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Scenario Evaluator for Electrical Resistivity Survey Pre-modeling Tool.

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Abstract

Geophysical tools have much to offer users in environmental, water resource, and geotechnical fields; however, techniques such as electrical resistivity imaging (ERI) are often oversold and/or overinterpreted due to a lack of understanding of the limitations of the techniques, such as the appropriate depth intervals or resolution of the methods. The relationship between ERI data and resistivity is nonlinear; therefore, these limitations depend on site conditions and survey design and are best assessed through forward and inverse modeling exercises prior to field investigations. In this approach, proposed field surveys are first numerically simulated given the expected electrical properties of the site, and the resulting hypothetical data are then analyzed using inverse models. Performing ERI forward/inverse modeling, however, requires substantial expertise and can take many hours to implement. We present a new spreadsheet-based tool, the Scenario Evaluator for Electrical Resistivity (SEER), which features a graphical user interface that allows users to manipulate a resistivity model and instantly view how that model would likely be interpreted by an ERI survey. The SEER tool is intended for use by those who wish to determine the value of including ERI to achieve project goals, and is designed to have broad utility in industry, teaching, and research.

Introduction

Motivation

Geophysical methods are applicable to a broad range of disciplines and have great potential for gathering information about properties and states of interest at unique spatial scales with

Authors' Note

The SEER tool is available for download at Terry et al. 2017. The authors do not have any conflicts of interest or financial disclosures to report.

relatively little effort and/or cost. However, the success of individual geophysical approaches for achieving project goals depends on several factors, such as site conditions and the resolution of the particular method. Unfortunately, geophysical methods are sometimes oversold or results are overinterpreted. Such experiences, to the practitioner, may give the erroneous impression that geophysical methods do not work, despite the great potential to provide high resolution data, save time and resources, minimize field efforts, and guide decision making.

Therefore, simple-to-use tools are needed that inform geophysical method selection and survey design for those who wish to consider using geophysics as part of their projects. For example, the Fractured Rock Geophysical Toolbox Method Selection Tool (FRGT-MST) is an Excel-based tool that provides a suitability assessment for a wide array of geophysical techniques given basic site information and project objectives entered by the user (Day-Lewis et al. 2016). While the FRGT-MST tool provides qualitative guidance on the techniques to use in fractured rock (and other) environments, this is only the first step in determining if geophysics is likely to work for a particular objective at a specific site. In many cases, this step should be followed by more rigorous, quantitative pre-modeling analyses (Figure 1) before a geophysical survey is carried out. This “pre-modeling,” or “synthetic modeling,” process consists of a (1) a forward modeling step to generate hypothetical data for a hypothetical target; and (2) an inverse modeling step applied to the hypothetical data to predict the geophysical result (see, e.g., Dahlin and Loke 1998). The basic principle of this approach is to simulate data from a model based on anticipated conditions at the project site (forward modeling), then to process and solve for these data as one would using actual data from the field, including expected measurement errors (inverse modeling). The outcome of this process provides a realistic model of the best obtainable result from a geophysical survey. Although the forward/inverse modeling paradigm is common in academic and research communities, it is not frequently used by practitioners due to the added time and cost often needed to perform these analyses.

Typically, pre-modeling steps are performed separately, using for example RES2DMOD (Geotomo software, Penang, Malaysia) to generate forward modeled data, adding noise to those data, then inverting the data using, for example, RES2DINV (Geotomo software). Other software (e.g., R2 by A.B. of Lancaster University) contains both forward modeling and inverse modeling capabilities, but this software lacks a graphical user interface. Analysis of several different scenarios may therefore be somewhat time-consuming, as each step of the forward/inverse modeling procedure must be executed independently.

To facilitate the practice of pre-modeling, we present the Scenario Evaluator for Electrical Resistivity (SEER), a spreadsheet-based tool that allows the user to interactively evaluate forward/inverse modeling scenarios for electrical resistivity imaging (ERI). The ERI technique is chosen because it is perhaps the most widely used geophysical method for hydrological characterization given its applicability to a wide range of spatial scales (i.e., submeter to tens of meters) and its sensitivity to pore-fluid conductivity, pore connectivity, porosity, saturation, and clay content. The numerical sensitivity of ERI to these properties is governed by survey design, measurement errors, and the electrical properties of the site

itself. The SEER tool provides a quick and simple method to experiment with these variables to assess the likely outcome of utilizing ERI for a particular project.

Background

The following section describes basic aspects of ERI surveys, forward modeling, and inversion. For more complete detail on these subjects, refer to the summary by Binley (2015).

Preparation for an ERI survey involves implanting electrodes in the ground surface, in boreholes, or in both, and connecting those electrodes to a resistivity instrument. Typical ERI surveys involve hundreds or thousands of measurements, each consisting of a reading of the potential difference across one electrode pair in response to current injected between another electrode pair. The electrical resistivity of the medium determines the potential difference that is measured from this transmitted current. Commonly, measurement errors are quantified by (1) repeating each measurement several times to calculate a standard error; and/or (2) swapping the current and potential pairs to obtain a reciprocal measurement.

Forward modeling of ERI data is typically performed numerically using a finite-difference or finite-element approach. First, a grid or mesh representing the medium of interest is generated and an electrical resistivity is assigned to the medium represented at each cell or element in the mesh. Then, electrical potentials at electrode positions are found by simulating electrical current flow using boundary conditions appropriate for the specific problem under consideration. The potential difference between electrodes can thus be used to provide simulated data for any survey configuration.

Inverse modeling of ERI attempts to estimate a resistivity distribution from data; that is, transfer resistances are computed from a distribution of potential differences recorded with known current sources. The inverse problem is typically nonlinear and nonunique, in that there are more unknown parameters (resistivity values) to identify than measurements acquired. Therefore, iterative numerical methods and regularization are normally used to solve inverse problems. These methods operate by minimizing differences between observed and simulated resistivities (the objective function), subject to data misfit and regularization constraints (such as model smoothness or similarity to a starting model) to below a specified tolerance (see, e.g., LaBrecque et al. 1996).

SEER is a tool that allows the user to experiment with simple forward/inverse modeling scenarios without the need for full, time-consuming numerical inversion. We accomplish this through a linear approximation of the inverse solution to ERI, given a set of model parameters, $\mathbf{m}_{\text{true}}$, and a preestimate of the model resolution matrix (Day-Lewis et al. 2005). The model resolution matrix, $\mathbf{R}$, is a way to express the collective effect of the inversion on $\mathbf{m}_{\text{true}}$. In problems that are approximately linear, $\mathbf{R}$ is effectively independent of $\mathbf{m}_{\text{true}}$,

$$\hat{\mathbf{m}} \approx \mathbf{R}\mathbf{m}_{\text{true}} \quad (1)$$

where $\hat{\mathbf{m}}$ contains the estimated parameter values from the inversion and

$$\mathbf{R} = [\mathbf{J}^T \mathbf{C}_D^{-1} \mathbf{J} + \alpha \mathbf{D}^T \mathbf{D}]^{-1} \mathbf{J}^T \mathbf{C}_D^{-1} \mathbf{J} \quad (2)$$

where $\mathbf{J}$ is the Jacobian matrix (which contains the sensitivities of changes in forward modeled resistances to changes in model parameters), $\mathbf{C}_D$ is a covariance matrix with diagonal elements that contain the measurement-error variances (whose reciprocals are the data weights), $\mathbf{D}$ is a model weighting regularization matrix, and α is a regularization parameter that determines the balance between data misfit and smoothing.

Research Method

Excel-Based Implementation

SEER is an Excel-based tool that allows the user to freely manipulate resistivity values in cells of the worksheet (i.e., each cell represents a specific resistivity value in the mesh described above) and to immediately view the effect on the predicted ERI results. Consequently, the user can change the hypothetical target's shape, extent, and depth; view the ERI results, and rapidly gain insight into the ability of a given survey to image that target. Drop-down menu options for survey type, electrode spacing, borehole options (a fixed set of boreholes or no boreholes), and noise level are available, and allow the user to consider a total of 54 options for survey design. Based on these user selections, the appropriate precomputed $\mathbf{R}$ (see next section for details) is loaded from separate files stored in the SEER folder, and Equation 1 is used to predict the inverse result; this process takes several seconds on modern computers. Although the user is free to enter any resistivity target, SEER includes four starting scenarios: (1) a complex dense nonaqueous-phase liquid (DNAPL) target; (2) a light nonaqueous-phase liquid (LNAPL) pool floating on the water table; (3) an underground storage tank (UST); and (4) a configuration of discrete blocks. The targets in these scenarios are embedded in homogenous or layered resistivity cross sections; however, the user can increase or decrease complexity by building a custom resistivity model, manually changing resistivity values in the worksheet cells. A help file accompanying the SEER code provides additional information.

Precalculation of Resolution Matrices

We calculated each resolution matrix numerically given a cross-sectional model. To do this, we constructed a two-dimensional (2D) mesh with 408 elements in the x (horizontal) direction and 90 elements in the z (vertical) direction. Each element was square with 0.25 m sides, with the exception of edge elements, which were log-spaced in size to extend the model 100 m in each direction to accommodate the assumption of infinite current flow. All elements were assigned a 100 ohm-m resistivity (homogenous earth). For parameter estimation, the model elements were grouped into parameters that consisted of 6×6 -element patches (1.5×1.5 m). Each patch directly corresponds to a resistivity model cell in SEER. Of course, other discretizations are possible, and future releases of SEER may include options for other meshes; however, the current version is limited to a modeling domain of 68×15 patches, each of which corresponds to 1.5 m^2 .

Forward modeling of ERI data was achieved using R2 version 3.0. R2 is freely available software for 2D forward and inverse ERI modeling and is downloadable at (<http://www.es.lancs.ac.uk/people/amb/Freeware/R2/R2.htm>). We simulated data for the following combinations of scenarios: three surface-electrode spacings (1, 2, and 4 m), three survey types (Wenner, dipole-dipole, and both), and two borehole options (no boreholes and two boreholes added). The two latter cases consider two boreholes centered laterally within the study domain, spaced 12.5 m apart, with 20 electrodes that extend to 20 m depth. Skip-1 and Skip-8 dipole-dipole measurements were added in the two-borehole case. Skip-1 and Skip-8 refer to dipole-dipole survey types with one and eight electrodes between each current and potential electrode pair, respectively (diagrams of the survey types are shown in the SEER help file). Note that the boreholes are fixed in their positions and cannot be adjusted by the user. Three noise levels (1%, 5%, and 10%) were simulated by adding random Gaussian errors to each dataset.

The noise-contaminated, forward-modeled data were inverted in R2 and $\mathbf{J}$, $\mathbf{D}$, $\mathbf{C}_D$, and α were output. Each $\mathbf{R}$ was subsequently computed in Matlab (Mathworks, Natick, Massachusetts) using Equation 2. In total, there were 54 $\mathbf{R}$ matrices when all combinations of electrode spacings, survey types, borehole options, and noise levels were simulated.

Linear Inverse Approximation

An example comparison of the results obtained from our linear approximation to the inversion (Equation 1) vs. results from a numerical inversion is shown in Figure 2. Figure 2a shows the true model, consisting of a 4.5×4.5 m conductive (100 ohm-m) underground storage tank (UST) embedded within a 500 ohm-m resistive soil. In reality, such a target would exist in three dimensions, and as such the 2D forward/inverse modeling represents a simplified case, wherein the 2D slice is assumed to extend infinitely in the third dimension. A UST would not likely extend far outside of the 2D plane, and therefore our modeling presents a simplified scenario. Furthermore, such a feature would exist in an electrically heterogeneous soil and thus this model represents an idealized case. Therefore, while this example demonstrates the use of the method presented in this study, we concede that such a model greatly simplifies true field conditions.

Figure 2b and 2c depicts the result of our linearized approach (Equation 1) and a full numerical inversion, respectively. Whereas the former is a simple matrix multiplication amenable to calculation in Excel taking a few seconds or less on a typical laptop, the second typically entails execution of code requiring CPU time on the order of minutes to tens of minutes; hence our use of the linear approximation in SEER. This scenario used 1-m spaced electrodes, a combined Wenner and dipole-dipole data-collection configuration, and 1% noise. The approximate location of the UST is visible in both the linearized approach used by SEER (Figure 2b) and the numerical inversion (Figure 2c); although the boundaries of the UST and the magnitude of the resistivity contrast are somewhat better resolved in the numerical approach, as expected. The addition of borehole electrodes around the UST improves the edge definition of the UST considerably in the linear approach (Figure 2d), as well as the numerical approach (Figure 2e), although with some artifacts present in both cases. These results demonstrate that the linearized approach can approximate the results of

full inverse modeling; however, the accuracy of predictions based on a precomputed resolution matrix is expected to break down as resistivity contrasts become very large (more than several orders of magnitude) and the inverse problem becomes more nonlinear. Another useful outcome of this modeling is the identification of likely inversion artifacts, which are often misinterpreted as real features in field data. For example, Figure 2d indicates a conductive anomaly below the UST that is also seen in Figure 2e. Such a result helps to clarify the benefits and limitations of ERI in showing that ERI will likely succeed in imaging this target, but that the user should take heed of possible inversion artifacts when drawing conclusions from field data.

Example

To further demonstrate the capabilities and benefit of using the SEER tool, we consider a conductive (40 ohm-m) DNAPL plume embedded within a saturated zone with a resistivity of 100 ohm-m and underlying a 7.5-m thick unsaturated zone (500 ohm-m) (Figure 3a). Two scenarios were evaluated: (1) a combined Wenner/dipole-dipole survey configuration with 1-m electrode spacing and 1% noise and (2) the same scenario with two boreholes added in the region of the plume. The results indicate a limited ability to delineate the plume using surface electrodes only (Figure 3b), whereas lateral and vertical extents are much better constrained with boreholes (Figure 3c). This exercise demonstrates that, despite the added cost of ERI borehole installation (such boreholes cost considerably less than monitoring wells), adding boreholes may be worthwhile in this scenario. This pre-modeling exercise is achieved through simple drop-down menus available in SEER (Figure 3d).

The success of ERI depends on the target of interest having a sufficient resistivity contrast from the surrounding material, being of sufficient size, and being located in an area of sufficient sensitivity. It is often convenient for modeling purposes to consider a target embedded within a homogeneous medium, although real earth materials are electrically heterogeneous. It is important to consider that even with promising synthetic results from SEER, geological heterogeneity, which is difficult to estimate, can potentially mask the anticipated target at the field site. Adding heterogeneity is a simple matter in SEER, achieved by the user simply entering resistivity values at the desired locations in the mesh (i.e., cells within the model). An example is included in Appendix S1, Supporting Information of this manuscript.

Summary

Pre-modeling, also known as synthetic modeling, of geophysical data is a crucial step in determining if a geophysical approach is suited to a project's objective(s) and has potential to successfully answer salient questions. Yet, this step is often overlooked outside of academic and research communities, in part due to the time and expertise required to perform forward and inverse modeling scenarios. The SEER tool provides a rapid, simple-to-use means of assessing realistic outcomes from ERI surveys, and helps to avoid unrealistic interpretations from simulated field data. Additionally, SEER may serve to offer basic guidance on the relative benefit of different survey configurations prior to field data acquisition, in that a suite of survey configurations can be rapidly evaluated for a given

model. Our results suggest that the linearized model-estimation approach used within SEER provides comparable results to numerical modeling. Nevertheless, SEER is: (1) presently limited to preselected electrode configurations and model geometries; and (2) based on a linear approximation that may underestimate the resolving power possible with full, nonlinear inverse modeling. It is advised that synthetic modeling using numerical forward and inverse modeling (e.g., through R2 or similar software) be performed as a second step after SEER has demonstrated that ERI is likely to be successful for the specific target and site conditions. Such advanced synthetic modeling, while requiring greater expertise to implement, provides substantial flexibility in evaluating the likely results from a limitless number of survey design configurations, and may provide better resolution in highly nonlinear cases (e.g., for resistivity models that are highly heterogeneous).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1.

Conceptual schematic showing forward and inverse “pre-modeling” steps for a hypothetical target, in this case an LNAPL pool.

Figure 2.

Comparison of results from the linear inversion approach (b, d) used for the SEER tool vs. results obtained from a numerical inverse approach (c, e) based on the underground storage tank model shown in panel (a). Results shown for 1-m spaced surface electrodes and 1% noise are shown in panels (b) and (c) whereas two sets of 1-m spaced borehole electrodes are added in panels (d) and (e). All images use same color scale.

Figure 3.

Experimentation with survey design to use ERI to detect a conductive dense nonaqueous phase liquid plume using the SEER tool. (a) The true model. (b) SEER predicted inversion result with a combined dipole-dipole and Wenner survey geometry, 1-m spaced electrodes, and 1% error. (c) The effect of this same scenario with borehole electrodes added. (d) Screen capture of the options used to generate the result shown in panel (c).