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RPPR Final Report
as of 14-Dec-2021

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Final Report for Period Beginning 30-Sep-2018 and Ending 29-Sep-2021

Title: DOD MI Research and Education Program

Begin Performance Period: 30-Sep-2018

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STEM Degrees: 1

STEM Participants: 9

Major Goals: Earth Materials and Processes research

The overarching objective of the Earth Materials and Processes research in this project was to improve understanding of the relationships between low-frequency (sub kHz) electrical properties of soils/sediments and the physical properties determining deformation, strength and failure. The research examined to what extent geotechnical measurements of sediment deformation/failure can be predicted electrical geophysical measurements. The project investigated three hypotheses: [1] Measurable changes in electrical properties will result from variations in effective stress on unconsolidated sediments due to soil matrix compression/expansion; [2] Relationships between electrical properties and soil strength/failure criteria exist due to the mutual dependence of both on the structure of the porous matrix in unconsolidated sediments; [3] Existing models for predicting electrical properties of unconsolidated sediments can be improved by incorporating information on particle shape and orientation; incorporating such effects will improve prediction of mechanical properties from electrical measurements.

In a secondary objective, the potential to monitor chemical and microbial-induced strengthening of soil structure using electrical geophysics was explored. Recent research has identified this opportunity, but a physical understanding of the source of the electrical signals that result from soil strengthening is currently lacking. Basic research is needed to understand whether the observed signals result from the minerals themselves that form during the process, or if it is how the minerals modify the electrical characteristics of the pore structure of the soil

RPPR Final Report as of 14-Dec-2021

framework. Laboratory work was performed to understand specific contributions of different components that make up the complex system of a soil during the formation of new mineral phases. Pursuit of this objective took advantage of collaborations between Rutgers University Newark and the Cold Regions Research Engineering Laboratory (CRREL) that developed in in this project.

Computing Science Research

The overarching objective of the Computer Science research in this project was to develop a programmatic method for explaining the results of a broad class of models to domain (but not necessarily technical) experts. Such a method was proposed in this research. The approach uses the natural common language between users and models---the data---to explain a model's inferences. There were three complementary goals: [1] further developing the mathematical foundations of cooperative inference; [2] applying the algorithms for image processing focusing on supervised learning algorithms: deep neural networks such as ResNet and similar state of the art algorithms; [3] empirically testing human-machine cooperative inference defining a class of tasks related to decision making based on the corpora of images analyzed with the algorithms described under Goal 2.

Accomplishments: Earth Materials and Processes Research

In the final reporting period, the triaxial testing system (purchased under 74834-EV-RI) was finalized, complete with support for 'on-sample' electrodes as well as continuous measurements of saturation changes during a shear test. A major development was the design and construction of a flexible sample holder capable of a concurrent triaxial shear test and 1D complex conductivity measurements. A two-phase study was completed with the instrumentation. Phase 1 involved complex conductivity monitoring of soils under vertical compression. Phase 2 involved complex conductivity monitoring of soils under triaxial stress. The major experiments conducted in Year 3 focused on monitoring complex conductivity signatures evolving during compressive deformation and failure of soils. Multiple experiments were designed and performed during this research to identify different complex conductivity signatures of soils undergoing dynamic loading. These experiments showed that imaginary conductivity (equivalent to the surface conductivity) abruptly decreased at the failure point (similar to the decrease in stress), whereas the real conductivity (σ') signal was insensitive to the failure. The dominant geophysical length scale (related to pore size) determined from the complex conductivity phase spectra showed a strong inverse linear dependence on compression. Subsequent experiments were performed to evaluate the complex conductivity during shearing (beyond failure). In this case, the surface conductivity closely tracked changes in the sample stress, suggesting a high sensitivity to changes in electrical properties caused by rearrangement of soil structure under stress. In contrast, the real conductivity was minimally sensitive to such changes in soil structure. Subsequent experiments evaluated the frequency dependence of the soil failure/deformation. Regardless of the frequency, the magnitude of change in the imaginary conductivity was much higher than the magnitude of change in the real conductivity. Further details of this work, foremost conducted by postdoctoral scientist Sina Saneiyan, are provided in the PDF supplement.

Underrepresented minority (URM) PhD candidate Alejandro Garcia completed his experiments on complex electrical signatures of carbonate precipitation during this final reporting period. Experiments involved both the precipitation of calcite in suspension as well as precipitation of calcite within a solid porous medium (in this case uncompacted sand). These experiments were achieved using a novel double diffusion setup, whereby reactants are transported into a sample chamber through passive diffusion, developed in prior project years. One experiment involved repeating measurements on calcite suspended in gel (Figure 2) in order to validate previous results and obtain higher quality measurements. This experiment confirmed that, in isolation, calcite crystals do not produce a measurable change in the polarizability of a material. Further experiments focused on testing the theory that it is the presence of a porous medium and the changes that occur in the pore geometry that produce measurable increases to the polarizability of a material during calcite precipitation. These experiments showed that, during the precipitation of calcite within a non-conducting porous matrix, a significant drop in the real conductivity is observed, which is concurrent with an increase in the imaginary component. This is attributed to the formation of a calcite barrier in the center of the sample holder. A similar effect was seen in a sample with a volume fraction of magnetite. In this case, blockage of the pore space by calcite forces current to travel through magnetite grains thereby creating an increase in the measured imaginary conductivity that is distinct from that seen in the sample without magnetite. Further details of this work are provided in the PDF supplement.

Computer Science Research

Scientific accomplishments during this final reporting period include development of a new, more advanced method

RPPR Final Report as of 14-Dec-2021

of explanation for AI agents. Our approach is based on explaining deep learning based neural networks by severing the last layer and replacing it with a probabilistic method that allows application of our Bayesian teaching approach. The new method extends the Bayesian logistic regression (BLR), with human informed functions. Whereas the previous version incurred a significant decrement in the performance of the neural network (top-5 accuracy decreasing from ~90% to ~60% for ResNet), the new version incurs essentially no decrement in performance. Moreover, empirical tests show that the new version enables improved explainability for simple errors and natural adversarial images. In experiments designed to assess people's ability to predict the AI's behavior with and without explanations, we see that explanations improve predictability by ~25% on average, with the highest performing individuals achieving ~80% accuracy. The results have been published in Scientific reports. Moreover, we have extended the approach to apply to medical images and tested the effectiveness on medical images. We have specifically shown that, for AI classifying pneumothorax, our explanations facilitated professional radiologist's predictions of whether to trust the AI. In fact, the explanations enable radiologists to predict the AI's accuracy at a rate greater than the actual agreement between doctors. We are currently extending the approach to apply to melanoma diagnosis.

Theoretical accomplishments are the development of two papers: A mathematical theory of cooperative communication (published in Advances in Neural Information Processing Systems, NeurIPS) and Sequential cooperative Bayesian inference recently published in the International Conference on Machine Learning (ICML), the two premier venues for machine learning research. These two papers present theoretical foundations for cooperative information transfer. The first paper unifies existing theories of human and machine (robot) cooperative communication under the mathematical framework of optimal transport and proves a variety of critical, foundational results for single episode information sharing events. The second proves the consistency, convergence and stability of cooperative information sharing in iterative settings, which further contributes to the basic mathematical foundations. Moreover, we have extended the approach to optimizing discrete approximations of communication for continuous domains.

Training Opportunities: Earth Materials and Processes Research

PhD student Alejandro Garcia received further mentorship from CRREL researchers Dr. Emily Asenath-Smith and Mr. Danney Glaser during this final reporting period. Both Garcia and postdoctoral student Saneiyan received continuous mentoring and training on electrical geophysics from PI Slater in his role as their primary adviser. Saneiyan completed his postdoctoral fellowship on this project towards the end of this reporting period and subsequently obtained a tenure-track faculty position at the University of Oklahoma. Saneiyan securing such a competitive position at a top tier university is considered a positive outcome of the project.

As in previous reporting years, training opportunities this project period included mentorship and engagement of undergraduate students by the postdoctoral student (Saneiyan) and graduate student (Garcia). Undergraduate student Ethan Siegenthaler, supervised by Saneiyan during the prior reporting period, presented the results of his work at the 2020 American Geophysical Union (AGU) Fall meeting. Saneiyan also trained graduate student Garcia on the operation of the complex conductivity during triaxial testing system developed under this project. Garcia was also trained in the creation of customized sample holders and the performance of simultaneous SIP and shear test measurements on loose soils.

Computing Science Research

The major training opportunities afforded during this period are those for the graduate students: Alejandro Vientós and Xioaran Hao. Alejandro's previous experiences were in game theory at MIT, and he received training in our approaches to probabilistic models of cooperation and information transfer.

Xioaran is a rising fourth year graduate student, and his research is more advanced. He collaborated closely with one of the postdocs in the lab who has been developing novel methods for interpretable deep learning via Deep Gaussian Processes. Xioaran has focused on developing a novel approach to autoencoders, an unsupervised method for learning the structure of data, by combining neural networks and Gaussian processes. The approach aims to induce correlation structure in the latent representation, which seeks smooth manifold-like structure in the latent representation to enable systematic and sensible generalization. A third student, Arash, worked to apply Optimal Transport based methods to Reinforcement learning. The result is a new method for imitation learning, exploration, and safety aware RL. Arash defended his dissertation and has obtained a position in finance. A fourth student, Ravi, is working on studying Computational Optimal Transport, and the foundations of Reinforcement Learning and plans to extend Arash's research by unifying our work on cooperative cooperation and reinforcement learning.

RPPR Final Report

as of 14-Dec-2021

Results Dissemination: Earth Materials and Processes Research

PI Slater and postdoctoral scientist Saneiyana published a paper describing results obtained with the complex conductivity during triaxial testing system in the journal Engineering Geology. They also presented an expanded abstract on this work at the First International Meeting for Applied Geoscience & Energy (IMAGE21). Saneiyana and undergraduate researcher Siegenthaler both gave first author presentations and abstracts at the fall 2020 American Geophysical Union meeting.

PI Slater gave the following invited talk, as a distinguished lecture:

Lee Slater: "Engineering Applications of Induced Polarization", Sixth International Conference on Engineering Geophysics (ICEG), Oct 25-28, 2021, Distinguished Lecture (virtual)

The talk primarily focused on research performed under this project.

Computing Science Research

Co-PI Shafto presented the research as an oral presentation at Advances in Neural Information Processing Systems (<1% of submissions selected). He also presented to industry and academic audiences including: Microsoft research, Google X tech talk, University of Wisconsin Human and Machine Learning seminars, colloquia at Central European University and SRI, and at DIMACS workshop on the co-development of Computing and the Law.

Honors and Awards: Earth Materials and Processes research:

Nothing to report this period

Computing Science Research

Co-PI Shafto was selected as a member at the Institute for Advanced Study in Princeton and as a panelist for DARPA ISAT during this reporting period.

Protocol Activity Status:

Technology Transfer: Earth Materials and Processes research:

PI Slater continued to build a partnership with the Cold Regions Research Engineering Laboratory (CRREL) during this reporting period. Mr. Danney Glaser (Research Geophysicist, CRREL) is now in his third year of his PhD degree under the guidance of PI Slater. Mr. Glaser is performing research directed at improving his understanding of the complex electrical properties of soils. His PhD knowledge will benefit his future research activities at CRREL.

Computing Science Research

Co-PI Shafto has founded a start-up company which is focused on machine learning for high stakes settings. This work has received significant support from, and has important implications for, the military. The company is currently supported by DARPA, a host of companies in agriculture technology, and in commodities finance. We are also exploring the possibility of founding a company focused on explainable AI.

PARTICIPANTS:

Participant Type: PD/PI

Participant: Lee Slater

Person Months Worked: 1.00

Project Contribution:

National Academy Member: N

Funding Support:

Participant Type: Co PD/PI

Participant: Pat Shafto

Person Months Worked: 1.00

Funding Support:

RPPR Final Report
as of 14-Dec-2021

Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Sina Saneiyani

Person Months Worked: 10.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Graduate Student (research assistant)

Participant: Alejandro Garcia

Person Months Worked: 10.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Ethan Siegenthaler

Person Months Worked: 1.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Ben Sheller

Person Months Worked: 12.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Libby Barak

Person Months Worked: 4.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Erin McGowan

Person Months Worked: 4.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Undergraduate Student

Participant: Anitej Biradar

Person Months Worked: 2.00

Funding Support:

Project Contribution:

National Academy Member: N

RPPR Final Report
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Participant Type: Undergraduate Student
Participant: Valentina Blaustein
Person Months Worked: 4.00
Project Contribution:
National Academy Member: N

Funding Support:

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Journal: Engineering Geology

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Volume: 291

Issue:

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Date Submitted: 11/26/21 12:00AM

Date Published: 9/1/21 12:00PM

Publication Location:

Article Title: Complex conductivity signatures of compressive deformation and shear failure in soils

Authors: Sina Saneiyan, Lee Slater

Keywords: Shear failure; Soil failure; Geophysical methods; Complex conductivity; Surface conductivity; Uniaxial stress; compressive strength

Abstract: Cooperation is often implicitly assumed when learning from other agents. Cooperation implies that the agent selecting the data, and the agent learning from the data, have the same goal, that the learner infer the intended hypothesis. Recent models in human and machine learning have demonstrated the possibility of cooperation. We seek foundational theoretical results for cooperative inference by Bayesian agents through sequential data. We develop novel approaches analyzing consistency, rate of convergence and stability of Sequential Cooperative Bayesian Inference (SCBI). Our analysis of the effectiveness, sample efficiency and robustness show that cooperation is not only possible but theoretically well-founded. We discuss implications for human-human and human-machine cooperation.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Proceedings of Machine Learning Research

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Volume:

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Date Published: 6/1/20 4:00AM

Publication Location: United States

Article Title: Sequential Cooperative Bayesian Inference

Authors: Wang, J., Wang, P. and Shafto, P.

Keywords: machine learning

Abstract: Cooperation is often implicitly assumed when learning from other agents. Cooperation implies that the agent selecting the data, and the agent learning from the data, have the same goal, that the learner infer the intended hypothesis. Recent models in human and machine learning have demonstrated the possibility of cooperation. We seek foundational theoretical results for cooperative inference by Bayesian agents through sequential data. We develop novel approaches analyzing consistency, rate of convergence and stability of Sequential Cooperative Bayesian Inference (SCBI). Our analysis of the effectiveness, sample efficiency and robustness show that cooperation is not only possible but theoretically well-founded. We discuss implications for human-human and human-machine cooperation.

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Journal: Proc. SPIE 11746, Artificial Intelligence and Machine Learning for Multi-Domain Operations Applications III
Publication Identifier Type: Other **Publication Identifier:**
Volume: **Issue:** 117462J **First Page #:**
Date Submitted: 11/26/21 12:00AM **Date Published:** 8/1/20 4:00AM
Publication Location:
Article Title: Explainable AI for medical imaging: Explaining pneumothorax diagnoses with Bayesian Teaching
Authors: Folke, T., Yang, S. C-H, Anderson, S. and Shafto, P.
Keywords: machine learning
Abstract: Cooperation is often implicitly assumed when learning from other agents. Cooperation implies that the agent selecting the data, and the agent learning from the data, have the same goal, that the learner infer the intended hypothesis. Recent models in human and machine learning have demonstrated the possibility of cooperation. We seek foundational theoretical results for cooperative inference by Bayesian agents through sequential data. We develop novel approaches analyzing consistency, rate of convergence and stability of Sequential Cooperative Bayesian Inference (SCBI). Our analysis of the effectiveness, sample efficiency and robustness show that cooperation is not only possible but theoretically well-founded. We discuss implications for human-human and human-machine cooperation.
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Journal: Scientific Reports
Publication Identifier Type: DOI **Publication Identifier:** 10.1038/s41598-021-89267-4
Volume: 11 **Issue:** 1 **First Page #:**
Date Submitted: 11/26/21 12:00AM **Date Published:** 5/1/21 4:00AM
Publication Location:
Article Title: Mitigating belief projection in explainable artificial intelligence via Bayesian teaching
Authors: Scott Cheng-Hsin Yang, Wai Keen Vong, Ravi B. Sojitra, Tomas Folke, Patrick Shafto
Keywords: artificial intelligence
Abstract: Cooperation is often implicitly assumed when learning from other agents. Cooperation implies that the agent selecting the data, and the agent learning from the data, have the same goal, that the learner infer the intended hypothesis. Recent models in human and machine learning have demonstrated the possibility of cooperation. We seek foundational theoretical results for cooperative inference by Bayesian agents through sequential data. We develop novel approaches analyzing consistency, rate of convergence and stability of Sequential Cooperative Bayesian Inference (SCBI). Our analysis of the effectiveness, sample efficiency and robustness show that cooperation is not only possible but theoretically well-founded. We discuss implications for human-human and human-machine cooperation.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: Y

CONFERENCE PAPERS:

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Conference Name: American Geophysical Union
Date Received: 13-Aug-2020 **Conference Date:** 09-Dec-2019 **Date Published:** 01-Mar-2020
Conference Location: San Francisco, USA
Paper Title: Studying the Spectral Induced Polarization Signal of Calcite Crystal Growth through Double Diffusion in Porous Media
Authors: Garcia, A, Asenath-Smith, E., Glaser, D.R. II and L. D. Slater
Acknowledged Federal Support: Y

RPPR Final Report
as of 14-Dec-2021

Partners

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PI Slater has continued to work with collaborators at Cold Regions Research Engineering Laboratory (CRREL). The

I certify that the information in the report is complete and accurate:

Signature: Lee Slater

Signature Date: 11/29/21 10:15AM

W911NF-18-1-0442

**ENHANCING RESEARCH CAPACITY IN COMPUTING SCIENCE AND
EARTH**

**SCIENCES THROUGH BASIC RESEARCH ENGAGING
UNDERREPRESENTED MINORITY (URM) GRADUATE STUDENTS**

Supporting materials for Interim Report covering the project period July 31st, 2020-July
31st, 2021.

Monitoring complex electrical conductivity during soil deformation and failure

Recap on triaxial system designed in Year 2

In order to perform a complete triaxial shear test and monitor it with the complex conductivity method, an ASTM D standard compatible triaxial unit was customized to support on-sample electrodes as well as continuous measurements of saturation changes during a shear test. This customization included designing and producing a flexible sample holder capable of a concurrent triaxial shear test and 1D complex conductivity measurements (Figure 1). A complete laboratory setup of the customized instrument is shown in

Figure 2.

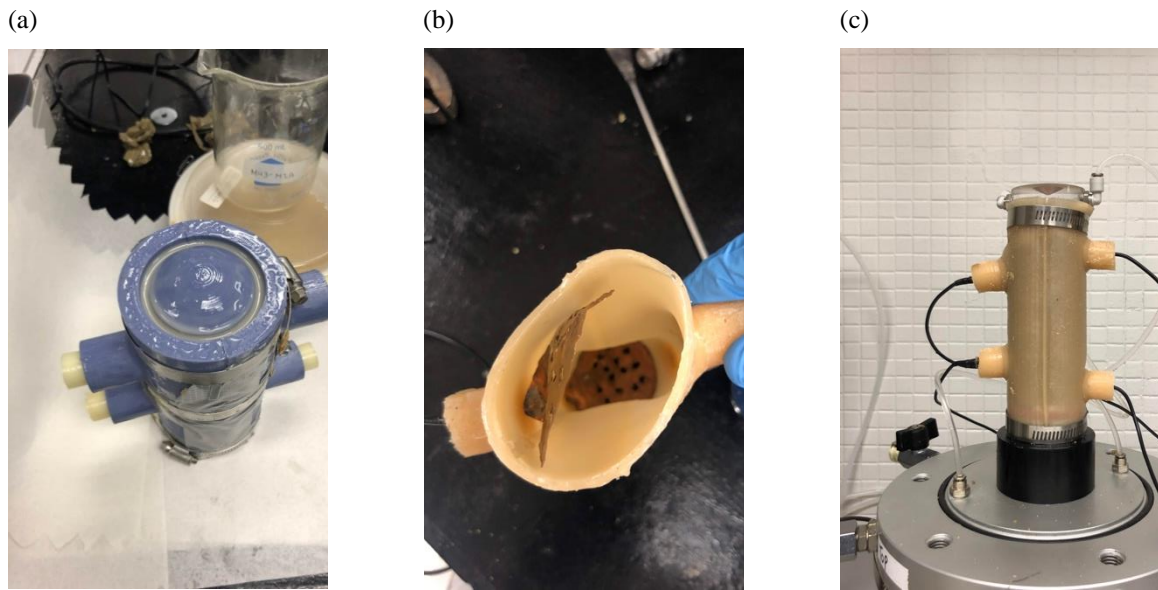


Figure 1: Building the flexible soil sample holder. a) 3D printed mold with liquid rubber compound curing inside, b) final flexible sample holder with mounted electrode inside and c) flexible sample holder filled with unconsolidated soil sample mounted on the triaxial pedestal unit.

To fully understand the efficacy of complex conductivity in monitoring soil deformation under stress, we designed and conducted a two-phase study.

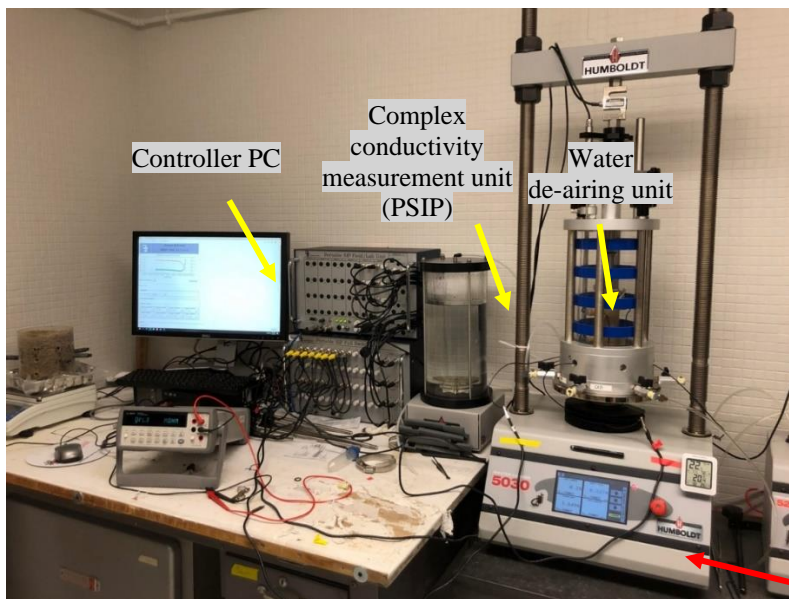
Phase 1: complex conductivity monitoring of soils under vertical compression

Phase 2: complex conductivity monitoring of soils under triaxial stress.

In this experiment, an unconsolidated soil mixture of 98% sand (grain size: 250 – 300 μm) and 2% kaolinite powder was wet packed into the flexible sample holder (Figure 1c). The wet packing procedure was chosen to reduce the chance of forming air bubbles inside the soil mixture. The sample was placed into a triaxial cell and loaded in the load frame (

Figure 2). A very slow and fixed compression rate was applied on the sample, along its long axis (vertical stress).

(a)



(b)

PSIP cables for CC measurement



Load frame Pressure/volume controller Control panel

Figure 2: Complete triaxial setup with complex conductivity measurement capability. a) computer and complex conductivity controller unit and b) automatic triaxial setup

The slow compression rate allowed for measurement of a broad frequency spectrum during complex conductivity monitoring, which ranged from 100 mHz to 10 kHz. In addition, the effluent volume during the compression was accurately measured every 5 minutes.

The early results showed that the imaginary part of the complex conductivity tracks two forms of soil deformation due to axial compression, 1) soil grain rearrangement or formation of micro fractures and shear failure.

Experiments run in Year 3

Complex conductivity signatures of compressive deformation and shear failure in soils¹

In this research, we investigated complex conductivity signatures resulting from soil deformation and failure during an unconfined compression test. A synthetic soil composed of silica sand (98%) and kaolin powder (2%) was saturated below its liquid limit and packed inside a

¹ Saneiyan, S., & Slater, L. (2021). Complex conductivity signatures of compressive deformation and shear failure in soils. *Engineering Geology*, 106219, <https://doi.org/10.1016/j.enggeo.2021.106219>

flexible sample holder custom-equipped with four electrodes under zero confining stress to simulate an unconfined condition (Figure 3).

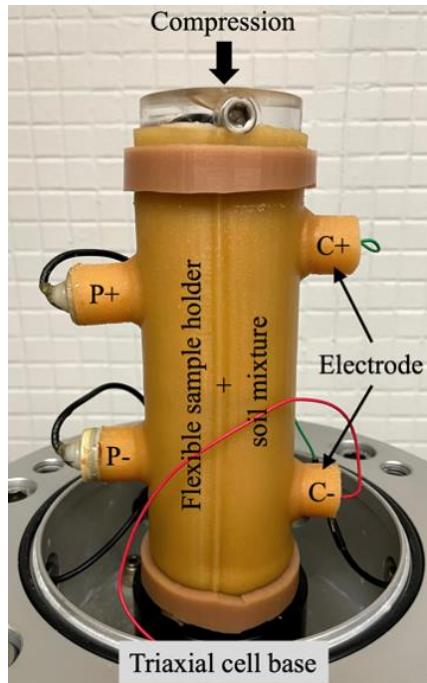


Figure 3 – Soil packed into a flexible sample holder with complex conductivity electrodes, mounted on a triaxial cell base.

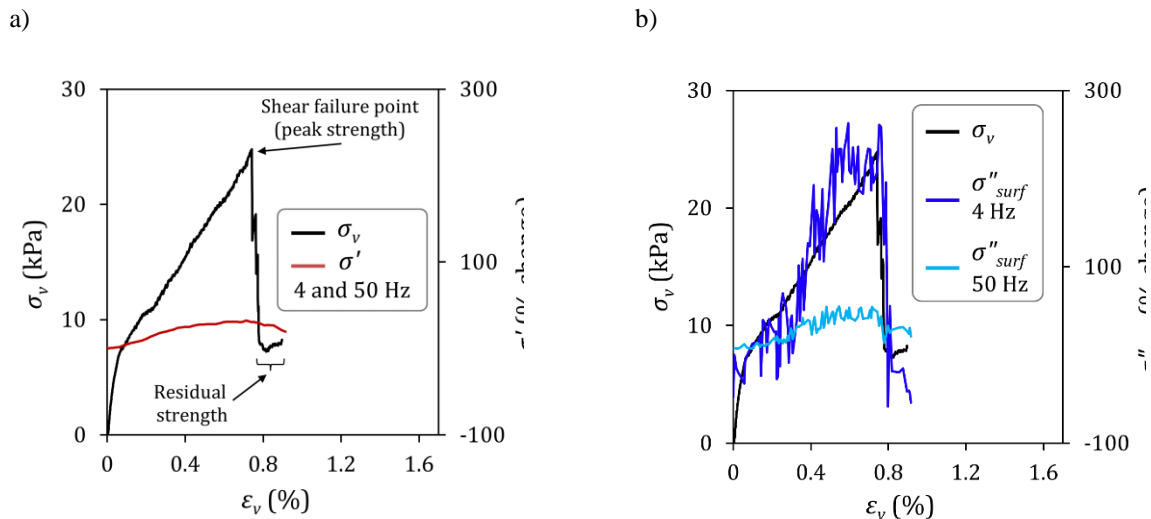
This soil sample underwent a constant and slow rate of compression. Soil stress, strain, effluent volume, along with the frequency dependent real and imaginary parts of the complex conductivity were recorded over distinct time intervals. Multiple experiments were designed and performed during this research to identify different complex conductivity signatures of soils undergoing dynamic loading. The first experiment focused on the sensitivity of complex conductivity to soil failure. Imaginary conductivity (equivalent to surface conductivity - σ''_{surf}) abruptly decreased at the failure point (similar to the decrease in stress) compared to the real conductivity (σ') signal (Figure 4). The dominant geophysical length scale L^2 (related to pore size) determined from the complex conductivity phase spectra (Figure 5) exhibits an inverse linear dependence on compression (Figure 6). Performing Debye decomposition inversion of the complex conductivity spectra revealed that proxy pore sizes generally reduced with compression in our test (Figure 7), including past the soil failure point. This suggests that soil failure did not

cause changes to the overall trend of decreasing porosity and only caused a local shear fracture inside the soil column².

The second experiment focused on the complex conductivity during shearing (beyond failure). In this case, the surface conductivity (σ''_{surf}) closely tracked changes in the sample stress (Figure 8b). In both experiments, imaginary (or surface) conductivity is highly sensitive to changes caused by rearrangement of soil structure under stress (i.e., deformation and failure). In contrast, the real conductivity is minimally sensitive to such changes in soil structure.

By measuring the soil saturation changes during the compression stages at both of the above experiments, the electrolytic part of the conductivity (dominating the real conductivity in our case) is insensitive to soil structural rearrangement during compression and instead depends on the degree of saturation. Saturation and electrolytic conductivity (σ_{ele}) changes for the first and second experiments are shown in Figure 9a and Figure 9b respectively.

The third and fourth experiments were designed to evaluate the frequency dependence of the soil failure/deformation. We found out that, regardless of the frequency of the measurements (30 Hz in Figure 10a or 100 Hz in Figure 10b), the magnitude of change in the σ''_{surf} signal is much higher when compared to the σ' signal.



² Saneiyani, S., & Slater, L. (2021, September). Complex conductivity porosimetry during unconfined soil compression. In *First International Meeting for Applied Geoscience & Energy* (pp. 1971-1975). Society of Exploration Geophysicists

Figure 4 –Results of complex conductivity monitoring during a compression test leading to soil failure. a) Vertical stress (σ_v) and real conductivity percentage changes (σ' at 4 and 50 Hz) versus strain (ε_v). Note, both 4 and 50 Hz responses overlap, thus shown as one legend entry, b) σ_v and surface conductivity percentage changes (σ''_{surf} at 4 and 50 Hz) versus ε_v . Both σ' and σ''_{surf} increase with σ_v prior to failure and decrease after sample failure. However, σ''_{surf} changes are much larger and drop sharply at sample failure. Note, x-axis (ε_v) is scaled to 1.6% strain to facilitate direct comparison with test results shown in Figure 8.

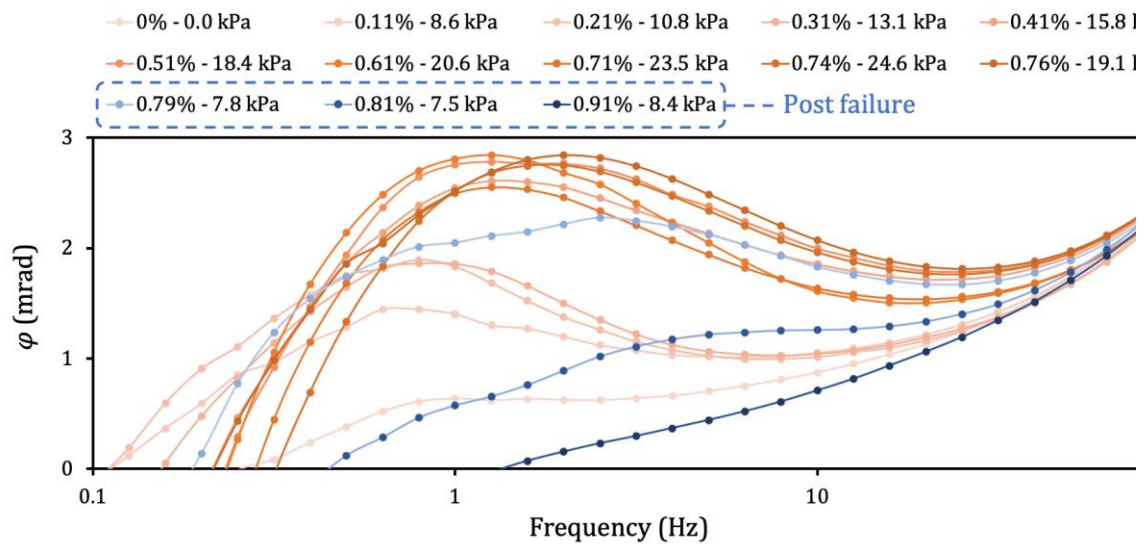


Figure 5 – Variations in phase (ϕ) spectra during an unconfined compression test. Graph legend shows selected $\varepsilon_v - \sigma_v$ values for each measurement. Data are selected for plotting at 0.1 % strain intervals, except close to failure ($\sim 0.76 - 0.79\%$ strain) to better show the sharp drops in ϕ_{peak} magnitude during shear failure.

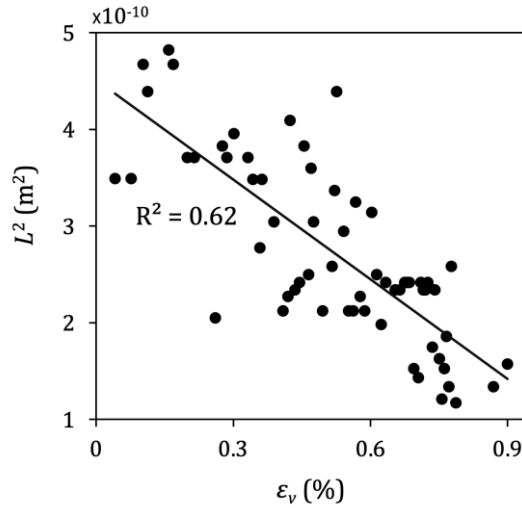


Figure 6 – Decrease in estimated length scale L^2 (related to pore size) with increasing ϵ_v .

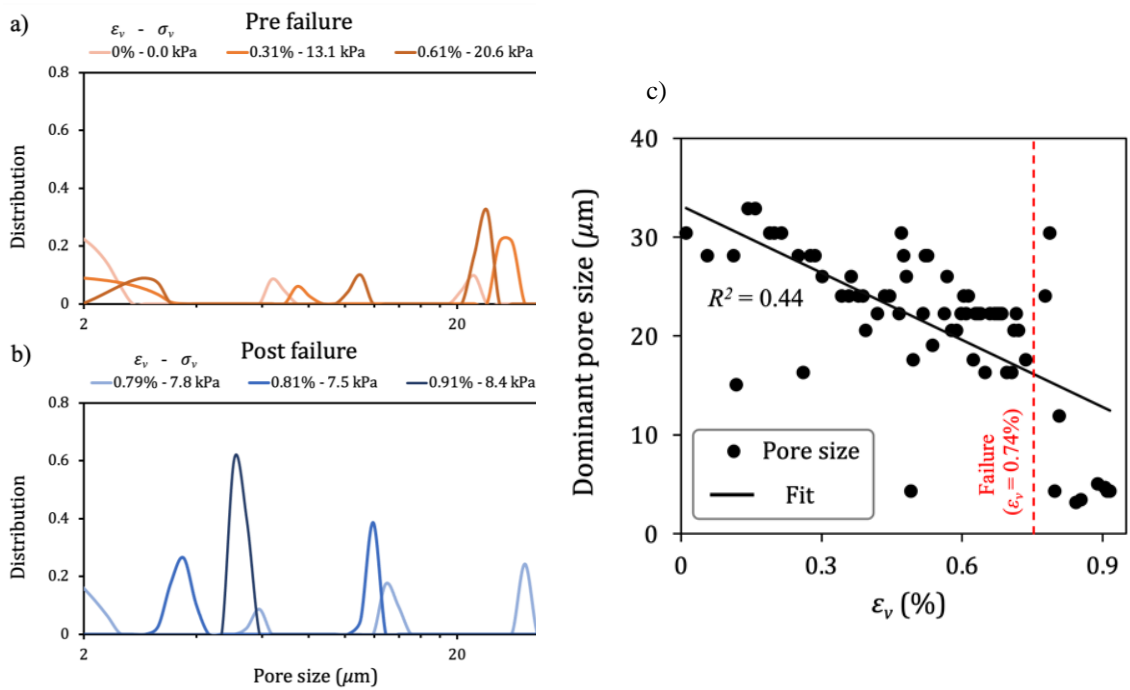


Figure 7 – Pore size distribution from Debye relaxation time distribution for pre soil failure stages at $\epsilon_v = 0, 0.31$ and 0.61% (a) and post soil failure stages at $\epsilon_v = 0.79, 0.81$ and 0.91% (b). Notice the most dominant peak in the pore size distribution shift towards smaller sizes as ϵ_v increases. c) Changes in dominant pore size with compression (increase in ϵ_v) during the UCS test. Red dashed line indicates soil failure point at $\epsilon_v = 0.74\%$ (the large range in the absolute pore size estimate may be an artifact of the inversion routine).

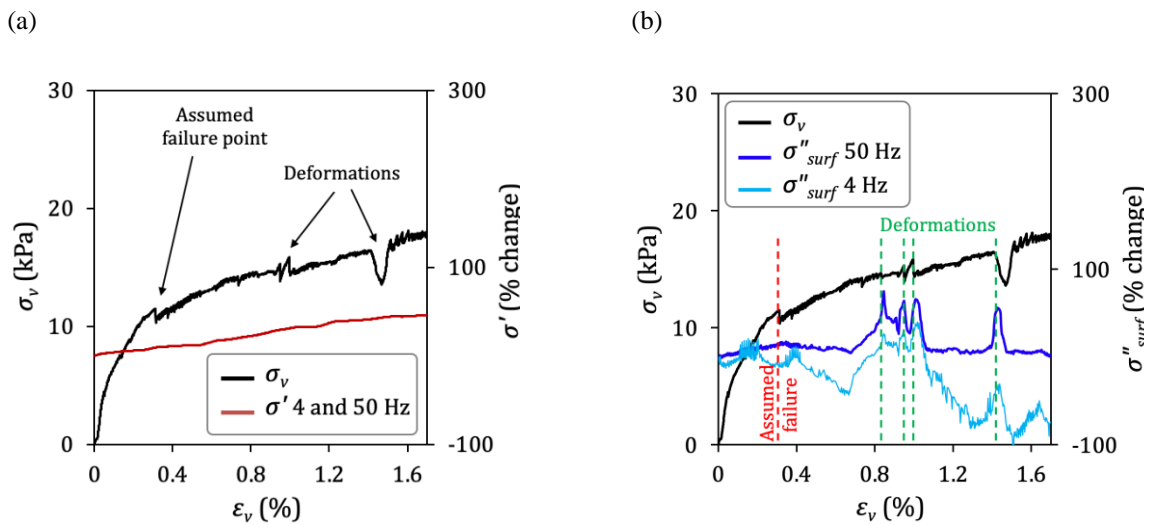


Figure 8 – Soil deformation during compression test and complex conductivity monitoring. a) Vertical stress (σ_v) and real conductivity changes (σ' at 4 and 50 Hz) versus strain (ϵ_v). Note, both 4 and 50 Hz responses overlap, thus shown as one legend entry. b) σ_v and surface conductivity changes (σ''_{surf} at 4 and 50 Hz) versus ϵ_v . σ' increases with σ_v and σ''_{surf} shows distinct peaks at deformation points.

(a)

(b)

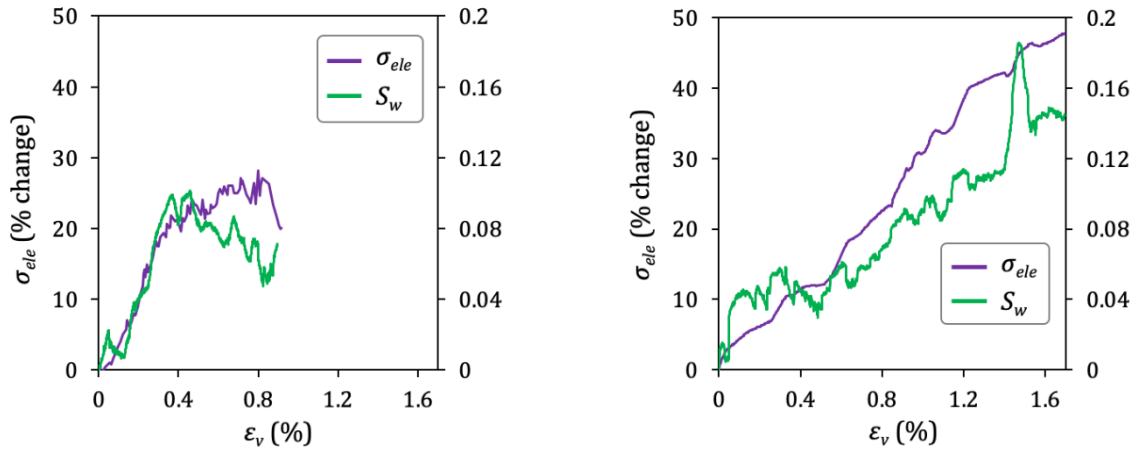


Figure 9 – Saturation (S_w) and electrolytic conductivity (σ_{ele}) changes versus ε_v . a) First experiment – monitoring up to the distinct shear failure point, b) Second experiment – monitoring deformation past the assumed failure point. In both experiments, S_w and σ_{ele} increased with compression (i.e., increase in ε_v).

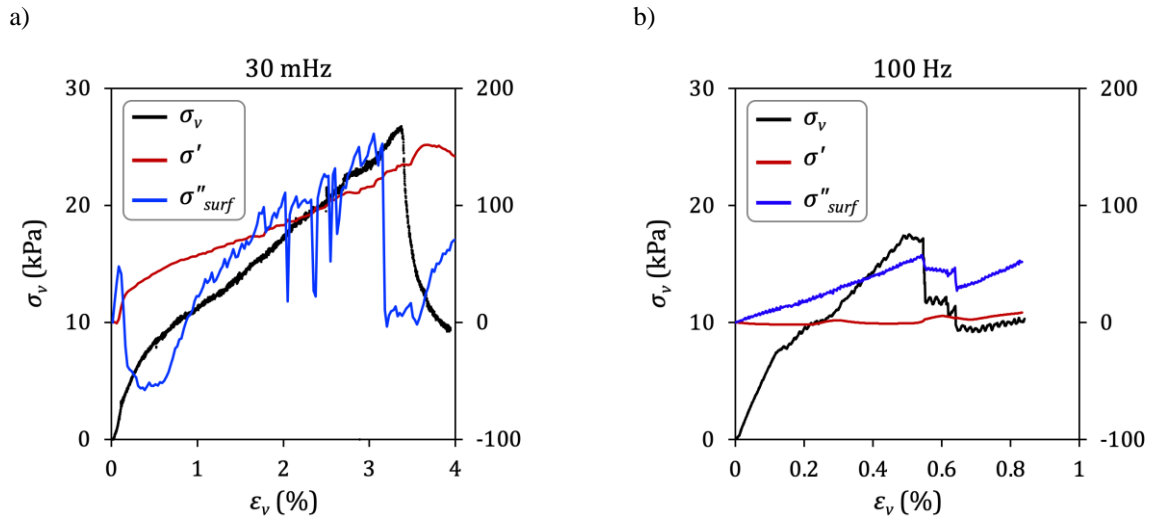


Figure 10 – Results of complex conductivity monitoring during two separate compression tests leading to soil failure/deformation. a) Response recorded at 30 mHz in one experiment, b) response recorded at 100 Hz in a different experiment. Vertical stress (σ_v), real (σ') and surface (σ''_{surf}) conductivity percentage changes are shown versus strain (ε_v). In both experiments, both σ' and σ''_{surf} increase with σ_v prior to failure and decrease after sample failure. However σ''_{surf} changes are much larger and drop sharply at sample failure. Note that a deformation-past-failure point is observed at around $\varepsilon_v = 0.6\%$ in (b) which affected the σ''_{surf} signal.

Deformation and failure are physical phenomena that impact pore geometry and thus the petrophysical properties of soils controlling electrical conduction and polarization. Our findings indicate that complex conductivity is capable of tracking mechanical changes of soils under stress and during failure foremost through the surface conductivity. Complex conductivity, specifically the imaginary (or surface) conductivity, is highly sensitive to both soil deformation and failure. However, the electrolytic part of the conductivity (dominating the real conductivity in our case) is insensitive to soil structural rearrangement during compression and instead depends on the degree of saturation.

Finally, we performed a complete consolidated undrained triaxial shear test on the soil to see if our findings are valid in real situations, where substrate soil is under vertical and lateral stress simultaneously. In this test, the synthetic loose soil sample (98% - weight percentage - quartzitic sand, 2% fine kaolin powder) was fully saturated with de-aired water (conductivity = 0.026 S/m). The saturation stage was followed by a consolidation stage which ensured full compaction of the soil sample. Full consolidation was confirmed by measuring effluent volume changes, reaching lower than 5% change after 24 hours.

The consolidated undrained (CU) shear test was then performed on the sample until a clear failure point (sharp drop in the deviatoric stress – $\sigma_{dev} = \sigma_v - \sigma_h$) was observed. We continued the shearing until a critical state or residual strength (observing no changes in the deviatoric stress) was achieved. Continuous SIP measurements were collected during this test using the novel instrumentation (Figure 3).

Figure 11 shows changes in the magnitude of σ' and σ'' with changes in axial strain (ϵ_v). Changes in the active (deviatoric) stress (σ_{dev}) are also shown. Figure 11 highlights the strong sensitivity of σ'' to changes in σ_{dev} , indicating that sudden rearrangements of soil structure are manifested as sudden changes in polarization. In contrast, changes in σ' are minimal throughout the experiment. This result further confirms the strong sensitivity of σ'' ($\sim \sigma''_{surf}$) to soil deformation/failure, regardless of stress/strain conditions.

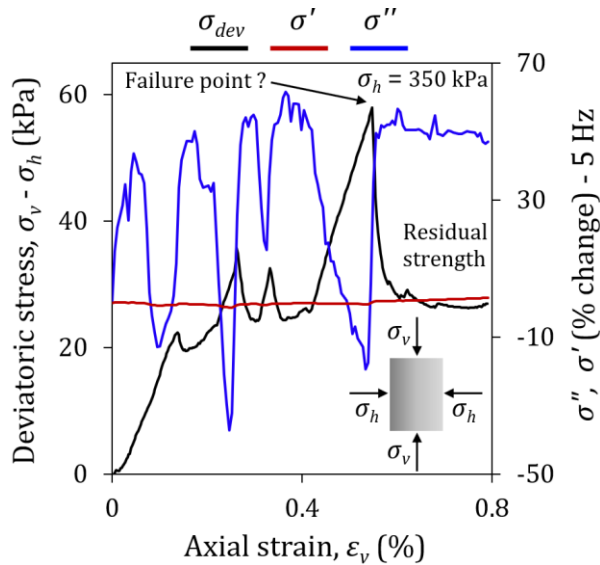


Figure 11 – Changes in σ_{dev} , σ' and σ'' with ε_v . The hydrostatic stress (σ_h) on the sample was 350 kPa. The σ_{dev} and σ'' show similar sharp changes as the ε_v increases.

Training students

During this project, two undergraduate students (Claire Osei and Ethan Siegenthaler) were trained by the postdoctoral scholar (Sina Saneiyani) to work with the SIP unit. Both these students worked on electrical properties during drying of swelling versus non-swelling soils. The results of this work were presented at the American Geophysical Union (AGU) Fall meeting 2020 by Ethan Siegenthaler³.

A graduate student (Alejandro Garcia) was trained by the postdoctoral scholar (Sina Saneiyani) to perform triaxial tests on the new customized machine. Additionally, the graduate student was trained to create customized sample holders and perform simultaneous SIP and shear test on loose soils.

³ Siegenthaler, E., Saneiyani, S., & Slater, L. D. (2020, December). Petrophysical Characterization of Swelling and Non-Swelling Clays by Geoelectrical Measurements. In *AGU Fall Meeting 2020*. AGU.

W911NF-18-1-0442

ENHANCING RESEARCH CAPACITY IN COMPUTING SCIENCE AND EARTH SCIENCES THROUGH BASIC RESEARCH ENGAGING UNDERREPRESENTED MINORITY (URM) GRADUATE STUDENTS

Supporting materials for Interim Report covering the project period July 31st, 2020-July 31st, 2021.

Investigating the complex electrical conductivity signatures resulting from calcite precipitation

This supplemental document provides a summary of the experimental work performed by underrepresented minority (URM) PhD candidate Alejandro Garcia during the period of July 31st, 2020 through July 31st, 2021.

The primary research focus was the completion of experiments relating to the Spectral Induced Polarization (SIP) response of calcite precipitation which were begun during the prior year in collaboration with researchers at the Cold Regions Research and Engineering Laboratory (CRREL). This involved both the precipitation of calcite in suspension as well as precipitation within a solid porous medium (in this case uncompacted sand). This was achieved using a double diffusion setup whereby reactants are transported into a sample chamber through passive diffusion, thereby creating a controlled precipitation front (Figure 1).

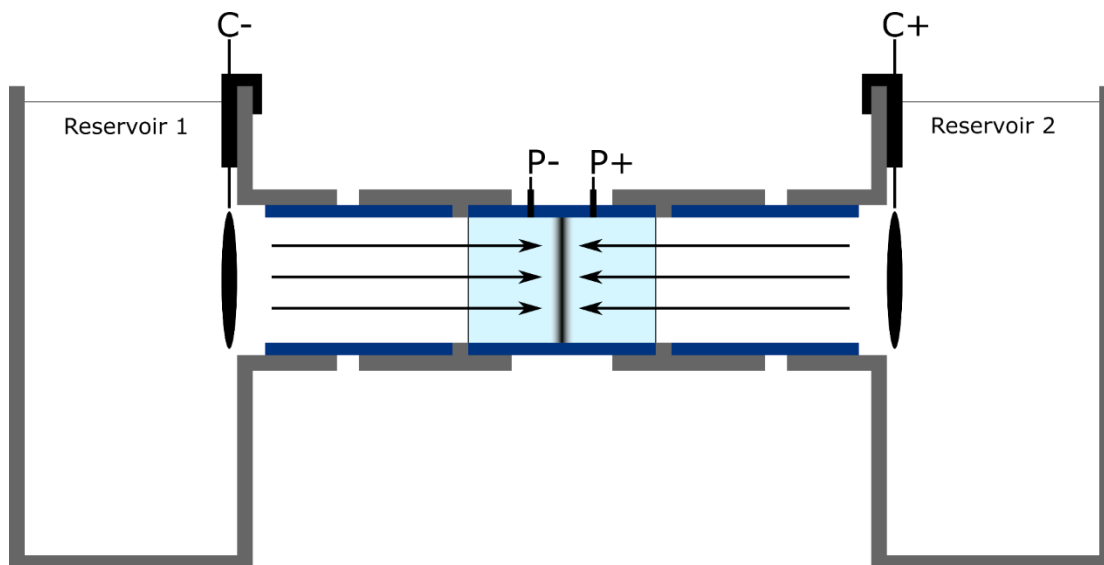


Figure 1 Schematic of a double diffusion setup similar to the one used in this study (not to scale). Diffusion from two fluid filled reservoirs causes the formation of a band of precipitation within a centrally positioned gel. The gel is self-supporting and only attached to the PVC column at the walls. The figure also shows the position of current and potential electrodes used for SIP measurements.

One of the research goals set out during this period of time was to repeat measurements of calcite suspended in gel (Figure 2) to validate previous results and obtain higher quality measurements. We conclude once again that, in isolation, calcite crystals do not produce a measurable change in the polarizability of a material, being in agreement with the traditional understanding of the polarization of low surface area non-metallic minerals.

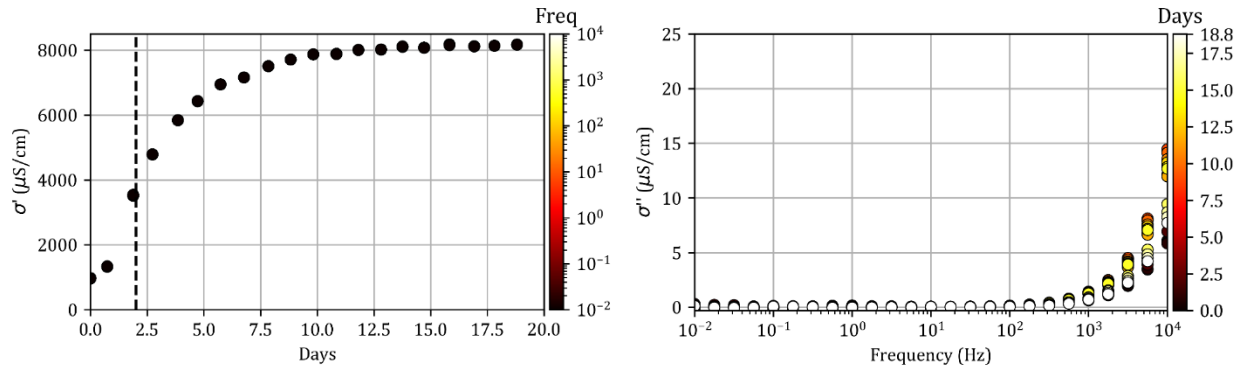


Figure 2 Complex conductivity measurements for calcite crystals precipitated within an agarose gel, absent of any other medium. (Left) The real component of the conductivity plotted both as a function of frequency (colorscale) and time. (Right) The imaginary component, the colorscale represents the time a measurement was taken. The dispersion of $\sigma'(f)$ is negligible so the colors cannot be differentiated.

The next set of the experiments focused on testing the theory that it is the presence of a porous medium and the changes that occur in the pore geometry that produce measurable increases to the polarizability of a material during calcite precipitation. We repeated the prior procedure using a gel-saturated sand as well as a gel-saturated mixture of sand-magnetite. The latter experiment was performed to explore the effects of precipitation of calcite within a highly polarizable matrix. Precipitation was visible in both samples as a thin bisecting layer of calcite (Figure 3).

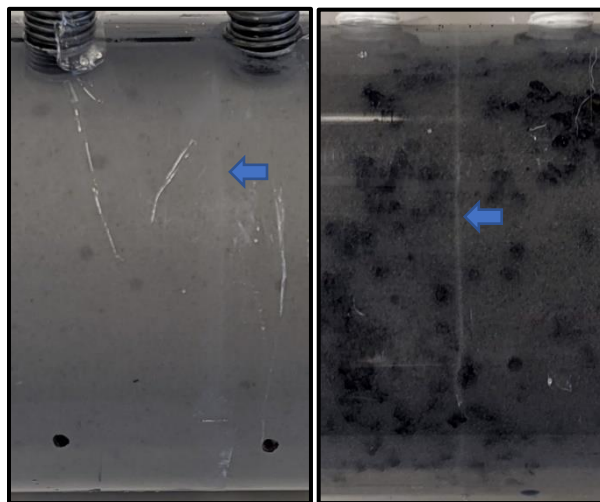


Figure 3 Photos of calcite precipitation within a gel saturated sand (left), and a gel saturated sand-magnetite mixture (right). A blue arrow indicates where the precipitation is visible.

We show the results for the gel-saturated sand in Figure 4. During the precipitation of calcite, a significant drop in the real conductivity is observed which is concurrent with an increase in the imaginary component. This is attributed to the formation of a calcite barrier in the center of the sample holder.

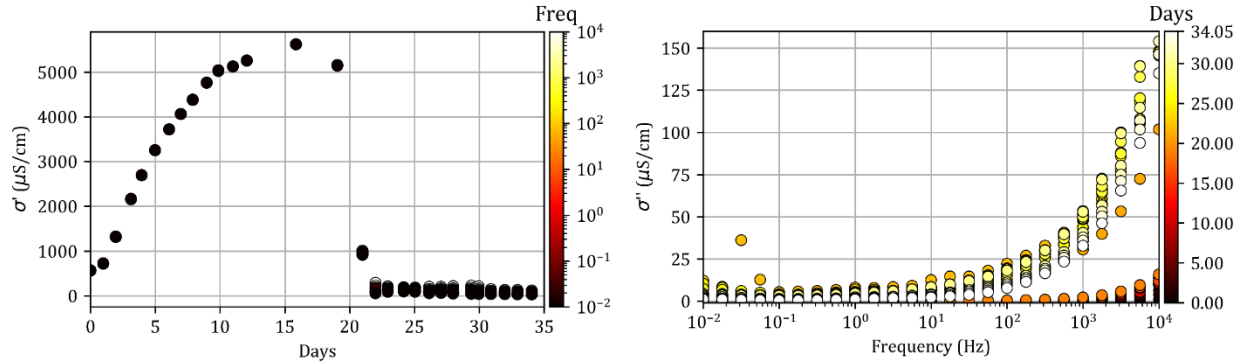


Figure 4 Complex conductivity measurements for calcite crystals precipitated within gel-saturated sand. (Left) The real component of the conductivity plotted both as a function of frequency (colorscale) and time. (Right) The imaginary component, the colorscale represents the time a measurement was taken. The dispersion of $\sigma'(f)$ is negligible so the colors cannot be differentiated.

We see a similar effect in the sample with magnetite. In this case blockage of the pore space by calcite forces current to travel through magnetite grains thereby creating an increase in the measured imaginary conductivity that is distinct from that seen in the sample without magnetite.

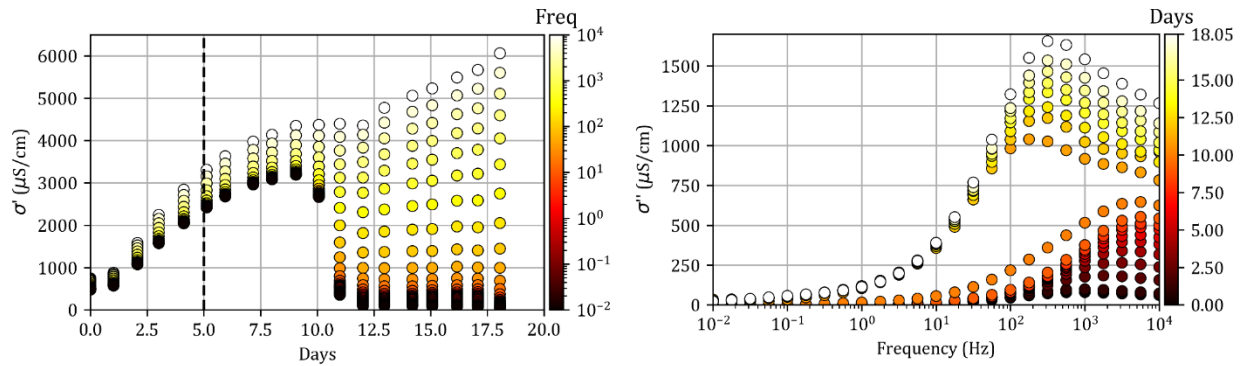


Figure 5 Complex conductivity measurements for calcite crystals precipitated within a gel-saturated sand-magnetite mixture. (Left) The real component of the conductivity plotted both as a function of frequency (colorscale) and time. (Right) The imaginary component, the colorscale represents the time a measurement was taken. The dispersion of $\sigma'(f)$ is significant with high frequency values shown to be dependent on ion concentrations.

We have been able to show through our experiments that under certain circumstances it is possible for the precipitation of calcite (and potentially other non-conducting minerals) to produce an increase in the measured SIP response. Currently we are nearing completion of a draft publication that we hope to submit for review towards the end of November 2021.