LBNL FORGE Project 3-2535 Report for Milestone 4.2

Numerical Modeling of Energized Steel-Casing Source for Imaging Stimulated Zone at FORGE site

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1. Introduction

In FORGE project 3-2535, Lawrence Berkeley National lab is planning on using a casing source electromagnetic (EM) method (Daily et al., 2004; Marsala et al., 2014; Commer et al., 2015) for detecting and imaging a deep localized stimulated fracture zone at the Utah FORGE site. In this configuration, one electrode is directly connected to, and energizes a steel-cased well while the other electrode is placed on the surface sufficiently away from the well. Figure 1 shows two common casing source configurations. The steel-cased well can be viewed as a 'boosting' vertical antenna that enables large source dipole moments and greater imaging depths than a conventional surface EM method, with the additional computational complexity of needing to model EM interactions between the current source, the steel cased well, and the resistivity structure of the Earth.

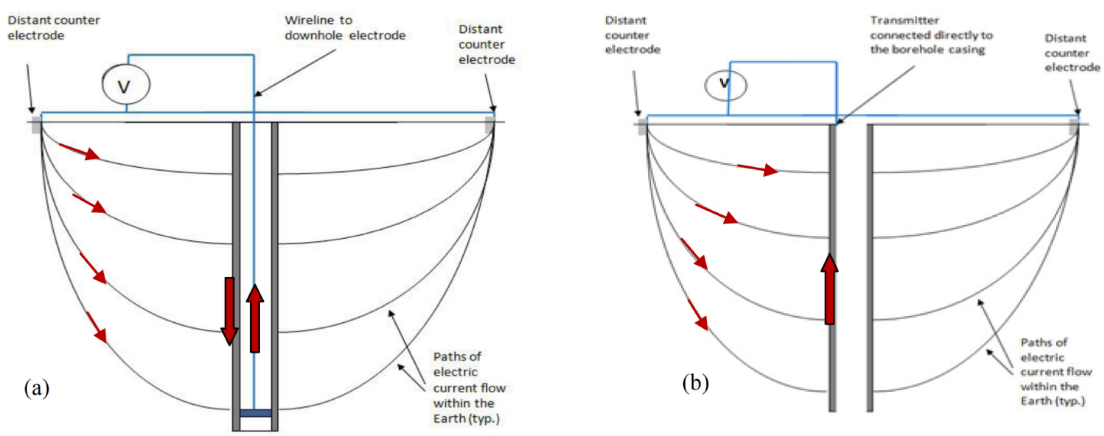


Figure 1. Schematic diagrams (Marsala et al., 2014) for casing source EM configurations. (a) The downhole source configuration. (b) The top casing source configuration. The red arrows show the direction of current flow.

In general, it is numerically challenging and impractical to directly discretize an arbitrarily-oriented steel-cased well in a 3D reservoir-scale or regional-scale EM earth model. The 3D discretization requires using a number of very small elements/cells because a typical steel well casing is only millimeters thick, while at the same time it is a million times more conductive than surrounding geology. The number of elements required for discretizing such a well casing exponentially increases as the well length increases, making 3D EM modeling using the true casing dimensions intractable even on a large-scale parallel computer (Commer et al., 2014; Um et al., 2020).

In this project, we plan to electromagnetically energize Well 16A and/or 16B. The measured length of these wells is about 3.35km, and they deviate at about 65 degrees from its vertical surface trajectory after reaching 1828 meters in depth (Winkler et al., 2021). Due to the aforementioned problems of accurately discretizing and modeling a deviated steel casing, we do not attempt to directly simulate the completed well but rather will approximate the effects of the energized steel-cased well by replacing the energized casing with a series of equivalent electric dipole sources (Tang et al., 2015; Kohnke et al., 2018). This approximation approach enables us to simulate the casing-source EM responses to a 3D FORGE EM model without critically increasing computational costs and complexity. The goal of this milestone report (milestone 4.2) is to demonstrate the accuracy of the 'equivalent source' method mentioned above by presenting a comparison between this approximation and more rigorous solutions to an electrically energized casing embedded in a simple Earth model. After validation this approximate technique for simulating the earth response to an energized steel casing will then be applied within an EM survey design study for the 3D FORGE resistivity model that has been derived from the 3D inversion of magnetotelluric (MT) data as reported in Wannamaker et al., (2020[a] and 2020[b]), and shown in a Powerpoint presentation that was submitted as the deliverable for Milestone 4.1 of this project.

2. Casing Modeling Methodologies

In order to implement the casing source in the 3D FORGE model where the lower part of the source well, 16A is deviated, we propose the following steps. First, we construct a layered Earth model whose resistivity structure is consistent with resistivity that exists along the trajectory of well 16A in the 3D FORGE MT model. Next, a vertical steel-cased well whose true depth is the same as the measured length of the deviated well is inserted into the layered model. Third, we simulate the EM casing-source using 3D SimPEG (Heagy and Oldenburg, 2022). SimPEG is an open-source Python package for simulation and gradient-based parameter estimation in geophysical applications. While the great majority of 3D EM geophysical modeling algorithms uses the 3D Cartesian coordinate system, SimPEG supports a cylindrical coordinate system and enables us to simulate the vertical casing source responses at low computational costs (e.g., several hours on a high-end workstation computer) because a vertical well naturally fits within the cylindrical coordinate system without excessive mesh refinement. After this simulation, we extract vertical current densities (complex quantities) along the outer surface of the steel cased well. This set of the extracted current densities are then mapped to a series of electric dipoles along the well trajectory, where the dipole magnitudes and phases are adjusted appropriately approximating the effects of an energized steel-cased well (Tang et al., 2015; Kohnke et al., 2018). Using this technique allows to approximate the current density vectors along the trajectory of well 16A in the 3D earth model, and thus we can simulate the casing-source EM responses to the 3D FORGE resistivity model.

3. Modeling and Comparison

In this task, we have not developed any new numerical modeling codes for simulating casing EM source. Rather, we have developed a workflow that uses results from available codes as described above. As mentioned before, we use the SimPEG for simulating 3D EM responses to an energized steel-cased well. Figure 2 shows cylindrical meshes used for discretizing a 1km long vertical well. Fine cells are used for resolving the hollow geometry of the vertical well which is placed at the center of the meshes. To reduce the model size and suppress model boundary effects, cell sizes gradually grow away from the well.

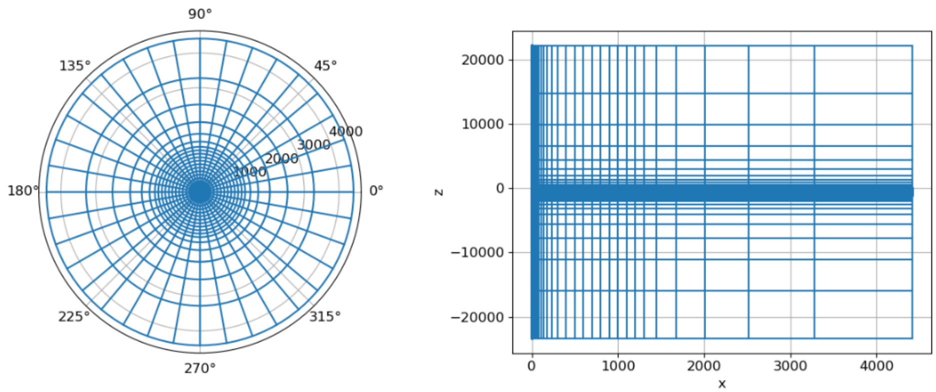
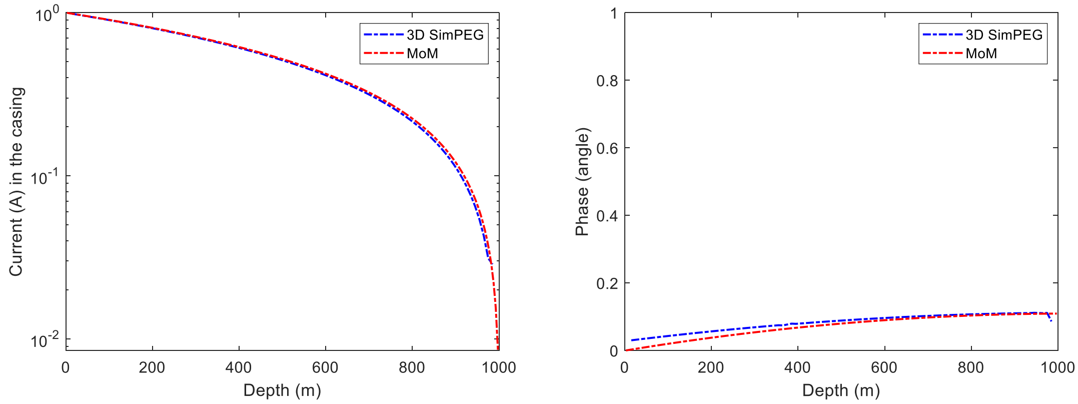


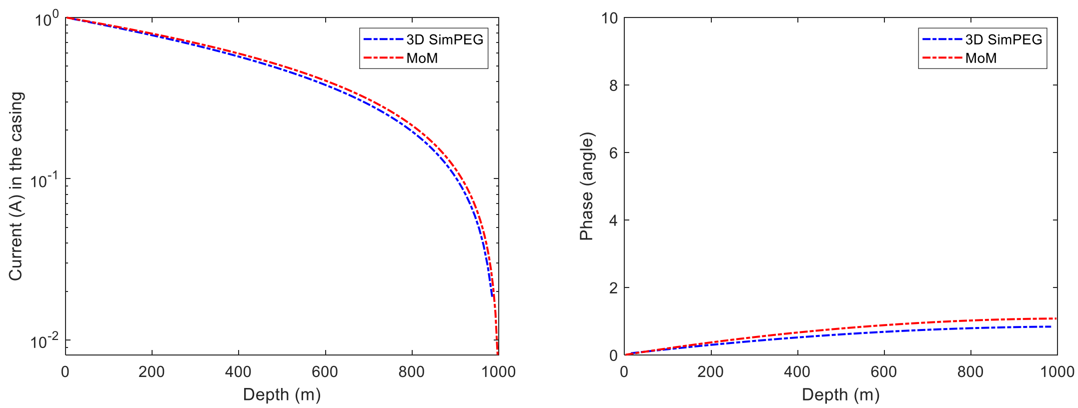
Figure 2. An Example of cylindrical meshes used for discretizing a 1km steel-cased well (electrical resistivity: 1E-6 Ohm-m, outer diameter: and thickness:). (a) The *xy* plan view. (b) The *xz* cross-sectional view.

In order to verify the accuracy of the casing current densities extracted from the SimPEG model, we first compare the SimPEG calculated currents against a method of moments (MoM) solution (Tang et al., 2015). The MoM technique divides the casing into a number of small segments and assumes that the vertical current density of each small segment is uniform as the radius of the highly conductive casing is much smaller than its length. A linear system of equations **Aj**=**b** is then formed, where **A** is a matrix that describes casing interactions, **j** is the vector of current densities for each casing segment that we want to solve for, and **b** is a vector of values of the electric field induced by an external source within the location of each casing segment. Figure 3 compares the casing current density vectors calculated between MoM and SimPEG which shows good agreements with each other, indicating that the current density vectors extracted from SimPEG are accurate and can be used for future 3D modeling works for designing optimal EM survey configurations for monitoring a stimulated zone at the FORGE site.

Once the accuracy of the casing current densities extracted from the SimPEG model is verified, we compare 3D borehole EM responses between the true casing geometry (i.e., SimPEG solutions) and the equivalent sources. To do this, the set of equivalent sources are embedded into a 3D finite-element (FE) resistivity model, and the FE EM modeling and inversion code of Um et al. (2020) employed to calculate the EM response. Inside the FE simulator, the equivalent sources are excited simultaneously for generating the EM responses equivalent to the true casing geometry. Figure 4 compares the electric and magnetic fields from the two solutions for a well 500m away from the energized casing and shows good agreement with the amplitude curves lying nearly on top of each other, and maximum phase errors of around 1^{o}. From these results, we conclude that the proposed workflow is accurate for modeling a vertical well. Furthermore, given the minimal differences between the full SimPEG and distributed source FEM solutions, and because there is no computationally tractable way to fully simulate a deviated steel cased well, we believe that this workflow provides the best method to completing the 3D EM modeling / survey design work that ultimately will be used for estimating the size / porosity of the stimulated reservoir for the FORGE experiment.

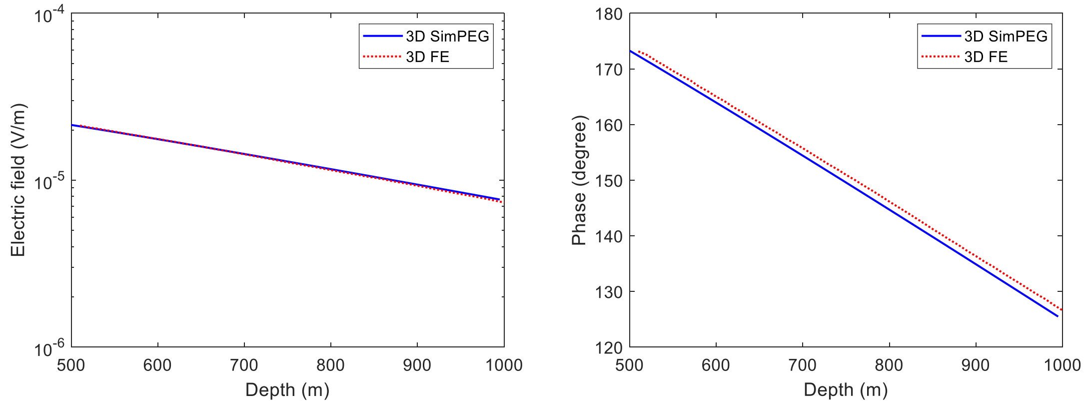


(a)

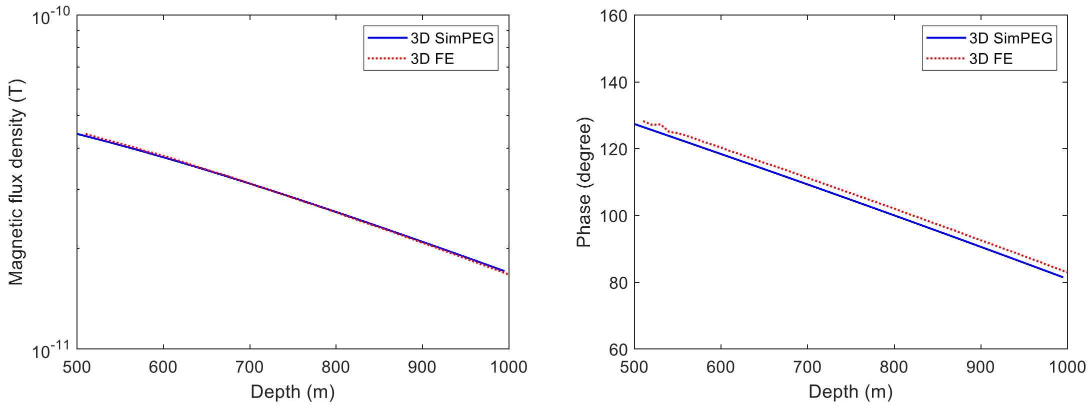


(b)

Figure 3. Comparisons between the current density vectors (complex quantities) calculated using the 3D SimPEG and MoM method. The steel-cased well is 1km deep. The source electrode is connected to the top of the well casing (electrical conductivity: 10^{-6} S/m; outer radius: 0.1m, thickness: 0.02m) and the return electrode is located 2km away from the well head. The source is operating at 1Hz. (a) 10^{-3} S/m half-space model. (b) 10^{-2} S/m half-space model.



(a)



(b)

Figure 4. Comparisons between borehole EM responses calculated using true casing geometry (SimPEG) and equivalent sources (3D FE solutions). The source well is 1km deep, and the observation well is 500m away from the source well. The background is set to 100 Ohm-m. The top-casing source is operated at 100 Hz. (a) Amplitude and phase of vertical electric fields (Ez). (b) Amplitudes and phases of horizontal magnetic fields (Bx).

5. Conclusions and Future Work

In this work, we have presented a modeling workflow that simulates an energized steel-cased well by replacing it with a number of small equivalent current density vectors. We have verified the equivalence by comparing SimPEG solutions first to a MoM solution to verify accuracy of the full casing solution, and then to a distributed source solution that involve computation using a 3D FE algorithm. This modeling workflow enables us to simulate the casing-source EM method without critically increasing computational costs, time and complexity. In the next step (Milestone 4.3), we will use this workflow and evaluate several different casing source configurations coupled to borehole measurements for optimally sensing a deep stimulated zone at the FORGE site. Realistic noise levels and EM instruments' characteristics will be considered during our modeling analysis.

5. References

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