Chapter 1

What Is Near-Surface Geophysics?

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Near-surface geophysics uses the investigational methods of geophysics to study the nature of the very outermost part of the earth's crust. Man interacts with this part of the earth's crust: he walks on it; he drills and excavates into it; he constructs structures on and in it; he utilizes its water and mineral resources; and his wastes are stored on and in it and seep into it. The very outermost part of the Earth's crust is extremely dynamic—in both technical (physical properties) and nontechnical (political, social, legal) terms—which leads to both technical and nontechnical challenges that are much different than the challenges faced by "traditional" applications of geophysics for regional geologic mapping and for oil and gas exploration (see Chapter 2).

Near-surface geophysics investigations include numerous and varied application areas and both basic and applied research in support of those applications (National Research Council, 2000). These application areas are characterized by various descriptors, e.g., engineering, geotechnical, environmental, groundwater, mining, archaeological, forensic. Some typical examples of these application areas are:

- Engineering and geotechnical geophysics: characterization of the foundation beneath critical structures; mapping top of rock; nondestructive evaluation of engineered structures, e.g., bridges, buildings, dams, etc.; cavity and tunnel detection; geologic mapping
- Environmental geophysics: mapping contaminant plumes in groundwater; locating buried cultural features, e.g., metal containers, unexploded ordnance (UXO), landfills, underground storage tanks; monitoring changes in the hydrogeological regime; geologic mapping
- Groundwater geophysics: locating optimal water-well drilling sites; mapping the water table; locating fracture zones; groundwater quality assessment; defining geology (stratigraphy, structure, aquifers, and aquicludes, etc.) for input to groundwater modeling efforts
- Mining geophysics: mapping geologic structure; locating and characterizing ore deposits; ore quantity and quality estimates
- Archaeological geophysics: locating and assessing archaeological sites; cultural resource management; locating historic and prehistoric graves, hearths, burial pits, etc.; mapping building foundations; locating artifacts
- Forensic geophysics: clandestine burials; crime scene investigation; drug and weapons caches; intrusion tunnels.

The near-surface geophysics application areas listed above are characterized and distinguished by

- shallow depths of investigation or interest
- requirements for high resolution, vertically and horizontally
- the possibility of near-real-time confirmation, verification, or validation of the results
- program planning, field and laboratory execution, and results interpretation and presentation that are subject to public health and safety concerns and constrained by legal and regulatory considerations

Surprisingly, one of the first difficulties encountered in discussing near-surface geophysics is exactly what is meant by "near surface." In other words, what is the depth range of interest in near-surface geophysics investigations? Many practitioners would argue that a significant percentage of near-surface investigations involve depths of interest less than 10 meters, and most practitioners would agree that most common applications of near-surface geophysics involve depths less than 30 meters. However, there are occasional investigations to depths of 300 meters or more (see Figure 1).

The requirement for high resolution is epitomized by surveys conducted to detect unexploded ordnance (UXO; e.g., Butler, 1997). UXO of interest range in size from 20-mm diameter projectiles to 2000-lb bombs, and depths of interest range from the surface to 10 m or greater. Geophysical surveys for UXO detection commonly require data acquisition with line spacing of 0.25–0.5 m and data spacing along lines of 0.05–0.25 m (Figure 2). An estimated 11–25 million acres (11 million acres is approximately 45 000 km^2 or 17 200 mi^2, approximately the size of New Hampshire and Vermont combined) are potentially contaminated with UXO. Thus, while many sites with UXO are comparable to areas commonly involved in petroleum exploration geophysics, the required *resolution* is less by a factor of 10^3 or more. As another example, a common

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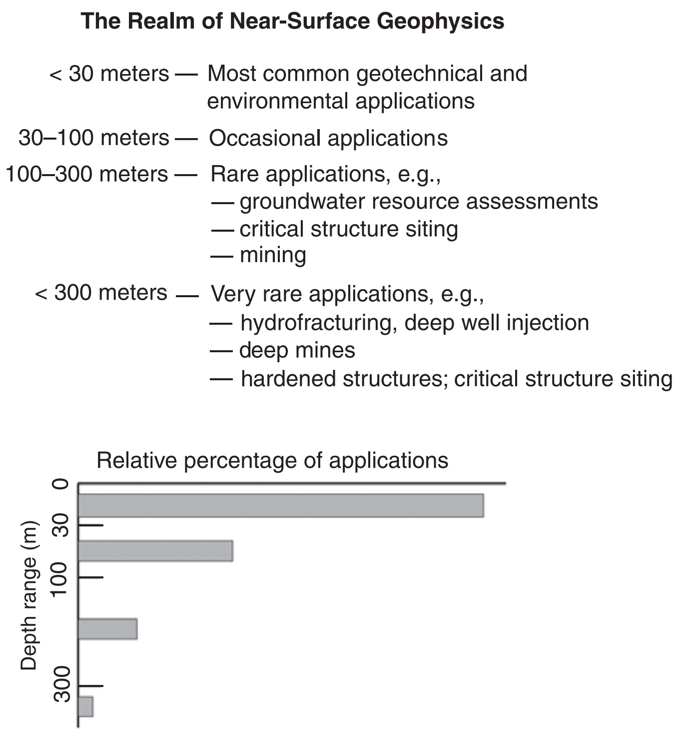

Figure 1. Illustration of relative percentages of near-surface geophysical applications in selected depth ranges.

objective of geophysical surveys for water well placement in areas with low permeability "bedrock" is the location of fractures and fracture intersections. Errors in location of a fracture by as little as 0.5–1.0 m can result in drilling a dry hole. Both of these applications require closely spaced measurements and highly accurate positioning of the measurements.

The near-surface geophysicist always faces the possibility of near-real-time validation, verification or confirmation of geophysical survey results and interpretation. This immediacy of follow-on validation is illustrated by the example in Figure 3, where the pressure of a real-time validation is compounded by the significant safety issue involved. The example in Figure 3 involved determining the location and alignment of a large natural gas pipeline at multiple locations using electromagnetic induction (EMI) surveys. At each location, the depth to top of the pipe was then determined by GPR surveys. Immediately following the GPR survey and interpretation, a trench was excavated to within approximately 0.5 m of the top of the pipeline. For other applications, the validation may not occur for weeks or months (but likely never years). In any event, the validation still follows quickly relative to other types of geophysical applications, such as prospect development in petroleum exploration.

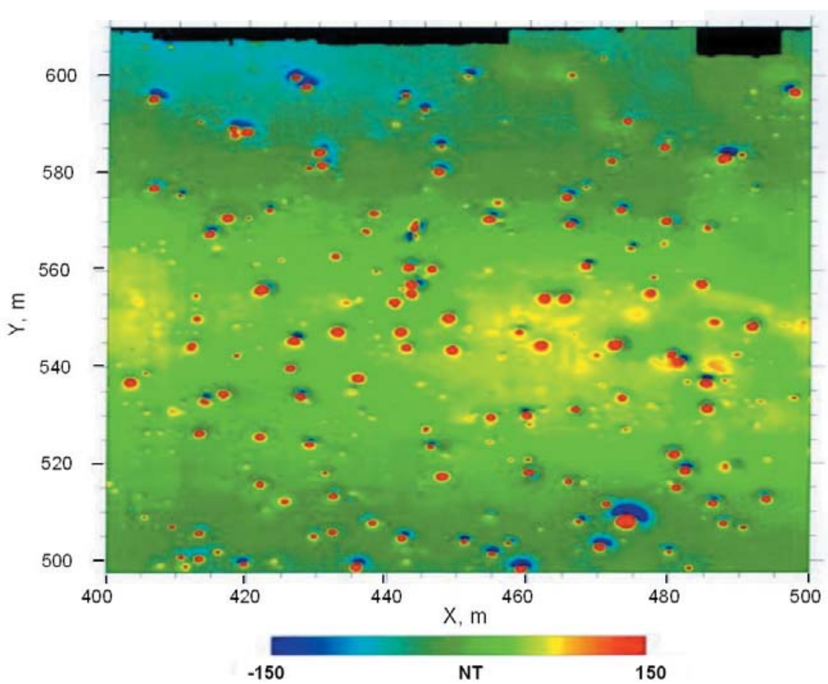

Figure 2. Example of a high-resolution, total-magnetic field survey for UXO Detection: Naval Research Laboratory's Multiple Towed Array Detector System. Measurement spacing 0.25 m ¥ 0.10 m. Survey location—Buckley Field, Arapahoe County, Colorado.

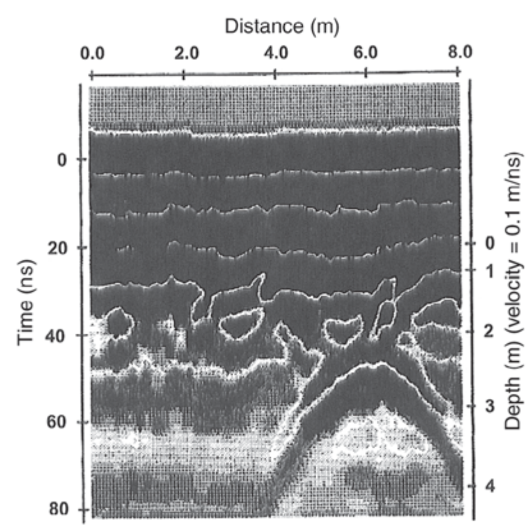

Figure 3. Ground penetrating survey (GPR) across a 1.2-m diameter gas pipeline; 100-MHz center frequency. Excavation to within 0.5 m of the top of the pipeline followed immediately after the GPR depth determination (Butler et al., 1997).

A significant percentage of near-surface geophysics projects, particularly under the general classifications of environmental and archaeological applications are "driven" by law and constrained by regulatory agencies (see Chapter 2). Examples of this relationship between applications (issues) and controlling legislation (laws) are given in Figure 4. This close relationship between issue or problem or application and regulatory agencies and laws and public interests gives more exposure and scrutiny to near-surface geophysics than other areas of geophysics.

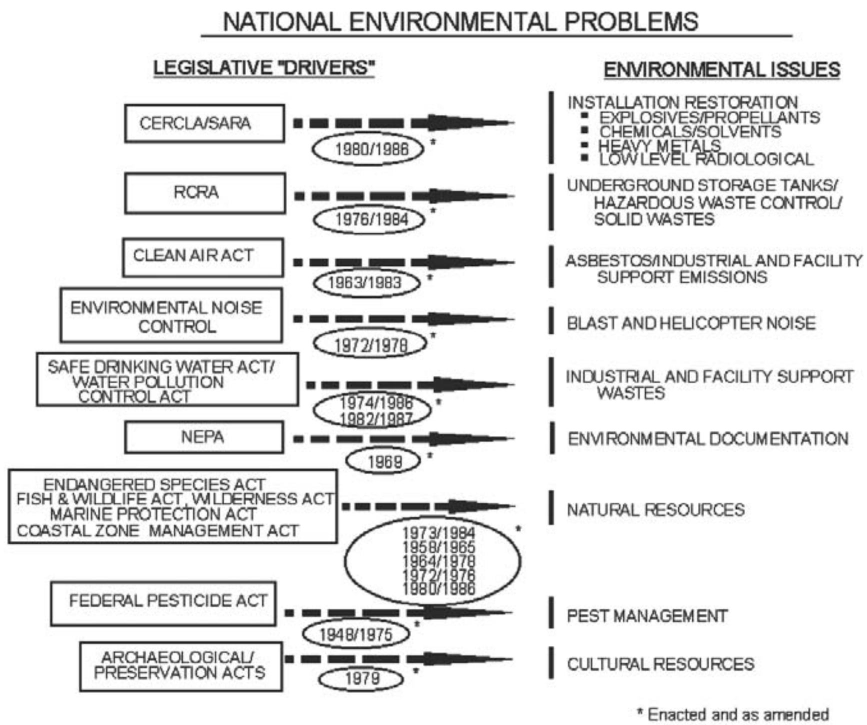

Figure 4. Examples of laws and the environmental issues they address, ca 1990 and as amended.

Near-Surface Geophysics: Practitioners and Users

Practitioners of near-surface geophysics fall into two broad categories: (1) those formally educated and trained by experience as geophysicists; (2) those trained primarily by experience in geophysical applications (Figure 5). Increasing numbers of geophysicists are truly *near-surface geophysicists*, i.e., they have formal education in near-surface techniques and applications and in the physical nature and special challenges of the near surface. Other geophysicists have transitioned to near-surface geophysics from other application areas of geophysics. Nongeophysicist practitioners of near-surface geophysics are scientists and engineers or technicians who, by virtue of experience, consider themselves near-surface geophysicists and often perform quite effectively in this role.

Users of near-surface geophysics are professionals, formally trained in another discipline, who use geophysics in various roles to address near-surface problems. Among the users of near-surface geophysics are those that

- specify or propose applications of geophysics
- contract for geophysical services,
- monitor and/or review geophysical work and results
- conduct geophysical surveys
- interpret geophysical survey data
- utilize the results of geophysical investigations

Regardless of educational background and experience, the near-surface geophysicist is often "caught in the middle" of differing approaches, expectations, and conceptual understanding by the various types of users of near-surface geophysics. This is illustrated by the somewhat "tongue-in-cheek," hypothetical example (Figure 5) of a geophysicist presenting the results of a geophysical investigation and the different perceptions of the result by an engineer, a geologist, and a regulator. The geologist and engineer assess the geophysical result through the lens of their discipline and understanding. The engineer often fails to appreciate the value and significance of a remote, noninvasive determination and the associated error or uncertainty, while overemphasizing the intrinsic value of an "exact" determination through a direct, invasive technique. The geologist, likewise, often fails to appreciate the intrinsic ambiguity of a remote, noninvasive determination of a subsurface property. For the regulator, the geophysicist has simply answered the wrong question; the fundamental question for the regulator concerns contamination and public risk. The geophysicist has failed to communicate effectively in this setting.

Although their training might dictate otherwise, near-surface geophysicists must learn to give definitive answers, and then to address issues of accuracy, precision, ambiguity, and nonuniqueness as caveats to the answer rather than as part of the answer. Also, the near-surface geophysicist must make an effort to understand the real nature of the question being asked (i.e., what is the problem) and then to frame the presentation of results in the context of the question.

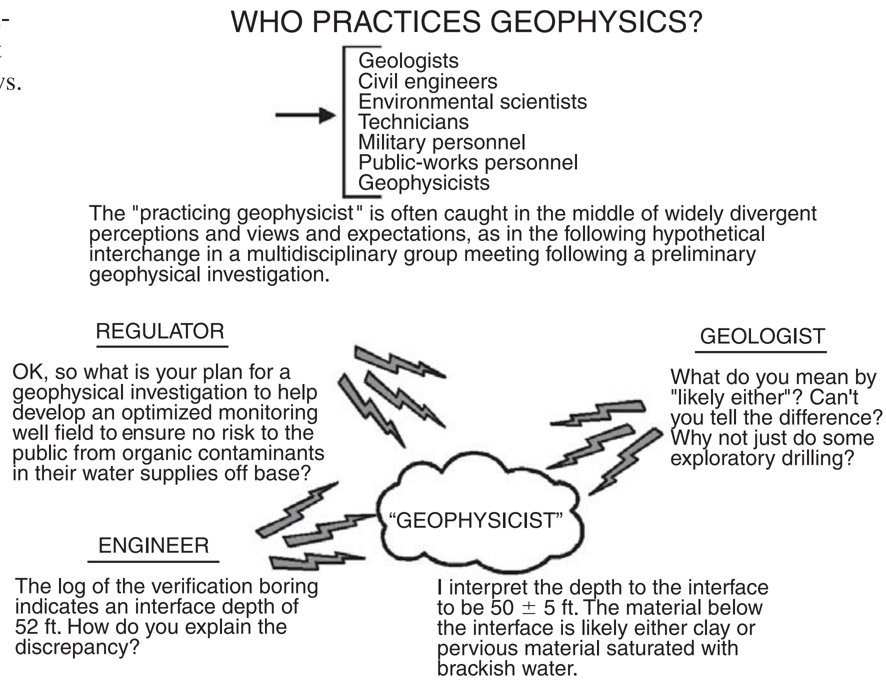

Figure 5. Cartoon illustrating the "geophysicist" as caught in the middle of an argument involving conflicting or divergent worldviews.

Another problem faced by the near-surface geophysicist is that of unrealistic expectations by users of near-surface geophysics. The regulator, office manager, military commander, or other user of near-surface geophysics often has the inclination to shop for the "silver bullet" technology rather than the systematic methodology and approach that the near-surface geophysicist applies to a problem. Unfortunately, where there are both the inclination and a source of funds, there are quacks and charlatans ready to provide the silver bullet (Park, 2000; National Research Council, 1996, 2000). The near-surface geophysicist must proactively present and defend a sound geoscience approach to problem solving and be prepared to positively address the claims of a silver-bullet approach and charlatans.

Traditional and Emerging Views of Near-Surface Geophysics

The *traditional* or *historical* view of the role and contribution of near-surface geophysics to a subsurface investigation program asserts that it

- can reduce the required drilling and sampling and lower the overall cost,
- is useful for integrating and correlating other types of information
- can detect localized anomalous conditions
- is useful for determining static corrections for seismic reflection surveys

This view of the role of near-surface geophysics manifests itself even today. In a common scenario, a program manager will spend 90 percent of the exploration or site characterization budget for drilling and sampling before attempting to answer outstanding questions with near-surface geophysics. The geophysicist is commonly a "subcontractor," i.e., not part of the project team, and does not have or is not given the full background of the site or the characterization work accomplished to date. Many geophysicists have horror stories of projects on which they were not given site data in order to prevent cheating.

This traditional view fails to recognize the full potential of near-surface geophysics to contribute to a fundamental understanding not only of geologic structure and stratigraphy but also conditions, processes, and spatial heterogeneity (National Research Council, 2000). A turning point came in the 1980s with the advent of major environmental cleanup programs. Program managers soon realized that it was too labor intensive and expensive to turn sites into "Swiss cheese" in order to achieve adequate site characterization. When the potential for site characterization by geophysics is demonstrated to be versatile, cost-effective, noninvasive, and integrative, program managers are generally eager to include geophysics as part of the site characterization program. This change in philosophy is noted in the following quotes regarding the emerging roles for and capabilities of near-surface geophysics:

> Geophysical applications to geotechnical and groundwater problems . . . have leaped from a role of merely a sensible, cost-effective substitute for boreholes or a scapegoat in difficult subsurface geology to one in which they are often the only means by

which an important problem can be addressed (Dobecki and Romig, 1985).

> There is great potential for these methods to define subsurface details with a level of accuracy, precision, economy and safety that can approach direct sampling but with a much greater areal coverage (National Research Council, 2000).

A major challenge for the near-surface geophysicist is to exploit this emerging understanding and potential of geophysics by being responsive to and cognizant of requirements, communicating clearly the capabilities and limitations of the methods, and framing results in terms understandable by managers and regulators. In the context of environmental applications, the four primary objectives that can be addressed by near-surface geophysics are

- assessment of the natural geologic and hydrogeologic system
- detection and assessment of contaminants within the natural system
- detection and assessment of buried wastes or objects, trenches, pipelines, underground storage tanks, unexploded ordnance
- condition change, remedial measures effectiveness, and postclosure monitoring

A key role for the geophysicist is to positively articulate and advocate these cradle-to-grave objectives that can be addressed with near-surface geophysics and how they integrate with overall program objectives. Even under the more favorable environment suggested by this emerging role for near-surface geophysics, however, the philosophy of site characterization programs must include

- objectives that include defining and characterizing the site to *the extent necessary* to aid and guide feasibility assessment and remediation functions and to avoid surprises and risks during subsequent site use
- efforts to solve and answer both general and specific problems and questions
- a mindset that seeks to minimize cost, while maximizing information

Models and Fundamental Parameters

Two major thrusts have revolutionized near-surface geophysics: (1) efforts to deduce fundamental soil and rock properties from measured parameters using fundamental physics-based models; and (2) increasing use of models and modeling for conceptualization and interpretation. The normal sequence of a near-surface site characterization or a laboratory investigation (Figure 6) proceeds from basic measurements (e.g., distance, time, voltage, current, meter units, etc.) to parameters calculated from the basic measurements (by simple relations, empirical correlations, instrument factors, etc.) to interpreted parameters or properties (e.g., by direct or inverse modeling). Practitioners of near-surface geophysics *often* limit data processing and interpretation to a simplistic approach of plotting profiles or contour maps of measured or calculated parameters. The product of this simplistic approach consists of identifying anomalies and recommending drilling locations. The use of physics-based modeling to proceed to a more detailed, quantitative, and fundamental properties interpretation is the key theme of this book (see especially Chapters 3 and 4).

The basic types of models and modeling are summarized in Figure 7. Conceptual models are invaluable for

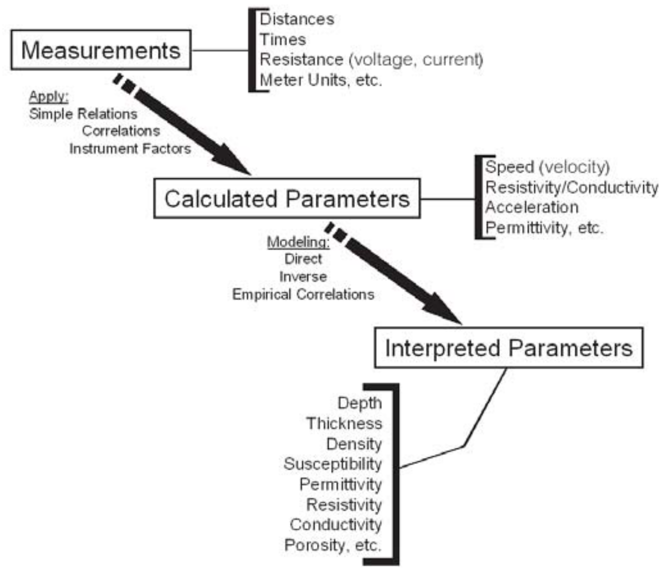

Figure 6. Illustration of the progression from field or laboratory measurements to interpretations.

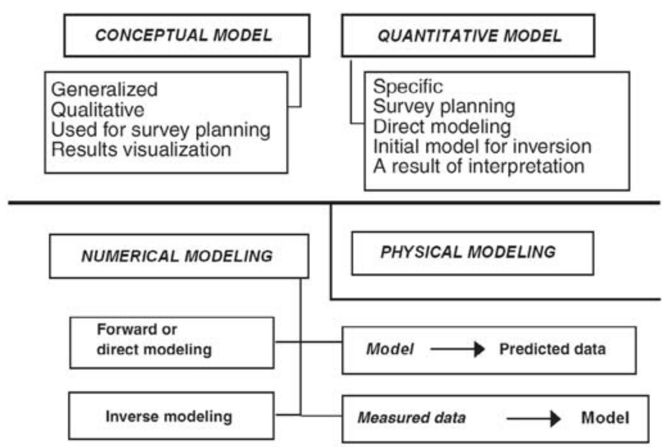

Figure 7. The types of models and modeling processes in geophysics.

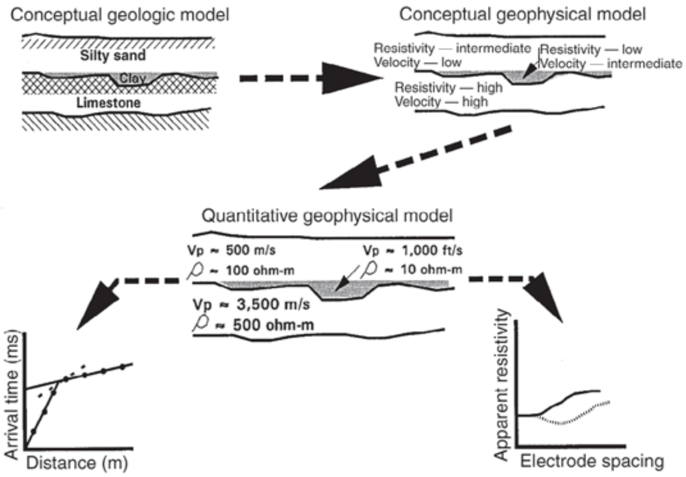

Figure 8. Illustration of conceptual and quantitative geologic and geophysical models.

planning near-surface laboratory or site characterization investigations (Figure 8). As suggested in the hypothetical example in Figure 8, both geological and geophysical conceptual models are utilized in planning and in interpreting near-surface investigations. While conceptual models are generally qualitative, near-surface geophysicists commonly base a quantitative geophysical model on the conceptual models, for use in planning surveys and assessing survey results.

A quantitative geophysical model of the subsurface is used in forward modeling procedures to predict measurements over the model, such as the example in Figure 8 for predicted seismic refraction time-distance plots and apparent resistivity-electrode spacing plots. The forward model results allow rational survey planning and alternative scenario assessments. Likewise, the results of inverse modeling are quantitative geophysical models. A systematic, generalized procedure for near-surface geophysical investigations can include both conceptual and quantitative models and both forward and inverse modeling (Figure 9). A systematic, model-based approach to planning, executing and interpreting near-surface geophysics investigations

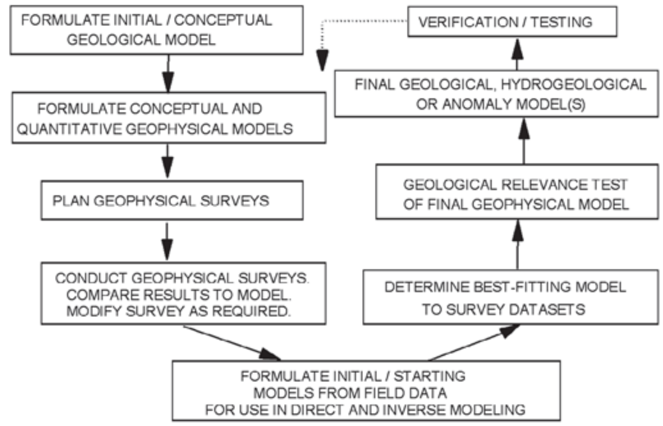

Figure 9. A generalized modeling procedure.

is essential for establishing and maintaining credibility and acceptance of results. This systematic approach is emphasized throughout this book: models and procedures for determining fundamental parameters of soil and rock (Chapters 3 and 4); concepts of geophysical inversion (Chapter 5); concepts of the methods of near-surface geophysics (Chapters 6–11).

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