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The effects of well casing corrosion and completion design on geo-electrical response in mature wellbore environments

Summary

Well integrity is one of the major concerns in long-term geologic storage sites due to its potential risk on well leakage and groundwater contamination. Evaluating changes in electrical responses at surface and along steel-cased wells has a significant potential to quantify and predict possible wellbore failures based on the fact that any kind of breakage or corrosion along highly-conductive well casings will have a strong impact on the distribution of subsurface electrical potential. On the other hand, realistic wellbore-geoelectrical models that can fully capture fine scale details of well completion design and state of corrosion at the field scale require extensive computational effort or can be intractable to simulate. To overcome this computational burden while still maintaining the model realism, we utilize "Hierarchical Finite Element Method (*Hi*-FEM)". The *Hi*-FEM enable us to represent material properties for each dimensional component of a finite element within an unstructured mesh, and therefore reduces the degree of freedom and the extensive mesh requirement. Here, we consider well completion designs with real-life geometric scales and well systems with highly-realistic, detailed corrosion scenarios to evaluate changes in electrical responses with the goal of using the changes in electrical properties as a method to detect failing wellbore integrity. All model scenarios use steel well casing, that is energized at the surface, as an electrical source. First, we compare various approaches to represent a well completion design. In addition, the effects of outer casing length and the coupling between concentric well casings on the electric response are investigated. We also examined the effects of the degree of corrosion and the depth of corrosion on the electrical responses. Our results suggest that electrical responses at the surface as well as along the well casing can be used for detecting and monitoring wellbore integrity failures associated with corrosion.

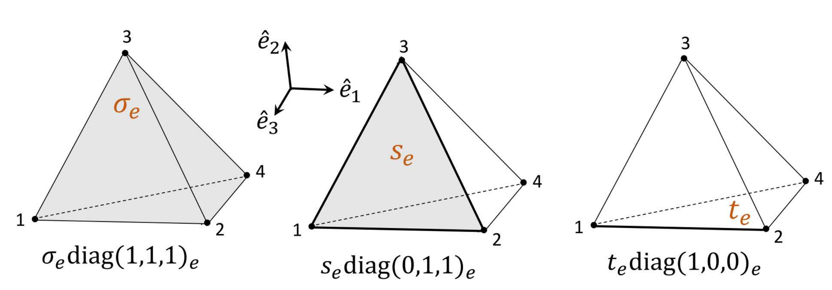
Hierarchical Finite Element Method (*Hi*-FEM)

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 potentials 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.



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

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

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

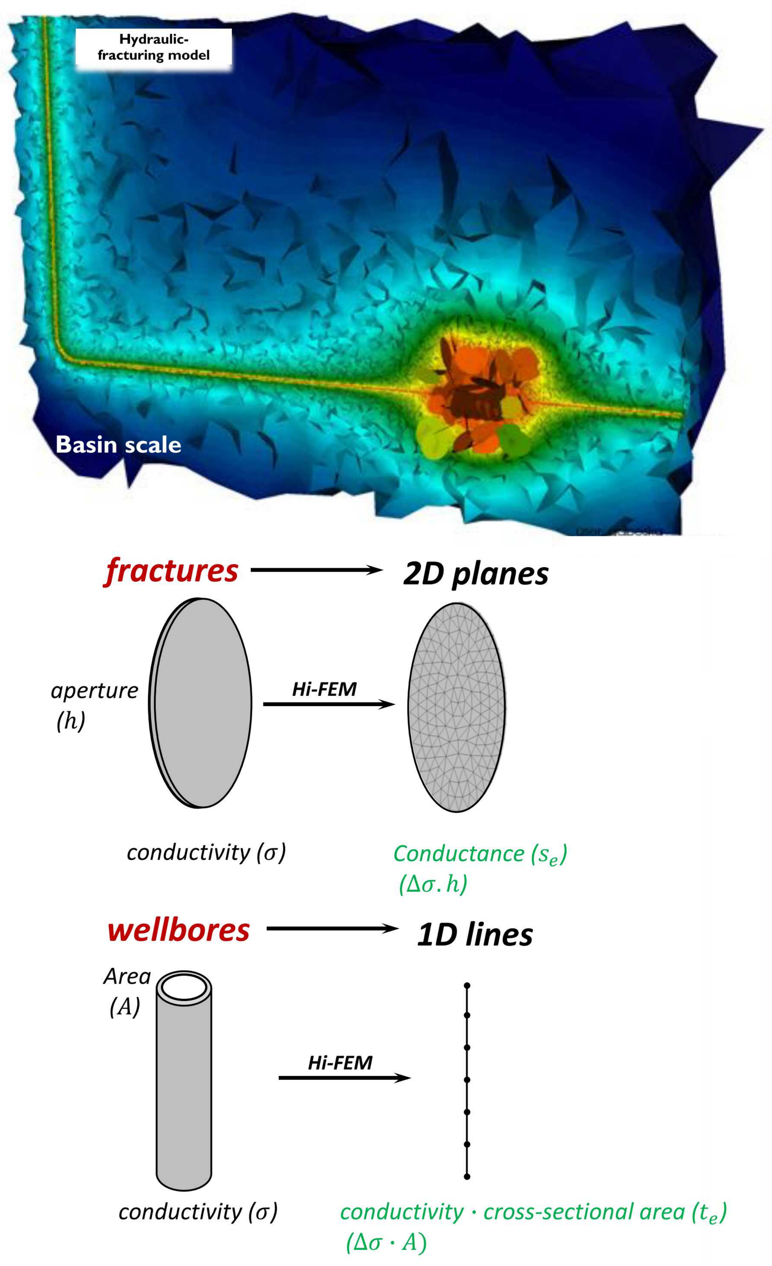
$$\sigma(\mathbf{x}) = \sum_{e=1}^{N_V} \sigma_e \Psi_e^V(\mathbf{x}) + \sum_{e=1}^{N_F} s_e \Psi_e^F(\mathbf{x}) + \sum_{e=1}^{N_E} t_e \Psi_e^E(\mathbf{x})$$

The element-stiffness matrix in the finite element analysis:

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

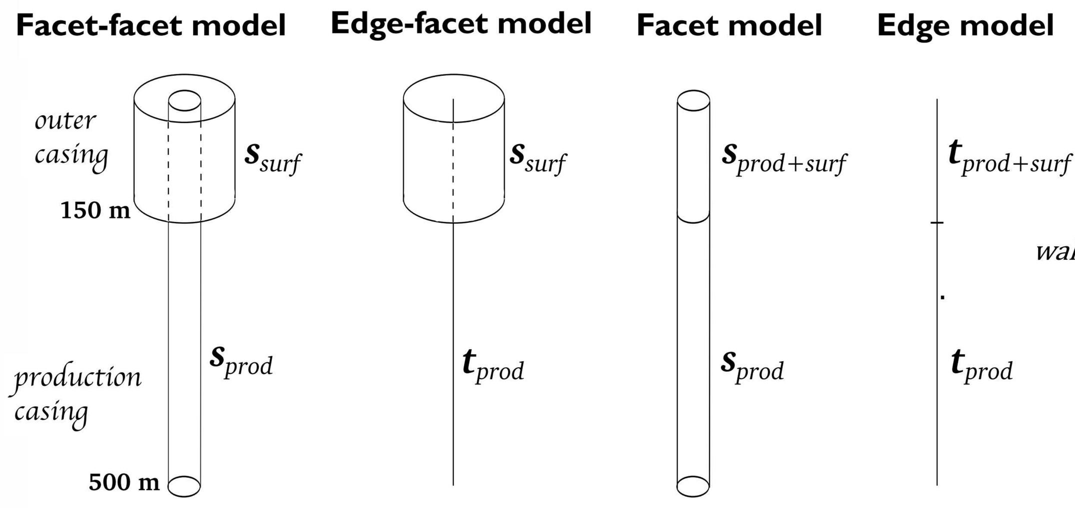
The global form of the linear system of equations is solved iteratively by using a Jacobi-preconditioned conjugate gradient (J-PCCG) solver (Weiss, 2001; Weiss, 2017):

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



Geo-electrical responses of well casing completion design and corrosion

Well completion design

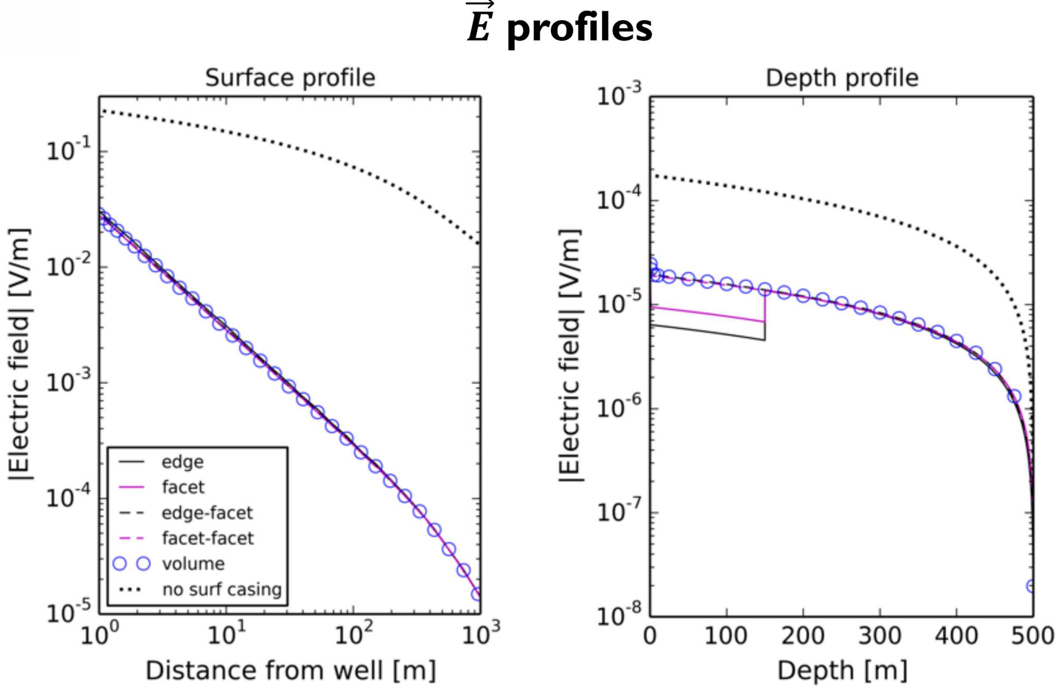


Completion design

wall thickness = 45 mm
$OD_{prod} = 0.75\ m$
$OD_{prod} = 0.75\ m$
$\sigma_{host} = 10^{-2}$ S/m
$s_{prod} = 2.25\times10^4 S$
$t_{prod} = 5.1\times10^4$ S · m

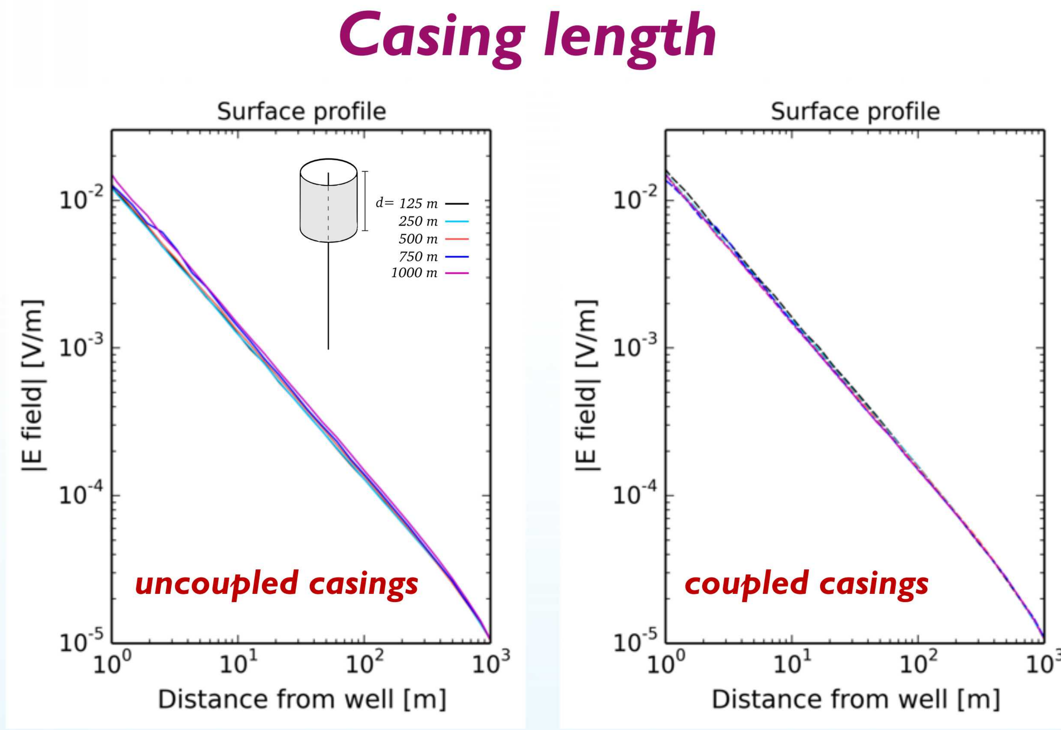
We compare the electric responses obtained from four possible representations of the well completion design to evaluate the efficiency of these discretization approaches on representing the 3D explicit geometric complexity of the well completion design.

$\vec{E}$ profiles



The electric responses are compared against the solution obtained from the fully-volumetric discretization as well as the solution of a single well. The plots indicate that the response of the concentric wells is quite different from the response of a single well. Moreover, the facet-facet and the edge-facet models where the geometry of the outer casing is explicitly defined provide the most consistent results with the fully-volumetric solution.

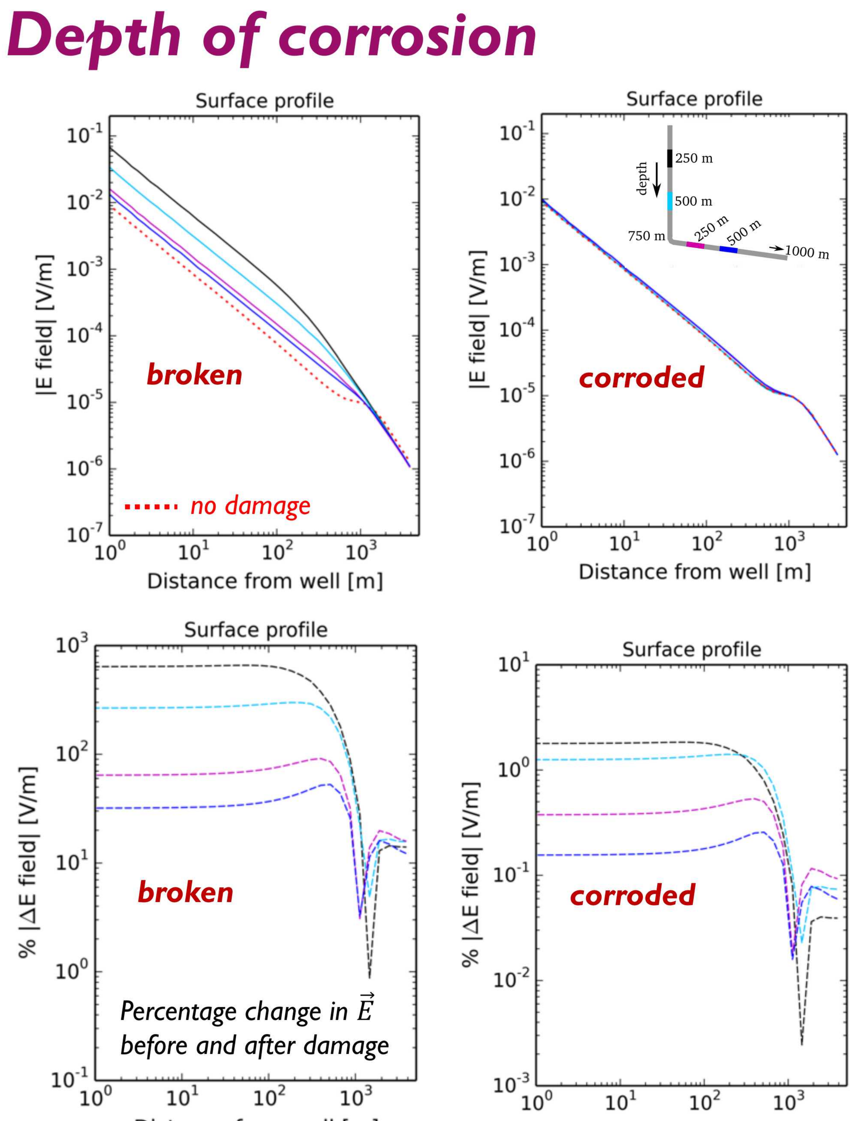
Casing length



The $\vec{E}$ surface profiles indicate that the electric response has minor sensitivity to the outer casing length and the coupling between concentric well casings.

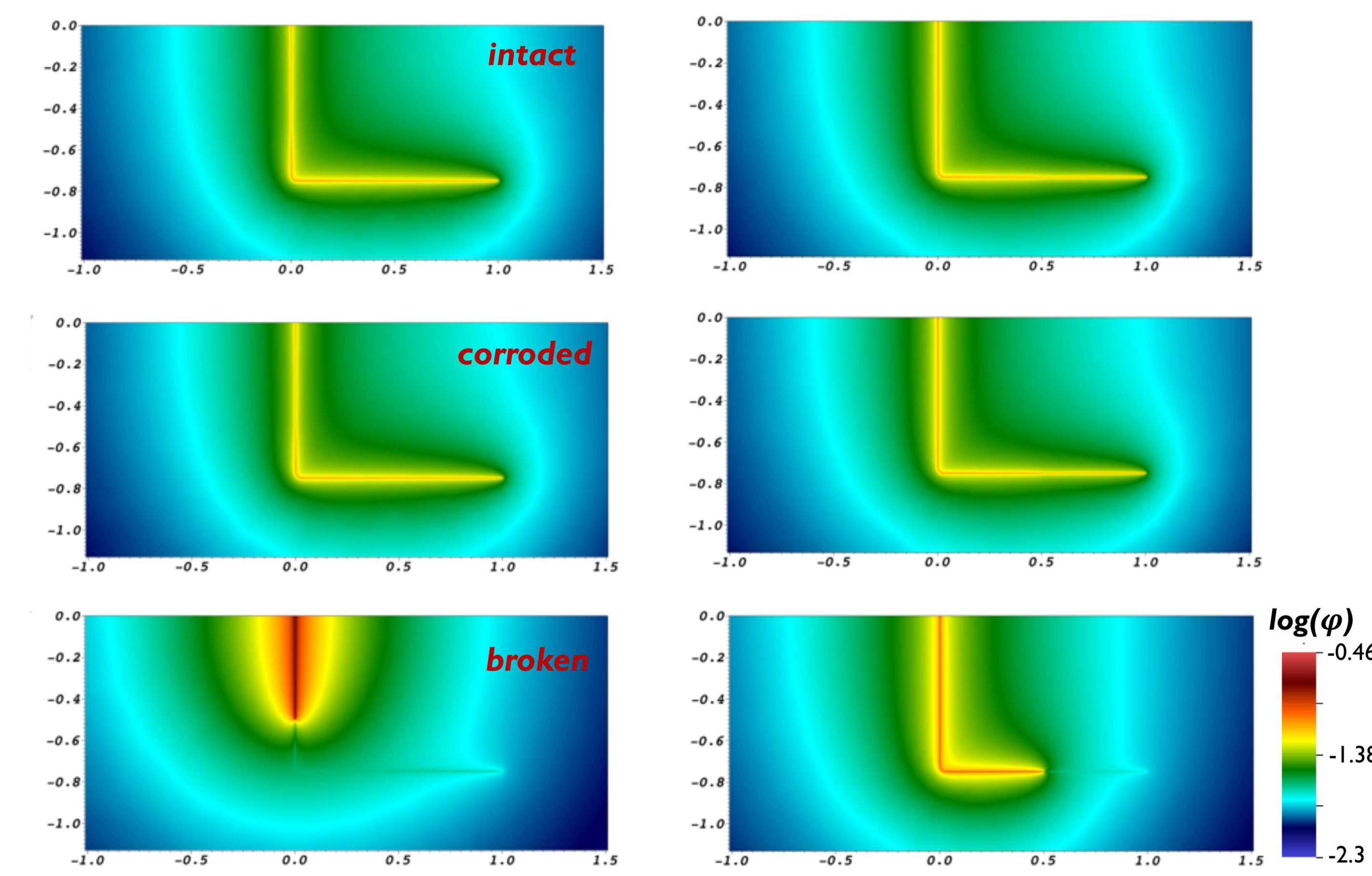
Damage on the well casing

Depth of corrosion

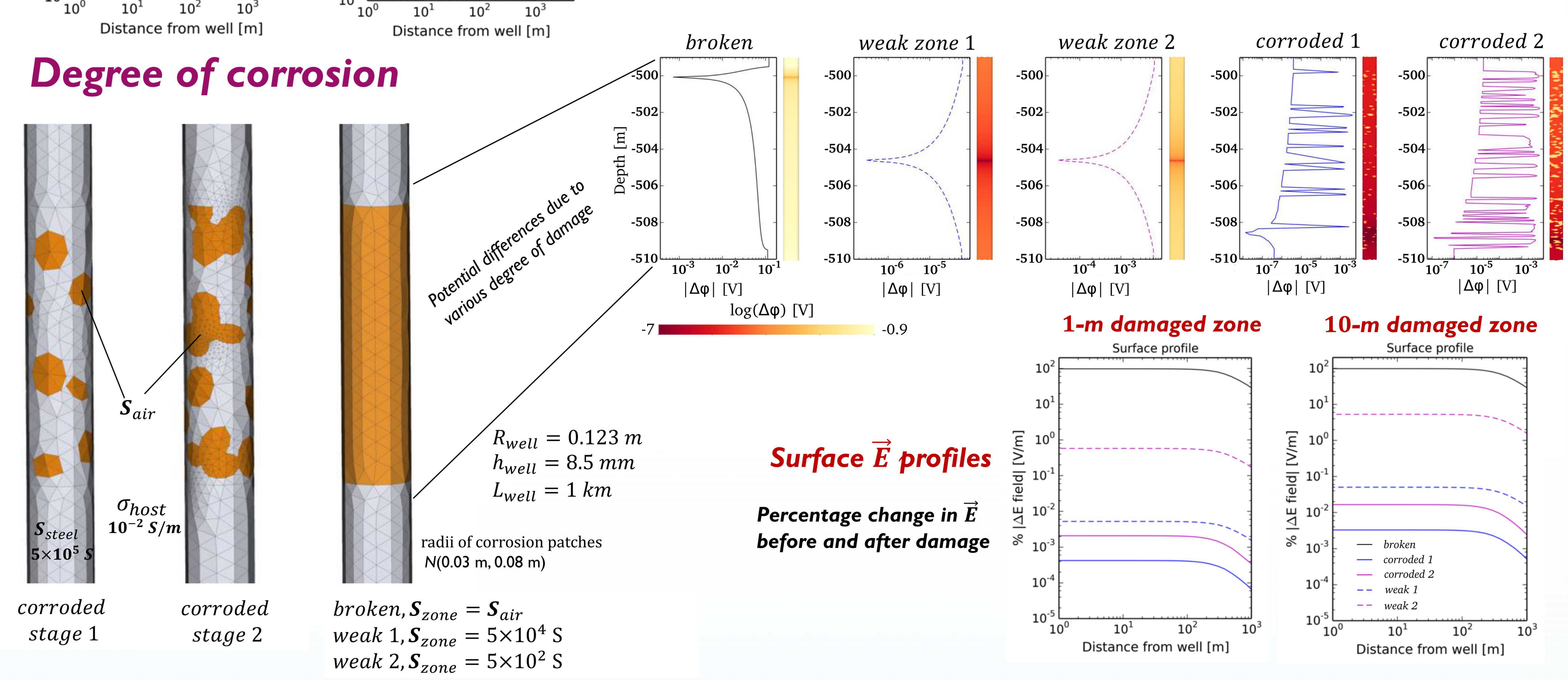


Damage in the **vertical depth of 500 m**

Damage in the **horizontal location of 500 m**



Degree of corrosion



Conclusion

- The electric response of a nested well completion design is quite different from the response of a single well, which implies the necessity of incorporating the actual geometry of well completion design into modeling.
- The volumetric, edge-based and facet-based representations of the well completion design result in the same simulated electric field at the surface. On the hand, the electric field along the well is much lower than the actual response in case the geometry of the outer casing is not explicitly represented.
- The length of the outer casing as well as the coupling between casings have minor effects on the electric response.
- The electric response shows sensitivity to the depth and the degree of damage, which suggests that monitoring the electric response may be diagnostic to locate and discriminate the type of damage or may be a prior indicative before a total breakage of wells.

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References

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- Weiss, C.J., (2017). Finite-element analysis for model parameters distributed on a hierarchy of geometric simplices. *Geophysics*, **82**, no. 4, pp. E155 – E167.
- *Finite-element meshes used for this analysis were generated by Cubit, available at http://cubit.sandia.gov*