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Deep Vadose Zone Monitoring Test Bed: FY23 Status Report

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Summary

A subsurface air injection at the Hanford Site's Deep Vadose Zone Monitoring Test Bed was completed to realize a change in subsurface hydrologic conditions in accordance with a soil desiccation remedy. The injection mimicked a previous injection at the site that was performed in accordance with a vadose zone treatability study. Unlike the previous test which relied on electrical methods only, the change in hydrologic conditions during the recent test was also monitored using cross-hole seismic sensing methods to assess the ability of the seismic methods to evaluate changes in moisture conditions of desiccated sediment at the field scale. Data from in situ neutron probes indicates a reduction of soil moisture in the vicinity of the injection well due to the air injection. Similar changes were observed in the time-lapse electrical resistivity and seismic data, which indicates a loss of soil moisture over time.

Tomographic inversions of the time-lapse geophysical data illustrate the 2D and 3D features of the soil moisture distribution over time. Time-lapse electrical resistivity tomography (ERT) results show a reduction in the electrical conductivity of the subsurface in the vicinity of the injection well, with most changes occurring within the screened interval. Similar patterns are observed in the seismic tomography results, with both methods illustrating two lobe-shaped features of reduced soil moisture.

Use of seismic and ERT technologies in tandem takes advantage of two complementary geophysical monitoring technologies, providing increased sensitivity to specific hydrologic conditions. The multiphysics approach, therefore, has the potential to improve the ability to estimate subsurface moisture conditions from sensor-based and remotely sensed geophysical data that will ultimately improve the ability of remediation contractors to evaluate remedy performance.

Introduction

The depth and spread of contamination in the deep vadose zone at the Central Plateau of the Hanford Site requires strategic advances in the science and engineering of subsurface characterization, monitoring, and control (DOE-RL 2010). Integrated monitoring approaches, which include spatiotemporal data from in situ sensors and geophysical methods, offer a comprehensive approach to characterizing geologic structure and monitoring changes in the hydrologic state of the subsurface. Whereas in situ sensors are unparalleled in measuring subsurface state variables where access is practical (e.g., boreholes), sensor data is limited in its ability to provide information for volumes away from the immediate vicinity of the sensor location, even short distances (e.g., greater than 0.50 m). Geophysical methods, however, are suitable for evaluating subsurface hydrologic state variables from the surface, or from borehole deployments, with the use of petrophysical relationships that relate geophysical properties to hydrologic variables of interest, e.g., soil moisture (Rubin and Hubbard 2005).

For this work, we use cross-hole seismic and ERT data to illustrate changes in soil moisture and matric potential during air injection, as this data is sensitive to shifts in moisture content and can be used to inform subsurface hydrologic conditions, i.e., flux to groundwater, between borehole locations. We detail a unique field experiment where a subsurface hydrologic perturbation is induced in the vadose zone using injected dry air to evaporate water, effectively reducing the relative permeability of the liquid phase and minimizing flux to groundwater. The objective of the experiment is to demonstrate the value of in situ and remote multi-physics monitoring for determining moisture conditions in the subsurface, which could be used with hydrologic models to estimate flux conditions. The experiment is monitored with an in situ sensor network for measuring changes in temperature, matric potential, oxygen content, and pressure. These point-scale datasets will be used in complement with geophysical data, including time-lapse cross-hole seismic and ERT data.

Field Site

A monitoring borehole network was previously constructed within the 200-BC-1 operable unit of the Central Plateau to support treatability testing by the site contractor (Truex et al. 2018). The clustered network consists of multiple boreholes containing thermistors, gas-sampling ports, heat dissipation units, and electrodes for cross-hole ERT (referred to herein as sensor boreholes). Each sensor borehole has an adjacent logging borehole replicate designed to accommodate the use of wireline and borehole geophysical tools, e.g., borehole radar, neutron probes, and seismic sources/receivers. Figure 1 shows a photo and map of the well field and Figure 2 shows the injection and monitoring system components.

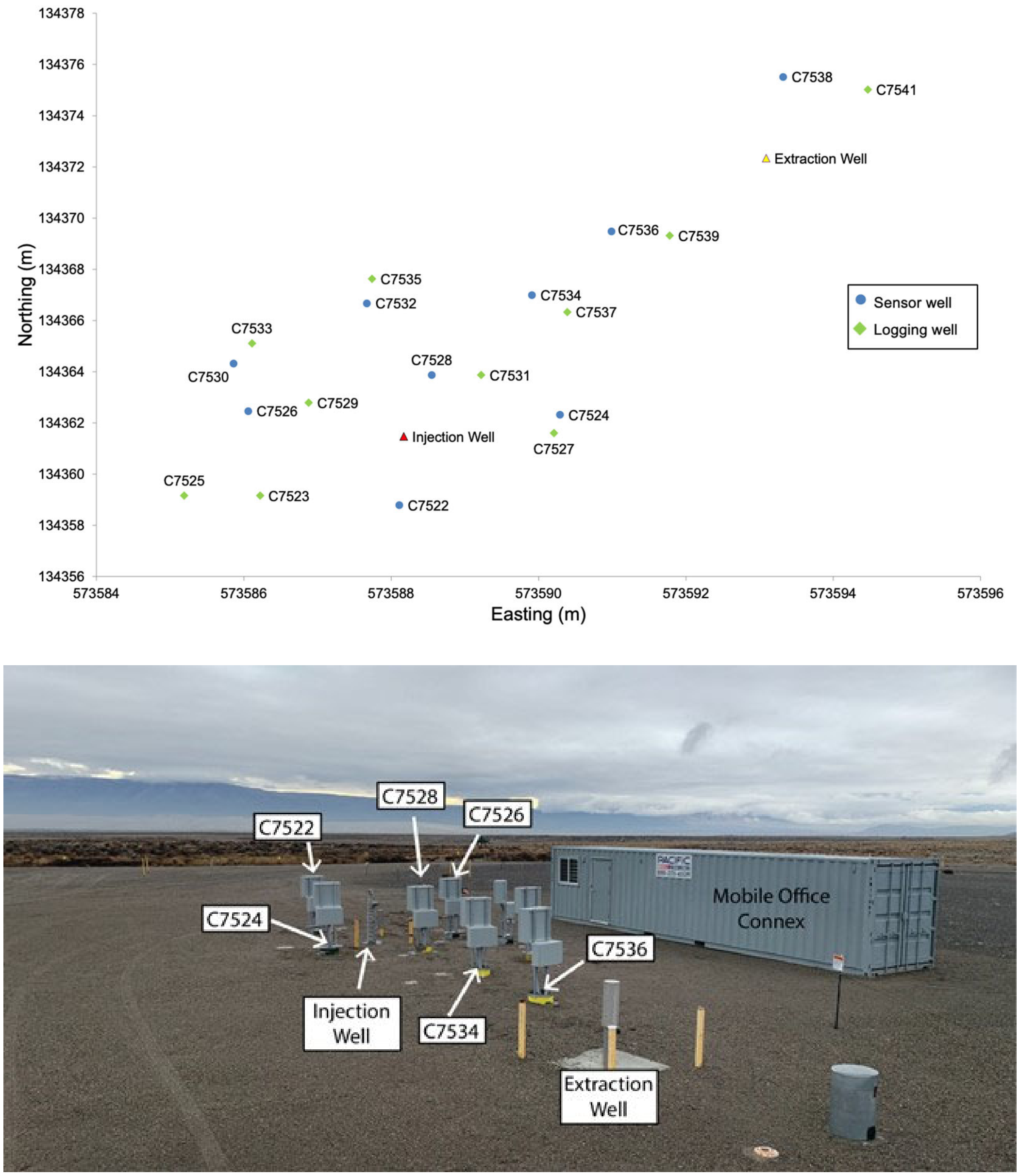

Figure 1. Top: Map of the field site boreholes; Bottom: photo showing distribution of boreholes in relation to the injection well. Some of the sensor boreholes are annotated (C7522 – C7536) in addition to the injection and extraction wells (For Information Only, FIO).

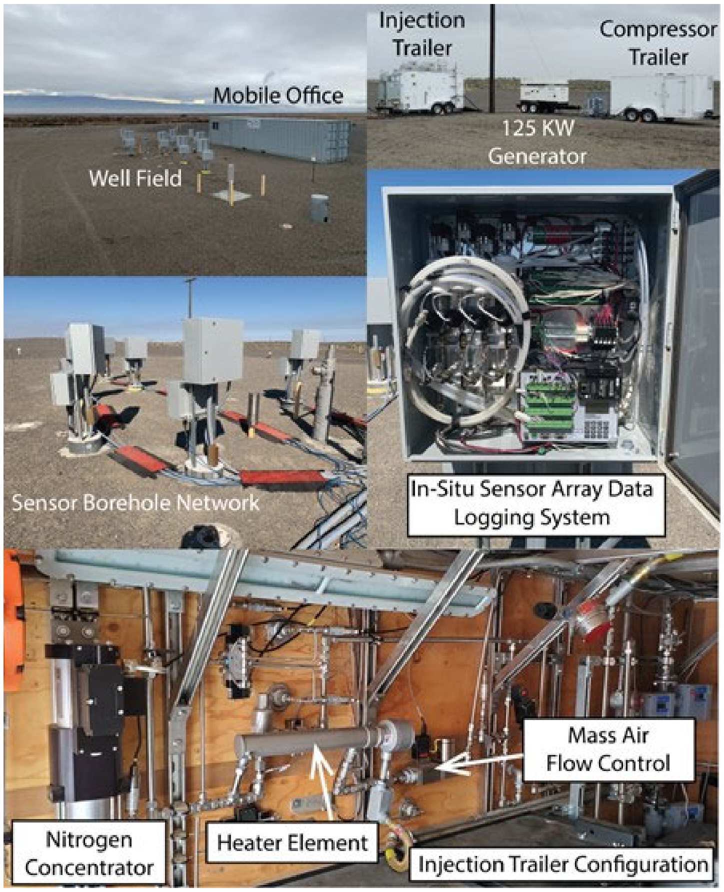

Figure 2. Components of the injection and monitoring system. The in situ sensor array data logging system logs data from thermistors, heat dissipation units (matric potential), and air pressure sensors while operating a gas sampling system that measures oxygen concentration for tracer tests.

The Field-Scale Desiccation Experiment

A field experiment was performed between May 2022 and January 2023 to collect time-lapse seismic and ERT geophysical monitoring data during a vadose zone air injection test. The injection was representative of a vadose zone soil desiccation remedy and more generally a perturbation in the hydrologic state of the subsurface. Air injection was accomplished using a dryer-equipped air compressor connected to a 125-kilowatt diesel generator. The dried, compressed air is fed to an injection trailer equipped with mass air flow controllers and a heating element. Heated, dried air is fed to the injection well at a nominal rate of 5000 standard liters per minute at a temperature of 5°C. Figure 3 shows the total cumulative volume of air injected over the duration of the injection experiment. Flat segments of the graph indicate pauses in injection due to system maintenance/repairs. While the injection began in mid-May 2022, near continuous operations were established from October 2022 to the end of the injection experiment in January 2023. Difficulties in maintaining continuous injection stemmed from the use of a diesel generator for electrical power, which required refueling and maintenance, and injection/compressor trailer issues from extreme temperatures.

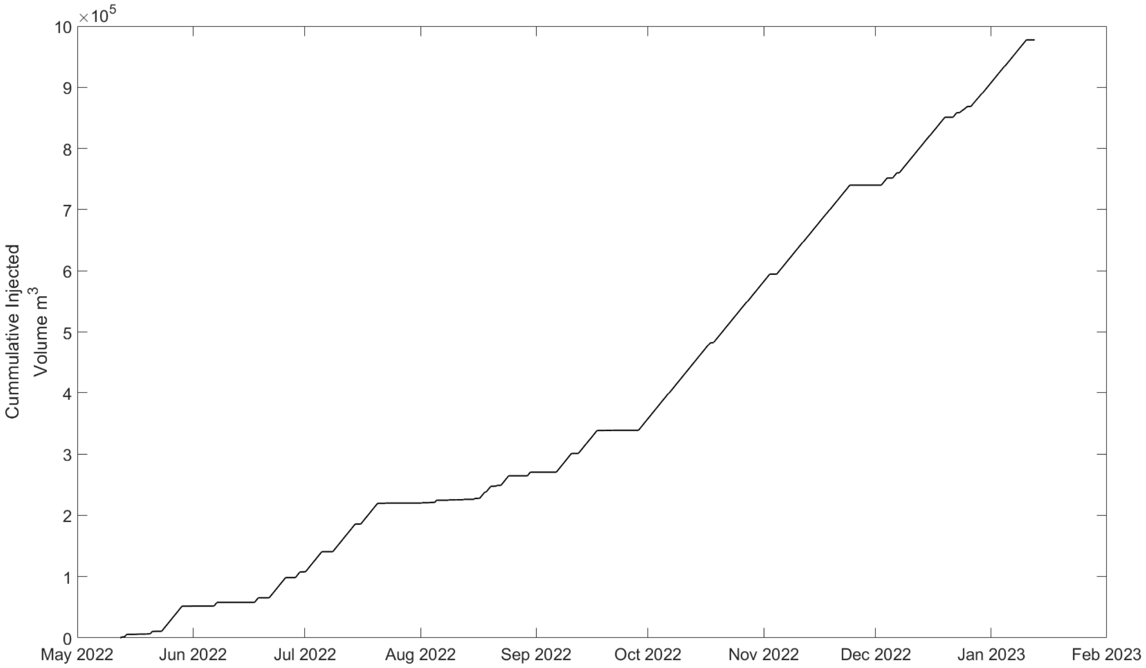

Figure 3. Cumulative air volume injected at the BC Cribs and Trenches test bed from May 2022 until January 2023. A total of approximately 1 million cubic meters of heated dry air was injected (FIO).

In fiscal year 2022, the task illustrated through empirical petrophysical relationships that seismic and ERT technologies can provide complementary information, and the combination of methods provides sensitivity over a broad range in water content (Binley and Slater 2020; Linneman et al. 2021). In general, at soil moisture values below residual water content, ERT is expected to lose sensitivity to changes in moisture or matric potential because the pore water exists in disconnected micropores or films. This is the primary medium for electrical conduction in the ground, given that pore water is more electrically conductive than soil. Despite dry conditions, some injected current will still travel along surface conduction pathways, e.g., through thin films and mineral grains. Alternatively, we showed that at soil moisture values less than residual moisture, there is a significant increase in the seismic wave velocity caused by the stiffening of the porous media, e.g., increase in effective stress due to increase in matric potential. The theoretical changes in seismic wave velocity with small changes in moisture provide increased sensitivity at low moisture conditions.

Borehole Neutron and Thermistor Response

Starting in May 2022, an air injection was targeted at a rate of roughly 5000 standard liters per minute at a nominal temperature of 50°C. Temperature data from in situ thermistors shows evaporative cooling effects from the injected air (Figure 4). The data shows that the magnitude of the cooling effect scales with distance from the injection well and distance from the screened interval. These same cooling effects were observed in DOE-RL (2012), but to a much greater degree, wherein freezing conditions were induced in the subsurface.

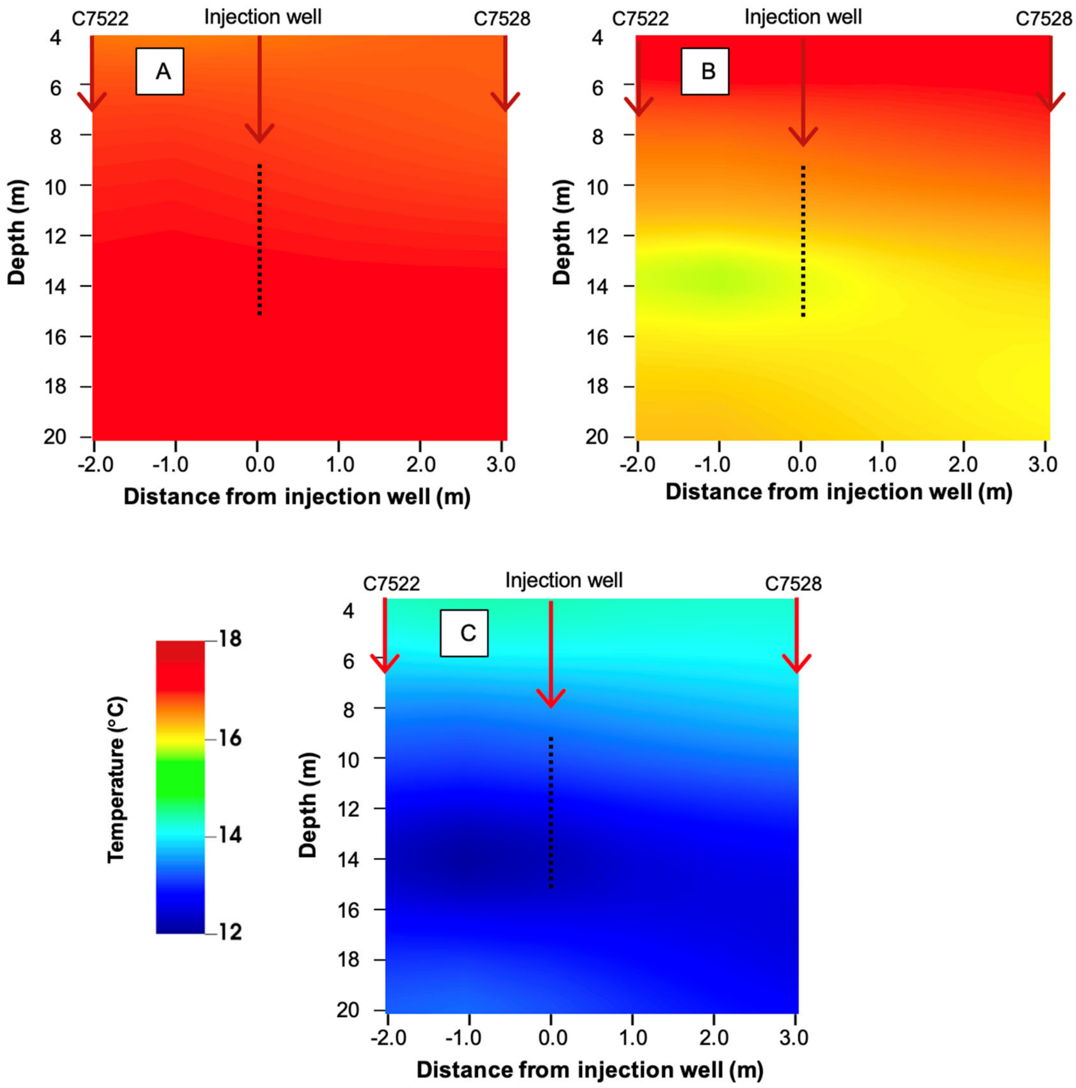

Figure 4. Vertical slice of interpolated temperature response between instrumented wells C7522 and C7528 (A) before air injection (April 2022), (B) after approximately 500,000 m^3 injected (October 2022), and (C) after 1,000,000 m^3 injected (January 2023). Temperature response indirectly shows desiccation through the evaporative cooling effect. The screened interval is indicated with a black dashed line (FIO).

Temperature data does not directly enable quantification of moisture content decreases. However, given that the injected temperature of the air is 50°C, and cooling is observed in the subsurface, we can infer that moisture removal is occurring via evaporation.

This is additionally confirmed with soil moisture information from borehole neutron data collected in each of the logging boreholes (Figure 5). In the boreholes located less than 4 m from the injection well (C7523, C7525, C7527, and C7531) a decrease in volumetric moisture content of 3–5% is observed around 14 m below ground surface (bgs). The wells further from the injection well show little observable change in volumetric moisture content. This data confirms that a volume extending at least 2 m laterally around the injection well was desiccated to moisture contents below residual moisture (~5%).

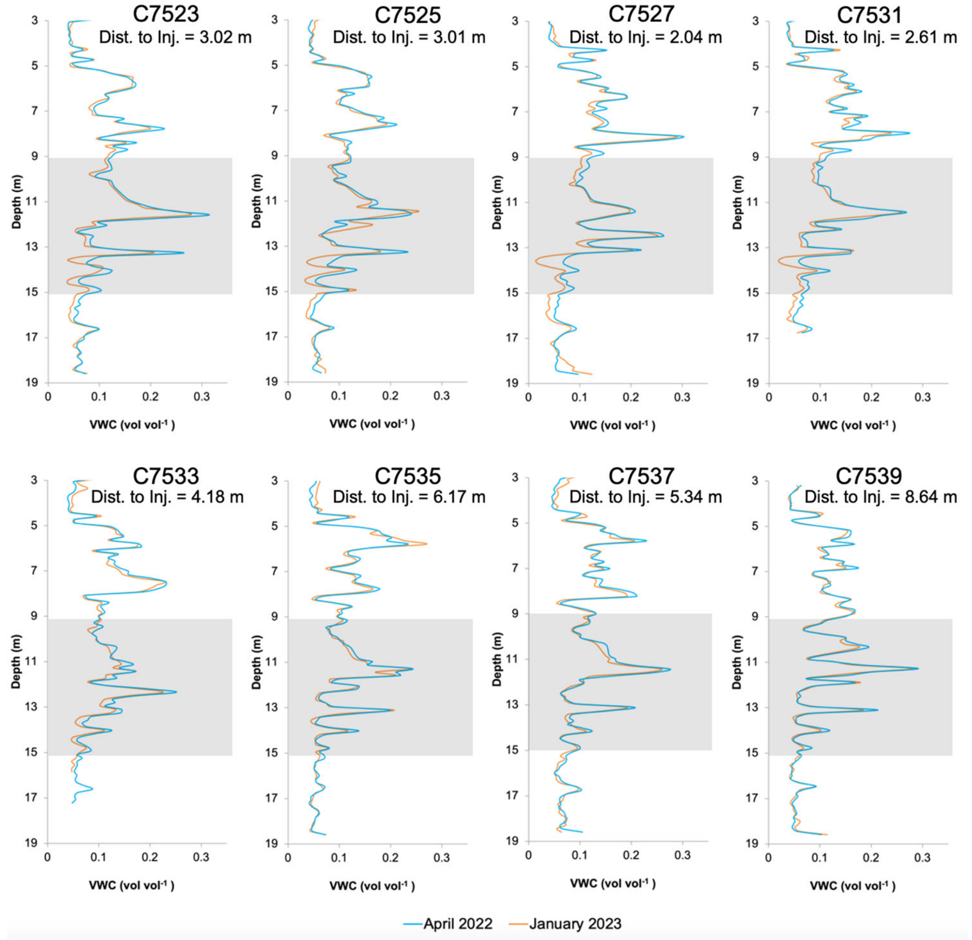

Figure 5. Volumetric soil moisture with depth in the eight logging boreholes before (April 2022) and after (January 2023) air injection activities. The depth interval corresponding to the screened depths of the injection well is shown with a shaded bar (FIO).

Time-Lapse Geophysical Surveys

Time-lapse ERT data was collected at a 4-hour interval throughout the duration of the injection using the array of electrodes installed on the sensor boreholes. A repeat seismic survey was performed after the termination of the experiment in January of 2023 to compare with the baseline data collected in April 2022.

The geophysical data (ERT and seismic) was inverted using E4D, a software designed to reconstruct subsurface property distributions based on geophysical measurements (Johnson et al. 2010; DOE-RL 2012; Truex et al. 2013). Figure 6 shows results of the timelapse ERT inversion. The ERT images are sliced vertically by a plane that intersects two of the logging boreholes (C7523 and C7531) and the injection well. The inversion was performed using time-lapse difference imaging, where the E4D inversion result of the ERT data collected on May 11, 2022 (pre-injection), is subtracted from the inversion result of the data collected on January 9, 2023 (post-injection). This highlights changes in the electrical conductivity of the subsurface associated with removal of water from the pore space via air injection. Two regions of reduced electrical conductivity appear on the ERT time-lapse inversion in the vicinity of the injection well. Using assumptions from the previous desiccation test, which are detailed in Truex et al. (2018), it is possible to present the change in electrical conductivity as a percent reduction in soil moisture. Using this relationship, the ERT data indicates a maximum reduction of moisture in the subsurface of 28%, with a broad region of moisture removal that averages a roughly 14% reduction. In general, this agrees with information from the neutron probe data; however, spatial trends are somewhat inconsistent. This is likely due to difference in sample volume, as the neutron probes are measuring an annular volume at the logging boreholes about 2 m away from the injection well, whereas the ERT data is interrogating the volume of soil surrounding the injection well encompassed by the borehole network.

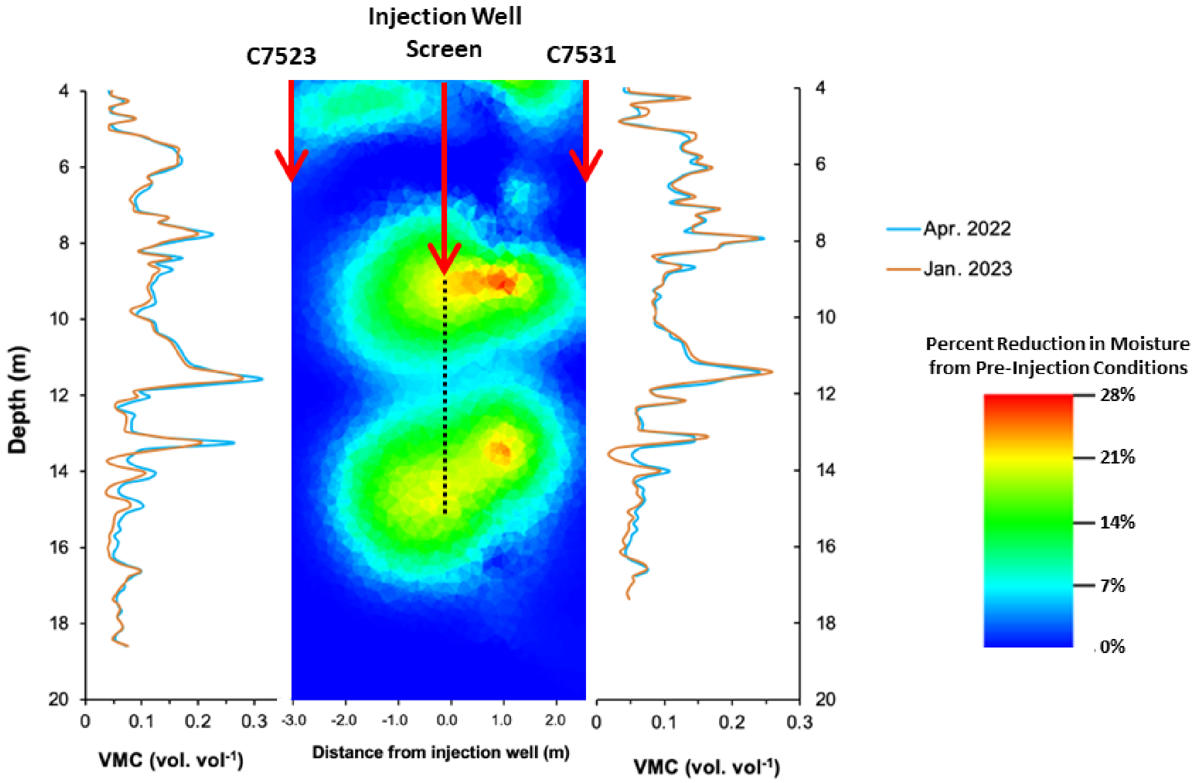

Figure 6. From left to right: Volumetric moisture content (VMC) before and after air injection with depth in logging well C7523 from neutron moisture logging; vertical slice of ERT inversion results between wells C7523 and C7531 showing the percent reduction in moisture from the injection as estimated by the time-lapse ERT data. The screened interval is indicated with a black dashed line; volumetric moisture content from neutron logging, before and after air injection, with depth in logging well C7531 (FIO).

Figure 7 shows the changes in seismic velocity between the pre-injection baseline data collected in April 2022 and the post-injection timelapse data collected in January 2023 on a vertical cross section of the test bed between wells C7523 and C7531. The injection well is indicated in between the logging wells and the screened interval is shown with a dotted black line. Velocity changes were observed just above the screened interval at a depth of around 6 to 8 m bgs as well as from approximately 11 to 16 m bgs. The maximum velocity increase is around 500 m/s, nearly a 100% increase from the average velocity at this depth of about 600 m/s measured from the baseline survey. This result is consistent with the range of velocity increases of 400-800 m/s corresponding to a ~5% decrease in volumetric moisture content as measured in laboratory experiments on variably saturated Hanford sediments (Linneman et al. 2021). The VMCs in wells C7523 (left) and C7531 (right) measured by neutron probe before and after the air injection are also shown. The region of greatest seismic velocity response corresponds well to the depths of greatest change in VMC.

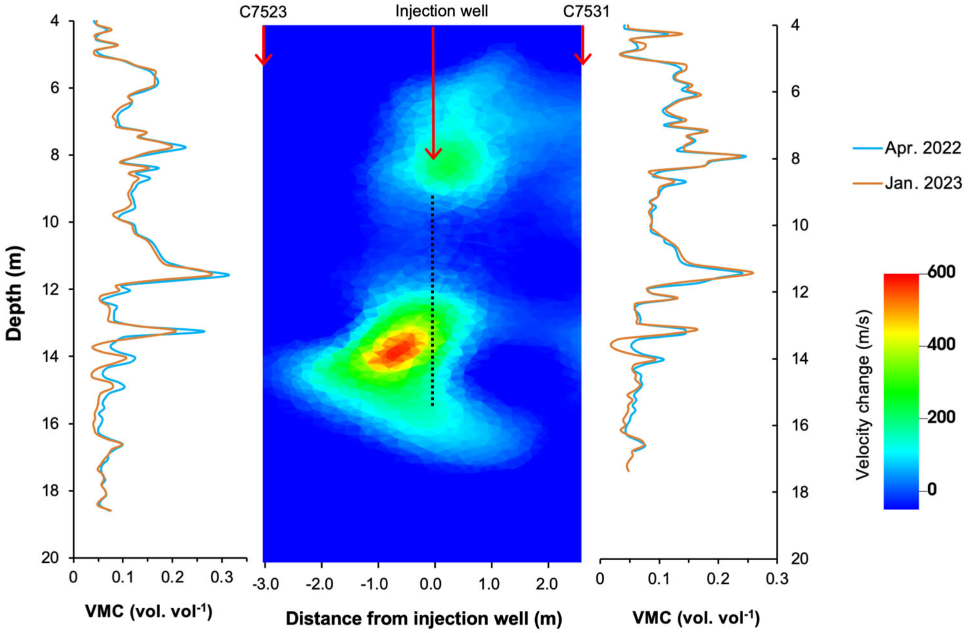

Figure 7. From left to right: Volumetric moisture content before and after air injection with depth in logging well C7523; vertical slice of seismic velocity inversion results between wells C7523 and C7531 showing change in seismic velocity between the April 2022 and January 2023. The screened interval is indicated with a black dashed line; volumetric moisture content, before and after air injection, with depth in logging well C7531 (FIO).

Conclusions from the Field-Scale Experiment

Overall, the experiment was successful in illustrating the potential for borehole seismic data to capture changes in vadose zone soil moisture associated with an air injection remedy. This establishes cross-hole seismic data as an additional tool for monitoring soil moisture conditions and complements previously established technologies like ERT and in situ sensors and may further improve the ability to remotely evaluate remedy performance. Next steps for the task are to perform additional data analysis associated with the development of this multi-physics monitoring test, including preparing the geophysical data sets to be jointly inverted. Joint inversion may better constrain hydrologic properties of the field site and allow predictions of changes to moisture flux through the subsurface resulting from the applied desiccation.

Quality Assurance

This work was performed in accordance with the Pacific Northwest National Laboratory Nuclear Quality Assurance Program (NQAP). The NQAP complies with the DOE Order 414.1D, *Quality Assurance*. The NQAP uses NQA-1-2012, *Quality Assurance Requirements for Nuclear Facility Application*, as its consensus standard and NQA-1-2012 Subpart 4.2.1 as the basis for its graded approach to quality. Any data presented in this document is preliminary, FIO, and subject to revision.

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