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Strategic Petroleum Reserve Enhanced Monitoring Compendium - FY 2022

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ABSTRACT

The Strategic Petroleum Reserve (SPR) is the world's largest supply of emergency crude oil. The reserve consists of four sites in Louisiana and Texas. Each site stores crude in deep, underground salt caverns. It is the mission of the SPR's Enhanced Monitoring Program to examine all available data to inform our understanding of each site. This report discusses the monitoring data, processes, and results for each of the four sites for fiscal year 2022.

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SUMMARY

This compendium is a collection of reports from throughout FY 2022. It discusses monitoring at all four SPR sites.

Bayou Choctaw is the most stable of the Strategic Petroleum Reserve (SPR) sites. Data from satellite-based Interferometric Synthetic Aperture Radar (InSAR), GPS, and tiltmeters indicate the site is extremely stable and there is no reason to believe any of the caverns have been structurally compromised. Although there is no overall subsidence, Bayou Choctaw exhibits small seasonal movements (approx. ±0.15 in. around the site average). With the help of InSAR we have been able to determine that seasonal movements are likely caused by near-surface water/soil interactions and not geological.

This year's Big Hill enhanced monitoring analysis looks at InSAR data and recent multi-arm caliper surveys. Results show that the highest subsidence rates between October 2017 and October 2021 are approximately 0.7 in./yr. and located above BH-104; however, InSAR results also show that rates are slightly increasing. The period between July 2020 and October 2021 shows the highest subsidence rates at approximately 0.9 in./yr. Despite this, there are no cavern integrity concerns at the site. There are, however, concerns regarding well casing deformation. This report also looks at potential links between well deformation and surface deformation. Currently, there are no direct links between the two. More studies are being completed to determine the cause of well deformation at the salt-caprock interface.

This year's Bryan Mound enhanced monitoring analysis looks at the most recent InSAR, GPS, and tiltmeter data at Bryan Mound. Results show the highest subsidence is in the area around BM-003 and BM-002 with rates of-0.36in./yr. and -0.28 in./yr., respectively. Rates are consistent with historical measurements and InSAR shows the subsidence is steady state. The tiltmeter above BM-003 shows a slight deviance beginning June 2021 and currently thought to be due to site activity from oil movement. This deviance is not seen in InSAR and GPS but will continue to be investigated. Given the current data there are no structural integrity concerns at Bryan Mound.

This year's West Hackberry enhanced monitoring analysis looks at the most recent InSAR data and reports from TRE Altamira. Results show the highest subsidence is in the area around WH-101 (-0.91 in./yr.). WH-102, 103, 104, 105, 106, 107, 109, and 115 also have subsidence rates with magnitudes greater than -0.80 in./yr. These rates are typical for West Hackberry and are slightly lower than historical rates measured using level-and-rod. The rates also correlate with Sandia's geomechanical model. Given the congruence between current InSAR results, historical data, and geomechanical models, there currently are no structural integrity concerns at West Hackberry.

NOMENCLATURE

Table 0-1. Nomenclature

Abbreviation	Definition
BC	Bayou Choctaw
BH	Big Hill
BM	Bryan Mound
CSK	COSMO-SkyMed
DOE	Department of Energy
DSM	Deep Soil Mixing
FFPO	Fluor Federal Petroleum Operations
GPS	Global Positioning System
InSAR	Interferometric Synthetic Aperture Radar
SPR	Strategic Petroleum Reserve
WH	West Hackberry

1. INTRODUCTION

Ensuring cavern integrity is paramount to a safe and operable storage facility. Although there is no direct measure of cavern integrity there are methods to infer the structural health of the cavern field. These methods include monitoring quantities like surface deformation, cavern shapes, and cavern pressures. This report considers each available dataset, presents an analysis, and discusses our best understanding of cavern integrity at all SPR sites.

For the Strategic Petroleum Reserve (SPR) to accomplish its mission we need to ensure the caverns holding the oil are structurally stable. One way to monitor this is observing the change in elevation at the surface deformation above the caverns. Most of the SPR sites - and the gulf coast at large - exhibit a loss of elevation over time. This phenomenon is typically referred to as subsidence. From subsidence, we can infer the structural integrity of the cavern field below. This is because stresses and movements in a cavern are eventually translated to the surface as subsidence. Subsidence is normal and expected, however, if the rates change unexpectedly or are too high it can be cause for concern. This is why the SPR program has been monitoring subsidence for over four decades and have recently added state-of-the-art monitoring techniques.

This compendium is a collection of four enhanced monitoring reports from FY 2022.

2. BAYOU CHOCTAW

2.1. History of Monitoring at Bayou Choctaw

Monitoring the Bayou Choctaw SPR site began in 1982 with traditional level-and-rod surveys. These surveys were conducted on an annual or biennial frequency and ground deformation was calculated using the change in elevation between surveys. For several decades it was the primary method of monitoring. Although most level-and-rod surveys returned consistent results, there had been many instances of large, unexplained elevation changes at surveyed locations. In addition to erroneous points, occasional surveys showed significant elevation change where the entire site would seemingly move up or down. Anomalous recordings were most likely caused by measurement error due to disturbed monuments, incorrect rod placement, etc.

Seeing this, SPR tried to improve the accuracy and reliability of level-and-rod surveys. Beginning in 2010 many of the survey markers were replaced with survey monuments. Survey markers - surveyed locations on infrastructure with shallow or no foundation - had experienced the majority of inconsistent measurements. Survey monuments, by contrast, are surveyed locations affixed to infrastructure with deep foundations or placed on piles driven to refusal. Newer survey monuments were more consistent because they were harder to accidentally disturb. By 2016, the survey markers at Bayou Choctaw had been phased out in favor of monuments.

Beginning in 2016, digital level-and-rod surveys were used to reduce human error. Both methods use the same level-and-rod concept to measure elevations; however, traditional level-and-rod surveys require the surveyor to manually read the rod measurements and potentially introduce error. A digital level uses a bar code on the survey rod to automatically measure the elevation, thus reducing where errors can occur.

In addition to improving site surveys, SPR looked at real-time monitoring of several caverns. In 2013, a GPS instrument and tiltmeter were placed on the wellhead of BC004. Another set of GPS and tiltmeter instruments were added to the wellhead above BC020 in 2017. Measurements are logged hourly and can be accessed for later analysis. Three of the four instruments have provided consistent and detailed information since they were installed. The last instrument – the Cavern 20 tiltmeter – has seemingly failed but is still generating data.

Despite continual improvements to the level-and-rod surveys, erroneous points still occurred. This led Sandia to investigate alternatives to level-and-rod surveys. The search ultimately led to the satellite based InSAR, or Interferometric Synthetic Aperture Radar. InSAR has the ability to measure tens of thousands of points across the site every 16 days. Each survey can measure deformation on a sub-millimeter scale. After a successful test at the Big Hill SPR site, InSAR was also used to monitor the Bryan Mound SPR site (in addition to level-and-rod surveys). In 2020, SPR made the decision to switch all four sites to InSAR as the primary method for measuring ground deformation. The last level-and-rod survey of Bayou Choctaw occurred February 2020.

2.2. Datatypes for Enhanced Monitoring

Bayou Choctaw uses several methods to measure ground deformations at the site. Currently, Interferometric Synthetic Aperture Radar, or InSAR is used to measure site-wide subsidence rates. InSAR is a satellite-based technology that measures surface deformation across the site. It surveys the site every 16 days. GPS and tiltmeters are also used over Caverns 4 and 20 to supplement the InSAR data. Additionally, there are plans to incorporate microseismic monitoring to visualize stress changes in the subsurface.

2.2.1. InSAR

This is the second year that InSAR has been the primary method for surveying site-wide ground movement. The raw InSAR data are collected and analyzed by TRE Altamira. This year's report was submitted to Fluor Federal Petroleum (FFPO) on September 8, 2021 [1]. General findings from that report indicate there are slight seasonal movements across the site with slightly greater movement in the southwest portion of the site. These seasonal trends have been seen in the GPS and tiltmeter instruments and will be examined later in this report.

Figure 2-1 shows ground deformation at Bayou Choctaw between January 2019 and June 2021. During this time, the site experienced near zero movement. The figure indicates that the southwest corner of the dome is experiencing greater subsidence. This is due to the start and end dates of the subsidence calculation. The southwest area of the site is more susceptible to seasonal movements and the end date is mid cycle. This means that data in the figure will show the most extreme amount of differential subsidence at the site.

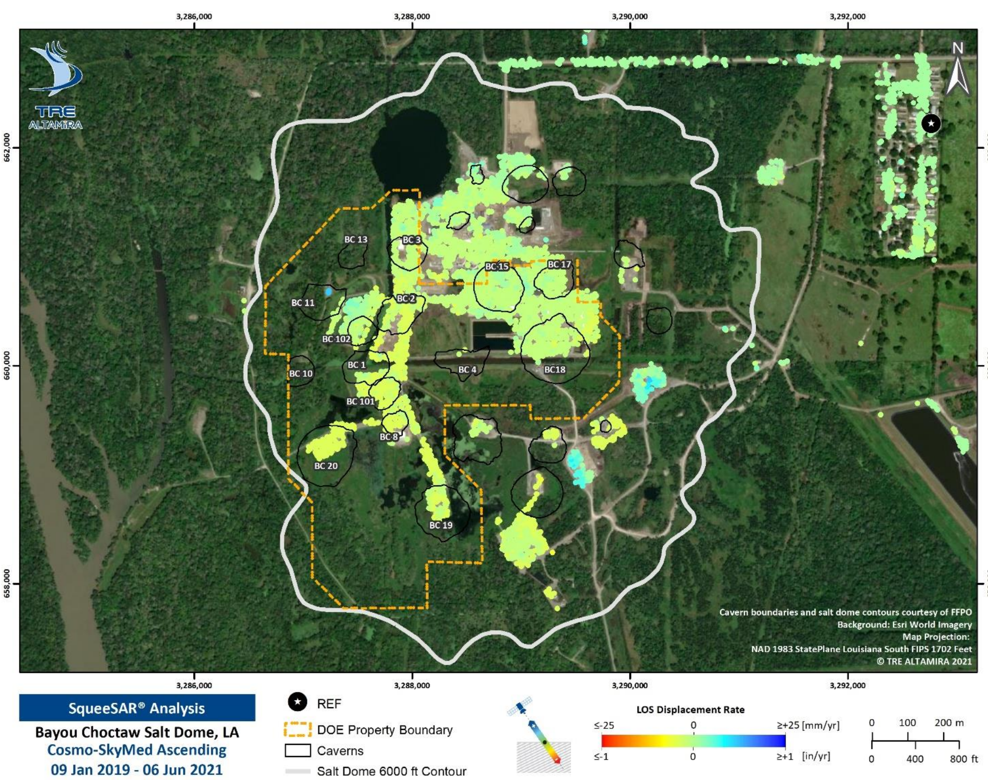

Figure 2-1. InSAR results at Bayou Choctaw.

There are also two Boardwalk well pads in the southeast experiencing uplift. We do not believe this is a geologic event. Uplift is confined to two specific well pads. Additionally, there is another well between the two uplifting well pads that shows no movement. It is likely this is a near surface movement that was impacted by resurfacing or re-engineering of the well pads.

Another way to look at the data is with a time series of displacement. Figures 2-3 through 2-5 show three areas that need to be observed closely. A map showing three areas of interest can be seen in Figure 2-2. Each time series shows the statistics of the InSAR measurements in that area. The black line represents the median value for all InSAR points in the region of interest. The gray area shows the range between the 25th and 75th percentiles while the black line shows the range between the 5th and 95th percentiles.

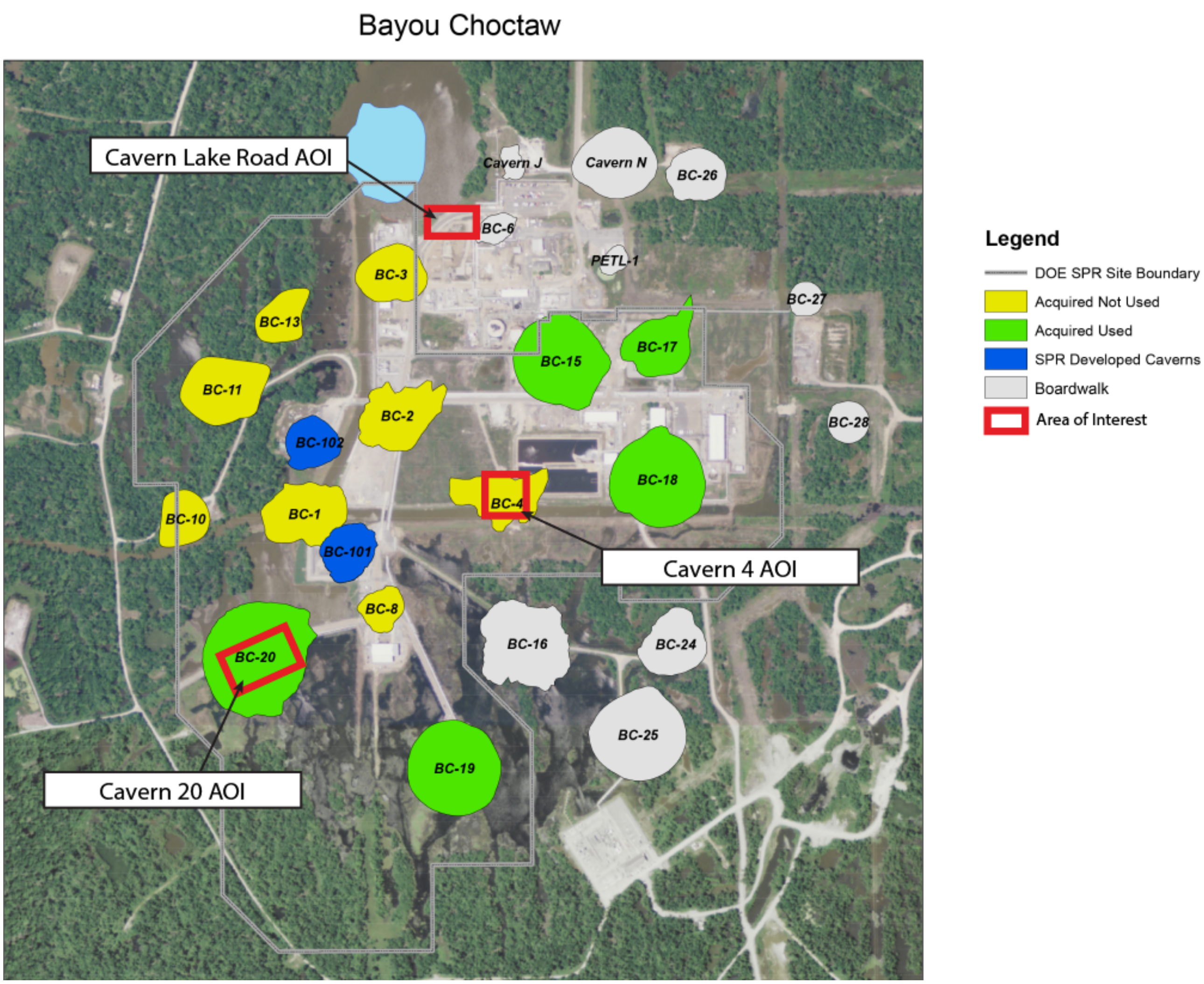

Figure 2-2. Bayou Choctaw map with area of interests and cavern outlines

Figure 2-3 shows the vertical displacement above Cavern 004. It should be noted that there are only two reflections being measured from the area above Cavern 004. This means that, for Figure 2-3, the black line is the average of the two displacements instead of the median values. These measurements show a small seasonal trend but little overall movement above Cavern 004. In fact, the time series shows there might be a slight uplift. Given the current InSAR measurements, there is no reason to believe that Cavern 004 has lost structural integrity.

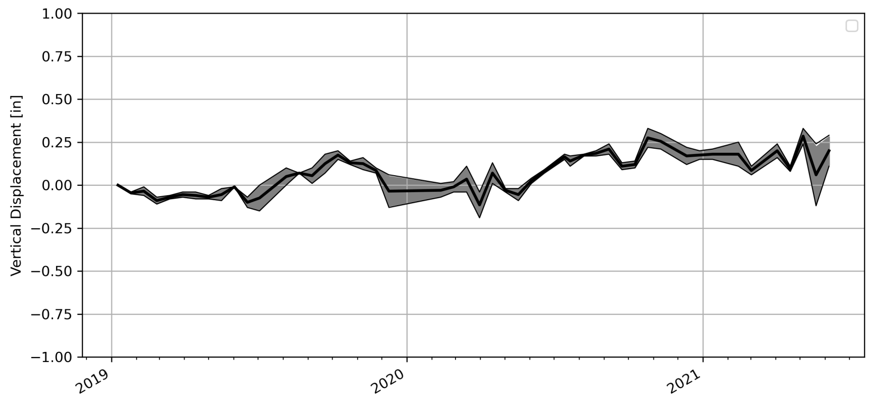

Figure 2-3. Time series of InSAR measurements above Cavern 4. Note: There are only two reflections in the sample set. The black line shows the average of the two lines.

Figure 2-4 shows the vertical displacement measurements for the Cavern 20 well pad. There is greater seasonal movement than Cavern 004 with uplift in the summer/fall and subsidence in winter/spring. This movement has been seen in the GPS but the extents of seasonal movements were previously unclear. InSAR has allowed us to see where the seasonality is greatest. Figure 2-4 also shows the range of displacements across Cavern 20 are uniform throughout (i.e. the gray area representing the 25th and 75th percentiles stays approximately the same). Like Cavern 20, there may be some slight uplift but there is no indication of structural integrity loss from the InSAR measurements.

Figure 2-4. Time series of InSAR measurements above Cavern 20.

Another area that has gained interest in the last two years is the area between Cavern Lake and the nearby road. Site personnel spotted cracks forming along the roadway in June 2019. A series of deep soil mixing, or DSM, piles were drilled to prevent soil sloughing and further cracking along the roadway. The first piles were drilled July 2020 and the job was completed in January 2021. Figure 2-5 shows the displacement statistics for the area between the road and Cavern Lake. There is a slight seasonal variation but little overall movement. Where this differs from other areas of the site is the differential subsidence experienced in the area (i.e. the values between the 25th and 75th percentiles begin to diverge). The higher subsiding areas are nearest the lake.

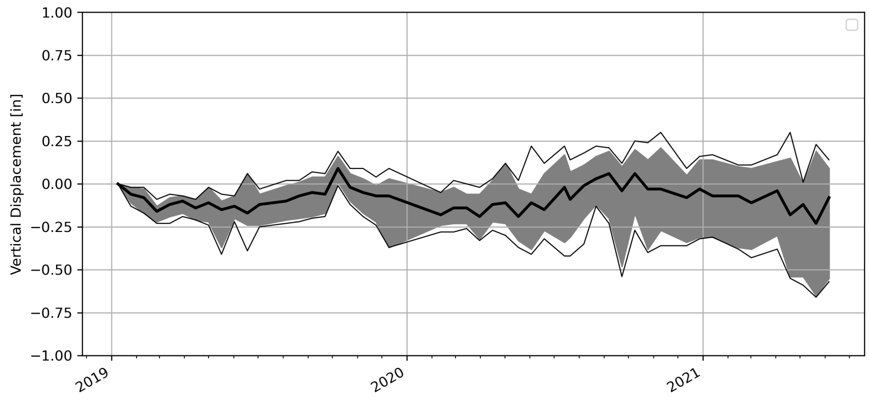

Figure 2-5. Time series of InSAR measurements above Cavern Lake Road.

It should be mentioned that some of the points on the edge of the lake were lost to InSAR. It is likely these points were lost during construction of the DSM piles. InSAR may lose points if ground movement is greater than half of the InSAR's wavelength. In this case, the COSMO-SkyMed (CSK) satellite has a wavelength of 3.1 cm. Any movement greater than 1.5 cm may result in the satellite being unable to track the point correctly. There is currently no geological concern and no immediate near surface concern; however, we will continue to monitor this area for abnormal subsidence.

2.2.2. Real-time Sensing Instruments

As part of the enhanced monitoring program, Bayou Choctaw also has four real-time sensing instruments in operation. GPS and tiltmeter instruments are currently present on both the BC004 and BC020 wellheads. The BC004 instruments were installed in 2013 while the BC020 instruments came into operation in 2017. Instruments were placed on the wellhead to:

1) Provide a rigid platform for the sensor under normal conditions. The well is one of the few pieces of infrastructure that provides a deep, pile-like foundation in the vicinity of their respective caverns. Deeper foundations have been found be less susceptible to near surface deformation.

2) Provide the earliest possible detection. By connecting the instruments to the only piece of infrastructure tethered to the cavern, any cavern deformation will most likely be transferred to the well first.

While placing the instruments on the wellhead has desirable qualities for monitoring, there are occasional logistical issues. Wellhead maintenance, well logging, and cavern sonars may require removal of the GPS and/or tiltmeter instrument. Another complication stems from the fact that the GPS and tiltmeter systems are digital. Like any digital system, they are susceptible to power outages or communication issues. If either occur, data cannot be recorded. Finally, it is also possible the instrument fails. Significant outages are presented in Table 2-1.

Table 2-1. Real-time sensing instrument outages

August 22, 2017 to September 27, 2017 (36 days) *All instruments* Failure of the control room receiving radio
July 17, 2018 to July 23, 2018 (6 days) *BC4 GPS, BC4 Tiltmeter* Removal of Cavern 4 wellhead instruments for sonar
July 25, 2018 to September 4, 2018 (41 days) *BC4 GPS, BC20 GPS* Failure of GPS power supply
September 25, 2018 to October 8, 2018 (13 days) *BC4 Tiltmeter* Removal of instrument for wireline
September 9, 2019 to October 28, 2019 (49 days) *BC20 GPS* Taken offline for routine well maintenance, discovered antenna and powercord were fused together from corrosion, both cables were damaged, and replacements had to be ordered

2.2.3. Bayou Choctaw Cavern 4 Instruments

Cavern 4 has a wellhead GPS and tiltmeter. Both instruments were installed to provide real-time sensing data above the cavern. The Leica GMX901 GPS was installed in 2013 and data are logged hourly. The Leica Nivel210 Tiltmeter began recording data in 2016 and also logs data hourly.

The GPS has shown little overall movement since it began recording. Figure 2-6 shows the hourly data. The black markers show the raw hourly data while the red line shows a median filter applied to the data. The filter has a window of 30 days. The figure shows a slight seasonal movement but no overall trend. Elevations at the site are slightly higher in the winter and lower in the summer.

Figure 2-7 shows tiltmeter data from the Nivel210. The format for the graph is similar to the GPS figure except there are two measurements represented. Orange markers show the hourly northing measurements while the blue shows the easting measurements. The respective lines show the data with a median filter applied. The median filter has a window of 30 days.

Data in Figure 2-7 begins in 2016; however, the instrument was installed in 2013. The 2016 subsidence report [2] shows the original data. It seems that data may have been lost during the transition to the Sensemetrics application. The data between 2013 and 2016 showed similar trends to current data. Current data shows little overall movement with some seasonal variation. The tiltmeter was recently removed for wellhead maintenance and it is highly likely the small jump in 2021 was caused by reinstallation of the instrument.

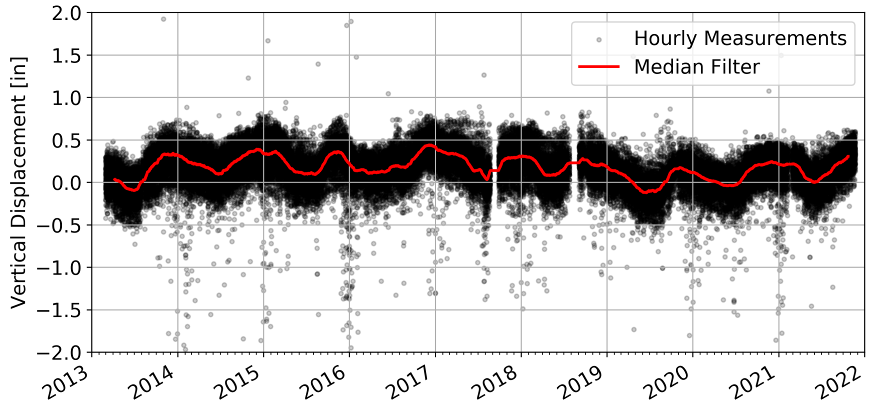

Figure 2-6. Bayou Choctaw 4 GPS measurements

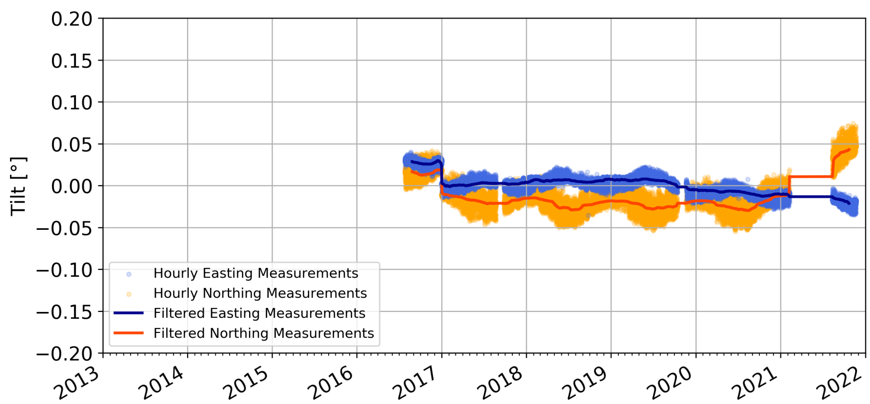

Figure 2-7. Bayou Choctaw 4 tiltmeter measurements

2.2.4. Bayou Choctaw Cavern 20 Instruments

A tiltmeter and GPS were installed over Bayou Choctaw 20, a cavern near the edge of salt. These instruments provide real-time sensing but also log data hourly for analytical purposes.

The Leica GMX910 is a newer version of the Cavern 4 GPS and has been taking hourly measurements since 2017. Data from the instrument are presented in Figure 2-8 and there is little overall elevation change. The only elevation change seen is seasonal.

The final instrument at the site is a Jewel Instruments Tuff Tilt Digital tiltmeter. Figure 2-9 shows the available data. It was installed in 2016 and has demonstrated seasonal deformations but little overall change. Unfortunately, it looks like the instrument has failed. Halfway through 2020 the tiltmeter began exhibiting strange measurements. Conversations with those familiar with the Cavern 20 tiltmeter also believe the instrument has failed.

Tuff Tilt Digital Tiltmeters like this one have also been deployed at Bryan Mound with poor results. Both borehole tiltmeters at Bryan Mound have experienced multiple failures and have since been taken offline.

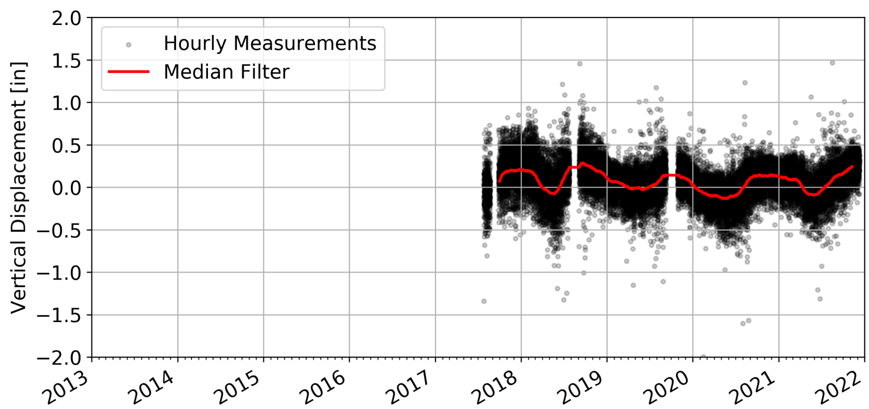

Figure 2-8. Bayou Choctaw 20 GPS measurements

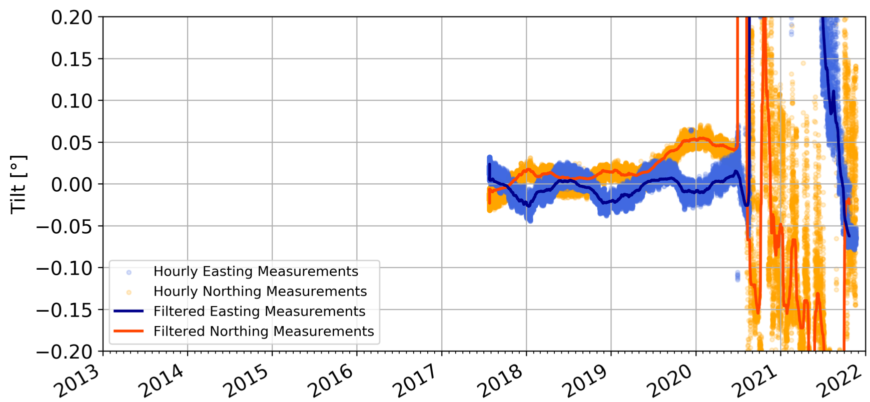

Figure 2-9. Bayou Choctaw 20 tiltmeter measurements

Other than the Cavern 20 tiltmeter - which seems to have failed - all the real-time sensors at Bayou Choctaw indicate no overall ground movement. Each of the instruments also show some seasonal variation. Given the current data, there is no reason to believe Caverns 4 or 20 have experienced any loss of structural integrity.

2.2.5. Data Comparison

We can also compare how the GPS and InSAR measurements compare. Figures 2-10 and 2-11 show the comparison between technologies for Cavern 004 and Cavern 020, respectively. The charts were created using the average InSAR measurements from the area around the wells. Cavern 004 used two measurements from the field around the well head. Cavern 020 used all InSAR measurements on the well pad. The initial InSAR measurement was then set at zero. Median filter measurements from Figures 2-6 and 2-8 were used for the GPS measurements. Since the InSAR had an arbitrary zero, GPS measurements were scaled to show the greatest overlap in measurements.

Most of the InSAR measurements hovered around the GPS values. There was a discrepancy in early 2019. We believe this may be due to the fact that InSAR measurements were just beginning. The GPS

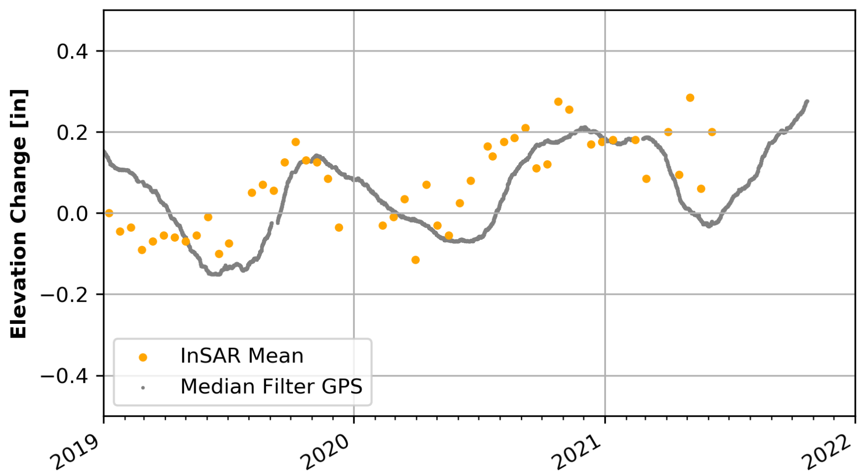

Figure 2-10. Comparison between InSAR and GPS data at Bayou Choctaw 004. The first InSAR measurement was placed at zero and then the GPS curve was overlaid on top.

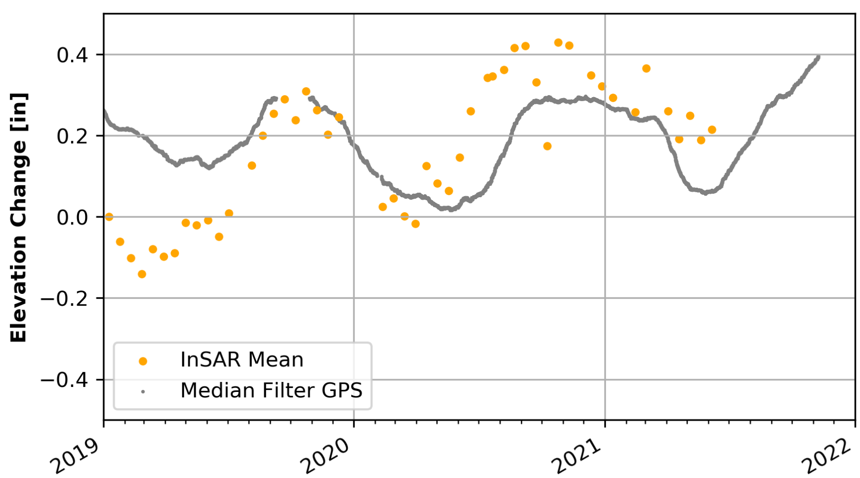

Figure 2-11. Comparison between InSAR and GPS data at Bayou Choctaw 020. The first InSAR measurement was placed at zero and then the GPS curve was overlaid on top.

instruments have been measuring for several years and exhibit typical patterns. The InSAR measurements do not exhibit the same subsidence in early 2019. It is also possible that daily GPS measurements are closer to the InSAR data than the figure shows. The median filter applied to the GPS data smooths the data and may not show the same variability seen in InSAR measurements.

2.3. Comprehensive Monitoring

Bayou Choctaw is the most stable SPR site. The only outstanding phenomenon is the seasonal movement experienced by most of the site.

2.3.1. Bayou Choctaw Seasonal Movements

Figure 2-12 shows the areas with the greatest seasonality in 2019 and 2020. The blue areas represent the most stable areas (movements less than or equal to 0.1 in.) while the green areas show the most variable locations (seasonal movement greater than or equal to 0.3 in.). The most variable locations are the areas that have the highest seasonal movement.

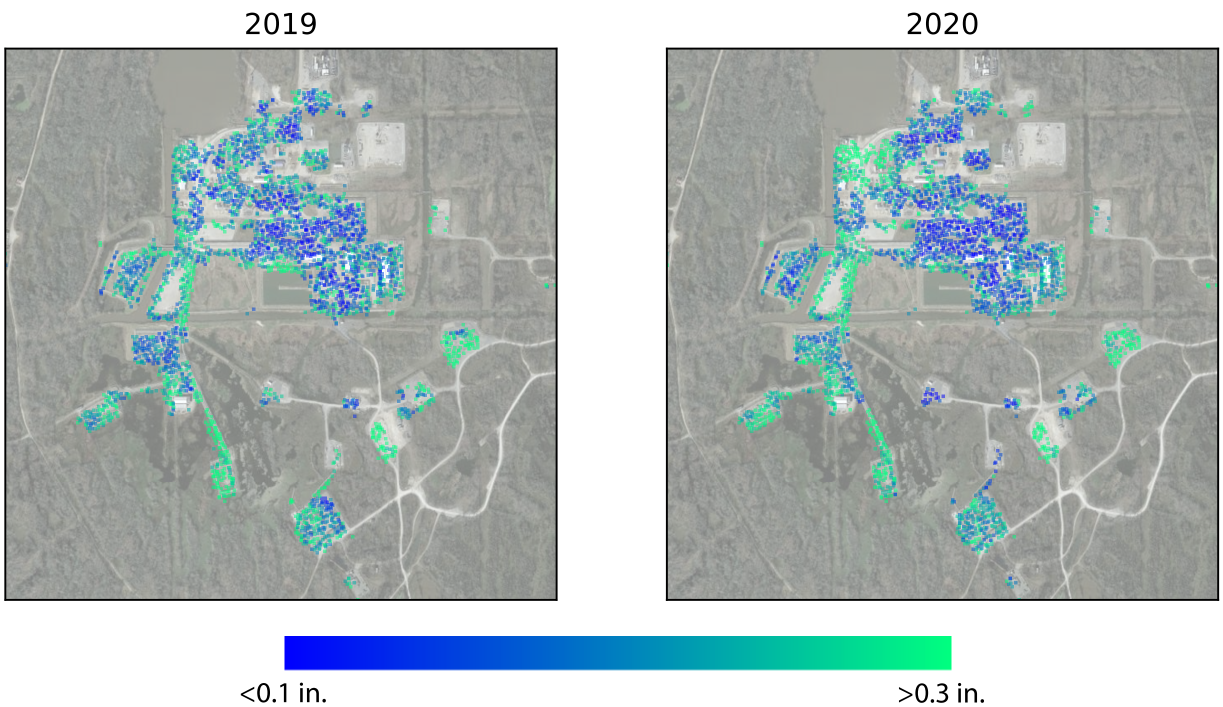

Figure 2-12. Seasonality at Bayou Choctaw during 2019 (left) and 2020 (right). Blue represents more stable areas while green represents areas with greater seasonality and/or greater overall movements.

Measurements were calculated using the amplitude of the seasonal movement. Specifically, data were detrended and then separated into complete years - 2019 and 2020. The highest and lowest elevations were used to calculate the range of values throughout the year. Since overall movement at the site is near-zero, the range of values also represents the amplitude of the seasonality measurements. It is important to remember that even the highest movements are still relatively insignificant. The green areas only vary ± 0.15 in. around the site average.

More isolated areas tend to have the highest variability, and by extension, seasonality. This is most prevalent in the southwest area of the site - in the areas surrounded by bayou. Other locations that experienced this are areas with new construction (Boardwalk) and on the periphery of established infrastructure.

Seasonality was generally consistent between 2019 and 2020. The biggest change occurred near Cavern Lake. As mentioned previously, there was construction during this time. The area likely experienced some settling during installation of the DSM piles. Due to the location and consistency of seasonal movements at Bayou Choctaw we believe the phenomena to be near surface and not geological. There is no correlation between the cavern field and seasonality, only between seasonality and land type. The greatest seasonality is seen near larger bodies of water and thought to be caused by some type of near-surface uplift from soil-water interaction.

Uplift from ground water change is hypothesized as one of the main causes for the seasonal movements. Thus, we wanted to compare ground movement to regional water levels. We initially compared GPS measurements to Mississippi River levels since there were consistent and reliable data from the nearby Mississippi River Station at Baton Rouge [3]. Figure 2-13 shows the daily river level of the Mississippi River (top) and the filtered hourly data from the Cavern 004 GPS (bottom). Although both values exhibit seasonal cycles, there is no obvious correlation.

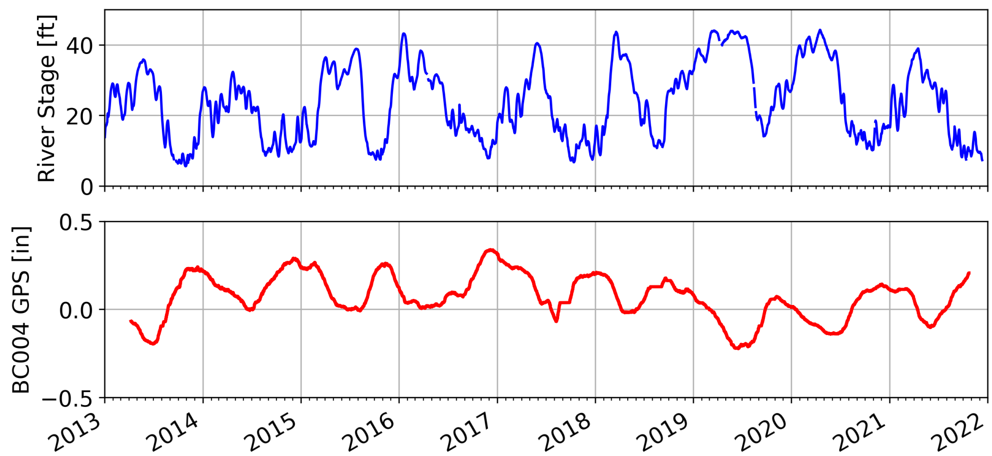

Figure 2-13. Comparison between Mississippi River Level (top) and Cavern 004 GPS measurements (bottom).

Since both datatypes have annual cycles, annual statistics for each value were also compared. Figure 2-14 shows deviation from expected linear subsidence at BC004. Figure 2-15 shows statistics for annual Mississippi river level, also known as stage.

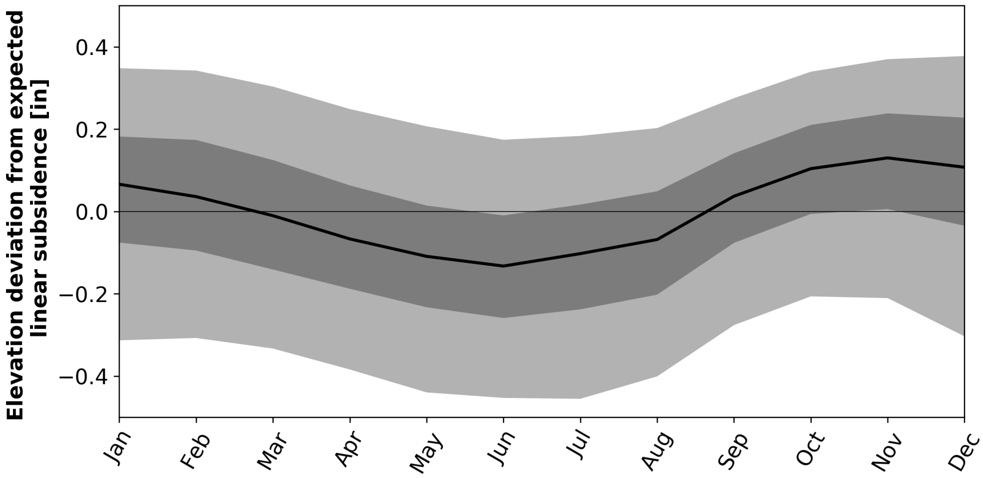

Figure 2-14. Seasonality of Bayou Choctaw 4 GPS measurements with the horizontal line showing the average throughout the year

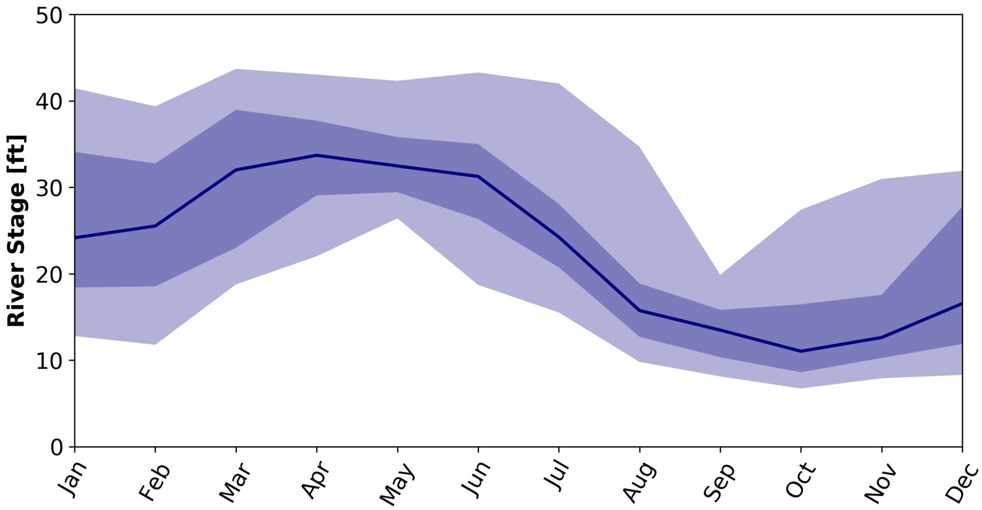

Figure 2-15. Monthly Mississippi River stage at the Baton Rouge Station. The blue line represents the median value. The blue area shows the range between the 25th and 75th percentile while the light blue area shows the range between the 5th and 95th percentile.

Results from the comparison are interesting. They are almost exactly inversely proportional. When the site is lower, the Mississippi River level is high and vice versa. They are correlated but we do not believe that one causes the other. There are additional mechanisms that may need to be considered in this analysis. For example, the Mississippi River may not be hydraulically connected to the site for parts of the year. There is also the nearby Port Allen Lock that acts as a spillway for the Mississippi River. The outlet of the lock feeds the bayous surrounding Bayou Corne. We would need to know when the lock is opened and closed to have a better understanding of regional hydraulics. It is possible that the Mississippi River impacts seasonal movements but we would need to understand how the river is controlled throughout the year.

Despite not being able to predict the cause of the seasonal ground movements we strongly believe it is a near-surface effect and there is no geological concern. InSAR has given us the resolution to determine where the seasonal movements are strongest. It is seen in areas of the site close to bodies of water and on the periphery of existing infrastructure. All of these areas are located on or near unengineered soil indicating some type of soil uplift from near-surface changes. Ultimately, the seasonal movements are extremely small - around a quarter of an inch in places with noticeable seasonality - and little cause for concern.

2.4. Conclusion

There are no cavern integrity concerns given current data from InSAR, GPS, and tiltmeters. All data indicate Bayou Choctaw has little overall subsidence. Any movement at the site is largely seasonal. The seasonal variation is correlated to Mississippi River levels and currently thought to be tied to groundwater levels; however, without groundwater measurements, it will be difficult to prove this theory. Despite not proving the cause of this phenomenon, InSAR has given us the ability to see the seasonal movements across the site. The seasonal movements are highest near open water and unengineered soils and not dependent on the cavern field. This leads us to believe that the movement is non-geological and near-surface.

3. BIG HILL

3.1. History of Subsidence Monitoring at Big Hill

Monitoring subsidence at the Big Hill SPR site began in 1989 with traditional level-and-rod surveys. These surveys were conducted on an annual or biennial frequency and ground deformation was calculated using the change in elevation between surveys. For 30 years it was the primary method of monitoring. Although most level-and-rod surveys returned consistent results, there had been many instances of large, unexplained elevation changes at a surveyed location. Anomalous recordings were most likely caused by measurement error due to disturbed monuments, incorrect rod placement, etc.

Seeing this, SPR tried to improve the accuracy and reliability of level-and-rod surveys. Beginning in 2016, digital level-and-rod surveys were used to reduce human error. Both methods use the same level-and-rod concept to measure elevations based on a reference point; however, traditional level-and-rod surveys require the surveyor to manually read the rod measurements and potentially introduces error. A digital level uses a bar code on the survey rod to automatically measure the elevation, thus reducing where errors can occur.

Despite continual improvements to the level-and-rod surveys, erroneous points still occurred. This led Sandia to investigate alternatives to level-and-rod surveys. The search ultimately led to the satellite based InSAR, or Interferometric Synthetic Aperture Radar. After a successful test at Big Hill, the SPR decided to use InSAR exclusively at the site. In 2020, SPR made the decision to switch all four sites to InSAR as the primary method for measuring sitewide ground deformation. The last level-and-rod survey of Big Hill occurred January 2019.

3.2. Datatypes for Enhanced Monitoring

Surface deformation at Big Hill is only monitored by InSAR. This is in contrast to the other SPR sites which are monitored by GPS and/or tiltmeters in addition to InSAR. GPS and tiltmeters are only installed if a cavern warrants closer monitoring. Since there are no such caverns at Big Hill, GPS and tiltmeters are not necessary.

InSAR has the ability to measure ground deformation on a sub-millimetric scale. It relies on natural reflectors - artificial reflectors are only necessary if there is a location at the site missing coverage. Big Hill is largely open field and provides good reflectors across the site. Thousands of points are measured in each InSAR image and new images are generated several times a month.

Another datatype used come from multi-arm caliper, or MAC, tools. As the name suggests, MAC tools have multiple arms that slide along the inside of the well to determine the internal geometry of each well.

Most tools have at least 56 arms and a vertical sampling rate as fine as 0.025 feet. These tools are used to measure the deformation within a well.

3.3. Surface Deformation

Traditionally, surface deformation had been measured by annual or biennial elevation surveys using level-and-rod. In FY 20 SPR decided to monitor ground movement using InSAR, a satellite-based technique. This method collects thousands of times more data and provides greater insight into the dynamics of surface deformation. This, in turn, should provide better understanding of cavern integrity.

3.3.1. Historical Level-and-Rod Surveys

Historical surveys at Big Hill began in 1989. There were initially 38 points but they were all clustered near the center of the site. Since then, the subsidence monitoring program has been working to improve accuracy and coverage across the site. In 2002 and 2003 an additional 131 monuments were established across the site. Figure 3-1 shows the cumulative elevation change seen in the level-and-rod surveys since the additional monuments were established. It shows subsidence at Big Hill is in the shape of a bowl with the highest subsidence being above BH-109. Typically, the highest subsidence is expected over the center of the cavern field but at Big Hill it is skewed to the western portion of the site. It is possible this is due to the thickness of the caprock or orientation of salt spines and the associated overlying fault at Big Hill.

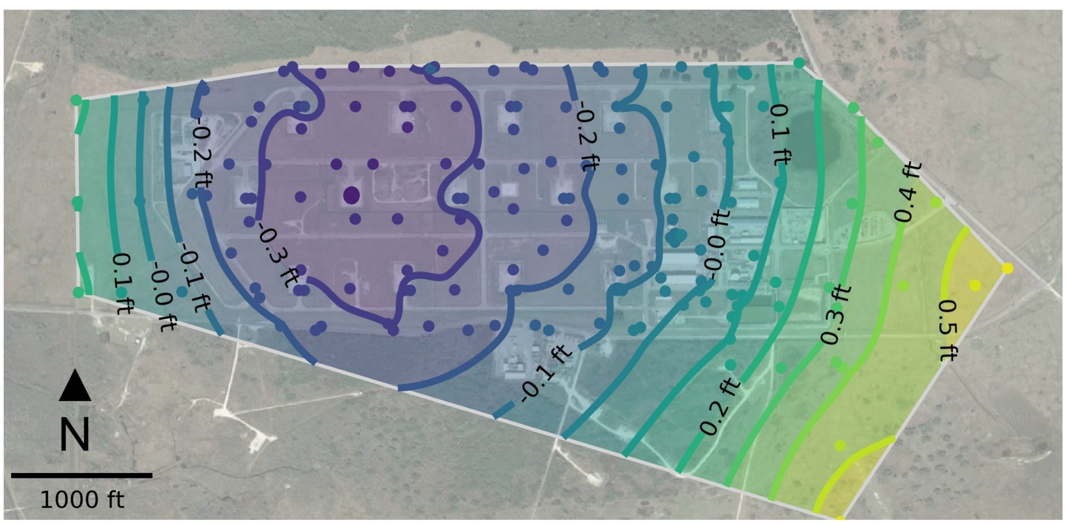

Figure 3-1. Cumulative elevation change of all available subsidence monuments between 2002 and 2018

The last elevation survey occurred in January 2019. It was shot by Jakubik & Associates and submitted to Sandia National Laboratories for review on February 8, 2019. There were 162 points surveyed. The most recent subsidence rates, calculated between January 2018 and January 2019, are shown in Figure 3-2. The highest subsidence is shown at the northern wellheads. Subsidence here is significantly higher than the surrounding monuments. Past surveys have shown that erroneous points taken at the wellheads may be due to an incorrectly surveyed location. The wellhead monuments are certain bolts on the wellhead and have been misidentified by surveyors in the past. Because nearby monuments do not demonstrate the same subsidence, it is likely the high rates at the wellheads are not actual subsidence events.

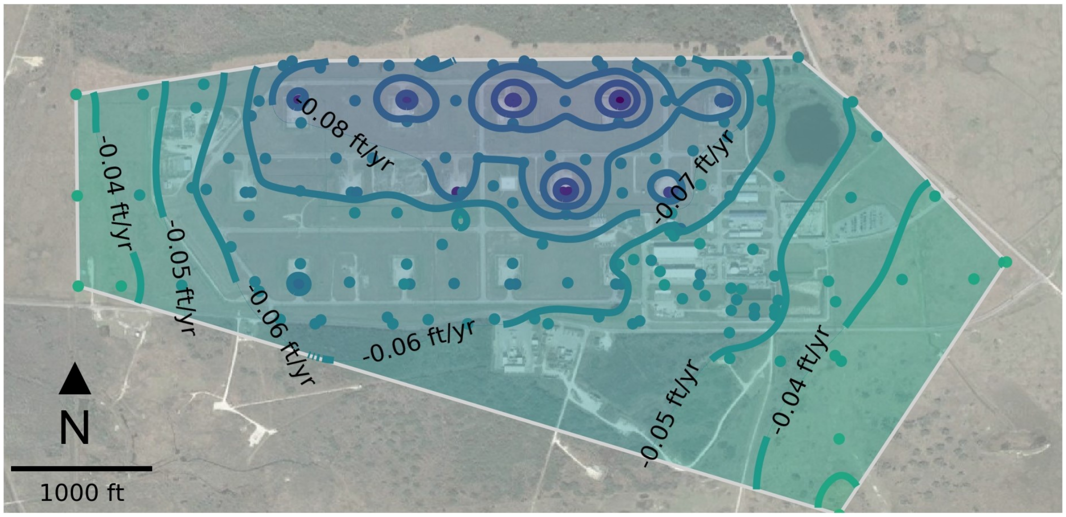

Figure 3-2. Most recent calculated deformation rates at Big Hill (January 2018 to January 2019).

Although the resolution of level-and-rod surveys - in both space and time - is nowhere near that of InSAR, there are three decades of measurements. This has given us an understanding of general site characteristics. We learned that, on average, subsidence formed a bowl shape with the highest subsidence over BH-109. We also learned that differential subsidence is higher west of BH-109. It was also the first data that suggested cavern pressures and subsidence could be related. The 30 years of level-and-rod data will continue to be utilized while InSAR at Big Hill is still in its infancy.

3.3.2. InSAR

In 2013, Sandia National Laboratories contracted CGG to perform an analysis of historical data above Big Hill. Data were acquired from the ERS and ALOS satellites and ran from 1992 to 2011. Initial results showed good coverage across the site. In 2017, Sandia contracted TRE Altamira to collect, analyze, and report site surveys using InSAR. This second contract used data from satellites specifically tasked to monitor Big Hill. Fluor Federal Petroleum Operations took over the contract with TRE in 2020 and is now the only method for monitoring subsidence at Big Hill.

The data have been collected from the TerraSAR-X and PAZ satellites - both of which have a spatial resolution of 3ft. X 3ft. The sampling runs from October 2017 to October 2021. Figure 3-3 shows the 2D subsidence rates calculated from InSAR between this time [4]. The reference point was to the northeast of the site off the dome (represented by a black dot in Figure 3-3). This year's Area of Interest (AOI) was expanded to include the last level-and-rod benchmark location. This led to the discovery of a previously unknown regional trend. Accounting for the trend caused some changes to deformation estimates; however, TRE Altamira has indicated this is the most accurate estimate of ground deformation so far.

During the four year period there were 132 surveys - or images - of the site. The satellite passes over the site from two different angles - ascending and descending. Each ascending frame had almost 32k measured points on the dome while each descending frame shot almost 42k locations in the same area. Both ascending and descending measurements are used to calculate true vertical and east-west movements. Each frame of this datatype had just over 3,600 points on the dome.

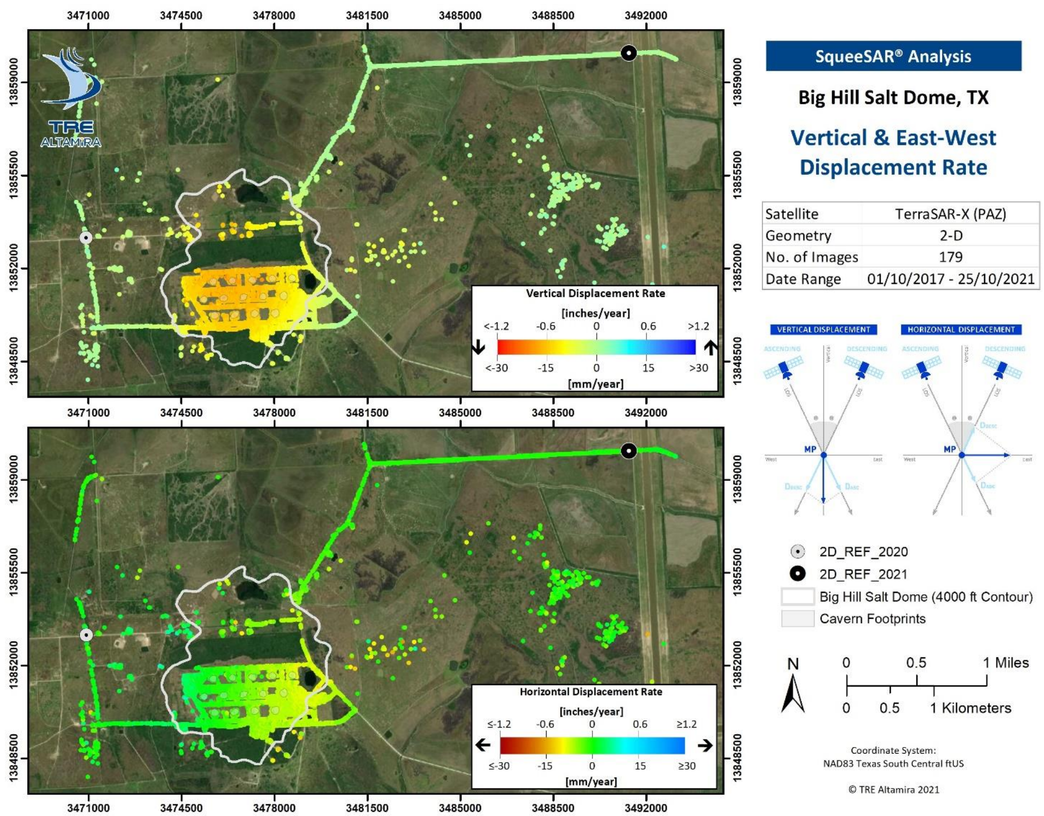

Figure 3-3. SqueeSAR 2D results over the Big Hill salt dome (2017 – 2021). From TRE Altamira Report

A closer image of the Big Hill site is shown in Figure 3-4. It shows a bowl shaped subsidence pattern with the highest rates over BH-104. In addition, there is slight East-West movement. Most of this movement above the cavern field was westward. To help visualize the movements across the site, Figure 3-5 shows both the magnitude and direction of movement at each wellpad. The vertical bar shows the average subsidence rate between October 2017 and October 2021 while the horizontal bars show the East-West velocity during the same time. The figure shows the magnitude of vertical movements are greater than any East-West movement. The highest East-West movement is over BH-101 and BH-106 while the highest vertical movement is over BH-104. There is also a change in horizontal, East-West movement between BH-109 and BH-110. The BH-110 wellpad shows eastward movement while BH-109 shows westward movement.

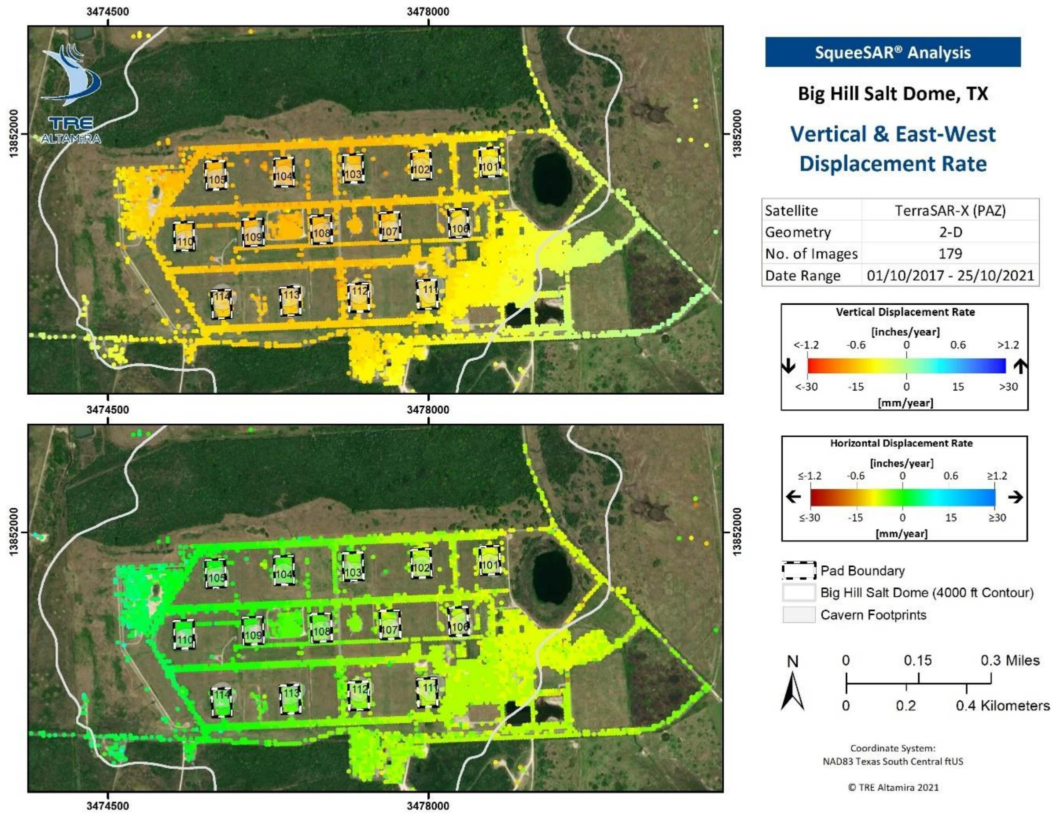

Figure 3-4. SqueeSAR 2D results over the Big Hill SPR site (2017 – 2021). From TRE Altamira Report

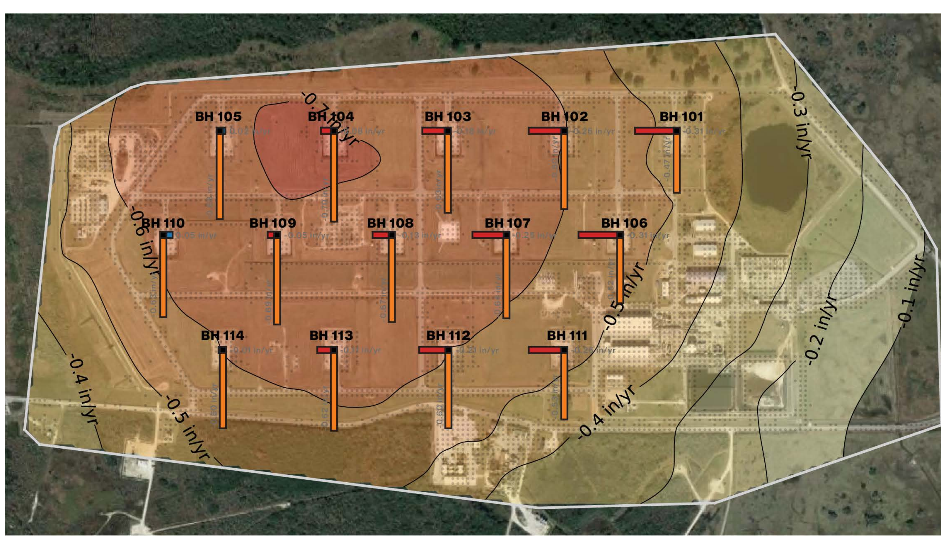

Figure 3-5. Average 2D InSAR results between October 2017 and October 2021. Vertical bars show the direction and magnitude of movements while horizontal bars show the direction and magnitude of the East-West horizontal movement. Contour plots showing the average deformation rates across are also shown in the figure.

We also need to look at the data though time. Figure 3-6 shows statistics for the InSAR measurements through time. The black line represents the median displacement at the site while the dark gray area represents the 25th and 75th percentiles. The light gray shading shows the 5th and 95th percentiles of displacement at the site. The figure shows there are three distinct time periods, each with almost linear subsidence within their respective time periods shown at the top of the figure.

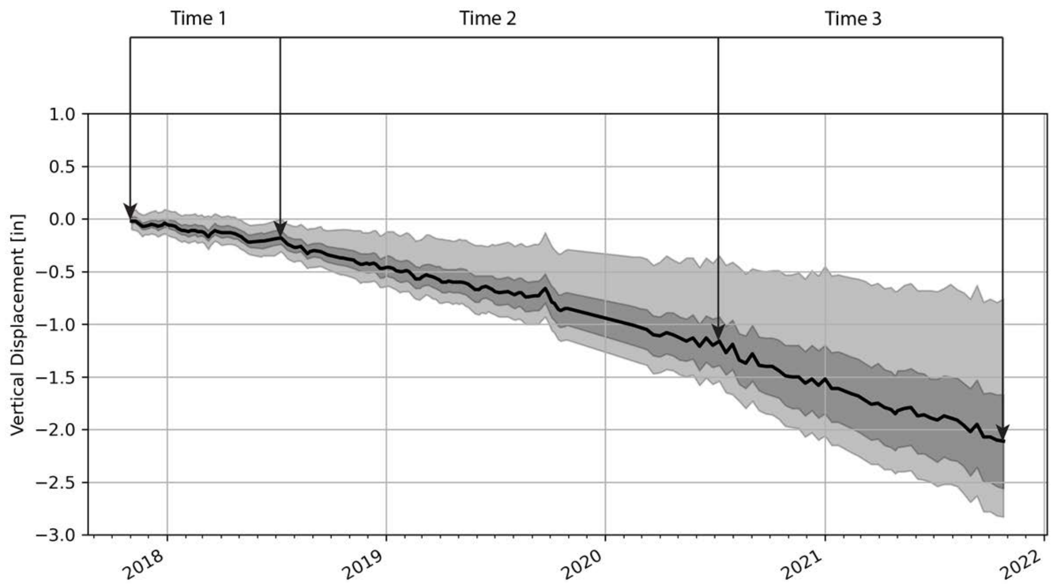

Figure 3-6. Plot displaying the vertical displacement time series across the Big Hill site. The black line represents the median displacement at the site while the dark gray area represents the 25th and 75th percentiles. The light gray shading shows the 5th and 95th percentiles of displacement at the site.

Figure 3-7 shows the calculated rates across the site for each of the three time periods indicated in Figure 3-6. The spatial contour plots, by time period, indicate that subsidence rates are increasing through time. The highest are consistently across the northern boundary but have migrated towards the west through time. The current trend depicts the highest rates are now over BH-104 and BH-109. Whereas the overall average across the entire time of acquisition is cavern BH-104.

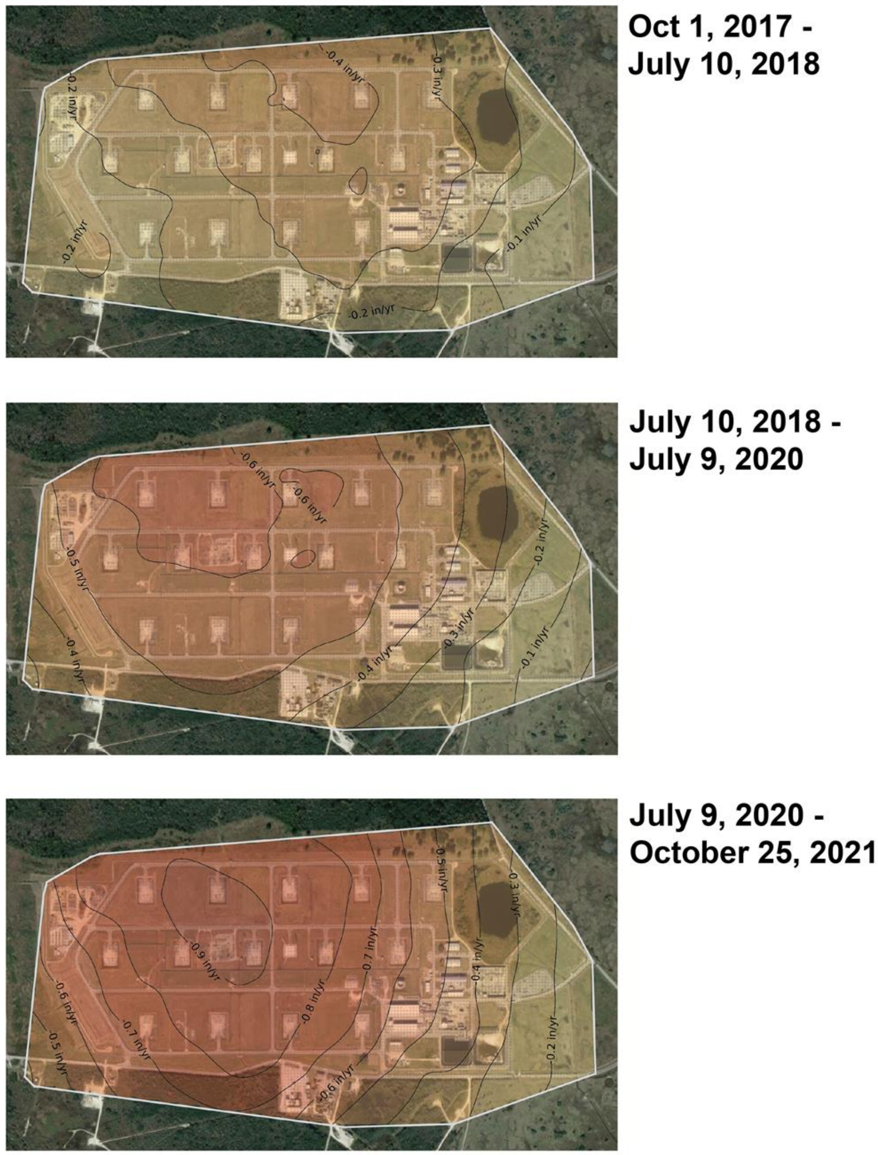

Figure 3-7. Contour plots displaying average subsidence rates at Big Hill over three different time periods identified from Figure 3-6

It is difficult to determine what the Big Hill subsidence pattern is responding too. It is known that across a cavern field the resultant surface behavior is predicted to display a subsidence bowl, with the highest subsidence occurring over the center of the cavern field. At Big Hill, the greatest subsidence is over the north and northwest portion of the site and may very well be the result of a shifting fault, as the shear zone is in that region.

3.4. Comprehensive Monitoring

Although there are no cavern integrity concerns at this time, Big Hill has had trouble with wells deforming at the salt-caprock interface. It is believed shear forces between the salt and caprock are causing the failures. One factor used to examine well deformation is the coefficient of variation (*CV*) of the well's internal diameter at each depth of the multi-arm caliper (MAC) survey. If the interior of a well is perfectly circular, then all the internal diameters from the multi-arm caliper would be the same and the *CV* value would be 0. If the well is out of round, or deformed, the *CV* is greater than 0. A greater *CV* value indicates a more deformed section of well.

Figure 3-8 shows the maximum *CV* values seen at the salt-caprock interface over time. The orange and blue lines show data from the A and B wells, respectively. The timeline runs from 2010 through 2026. The Y-axis runs from 0 to 0.05. Any remediated wells are denoted with a black outline on the point. There are several wells on the western half of the dome that have seen major deformations at the salt-caprock interface. These include BH-105, BH-104, BH-109, BH-113, and BH-114. Most of these wells are along a large salt spine running through the site. Curiously, BH-110 has not seen significant deformation but is adjacent to the three highest deforming wells.

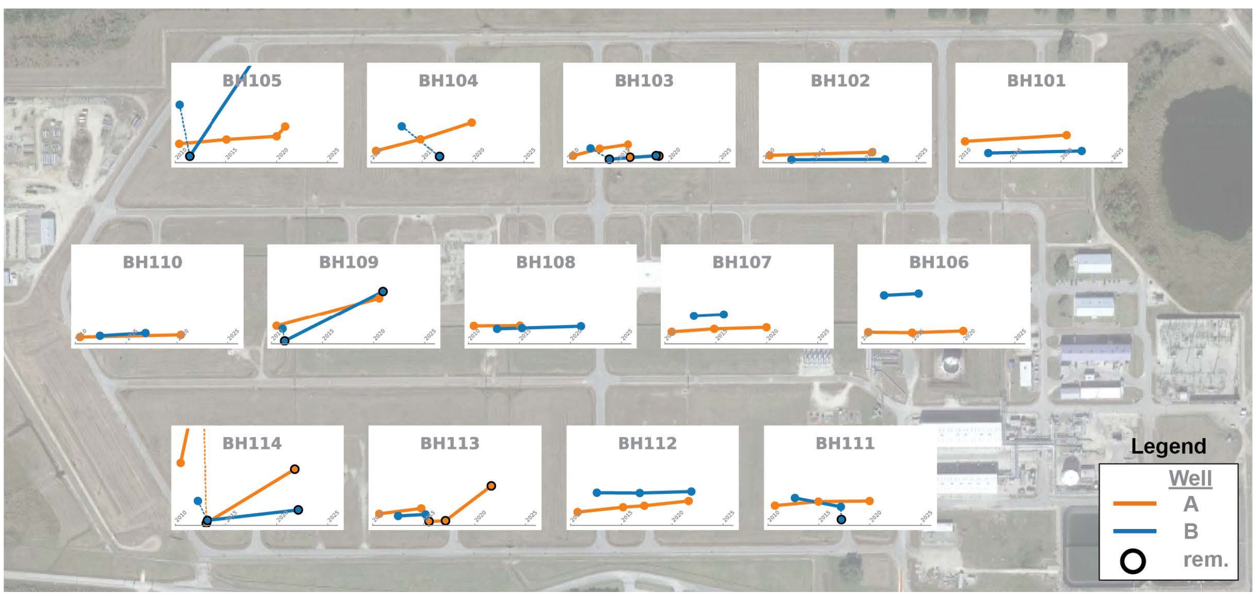

Figure 3-8. Maximum Cv value at the salt-caprock interface between 2010 and early 2022 for each well.

Although there is no direct correlation between well deformation and surface deformation, it is possible the two are linked. More work is ongoing to determine other factors that could impact the rate of well deformation. Additionally, there are a couple conclusions we can make about well deformation at the salt-caprock interface. From the limited number of MAC's run at Big Hill, remediation via installation of a liner does not slow the effects of deformation at the salt-caprock interface. Given this supposition, there is reason to believe remediated wells will continue to deform at the same or even greater rates in the future.

3.5. Conclusions

Over the past four years subsidence has slowly increased across the site. The cause of the increased subsidence is currently unknown but given the shape and depth of the caverns there is no reason to believe any of the caverns have been structurally compromised.

4. BRYAN MOUND

4.1. History of Monitoring at Bryan Mound

The subsidence monitoring program at Bryan Mound began in 1982 with annual level-and-rod surveys. In 2013, operators added a GPS and tiltmeter to supplement the level-and-rod data. Two more tiltmeters were also installed on the periphery of Cavern 3 but have since been decommissioned due to unreliability. Recently, the SPR has transitioned away from level-and-rod in favor of the satellite-based InSAR.

4.2. Datatypes for Enhanced Monitoring

Monitoring surface deformation is the most common method for inferring cavern integrity. Any stresses caused by changes in cavern structure propagate to the surface and result in surface deformation, often subsidence.

There are several ways the SPR monitors ground deformation. The first is by measuring elevation changes of survey monuments across the site. While this covers the entire site, it is impractical to physically survey the entire site more than once a year. To supplement the temporally sparse data the SPR decided to install real-time sensing instruments above caverns of concern. The main cavern of concern at Bryan Mound is Cavern 003. SPR has monitored this cavern extensively in the past decade because of the strange shape and lack of access to the cavern. Part of this monitoring included a GPS and tiltmeter at the wellhead. Tiltmeters at the northern and southern extents of Cavern 3 were also installed but have since been decommissioned due to unreliable instrumentation.

4.3. Surface Deformation

Traditionally, surface deformation had been measured by annual or biennial elevation surveys using level-and-rod. In FY'20 SPR decided to monitor ground movement using InSAR, a satellite-based technique. This method collects thousands of times more data and provides greater insight into the dynamics of surface deformation. This, in turn, should provide better understanding of cavern integrity.

4.3.1. Historical Level-and-Rod Surveys

The first survey in 1982 measured 92 locations using a level-and-rod. In total, there have been 29 annual level-and-rod surveys since. The last level-and-rod survey was taken in 2019. The last annual level-and-rod rates are presented in Figure 4-1. It shows the greatest subsidence over Cavern 3. Historically, the areas over abandoned Caverns 2 and 3 have seen the highest subsidence and the northeast area of the site has seen relatively little.

Figure 4-1. The most recent subsidence rates calculated at Bryan Mound (April 2018 to March 2019)

Although the resolution of level-and-rod surveys - in both space and time - is nowhere near that of InSAR, there are almost four decades of measurements. This has given us an understanding of general site characteristics. We learned that, on average, subsidence was highest over Caverns 003 and 002 with little to no subsidence in the northeast part of the site. The 38 years of level-and-rod data will continue to be utilized at Bryan Mound for historical reference.

4.3.2. InSAR

In 2016, Sandia decided to contract TRE Altamira to monitor Bryan Mound using InSAR. InSAR, or Interferometric Synthetic Aperture Radar is a satellite-based technology that measures the change in elevation above an area of interest. Under most conditions, vertical measurements have a sub-millimetric accuracy and surveys occur every one to two weeks depending on the satellite. For the Bryan Mound surveys, the Cosmo-SkyMed (CSK) satellite was used. This particular satellite has a pixel resolution of 10 ft. x 10 ft. and a 16 day revisit time[1]. Initially, Sandia used InSAR to learn more about the subsidence above abandoned Cavern 003. The initial results showed promising coverage across the site and in FY' 20 Fluor Federal Petroleum Operations (FFPO) took over the contract. With the last level-and-rod survey in

[1]The CSK satellite actually has an 8-day revisit time but Sandia thought a 16-day interval was the greatest value

2019, InSAR is now the primary method for measuring sitewide subsidence. The SPR has continuous InSAR data at Bryan Mound between October 2015 and May 2022.

Bryan Mound is one of SPR sites that use 2D InSAR measurements. This means that the site is measured from two different satellite orbits - ascending and descending. An ascending orbit means the satellite surveys the site with a south-to-north trajectory while a descending orbit has the satellite surveying the site using a north-to-south trajectory. Each orbit surveys the site from a different angle. TRE can use measurements from both orbits and calculate a 2D frame with true vertical and East-West horizontal surface movements[2] at the site. Since 2D measurements require data from ascending and descending data we only have 2D data between October 2016 and May 2022. Only 1D ascending data was collected between October 2015 and October 2016.

Figure 4-2 shows the 2D InSAR displacement rates between October 2016 and May 2022 [5] The left half of the figure shows the true vertical results while the right half shows the east-west horizontal movement. Even at a glance it is obvious that most of the surface deformation is occurring above Cavern 003. The true vertical InSAR shows the greatest area of subsidence is over Cavern 003 and extends towards Cavern 002. The areas above Cavern 003 and Cavern 002 are subsiding at rates of -0.36 in./yr. and -0.28 in./yr., respectively. While most of the site is subsiding, the northeast area of the site is experiencing near zero movement and the area above Cavern 111 is actually showing slight uplift (+0.05 in./yr.).

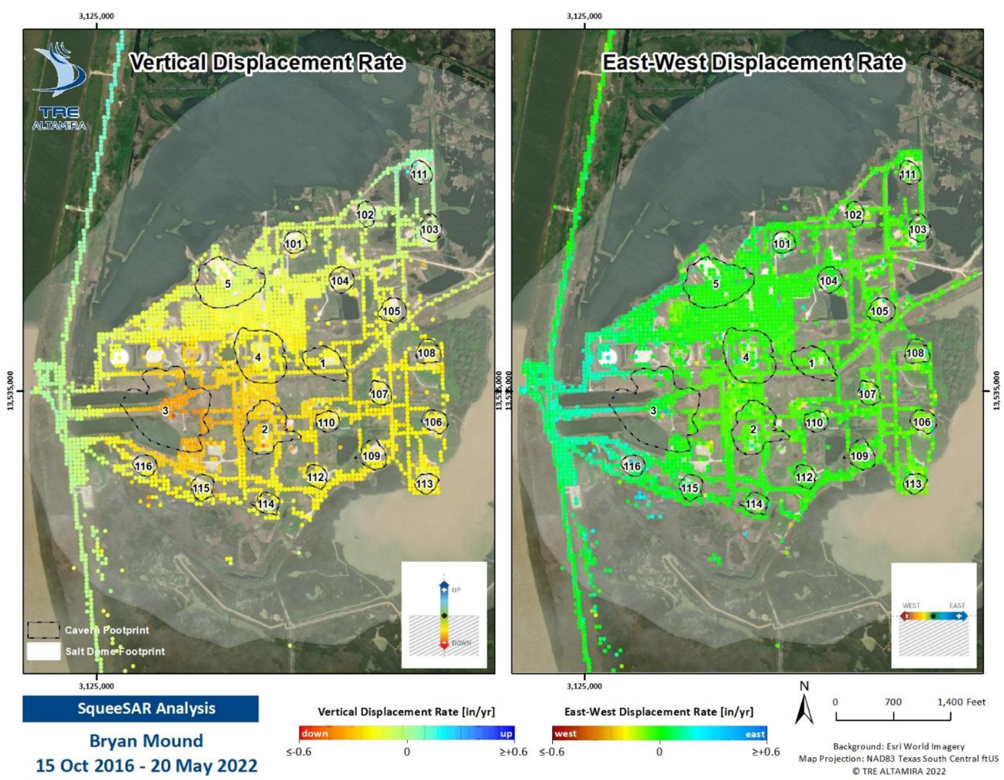

Figure 4-2. 2D InSAR results over the Bryan Mound salt dome (2019 – 2022). From TRE Altamira Report

[2] Although we can measure East-West movement, we cannot obtain any North-South vectors. This is due to the type and direction of InSAR satellite orbits

The horizontal 2D results in Figure 4-2 shows most of the site exhibiting near zero E-W movement or slight westward deformation. The only exception to this is the area above Cavern 003. This area shows East-West movement towards the cavern.

Although rates above Caverns 003 and 002 are the highest at the site, these are not the highest subsidence rates we have seen at the SPR. For comparison, West Hackberry has the highest rates with some of the site subsiding at 1 in./yr. (approximately 3x the highest rates at Bryan Mound). For structural integrity purposes, the most important aspect of subsidence is the acceleration. We do not want to see subsidence accelerate. This would indicate something has changed - potentially a loss in cavern integrity. Figures 4-3 and 4-4 show the elevation changes over time for Caverns 002 and 003. In both cases, the areas are showing extremely linear subsidence rates with no acceleration. This indicates the subsidence has reached steady state.

Overall, the spatial coverage at the site is much higher than historical level-and-rod surveys. InSAR has both the spatial and temporal resolution to show the subsidence is linear above Caverns 002 and 003.

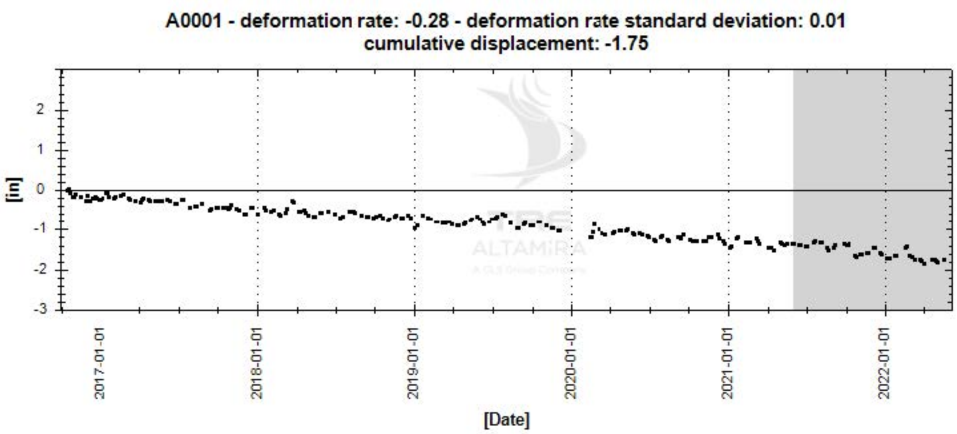

Figure 4-3. Vertical displacement above Cavern 2 between October 2016 and May 2022. From TRE Altamira Report

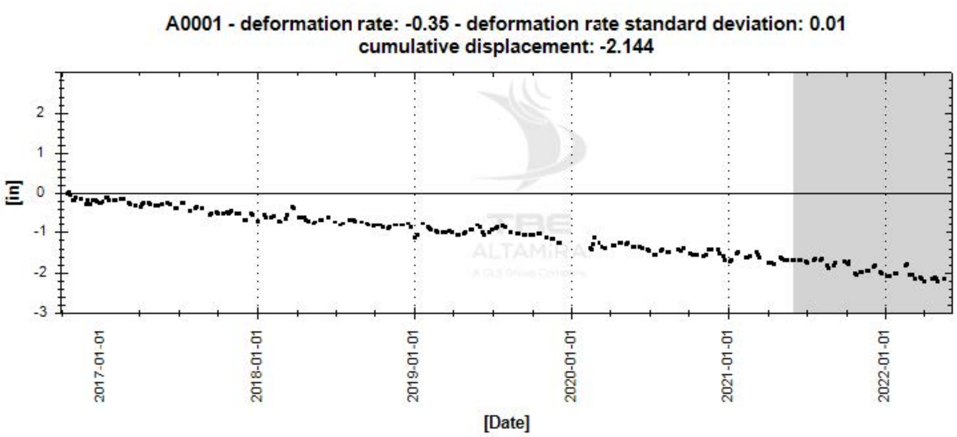

Figure 4-4. Vertical displacement above Cavern 3 between October 2016 and May 2022. From TRE Altamira Report

4.4. Realtime Sensing

In the early 2010's SPR decided to supplement level-and-rod data with real-time sensing instruments over caverns of concern. As mentioned in the previous section, the cavern of highest concern at Bryan Mound is Cavern 003. The last sonar of the cavern in 1979 revealed a flat-shaped cavern with several petals branching away from the center of the cavern. After the sonar, the well was plugged and abandoned. There is no access to the cavern and the only way to infer the health of the cavern is through surface deformations.

4.4.1. GPS

There is a single GPS unit at the site that was installed above Cavern 003 in early 2013. The GPS data in Figure 4-5 shows a linear subsidence rate of 0.31 in./yr. This is similar to the subsidence rates seen by level-and-rod and InSAR surveys. GPS was the first datatype to show us the area above Bryan Mound 003 was subsiding at a linear rate. It will continue to be an important component of monitoring Cavern 003. Any deviation from the linear subsidence rate would first be noticed by the wellhead GPS.

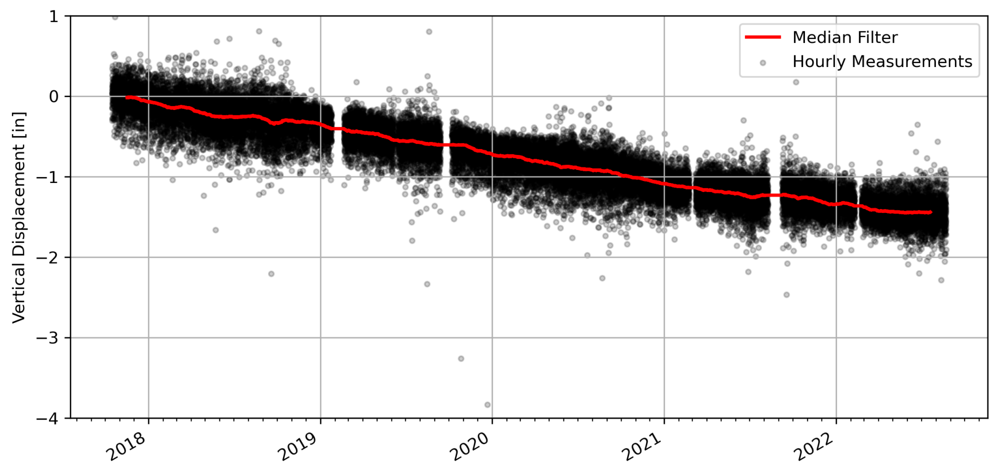

Figure 4-5. GPS measurements over Bryan Mound Cavern 3 between 2017 and 2022.

4.4.2. Tiltmeter

In addition to the wellhead GPS, there is also a wellhead tiltmeter. Data from the tiltmeter are shown in Figure 4-6. There are two measurements shown, tilt to the northern direction in orange and tilt to the eastern direction in blue. Positive northing measurements show tilt to the north while negative northing measurements show southern tilt. Similarly, positive easting measurements show tilt in the easterly direction and negative measurements show tilt to the westerly direction. Both Northing and Easting tilt measurements have two components: 1) the raw data shown as circles, and the filtered data represented with a line. The filtered data uses a median filter with a moving window of one month and is used to remove noise from the system.

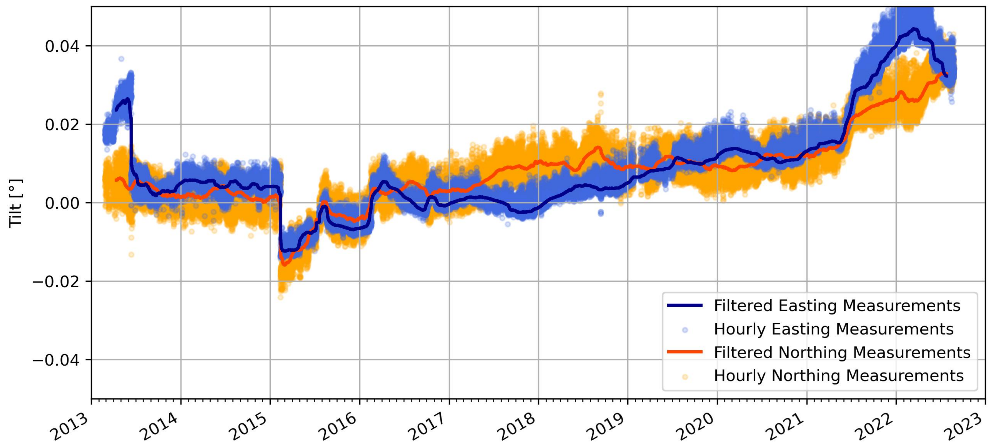

Figure 4-6. Tiltmeter measurements over Bryan Mound Cavern 3 between 2013 and 2022. From TRE Altamira Report

May/June 2013	Jump in data due to site personnel placing the tiltmeter in a metal enclosure.
February 2015	Jump in data from unknown source.
February / March 2016	Jump in data from unknown source.

Table 4-1. Cavern 003 wellhead tiltmeter data jumps.

The wellhead tiltmeter has shown little overall movement since it was placed in 2013. There are however, some exceptions. There are three jumps seen in the data early on. Table 4-1 shows the times for these jumps and any known reasons for the jumps. The reason for two of the jumps are unknown. It is quite possible these jumps were from slight physical disturbances to the tiltmeter or the metal enclosure. In addition, if the tiltmeter had to be removed for any reason it is near impossible to reset the instrument in the exact same orientation. Regardless, the rapid changes in tilt are relatively small and not thought to be caused by any natural phenomena.

Data from 2021 onward also shows an anomaly in the tilt. The change occurred in June and early July. Since then, the rates in the northern direction have continued to rise while the easting measurements rose and fell. According to staff familiar with the tiltmeter, there is no obvious reason the instrument would have been disturbed during that time. It is theorized that some of the site activity from oil sales may have disturbed the tiltmeter enough to create the change in rate. It should be noted that, while the change in rate is visible in the figure, the overall change is still small and there is no obvious change in rates in the GPS or InSAR. Sandia and FFPO plan to communicate with the make of the tiltmeter for any additional insights.

4.5. Comprehensive Monitoring

The most crucial area of the site - above Cavern 003 - is experiencing the highest subsidence. Both InSAR and GPS show similar subsidence rates - InSAR shows 0.36 in./yr. over the area while the GPS is estimating 0.31 in./yr. Both measurements are within standard error of each other and practically the same. Additionally, both InSAR and GPS are showing linear rates for the area above Caverns 002 and 003. The only contradictory information comes from the wellhead tiltmeter. Since June 2021, the tiltmeter has deviated slightly from its historical pattern. The current theory is that site activity from oil sales may have been enough to affect the tiltmeter results.

4.6. Conclusions

Based on information from InSAR, GPS, and tiltmeters there is no indication any of the caverns have been structurally compromised. The movement above Caverns 002 and 003 are extremely linear. This type of movement suggests the volume above the cavern has reached a steady state and does not indicate any loss of integrity.

Recently, there was a slight movement seen in the BM-003 wellhead tiltmeter. Sandia is currently looking into possibilities for this small but abrupt movement. We will continue to monitor data from the tiltmeter closely to ensure there is no further acceleration.

5. WEST HACKBERRY

5.1. History of Monitoring at West Hackberry

The subsidence monitoring program at West Hackberry began in 1983 with annual level-and-rod surveys. Initial calculations indicated West Hackberry was the highest subsiding SPR site. Although most of the caverns in the cavern field were created by DOE SPR, there are several older caverns - in the northeastern part of the site that SPR inherited. Although rates are high, there has been no indication that any of the caverns are structurally compromised. One of the more pressing concerns caused by subsidence is the increased flooding potential from the nearby water bodies. During the Life Extension 1 Project, much of the site was changed to increase resilience to flooding. In 2013, operators added a GPS and tiltmeter to supplement the level-and-rod data but both instruments have since been removed. Recently, the SPR has transitioned away from level-and-rod in favor of the satellite-based InSAR.

5.2. Datatypes for Enhanced Monitoring

Monitoring surface deformation is the most common method for inferring cavern integrity. Any stresses caused by changes in cavern structure propagate to the surface and result in surface deformation, often subsidence.

There are several ways the SPR monitors ground deformation. The first is by measuring elevation changes of survey monuments across the site. While this covers the entire site, it is impractical to physically survey the entire site more than once a year. To supplement the temporally sparse data the SPR decided to install real-time sensing instruments above key caverns. At the time, West Hackberry Cavern 006 was considered a cavern of concern. A tiltmeter and GPS were installed above the cavern but were removed in 2020 and 2021, respectively. They were removed after a reevaluation of the cost-benefit analysis showed there was little need for the information they provided at WH-006.

5.3. Surface Deformation

Traditionally, surface deformation had been measured by annual or biennial elevation surveys using level-and-rod. In FY'20 SPR decided to monitor ground movement using InSAR, a satellite-based technique. This method collects thousands of times more data and provides greater insight into the dynamics of surface deformation. This, in turn, should provide a better understanding of cavern integrity.

5.3.1. Historical Level-and-Rod Surveys

The first level-and-rod survey was taken in 1983 and measured 76 locations. In total, there have been 39 level-and-rod surveys over the 36-year period. The last level-and-rod survey was taken in May 2019 and included 114 locations measured across DOE and LA Storage properties. Most of the survey monuments were established in 1990 and have provided a consistent record of elevation change. Figure 5-1 shows the total elevation change seen by monuments with an unbroken measurement history between 1990 and 2019. The subsidence is in the shape of a bowl with a center between WH-102, WH-103, and WH-107 wellpads. The highest subsidence in this almost 29-year period is approximately 2.5 ft. Subsidence rates becomes smaller farther away from the center of the site but even on the periphery of the cavern field level-and-rod surveys have seen 1 ft. of subsidence over the 36-year period.

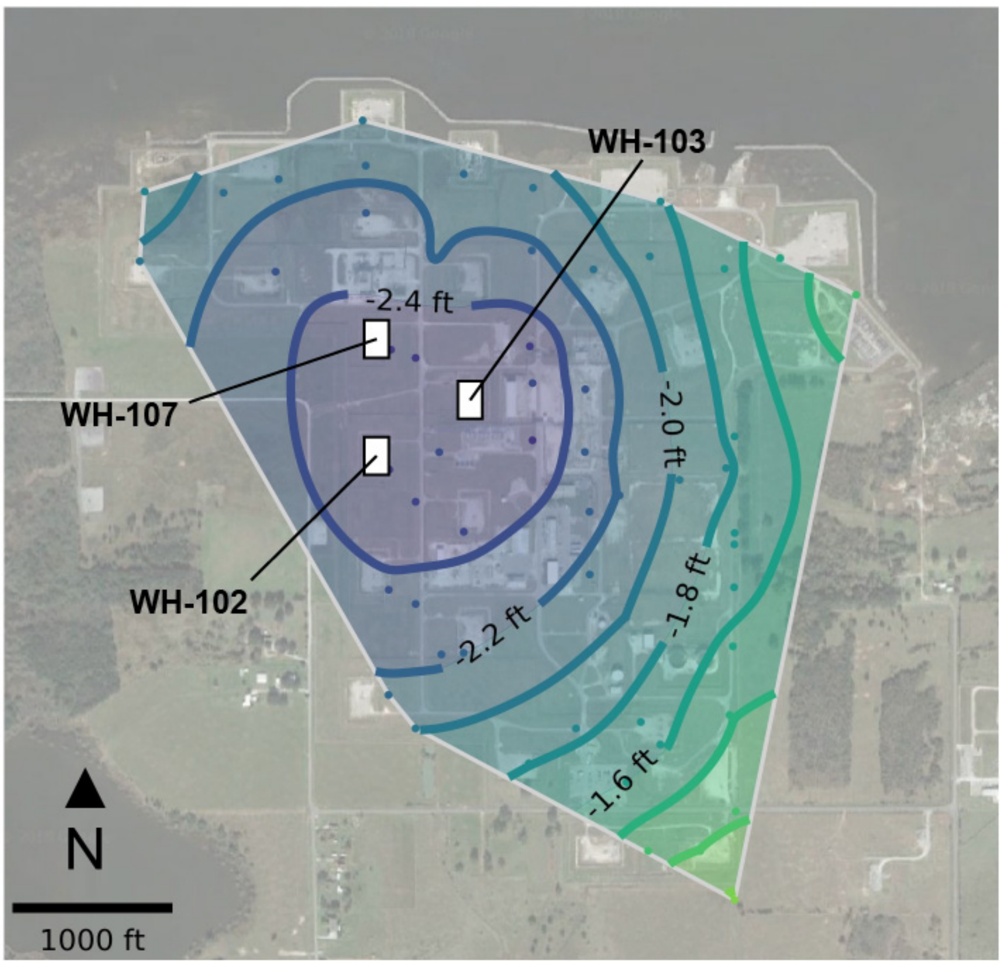

Figure 5-1. Cumulative elevation change of all available subsidence monuments between 1990 and 2019

At just over 1 inch per year, highest subsidence at West Hackberry is also the highest of all the SPR sites. Despite this, actual subsidence roughly matches predicted subsidence from cavern creep models. In addition, the pattern of subsidence is expected with the highest rates being near the center of the cavern field.

Although the resolution of level-and-rod surveys - in both space and time - is nowhere near that of InSAR, there are three decades of measurements. This has given us an understanding of general site characteristics. We learned that, on average, subsidence formed a bowl shape with the highest subsidence near the center of the cavern field. The 30 years of level-and-rod data will continue to be utilized while InSAR at West Hackberry is still in its infancy.

5.3.2. InSAR

In FY'20, Fluor Federal Petroleum (FFPO) made the decision to use InSAR as the primary method for measuring surface subsidence. TRE Altamira was contracted to collect, analyze, and report the data. TRE Altamira has experience analyzing SPR sites. They started analyzing Big Hill and Bryan Mound in 2017. The report was received by FFPO and Sandia on August 9, 2021 and covered May 2019 through May 2021 [6].

InSAR surveys over West Hackberry utilize the TerraSAR-X and PAZ satellites. The TerraSAR and PAZ are sister satellites and have the same acquisition parameters so data from both can be analyzed together. Both satellites are acquiring 1D data in a descending orbit[1]. 1D InSAR measurements survey any deformation directly toward or away from the satellite. This is in contrast to 2D which surveys the site from two different orbits and, subsequently, two different angles. 2D has the ability to measure true vertical movement and East-West movement. Although 2D provides more information we believe 1D InSAR is the most cost-effective technique at West Hackberry. A preliminary study looked at 2D information at West Hackberry and the difference between calculated 1D and 2D measurements was sufficiently close in vertical accuracy.

The TerraSAR and PAZ satellites are some of the most accurate satellites with a pixel resolution of 3 ft. x 3 ft. The smaller pixel size and higher point density led to tens of thousands of points being surveyed. TRE defines two categories of points: point scatter and distributed scatter. Point scatter is the measurement off a solid reflector within each 3 ft. x 3 ft. pixel. This is generally considered to be more accurate than distributed scatter. Distributed scatter is essentially an average of weaker reflections. For a survey point to be reported it must consistently reflect points throughout the entirety of the survey period. This means that each survey will show the same number of points over the analyzed period. In the first year of InSAR at West Hackberry, the TerraSAR and PAZ satellites were able to survey 41,001 points during each survey. There were 30,223 point scatters and 10,778 distributed scatters for an average point density of 4,543 pts/mi^2.

The area of interest analyzed by TRE Altamira can be seen in Figure 5-2. It covers the entire West Hackberry dome which includes all SPR property. Most of the subsidence is seen on the West Hackberry SPR site. The reference point for the survey is seen off the dome in the southeast corner of the map. This was the most stable point off the dome as determined by TRE Altamira.

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[1]A descending orbit means the satellite is heading from north to south as it passes over West Hackberry

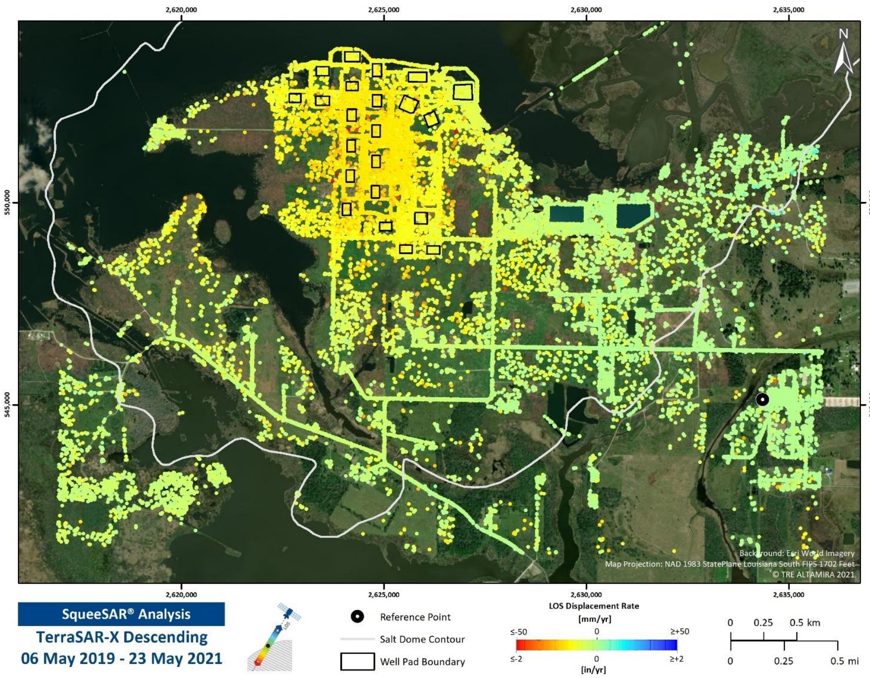

Figure 5-2. 1D InSAR results over the West Hackberry salt dome (2019 – 2021). From TRE Altamira Report

A closer image of the West Hackberry InSAR data (Figure 5-3) also shows that most of the subsidence is occurring near the center of the cavern field. Specifically, Caverns 101, 102 and 105 have the highest subsidence rates at the site. Average surface deformation rates for all wellpads are presented in Table 5-1.

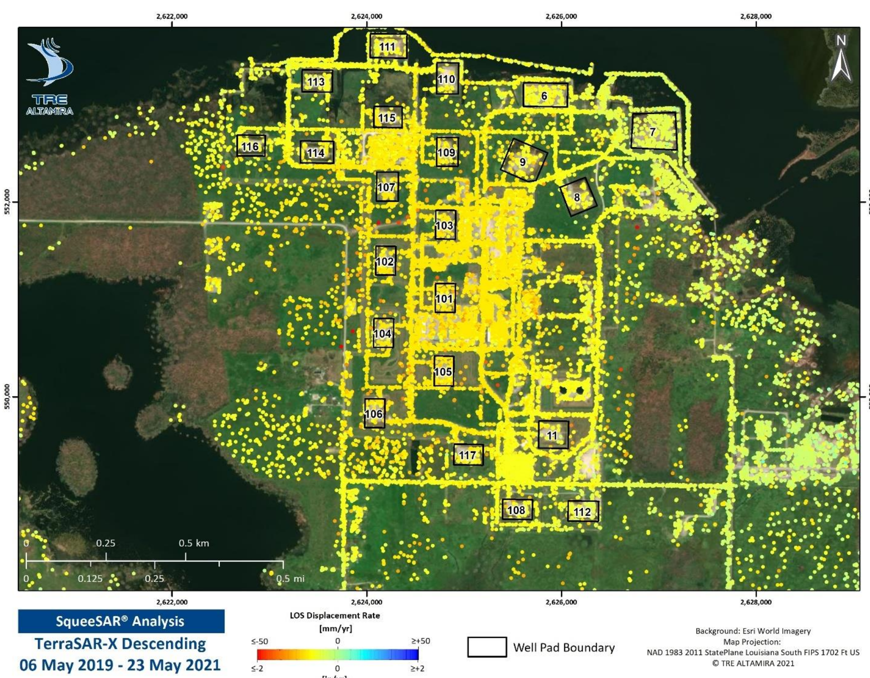

Figure 5-3. 1D InSAR results over the West Hackberry SPR site (2019 – 2021). From TRE Altamira Report

Table 5-1. Average wellpad surface deformation calculated by InSAR

Cavern	Disp. Rate (in./yr.)
006	-0.69
007	-0.49
008	-0.71
009	-0.78
011	-0.72
101	-0.91
102	-0.88
103	-0.87
104	-0.86
105	-0.88
106	-0.85
107	-0.84
108	-0.67
109	-0.85
110	-0.76
111	-0.65
112	-0.58
113	-0.66
114	-0.76
115	-0.82
116	-0.64
117	-0.76

Overall, the spatial coverage at the site is much higher than level-and-rod surveys and we expect the point density to become higher as more surveys are taken. The rates are also similar to rates seen in level-and-rod surveys with the highest subsidence rates around 1 in./yr. near the center of the cavern field.

5.4. Realtime Sensing (Historical)

In the early 2010's SPR decided to supplement level-and-rod data with real-time sensing instruments over key caverns. DOE believed that Cavern 006 was one of those key caverns due to the wide, bowl shaped cavern with a flat roof. A subsequent cost/benefit analysis of GPS and tiltmeters above Cavern 006 show they are not worth maintaining.

5.4.1. GPS

There was a single GPS unit at the site that was installed above Cavern 6 in early 2013. This GPS unit showed linear uplift and differed from the site-wide surveys that show the area above Cavern 6 is one of the most stable locations on the site. The discrepancy was caused by movement of the nearby reference GPS. The GPS was discontinued in 2021.

5.4.2. Tiltmeter

In addition to the GPS, there was also a tiltmeter above Cavern 006. During its operation there was little to no angular movement above Cavern 006. It stopped recording in 2020 and, while this tiltmeter was valuable for understanding the surface deformation above Cavern 006, it does not seem cost effective to reinstall another tiltmeter.

5.5. Comprehensive Monitoring

West Hackberry recently transitioned from level-and-rod surveys to InSAR as the primary method for measuring site-wide subsidence rates. In just a single year, InSAR has collected thousands of times more data than the entire history of level-an-rod. As more surveys are conducted the density and accuracy of measurements should increase. More data should also lead to a better understanding of seasonal movements at West Hackberry.

5.6. Conclusions

Although subsidence rates are still high, they do not seem to be accelerating. This indicates all of the caverns are retaining cavern stability. Additional data will allow for more informative analyses on baselines and trends.

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