SAND2018-3088C

Effects of completion design on electrically stimulated casing and its 3D response

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SUMMARY

To better understand the factors contributing to electromagentic (EM) observables in developed field sites, we examine in detail through finite element analysis the specific effects of casing completion design. The presense of steel casing has long been exploited for improved subsurface interrogation and there is growing interest in remote methods for assessing casing integrity accross a range of geophysical scenarios related to resource development and sequestration/storage activities. Accurate modeling of the casing response to EM stimulation is recognized as relevant, and a difficult computational challenge because of the casing's high conductivity contrast with geomaterials and its relatively small volume fraction over the field scale. We find that casing completion design can have a significant effect on the observed EM fields, especially at zero frequency. This effect appears to originate in the capacitive coupling between inner production casing and the outer surface casing. Furthermore we show that an equivalent "effective conductivity" for the combined surface/production casing system is inadequate for replicating this effect, regardless of whether the casings are grounded to one another or not. Lastly, we show that in situations where this coupling can be ignored and knowledge of casing currents is not required, simplifying the casing as a perfectly conducting line can be an effective strategy for reducing the computational burden in modeling field–scale response.

INTRODUCTION

We are interested in casing effects on observable electromagnetic (EM) fields and the currents carried by or induced in the casing for the general problem of subsurface characterization and, specifically, casing integrity analysis in developed field sites associated with economic resource development and/or subsurface containment/sequestration activities. Engineered infrastructure in such sites (well casings, pipes, storage tanks, etc) poses particular challenges to EM monitoring because of the strong and far-reaching footprint it imposes on the EM signals of interest. The problem is exacerbated by the fact that such infrastructure, typically, is volumetrically insignificant over field scales of several km. Thus, modeling these sites is difficult because a disproportionate amount of compute resouces (meshing, model specification, etc) is focused on an infinitesimal volume fraction of the model domain. For complex field sites, the problem of capturing all the infratructure is often simply intractible without resorting to simplifying assumptions. To that end, a number of practical strategies have emerged in the literature. These include representation of thin conductors by fatter, more computationally managable versions of themselves (e.g. Haber et al., 2016), specialized parallel algorithems for brute force discretization of maximum detail (e.g. Commer et al., 2015; Um et al., 2015; Puzyrev et al., 2017), equivalent resistor/impedance networks (Yang et al., 2016; Yang and Oldenburg, 2017), and hierarchical representations of material distributions (Weiss, 2017).

To test the hypothesis of whether detailed well completion design is a necessary concern in modeling the EM response of a developed field site, we focus attention here on a CO_2 sequestration site in southwest Alberta because we have data there, the geology is relatively simple, and the wells are shallow, thus enabling a brute force discretization if necessary. We use the hierarchical (Weiss, 2017) and full discretization (Um et al., 2017) finite element methods to model realistic completion design at the sequestration site in order to determine whether the details therein merit added concern. We also examine the feasibility of applying the "perfect electric conductor" (PEC) boundary condition in frequency domain EM calculations as a means to avoid excessive discretization of the well bore casing, noting that this is a limiting case of the hierarchical representation for infinite conductors.

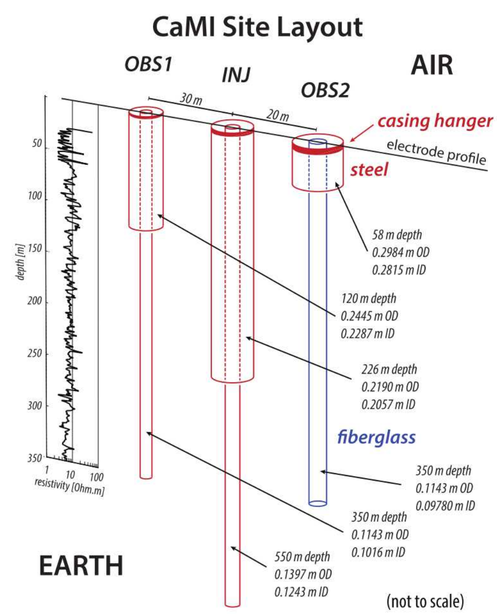

Figure 1: Sketch of the well layout and casing design for the CaMI site, annotated with outer and inner diameter (OD and ID, respectively) dimensions for shallow surface and deep production casing.

METHODOLOGY

The model under consideration is a CO_2 sequestration site at the Containment and Monitoring Institute (Alberta, CA, Figure 1). For the purposes of testing the effects of completion design on electromagnetic response, this site is attractive because the wells are shallow (less than 500 m depth), close to one another, vertical, and embedded in a geology with relatively uniform conductivity 0.125 S/m. Comparisons between modeling results and field data collected at the site are reported elsewhere (Wilt et al., 2018) and are generally favorable. Measurements of inline electric field are available along a profile over three well heads at the site: one injection (INJ) and two observation (OBS1 OBS2) wells. Two measurement configurations were deployed, each 5 Hz horizontal electric dipole grounded at one end 500 m laterally from well OBS2 and then grounded on the other end at well OBS1 or OBS2. For simplicity, results of OBS2 grounding point are only considered in the analysis that follows.

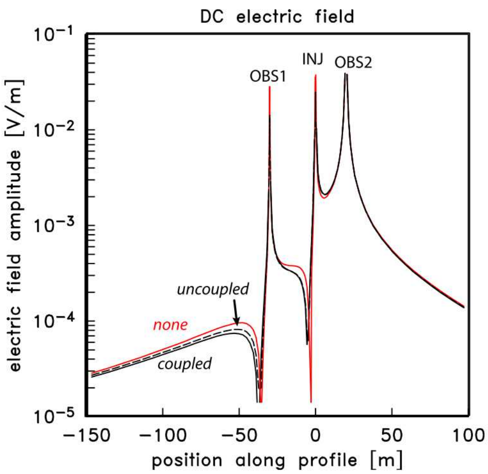

Figure 2: Electric field amplitude along a profile over well heads for three completion design scenarios where the OBS2 is grounded as one pole of the source antenna: (red) no surface casing; (black, dashed) surface casing isolated from production casing; and, (black, solid) surface casing electrically grounded to production casing by the casing hanger. Return pole is located 500 m orthogonal to the profile line from OBS2.

Electrostatic response of the CaMI site geometry (Figure 1) is computed using the hierarchical material representation described in Weiss (2017) for finite element analysis on an unstructured tetrahedral discretization. To summarize the concept, electrical conductivity σ is decomposed into a finite sum of volume–based conductivies σ_e over the tetrahedral volumes, a sum of thickness·conductivity products s_e over facets of tetrahedra, and area·conductivity products t_e over the edges. Doing so allows thin, strong conductors to be represented in the finite element model without a computationally explosive number of tetrahedra and permits rapid solution to, for example, fracture models and in the present study, casing effects studies. In the electrostatic analysis that follows, the central production casing of wells INJ and OBS1 are modeled as a continuous set of connected edges with area·conductivity product $t_e = 5 \times 10^4$ S·m. The surface casing is modeled as a thin shell with conductance $s_e = 5 \times 10^5$ S and diameter equal to the outer diameter reported in the completion design (Figure 1). An advancing front algorithm (cubit.sandia.gov) discretizes the Earth region of the model alone, with the air region handled implicitly through a homogeneous Neumann boundary condition on the air/earth interface. On the remaining sides of the mesh the electric scalar potential is assigned an inhomogeneous Dirichlet condition with values equal to those from a point source on a 0.125 S/m halfspace. The resulting linear system of equations is solved iteratively with Jacobi–preconditioned conjugate gradients in a matrix–free formulation (Weiss, 2001).

To simulate the combined inductive and galvanic EM response over 3D steel infrastructure, we use a 3D FE modeling algorithm in the frequency domain (Um et al., 2017). To formulate the algorithm, the Galerkin method with vector basis functions is applied to the electric field diffusion equation and determines the electric field distribution in an earth model. The resulting system of FE equations is solved by parallel direct solver, MUMPS (Amestoy et al., 2001, 2006). When necessary, magnetic fields at receivers are interpolated from the known electric fields via Faraday's law.

The algorithm utilizes tetrahedral meshes (Si, 2015) to discretize multi-scale 3D earth models, which includes metallic well casing and other steel infrastructure. The tetrahedral meshes allow local refinements in the computational domain such that fine meshes can be used around hollow wells for accurate discretization and coarse meshes elsewhere for efficient discretization. Although tetrahedral meshes can theoretically accommodate realistic steel infrastructures, their explicit discretization of a hollow long (e.g. a few km) steel cased well often becomes intractable because of large memory requirements and limitations of meshing algorithms (Weiss, 2017).

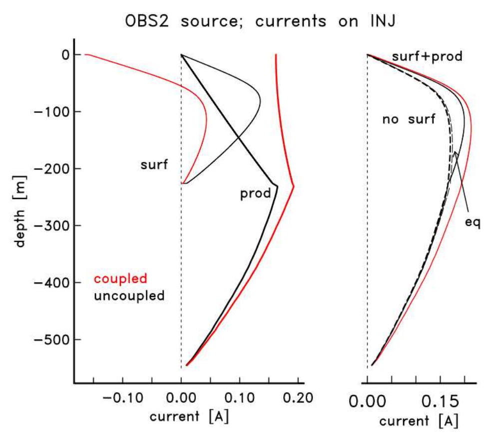

Figure 3: (Left) Longitudinal current amplitude along the INJ (Figure 1) production casing for two different nested casing models: surface and production casings electrically isolated (uncoupled, red); and, coupled by the casing hanger (black). (Right) Sum of production and surface casing currents (same color scheme as left figure) and addtional results where the surface casing is not explicitly discretized. In heavy dashed lines is the reponse of the production casing alone, represented by a uniform $t_e = 5 \times 10^4$ S·m, and in light dashed lines is the response when the upper 226 m is assigned area·conductivity product $t_e = 3.83 \times 10^5$ S·m to account for the additional amount of steel in the surface casing.

Alternatively, a hollow steel-cased well is often replaced with a solid cylinder when an electric source is placed outside the well. The cylinder has the same conductivity of the casing

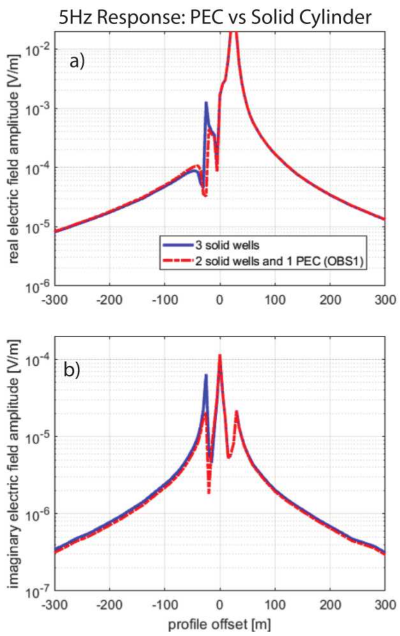

Figure 4: Real (top) and imagingary (bottom) components of the in-line electric field of Figure 1 are shown for the PEC (red) and solid cylinder (blue) models of OBS1 for the case of grounding the source antenna on the well head of OBS2. Wells INJ and OBS2 are modeled in each case as solid cylinders with a depth-dependent outer diameter equal to that of the production casing at depth, and the surface casing in the near–surface.

(Puzyrev et al., 2017; Um et al., 2017). The idea behind this replacement is that diffusive EM interactions between EM fields and the casing are mainly restricted to the surfaces of the casing due to the large conductivity contrast. By not discretizing the thin circular wall of the casing, the replacement not only reduces the total number of elements by an order of magnitude but also improves mesh qualities. This modeling approach is practically accurate enough to model wells especially when casing completion diagrams are not available or too complex to be directly modeled.

We examine the consequences when isolated steel wells are replaced with linewise perfect electric conductor (PEC) structures. Note that this approach is analogous to replacing hollow steel cased well with large solid prism such that both have the same conductance. When the linewise PEC approach is applied to modeling a steel–cased well, we reduce the volume of the well to zero, resulting in a linewise PEC structure. Linewise PEC is realized by aligning tetrahedral edges in a steel well direction. Subsequently, zero electric fields are applied to the edges. This internal boundary condition was first introduced for modeling highly conductive structures without finely discretizing them in 3D earth models (Alumbaugh and Newman, 1996). Like the hierarchical representation (Weiss, 2017) a major advantage of this PEC approach is to reduce the computational cost associated with the steel infrastructure because linewise PEC is volumeless. In contrast with the hierarchical represention where the electric field along such edges admits nonzero values due to their large but "imperfect" conductivity, the PEC boundary condition assigns, by definition, a zero electric field at these locations.

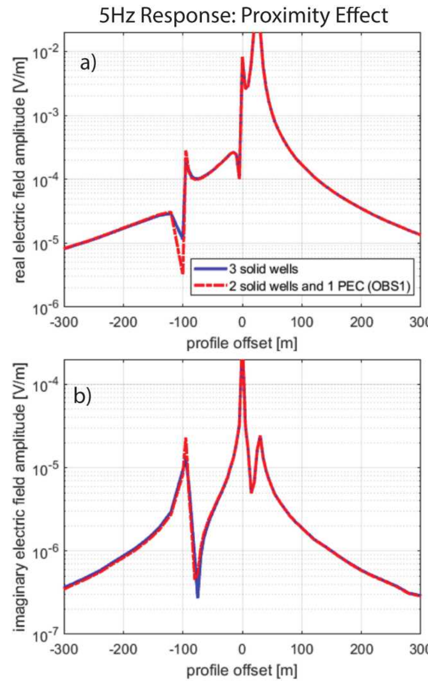

Figure 5: OBS1 is moved from an offset of 30 m to an offset of 100 from the injection well. Real (top) and imagingary (bottom) components of the in-line electric field are shown for the PEC (red) and solid cylinder (blue) models of OBS1 with an OBS2 grounding point for the source antenna. Red/blue color coding of the PEC/cylinder representation of OBS1 is the same as that in Figure 4.

RESULTS

Electrostatic response of the earth/casing system along the Figure 1 measurement profile shows that presence of surface casing (as modeled) is, in fact, significant and observable (Figure 2). Furthermore, we find that the error introduced by neglecting the surface casing is far greater (larger in magnitude and further in spatial extent) than the error introduced by neglecting the detail of whether the surface and production casings are electrically grounded. This result also shows that the effects of casing design reside both in the amplitude and character of the measured field, and hence, there is no obvious "correction factor" that can be applied *post hoc* to account for such effects.

Inspection of the longitudinal (up/down) currents carried by the production and surface casings gives some insight into why the effect of full completion design is so strong (Figure 3). The presence of an outer shell of surface casing elevates, through capacitive coupling to the inner casing, the magnitude of effective "combined" up/down current system of the two, to a degree that is not accomodated by simply increasing the conductivity of a single filamentary conductor. Hence, replacing the joint surface/production casing by some single, depth–dependent conducting line, is insufficient to replicate the observed (modeled) behavior.

To approximate frequency-dependent EM response over the three wells, we represent the three steel-cased wells (Figure 1) with solid cylinders. Specifically, OBS1 and INJ wells are modeled as coaxial solid cylinders; the diameters of the top and bottom cylinders are set to the outer diameter of the surface and production casing, respectively. OBS2 is replaced with a single solid cylinder. Such approximation would be a reasonable choice when well completion diagrams are not available or exact discretization of well completion is beyond meshing and/or computation capabilities. We use a 5 Hz electric dipole source whose configuration is the same as used in Figure 1. Figure 4 shows electric field responses (blue) along the profile. Notice that the real parts closely resemble their DC counterparts (Figure 2) and the imaginary part is smaller in magnitude by a factor of roughly 30.

Next, we replace OBS1 with linewise PEC while we model the other two wells as the same solid cylinders. Figure 4 compares their responses (red) with the responses to the three cylinder wells (blue). Although noticeable differences are observed around OBS1 and between OBS1 and INJ, elsewhere the two responses show good agreement.

We repeat the same numerical modeling experiments by moving PEC-based OBS1 70 m further away from the INJ well, making its total offset 100 m. Compared with Figure 4, Figure 5 shows that the overall agreement of the two models (blue vs. red) significantly improves when the PEC structure is more distant from the source. In this case, the PEC-based OBS1 can be an effective alternative to the steel well provided the solid-cylinder representation holds. These modeling results indicate that it is important to model details of the well completion if the well is adjacent to the source. Neglecting the capacitive and inductive coupling between surface and production casing, strict adherence to the exact casing diameter become less important when well structures are gradually distant from the source. By replacing the solid cylinder with PEC, we were able to reduce the problem size of Figure 4 and 5 from about 2.1 to 1.5 million elements. The reduction comes from the fact that linewise PEC does not require discretizing any volume but is realized by aligning edges in the well direction. Therefore, the problem size becomes less dependent on the total length of cased wells in a model. When a well is distant enough from the source, the inaccuracy due to its PEC approximation is highly localized around its location. Our modeling experiments imply that the PEC approximation can be a practical option for modeling complex steel infrastructures when they are isolated and reasonably distant from the source. However, because the PEC approximation, by definition, sets the electric field to zero along the edges representing the well casing, estimates of longitudinal casing current are simply not available along wells where PEC is applied.

CONCLUSIONS

For the present experiment, the error introduced into the predicted electostatic field data by neglecting surface casing is on the order of a few 10s of percent at distances up to 100 m from the well head. The relevance of these differences is, of course, dependent on their relative contribution to the overall interpretation of the data along the entire profile. Furthermore, we observe that the greatest error surrounds well OBS1 whose surface casing is shorter than that in the neighboring INJ well, thus suggesting a complex geometric interplay of charges and currents among all three wells at the CaMI site – an interplay whose effects may not defensibly be ignored by sequential simplification of well represention with increasing distance from the source antenna. Future work will investigate the dependence of the "completion effect" on additional factors such as background geology and source antenna frequency and configuration.

In situations where the surface and production casings are coupled at earth's surface via the casing hanger, the vertical current in each is non-zero at earth's surface owing to current continuity between the two. Superposition of these longitudinal currents reduces to an effective current system with the requisite zero-magnitude at the air/earth interface, but with an elevated amplitude in the near surface that is not wholly explained by an increase in bulk-averaged casing conductivity in this region. The latter holds for whether the surface and production casings are coupled or not. This suggests that a complete casing model which accounts for the capacitive effects between surface and production casings may be necessary for high-fidelity modeling of the macroscopic fields generated by such structures.

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE–NA-00003525.

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