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SAND2022-11484C

Well integrity monitoring with electric fields by using hierarchical geo-electric models

Summary

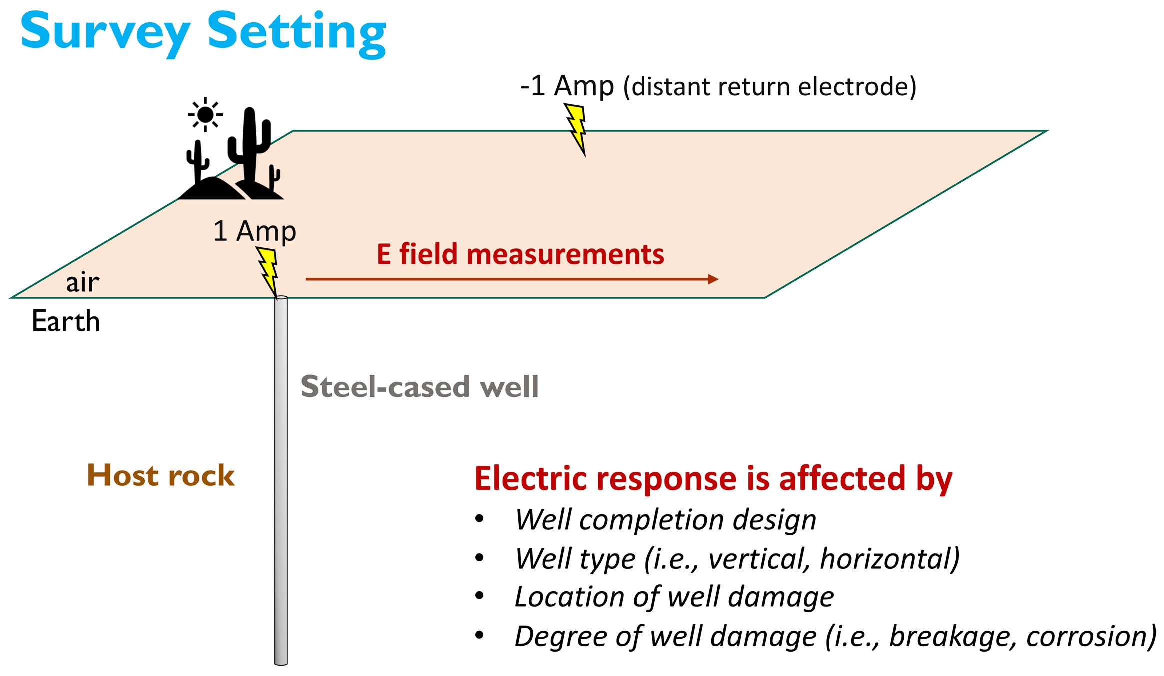
Failure of wellbore integrity is one of the key concerns in operating oil and gas fields as well as abandoned mature fields that are typically considered for long-term CO_2 storage, and may cause dramatic negative environmental impacts. Here, we present a numerical study on the well integrity monitoring by using electric (E) field measurements. The survey setting includes a steel-cased well whose condition is unknown (i.e., intact or damaged) and a surface profile along where the E field is measured once the casing is energized at the well head (i.e., the top-casing method; Wilt, 2016; MacLennan et al., 2018). The changes in the surface E field can be used to detect and constrain the location of well damage.

Here, we obtain the E field responses of the steel-cased wells from the simulated electrical potentials in the DC limit by utilizing the hierarchical finite element method (*Hi*-FEM; Weiss, 2017). The method allows us to represent the electrical conductivity not only on volume elements but also on lower dimensional elements such as facets (2D) and edges (1D) in the unstructured finite element mesh. Since the well casing is represented by a subset of connected edges within the 3D tetrahedral finite element mesh, the surface E field data can be simulated without the need of extensive mesh refinement and high computational cost. Our results support the findings of the previous studies that well breakage results in an anomalous increase in the amplitude of the surface E field inversely proportional to the length of the path from the wellhead. Moreover, our analysis of surface E field data obtained from an energized, damaged well also shows that regardless of the amount, type, and location of well damage, surface E field measurements can identify the presence of damage and provide a reasonable estimate for the compromised portion of the well. In this study, we present various model scenarios to investigate the feasibility of an automated well integrity monitoring with the surface EM data.

Monitoring well integrity

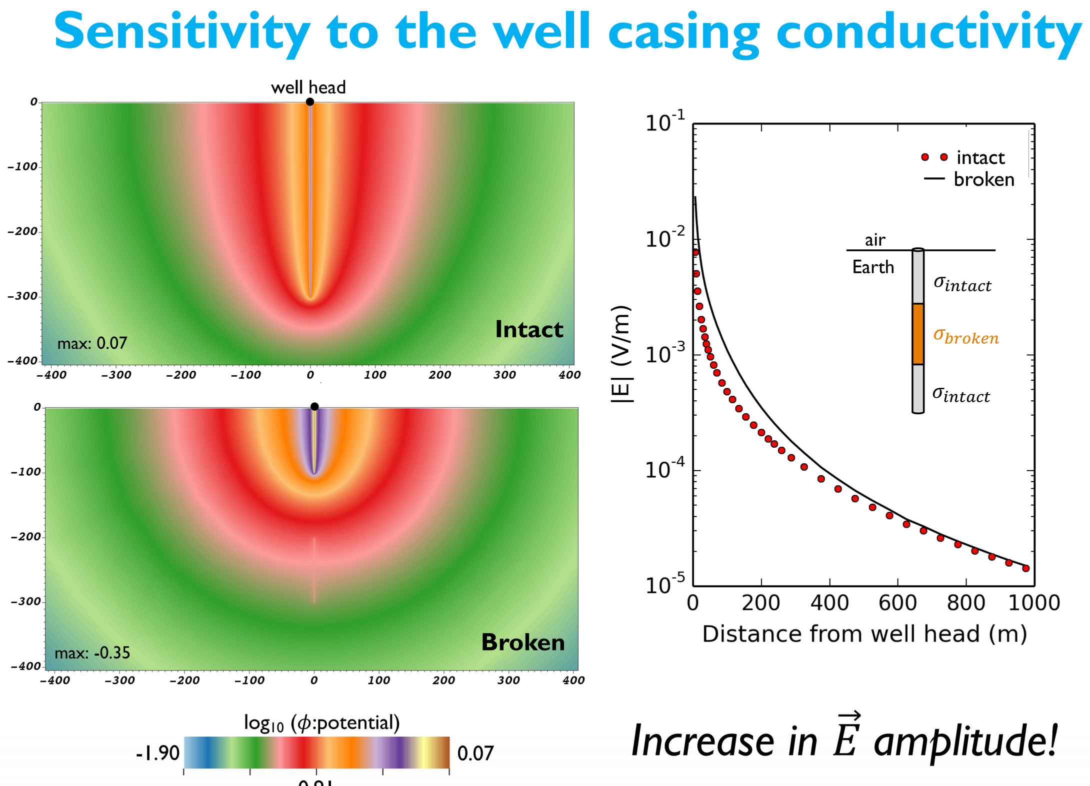
("top-casing method",** Wilt, 2016; MacLennan et al., 2018**)

Survey Setting



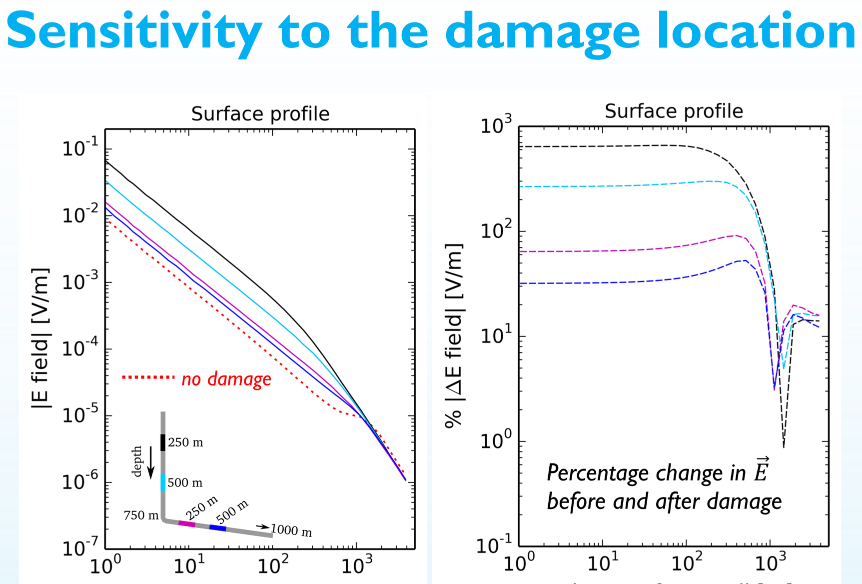
Electric responses of well damage

Sensitivity to the well casing conductivity



Increase in $\vec{E}$ amplitude!

Sensitivity to the damage location



(Beskardes et al., 2021)

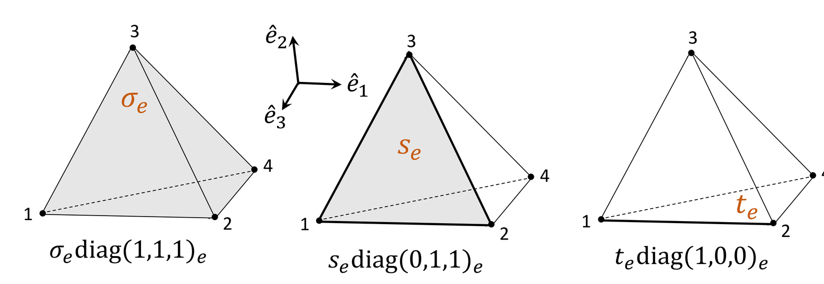
Hierarchical Finite Element Method (*Hi*-FEM)

The electric field $\mathbf{E} = \nabla u$ throughout a 3D conducting media subject to a given steady electric current density $\mathbf{J}_s$ is governed by the Poisson equation,

$$-\nabla \cdot (\sigma \cdot \nabla u) = \nabla \cdot \mathbf{J}_s$$

where u is the electrical scalar potential and σ is the electrical conductivity function.

The *Hi*-FEM recognizes not only the contribution of volumetrically-defined geologic structures but also the local contributions of 1D linear- and 2D planar-like geologic features to the overall electrical conductivity of a model within an unstructured tetrahedral mesh, and hereby allow us to simulate geologic models with important details at multiple scales of length in a computationally cost-effective way.



$$\Psi_e^V(\mathbf{x}) = \text{diag}(1,1,1)_e \begin{cases} 1 & \text{if } \mathbf{x} \in \text{volume } e \\ 0 & \text{otherwise} \end{cases},$$

$$\Psi_e^F(\mathbf{x}) = \text{diag}(0,1,1)_e \begin{cases} 1 & \text{if } \mathbf{x} \in \text{facet } e \\ 0 & \text{otherwise} \end{cases},$$

$$\Psi_e^E(\mathbf{x}) = \text{diag}(1,0,0)_e \begin{cases} 1 & \text{if } \mathbf{x} \in \text{edge } e \\ 0 & \text{otherwise} \end{cases}.$$

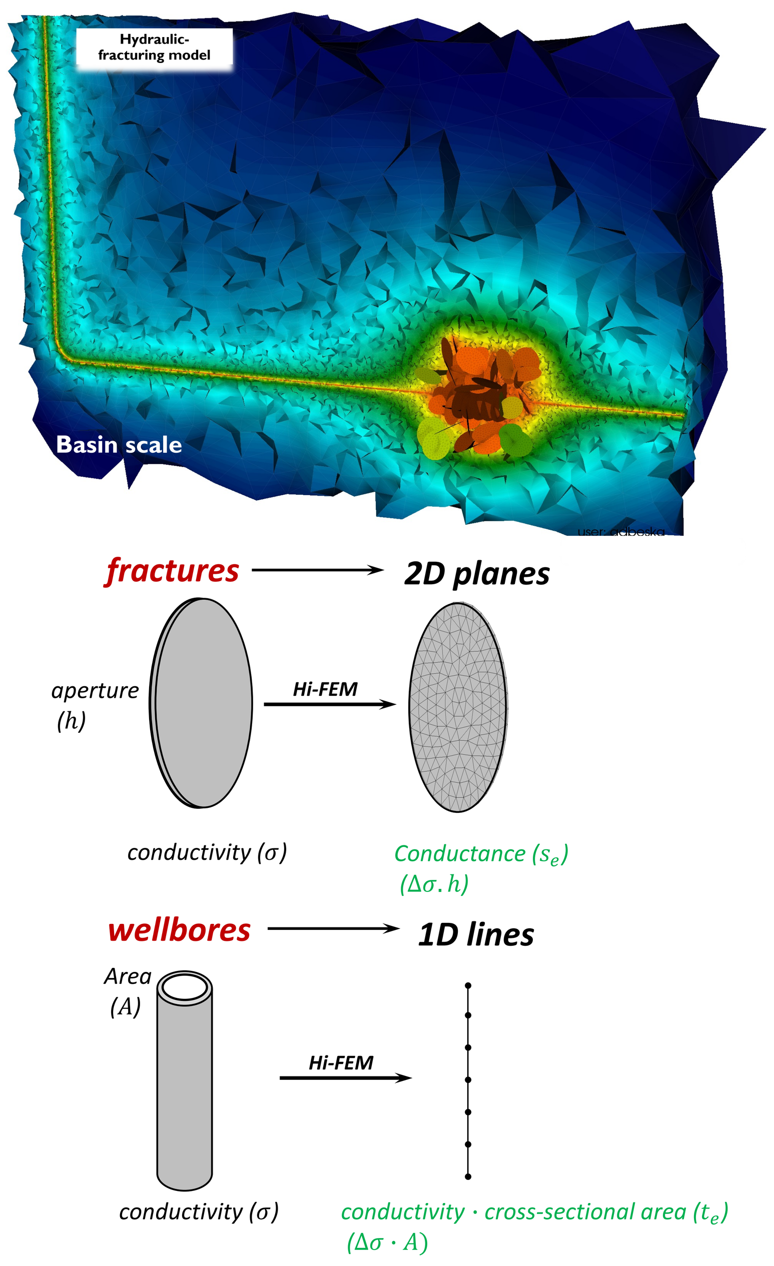
$$\sigma(\mathbf{x}) = \sum_{e=1}^{N_V} \sigma_e \Psi_e^V(\mathbf{x}) + \sum_{e=1}^{N_F} s_e \Psi_e^F(\mathbf{x}) + \sum_{e=1}^{N_E} t_e \Psi_e^E(\mathbf{x})$$ (Weiss, 2017)

The element-stiffness matrix in the finite element analysis:

$$\mathbf{K} = \sum_{e=1}^{N_V} \sigma_e \mathbf{K}_e^4 + \sum_{e=1}^{N_F} s_e \mathbf{K}_e^3 + \sum_{e=1}^{N_E} t_e \mathbf{K}_e^2$$

The global form of the linear system of equations is solved iteratively by using a Jacobi-preconditioned conjugate gradient (J-PCCG) solver (Weiss, 2001):

$$\mathbf{Ku} = \mathbf{b}$$

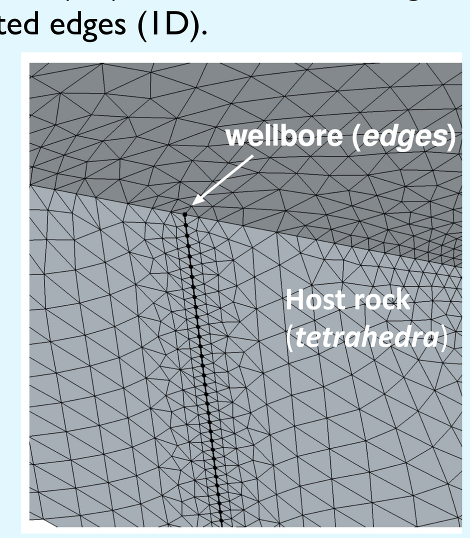


Inversion of E fields by using hierarchical conductivities

Edge-based inversion

Forward problem

We employ hierarchical geo-electric models where conductivities assigned at 1D, 2D and 3D can simultaneously coexist in a single 3D finite element model. The models consisted of the host rock as tetrahedra (3D) and the well casing as a set of connected edges (1D).



Inverse problem

We assume that the background conductivity is time-invariant and any change in the E field is associated with the state of the well integrity.

Levenberg-Malquart least squares inversion

$$\Delta m = (J^T J + \beta I)^{-1} J^T \delta d$$

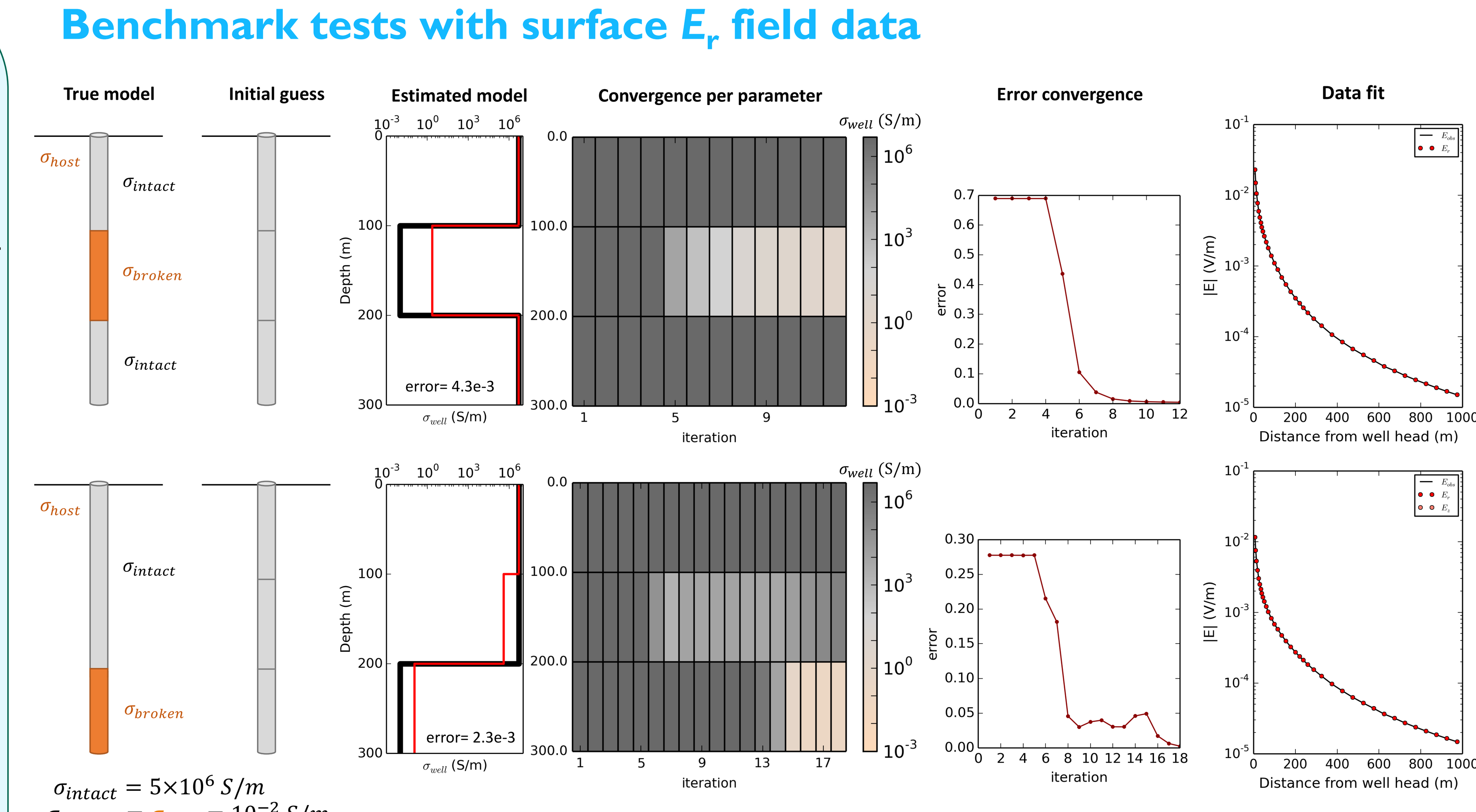
Calculate Jacobian matrix
MPI parallelization across parameters

Update model parameters with inequality bounds

$$a < m < b$$

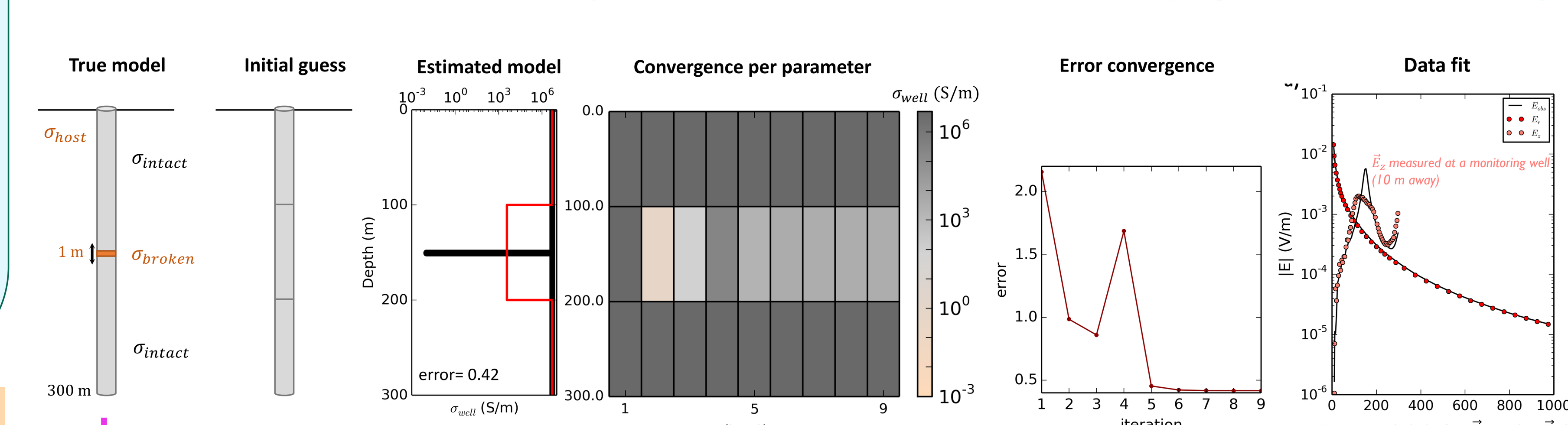
$$m^{updated} = \frac{a(b - m_0) + b(m_0 - a)e^{\Delta m}}{(b - m_0) + (m_0 - a)e^{\Delta m}}$$

Benchmark tests with surface E_r field data

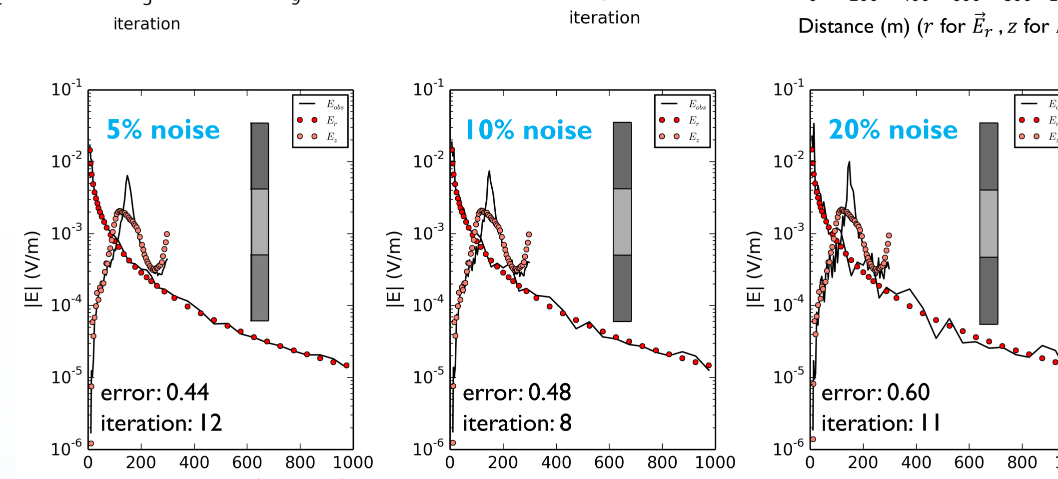


$\sigma_{intact} = 5\times10^6\ S/m$
$\sigma_{broken} = \sigma_{host} = 10^{-2}\ S/m$

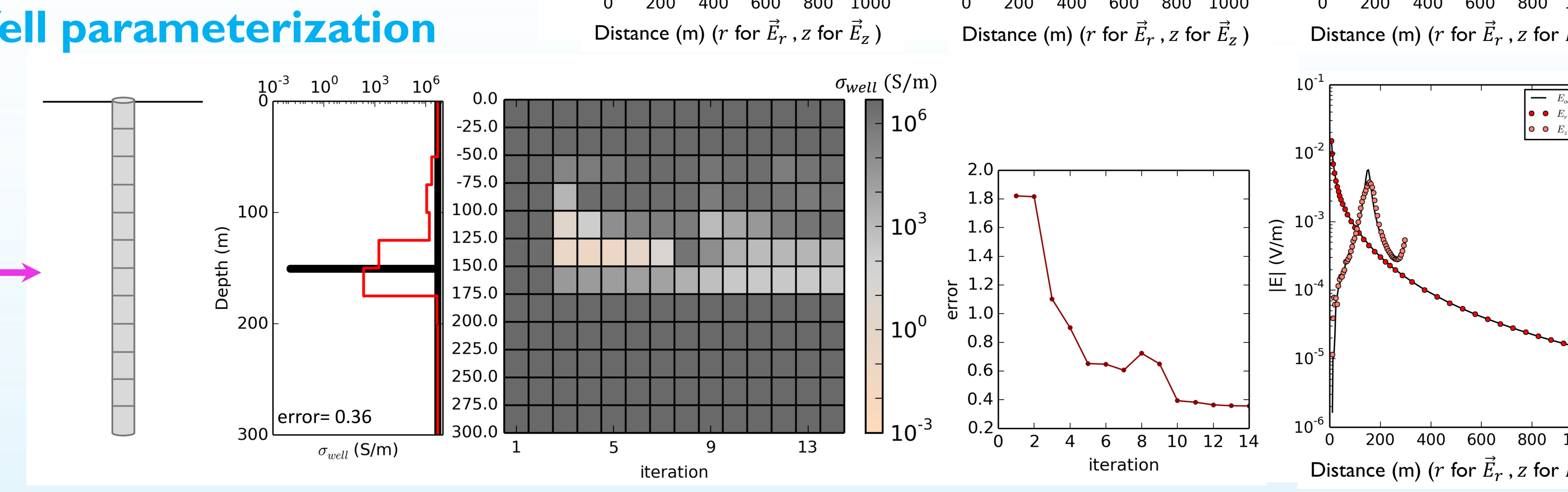
Inversion for both damage location and conductivity (E_r+ E_z field data)



Noise



Well parameterization



Results

- Our results suggest that it is possible to simultaneously invert for volume-, facet- and edge-based conductivities in a geo-electrical model by employing the *Hi*-FEM in the inverse problem.
- The inclusion of vertical E field data from a monitoring well significantly improves the convergence performance and better constrain the model parameters in depth.
- For different noise levels, the edge-based inversion performs well with the vertical E field and provides robust estimations.
- The number of model parameters in the initial well model controls the resolution but it does not have a strong impact on the ability for the identification of well damage.
- Finally, our initial analysis with the synthetic data supports that an automated well integrity monitoring is feasible by the inversion of both surface and vertical E field data obtained by energizing the metallic well casing.
- We used a multi-processor laptop to run the inversions for the models presented in this study.

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- *Finite-element meshes used for this analysis were generated by Cubit, available at http://cubit.sandia.gov*

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