designed and adequate sampling program;
- Trained personnel, familiar with the reasons for the investigation, must conduct and supervise the activities in the field;
- The validity of the test results and analyses is based entirely on the quality and extent of the field investigation on which they rely; and
- Overrefinement of analysis does not lead to improved design, which depends entirely on improved investigation.

4. ELEMENTS OF AN INVESTIGATION

Several proposals have been made concerning the design of an ideal investigation. All authors agree that the investigation process should be conducted in an iterative fashion. Clayton et al. (1982) suggested that the ideal investigation should follow a sequence of 11 stages (or events) as defined in Table 7-1. In contrast, Dowding (1979b) suggested that the investigation process should be considered in terms of only three steps, namely,

- Review available information and surface reconnaissance;
- Undertake detailed surface mapping, preliminary borings, initial laboratory testing, and preliminary analysis; and
- Undertake borings to recover specialized samples, geophysical surveys, test excavations (adits, test pits, calyx holes, etc.), and specialized testing.

Dowding further suggested that the results of each step should be integrated with the design process

TABLE 7-1
Ideal Order of Events for Site Investigation (Clayton et al. 1982)

EVENT	DESCRIPTION
1	Preliminary desk study or fact-finding survey
2	Aerial photograph interpretation
3	Site walkover survey
4	Preliminary subsurface exploration
5	Soil classification by description and simple testing
6	Detailed subsurface exploration and field testing
7	Physical survey (laboratory testing)
8	Evaluation of data
9	Geotechnical design
10	Field trials
11	Liaison by geotechnical engineer with site staff during project construction

in order to identify the unknowns that should be discovered in the next step or element.

Johnson and DeGraff (1988) suggested that an investigation should include five elements:

- Formulation of the investigation,
- Data collection,
- Data interpretation,
- Application of analysis techniques, and
- Communication of results.

Because landslides are continually changing phenomena, field investigations are not isolated or easily defined activities; they are frequently iterative in their application. New data generate new questions that require more data for resolution.

The critical aspects of a landslide investigation for each of the five investigation elements defined by Johnson and DeGraff (1988) are described briefly in the following sections.

4.1 Formulation of the Investigation

According to Johnson and DeGraff (1988), formulation of the investigation is the element that is most often forgotten or overlooked. This formulation involves two components:

- The identification of the question or questions that the investigation must answer, a clear definition of the purpose of the investigation; and
- Identification of other aspects of the investigation, including its scope, the area and depth to be investigated, and its duration.

Inadequate attention to formulation may cause the investigation to be conducted in an inefficient manner. It may take longer and cost more to complete, and, in some cases, the appropriate information is not obtained at all.

4.1.1 Purpose

Field investigations of landslides may be conducted for two distinct purposes:

- When new facilities are planned, to identify areas that are potentially or currently subject to landsliding; in the case of transportation facilities, this investigation would be conducted during the route-selection phase.
- When a landslide is adjacent to a facility, to define the landslide dimensions, features, and characteristics and to assess environmental factors that may contribute to the landsliding.

These two purposes require somewhat different approaches.

Unstable areas prone to landsliding usually exhibit symptoms of past movement and incipient failure. During preliminary planning stages, these may be identified by interpretation of aerial photographs or by remote-sensing methods. The potential for landsliding can also be evaluated by a number of numerical mapping and assessment methods. Other cases can only be identified by a detailed field investigation before design. Such investigations can show how to prevent, or at least minimize, future movements, and they can suggest alternate routes that are less subject to landsliding.

Once a landslide has developed, either during construction of a facility or subsequently, the investigation is undertaken to diagnose the factors affecting the movements and to determine what corrective measures are appropriate for preventing or minimizing further movements. Such investigations have much in common with other types of site-investigation programs. However, in many cases these investigations may have to be undertaken with some urgency because the landslide is a threat to property or public safety or is disrupting use of a transportation facility.

4.1.2 Scope

Sowers and Royster (1978) included a rather lengthy checklist of features that should be considered in planning a field investigation of a landslide (see opposite page). It is not expected that any single landslide investigation would involve all the items on this list.

4.1.3 Area

The area of an investigation is controlled by the size of the project and the extent of the topographic and geologic features that are involved in the landslide activity. At sites where there is potential for movement, the area that must be investigated cannot be easily defined in advance. The extent of the investigation can be better defined once a landslide has occurred. However, in either case, the area studied must be considerably larger than that comprising the suspected activity or known movement for two reasons:

Checklist for Planning a Landslide Investigation (Sowers and Royster 1978)

I TOPOGRAPHY
- A. Contour map
  1. Land form
  2. Anomalous patterns (jumbled, scarps, bulges)
- B. Surface drainage
  1. Continuous
  2. Intermittent
- C. Profiles of slope
  1. Correlate with geology (II)
  2. Correlate with contour map (IA)
- D. Topographic changes
  1. Rate of change by time
  2. Correlate with groundwater (III), weather (IV), and vibration (V)

II GEOLOGY
- A. Formations at site
  1. Sequence of formations
  2. Colluvium
     - a. Bedrock contact
     - b. Residual soil
  3. Formations with bad experience
  4. Rock minerals susceptible to alteration
- B. Structure: three-dimensional geometry
  1. Stratification
  2. Folding
  3. Strike and dip of bedding or foliation
     - a. Changes in strike or dip
     - b. Relation to slope and slide
  4. Strike and dip of joints with relation to slope
  5. Faults, breccia, and shear zones with relation to slope and slide
- C. Weathering
  1. Character (chemical, mechanical, and solution)
  2. Depth (uniform or variable)

III GROUNDWATER
- A. Piezometric levels within slope
  1. Normal
  2. Perched levels, relation to formations and structure
  3. Artesian pressures, relation to formations and structure
- B. Variations in piezometric levels [correlate with weather (IV), vibration (V), and history of slope changes (VI)]
  1. Response to rainfall
  2. Seasonal fluctuations
  3. Year-to-year changes
  4. Effect of snowmelt
- C. Ground surface indications of subsurface water
  1. Springs
  2. Seeps and damp areas
  3. Vegetation differences
- D. Effect of human activity on groundwater
  1. Groundwater utilization
  2. Groundwater flow restriction
  3. Impoundment and additions to groundwater
  4. Changes in ground cover and infiltration opportunity
  5. Surface water changes
- E. Groundwater chemistry
  1. Dissolved salts and gases
  2. Changes in radioactive gases

IV WEATHER
- A. Precipitation
  1. Form (rain or snow)
  2. Hourly rates
  3. Daily rates
  4. Monthly rates
  5. Annual rates
- B. Temperature
  1. Hourly and daily means
  2. Hourly and daily extremes
  3. Cumulative degree-day deficit (freezing index)
  4. Sudden thaws
- C. Barometric changes

V VIBRATION
- A. Seismicity
  1. Seismic events
  2. Microseismic intensity
  3. Microseismic changes
- B. Human induced
  1. Transport
  2. Blasting
  3. Heavy machinery

VI HISTORY OF SLOPE CHANGES
- A. Natural process
  1. Long-term geologic changes
  2. Erosion
  3. Evidence of past movement
  4. Submergence and emergence
- B. Human activity
  1. Cutting
  2. Filling
  3. Changes in surface water
  4. Changes in groundwater
  5. Changes in vegetative cover, clearing excavation, cultivation, and paving.
  6. Flooding and sudden drawdown of reservoirs
- C. Rate of movement
  1. Visual accounts
  2. Evidence in vegetation
  3. Evidence in topography
  4. Photographic evidence
     - a. Oblique
     - b. Stereo aerial photographs
     - c. Aerial photographs
     - d. Spectral changes
  5. Instrumental data
     - a. Vertical changes, time history
     - b. Horizontal changes, time history
     - c. Internal strains and tilt, including time history
- D. Correlations of movements
  1. Groundwater [correlate with groundwater (III)]
  2. Weather [correlate with weather (IV)]
  3. Vibration [correlate with vibration (V)]
  4. Human activity [correlate with human-induced vibration (VB)]

- The landslide or potential landslide must be referenced to the stable area surrounding it, and
- Most landslides enlarge with passage of time, and moreover many landslides are much larger than first suspected from the overt indications of activity.

As a rule of thumb, the area studied should be two to three times wider and longer than the area suspected. In some mountainous areas, it is necessary to investigate to the top of the slope or to some major change in lithology or slope angle. The lateral area must encompass sources of groundwater and geologic structures that are aligned with the area of instability.

4.1.4 Depth

The depth of the investigation is even more difficult to define in advance. Borings or other direct techniques should extend deep enough to identify those materials that have not been subject to past movement but that could be involved in future movement and the underlying formations that are likely to remain stable. The boring depth is sometimes revised hourly as field operations proceed. When instrumentation of a landslide yields data on the present depth of activity, planned depths are sometimes found to be insufficient and increases are necessary. The specifications should be flexible enough to allow additional depth of investigation when the data obtained suggest deeper movements. Longitudinal cross sections should be drawn through the center of the landslide depicting possible toe bulges and uphill scarps; circular or elliptical failure surfaces sketched through these limits can suggest the maximum depth of movement. Continuous, thick, hard strata within the slope can limit the depth. However, at least one boring should extend far below the suspected depth of shear: sometimes deep, slow movements are masked by the greater activity at shallower depths. Experience demonstrates that the depth of movement below the ground surface at the center of a landslide is seldom greater than the width of the zone of surface motion.

4.1.5 Duration

Ideally, the investigations should continue over periods of time adequate to evaluate the changing environmental factors and shifting topography. Often the duration of these investigations is constrained by the need for preventive or corrective design.

Since most landslides are influenced by climatic changes, a minimum period for investigation should include one seasonal cycle of weather—one year in most parts of the world. However, because long-term climatic cycles that occur every 11 or 22 years are superimposed on the yearly changes, it could be necessary to continue a landslide investigation for more than two decades. Such a long investigation is almost impossible, however, because of the need to draw conclusions and take corrective action.

Investigations made during a period in which the climatic conditions are less severe than the maximum will prove too optimistic, and those made during a period of bad conditions may appear too pessimistic. The worst climatic conditions that develop during the life of the project control the risk to engineering construction. Experience has indicated that many false conclusions have been reached regarding the causes of landslides and the effectiveness of corrective measures because worsened climatic changes were not considered by the engineers and geologists concerned.

4.2 Data Collection

Data collection involves both office and field studies. Office studies include the discovery and assembly of all existing pertinent information. These data are commonly found in diverse government sources and may include maps, reports, aerial photographs, and historical documents. The appropriate use of such information can materially assist the investigator before and during an initial site visit and guide the planning of the first steps in field data collection.

Field data collection may involve a variety of activities ranging from relatively simple, low-cost reconnaissance studies to sophisticated, frequently expensive specialized instrumentation installations. Investigations are generally most efficient when the simpler and more rapid reconnaissance methods are used initially to obtain a basic understanding of the site and the more expensive and time-consuming sampling methods are employed subsequently where they can be used for maximum benefit. These data collection activities are discussed in more detail in Chapters 8 through 11.

4.3 Data Interpretation

An investigation is incomplete without an interpretation of the data from the office and field studies. In most landslide investigations, data collection and data interpretation go on continuously and interactively. Interpretation of data gathered during initial stages of an investigation will usually suggest the need for additional volumes and types of data and modifications to the investigation process. An efficient investigation process requires a continual review and interpretation of the data as they are gathered.

Data interpretation usually begins with reduction and reorganization of the initial raw data. This activity results in the production of tables, graphs, maps, profiles, and cross sections. For most landslide investigations, spatial and temporal comparisons of the data are of great interest.

4.4 Application of Analysis Techniques

Once data are in manageable form, analysis of the data is usually fairly easy. Analysis may involve graphical techniques, but numerical methods, including both statistical analysis and mathematical modeling approaches, are increasingly being employed. Numerous slope stability analysis procedures are possible. Most involve simplifying assumptions. Slope stability analysis methods are discussed in Chapter 13 for soil slopes and in Chapter 15 for rock slopes.

4.5 Communication of Results

Many sources emphasize the need for clear and precise communication of investigation results (Osterberg 1979; Williams 1984). If the answers obtained by an investigation are not transmitted to those who will use them, the investigation will have served no purpose. Some landslide investigation results are reported to government boards, commissions, or similar entities. Numerous guides are available for authors preparing such documents (California Division of Mines and Geology 1975; Cochrane et al. 1979; Hansen 1991). Litigation may result from some landslides, and some landslide investigations may be developed for such applications. Kiersch (1969) provided guidance for geologists involved as technical (expert) witnesses in such litigation.

5. HIGH-QUALITY INVESTIGATIONS

Clayton et al. (1982) proposed six key factors for improving site investigations. The following are modifications of their factor descriptions that reflect the needs and realities of investigations at landslide sites:

- Insistence on the full use of available documentary evidence in a comprehensive factual survey during the early stages of the investigation process;
- Use of aerial photography, remote-sensing, and possibly numerical map analysis methods in the early stages of an investigation, preferably by trained and experienced personnel;
- Development of a plan of subsurface investigation that is specifically designed for the site and reflects expected geological and environmental subsoil conditions;
- Field supervision of drilling by experienced engineers, who should be aware of the aims of the investigation;
- Frequent revision of the aims and methods of the site investigation as information becomes available and as a result of liaison among geotechnical engineers, designers of the proposed corrective or preventive measures, and, where possible, the contractor who will undertake the work; and
- Close observation by an experienced team of geotechnical engineers during the construction.

6. OVERVIEW OF CHAPTERS 8–11

The major aspects of the investigation process for landslides are defined in the following four chapters.

The use of aerial photographs and other remote-sensor imagery products for landslide mapping is discussed in Chapter 8. Also described is the use of computer-based spatial mapping approaches in performing regional landslide hazard assessments.

In Chapter 9 the initial office and field data collection efforts, including various surface observations and geologic mapping methods, are reviewed. Various surveying methods to supply quantitative data on landslide movements are summarized.

Chapter 10 continues the discussion of field data collection activities for a landslide investigation, covering the entire range of exploration and sampling options to characterize the subsurface conditions. The merits of various geophysical exploration methods as well as the wide range of methods involving in situ testing, borings, test excavations, and sample handling procedures are surveyed.

Chapter 11 completes the data collection process with a discussion of the various field instrumentation options to identify and monitor subsurface movements.

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