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Subject: September 2016 Bayou Choctaw Subsidence Report

Executive Summary

Subsidence monitoring is a crucial component to understanding cavern integrity of salt storage caverns. This report looks at historical and current data at the Bayou Choctaw Strategic Petroleum Reserve Site. Data from the most recent land-based annual surveys, GPS, and tiltmeter indicate the subsidence rates across the site are approximately 0.0 ft./yr. Because of this, there is no evidence from the subsidence survey to suggest any of the DOE caverns have been structurally compromised.

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Introduction

This year's subsidence survey was completed in September 2016 and covers most of the Bayou Choctaw Strategic Petroleum Reserve (SPR) site and several locations outside the Department of Energy (DOE) boundaries. The data from the survey were subsequently given to Sandia National Laboratories for analysis. This report discusses the subsidence history of the site and, in accordance with the subsidence monitoring requirements set forth by the Louisiana Department of Natural Resources, also discusses the subsidence monitoring plan and interpretation of current results.

Subsidence surveys at Bayou Choctaw began in December 1982 and there have been 26 site wide surveys since. Several instances of collapsed caverns from around the world have shown that they subside at an accelerated rate before their eventual collapse (Ege). Therefore, ground movement is a primary indicator of cavern integrity. The surface elevations from the surveys also aid in determining flooding potential at the site and help to validate salt creep models of the cavern system. In addition to ground surveys there are also GPS and tiltmeter instruments over abandoned Cavern 4 located at the center of the site. These instruments were installed in early 2013 and give real-time feedback. Each of the instruments are set to trigger an alarm if there are any sudden changes in tilt or elevation. The data are recorded on an hourly basis and analyzed in this report.

The data from the annual survey, GPS, and tiltmeter are analyzed to determine cavern integrity under the site. Based on the survey there is little to no subsidence occurring at the site. Based on these results, there is no reason to believe that any of the SPR caverns have been structurally compromised.

Bayou Choctaw Subsidence History

The Department of Energy acquired Bayou Choctaw in 1977 and began storing crude oil in 1987. The site is located centrally over the salt dome as shown in Figure 1. The blue line shows the outline of the dome at 5000 ft. below mean sea level. Figure 1 also shows the locations and names of the DOE SPR wells. Many of the DOE SPR wells are located on the western part of the dome. In addition, there are wells from the other operator, Boardwalk Louisiana Midstream, LLC, on the eastern section of the dome. Some of their wellheads are now included in the land based surveys.

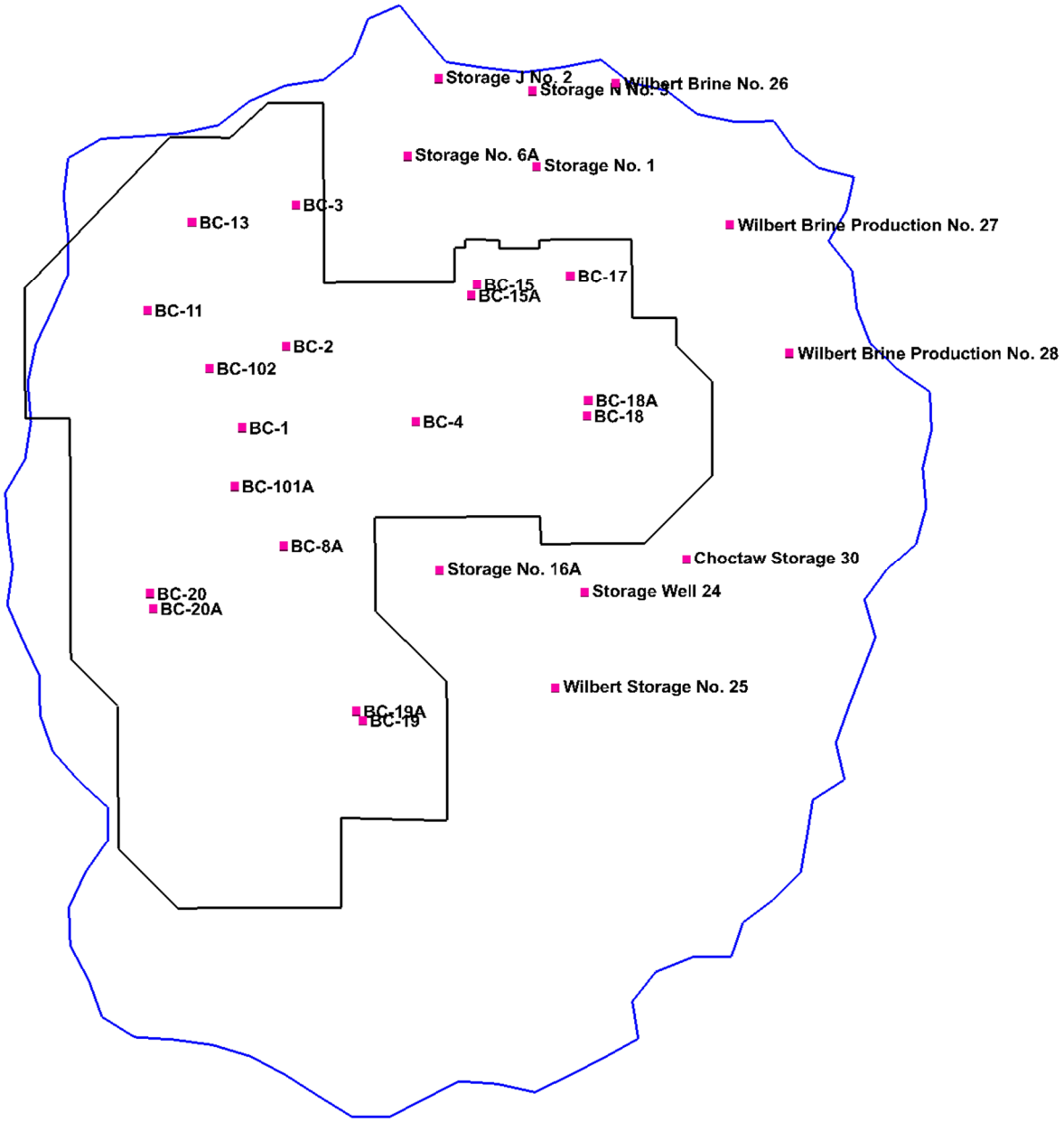


Figure 1 - Map of the DOE SPR Bayou Choctaw property in relation to the Bayou Choctaw Dome. The outline of the dome was taken at 5000 ft. below mean sea level.

The initial subsidence survey in 1982 measured elevations of 43 survey markers and 20 survey monuments. Survey markers are locations specified on current infrastructure while survey monuments are established at depth and less likely to be disturbed by site activity. For this reason, survey markers have been slowly phased out in favor of adding survey monuments. While there are still three survey markers in use at the site, the August 2015 survey saw the discontinuation of many of the existing markers.

Since 1982, Bayou Choctaw has experienced the lowest ground displacement of any SPR sites. Figure 2 illustrates the site wide subsidence rates over time. Most vertical ground movement occurs several years after the site began storing oil. Since 1993, however, ground movement is almost nonexistent. This can also be seen in Figure 3 which shows subsidence rates across the site over four time periods. The highest

subsidence rates are seen in the south and eastern areas of the site with the highest vertical ground movement at approximately -0.05 ft./yr. The period between 1990 and 2001 shows very little subsidence in these areas and almost no subsidence across the rest of the site. The last two time periods show almost no subsidence across the site. Figure 3 also shows the coverage and type of survey locations over the years. While the total number of survey locations have gone down, the site coverage has become greater over time and is still growing. Since 2010, the site has added an additional 28 monument locations with 9 that are being measured on the neighboring operator's site. This allows for a more complete understanding of vertical ground movement above the salt dome.

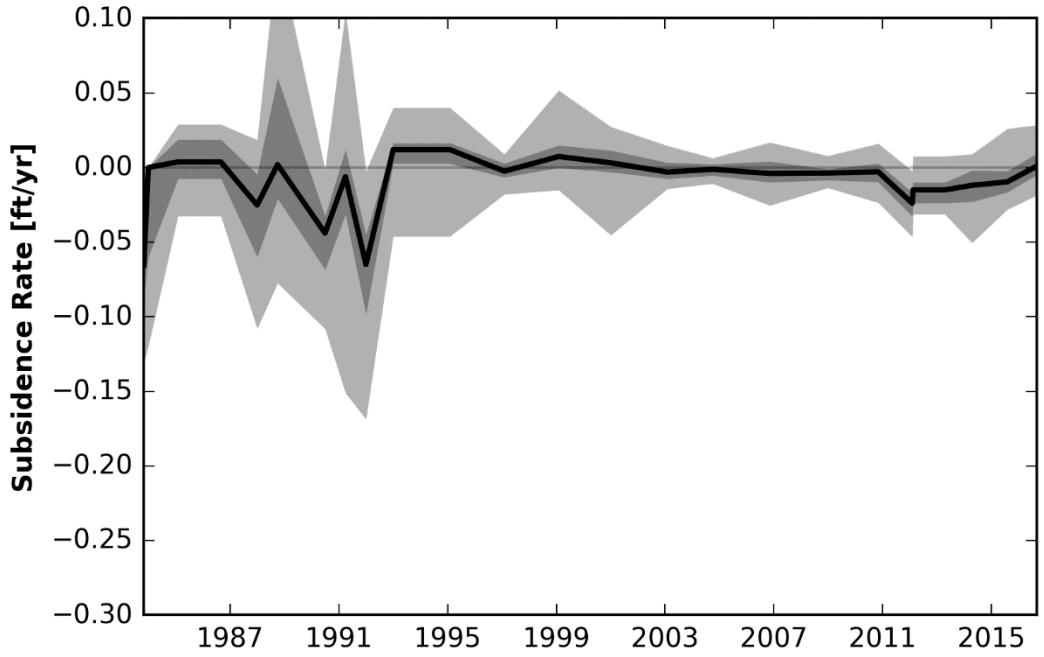
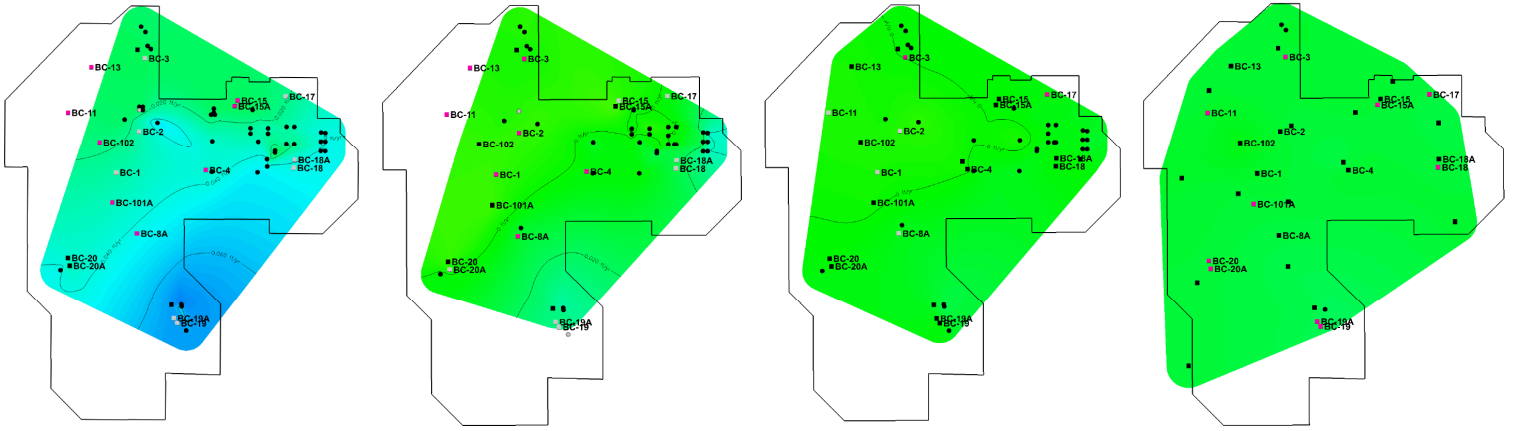


Figure 2 - The median subsidence rate at Bayou Choctaw (black line). The darker grey area represents the upper and lower quartiles while the lighter grey line represents the extends of the 10th and 90th percentiles.



December 1982 - June 1990
7.5 years

Average Rate
-0.0286 ft/yr (-0.342 in/yr)

June 1990 - January 2001
10.6 years

Average Rate
-0.0055 ft/yr (-0.066 in/yr)

January 2001 - November 2010
9.8 years

Average Rate
-0.0033 ft/yr (-0.040 in/yr)

November 2010 - September 2016
5.8 years

Average Rate
-0.0127 ft/yr (-0.151 in/yr)

Figure 3 - Subsidence rates at Bayou Choctaw for four time periods. The DOE SPR property line is shown as a black line. Black markers indicate surveyed locations while the grey markers show any locations that were not included due to survey error or survey point reset. Additionally, pink squares represent well locations that were not surveyed.

Current Survey

This year's subsidence survey was conducted by John T. Jakubik & Associates, LLC, a licensed surveyor in Louisiana. The survey was conducted in September 2016 and submitted to DOE SPR on October 10, 2016. The report was subsequently submitted to Sandia National Laboratories for analysis on January 11, 2017. 51 locations were measured based on the elevation of two benchmarks. The primary benchmark is DOE #35 located approximately 1.3 mi. ENE from center of the site. The alternative benchmark, a U.S. Coast and Geodetic Survey datum, is approximately 4.5 mi. ESE of the site. Of the 51 measured locations, 48 were survey monuments.

The subsidence rates from the most recent survey results can be seen in Figure 4. The subsidence rates between August 2015 and September 2016 show little vertical ground movement across the site. It should be noted that there were 10 recently reset monuments. Subsidence rates could not be calculated for those locations. The reset locations are represented as grey squares in Figure 4. While there are fewer surveyed locations than in previous surveys, the accuracy and coverage of elevation measurements have increased.

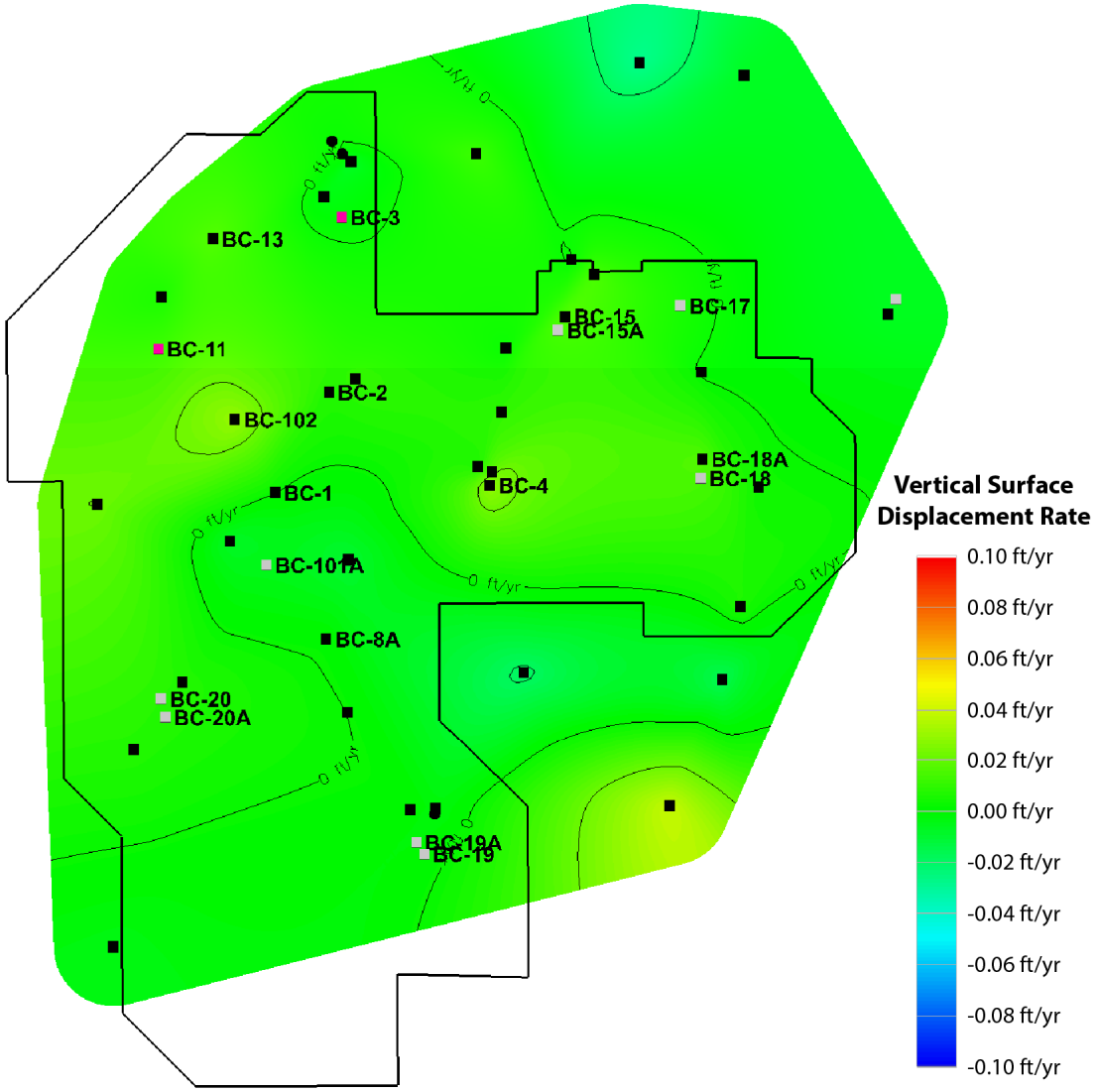


Figure 4 - Subsidence rates at Bayou Choctaw between August 2015 and September 2016. The DOE SPR property line is shown as a black line. The circles and squares represent the location of surveyed markers and monuments, respectively. Grey surveyed locations represent locations that were surveyed but were not included in the analysis due to survey error or survey location reset. Additionally, pink squares represent well locations that were not surveyed.

GPS and Tiltmeter

There is a GPS and tiltmeter installed at the abandoned Cavern 4 wellhead. The instruments have been recording hourly data since 2013. Figure 5 shows the raw hourly data along with a filtered version of that data. The figure also shows the linear regression. This is the best fit line and represents the linear ground movement rate. In this case, the linear ground movement rate is approximately 0.006 ft./yr. (0.07 in./yr.) in the upward direction. There is a slight seasonal trend where the GPS is lower in the summer and higher in the winter. If the linear subsidence rate is calculated for exactly three years beginning in 2014, the rate is much closer to zero. Specifically, the linear subsidence rate experienced by the GPS is just 0.003 ft./yr. (0.031 in./yr.). Hourly variation in GPS measurements can be caused by site activity as well as cloud and satellite coverage.

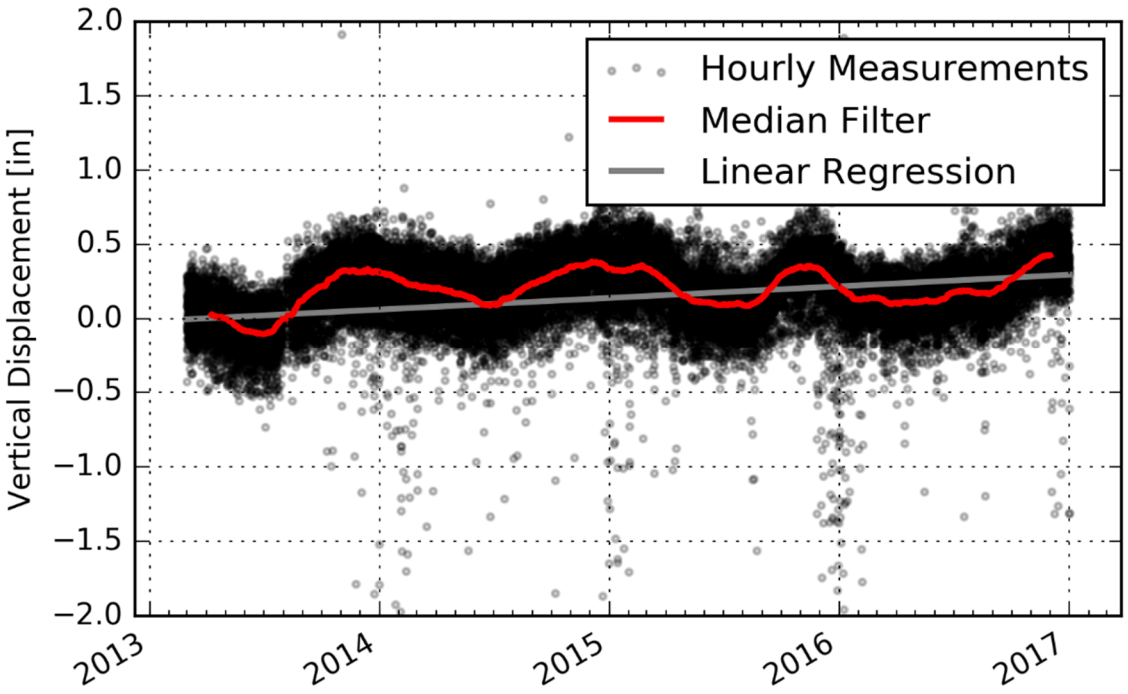


Figure 5 - Measured GPS data with grey circles representing the raw data. The red line represents the filtered data while the grey line represents the linear regression, or best fit line.

Data from the tiltmeter are represented in Figure 6. The raw northing and easting tilt data are represented by black and green circles, respectively. The raw data are also filtered using a median filter with a kernel size of 7 days. The filtered northing data are represented by a red line while the filtered easting data are shown with a black line. Since the tiltmeter was installed in 2013, there has been little to no change in overall tilt. There is a small seasonal pattern in both northing and easting tilt. The northing measurements were highest during the summer and lowest in late fall. The easting measurements displayed a similar quality but the highest value is reached in the late summer while the lowest is in the early spring. In addition, there are two periods of missing data in 2013. The first period occurred after the initial installation of the tiltmeter. The tiltmeter had to be turned off for realigning and failed soon after. The system was replaced in May 2013 but was turned off again in August 2013 to upgrade the electronics.

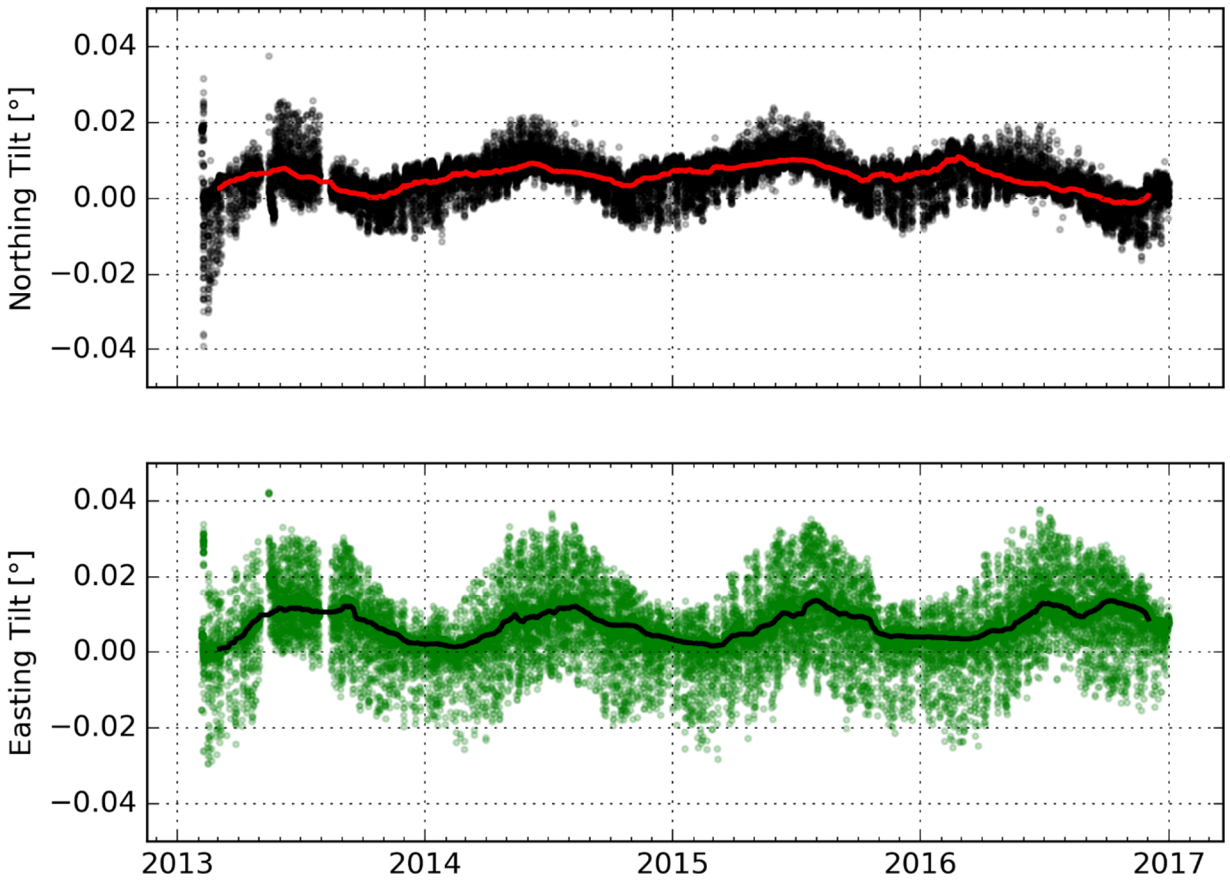


Figure 6 - Tiltmeter data showing raw northing (black circles) and easting (green circles) measurements. The filtered data for the northing and easting data are represented by red and black lines, respectively.

Conclusion

Based on information from the GPS, tiltmeter, and land based survey, there is little to no subsidence at the Bayou Choctaw SPR site. The lack of ground movement suggests there is no compromise to any of the SPR caverns at the site. It is also worth noting that there is no information to suggest any loss of structural integrity of Cavern 4.

References

Ege, John. *Surface Subsidence and Collapse in Relation to Extraction of Salt and Other Soluble Evaporites*. N.p., 1979. Print.

Additional Information

Seasonal Elevation Variation

As mentioned previously, there was a seasonal pattern in the GPS elevations. Elevations were higher in the winter and lower in the summer. This pattern was analyzed by calculating the statistics for each month and showing how they compare to a baseline. In this case, the baseline was the linear subsidence rate calculated for three full years beginning in 2014. Statistics from the analysis are shown in Figure 7. The black line shows the median value of the GPS elevation above the baseline subsidence rate. The darker line represents the upper and lower quartiles while the lighter grey area shows the extents of the 10th and 90th percentiles. The median seasonal elevation changes can vary from the -0.08 in. (June) to +0.17 in. (November). The elevations are closest to the linear subsidence rate in September and in a period between March and April. Therefore, it is suggested that subsequent land-based surveys be conducted at the same time each year, preferably either in March/April or in September.

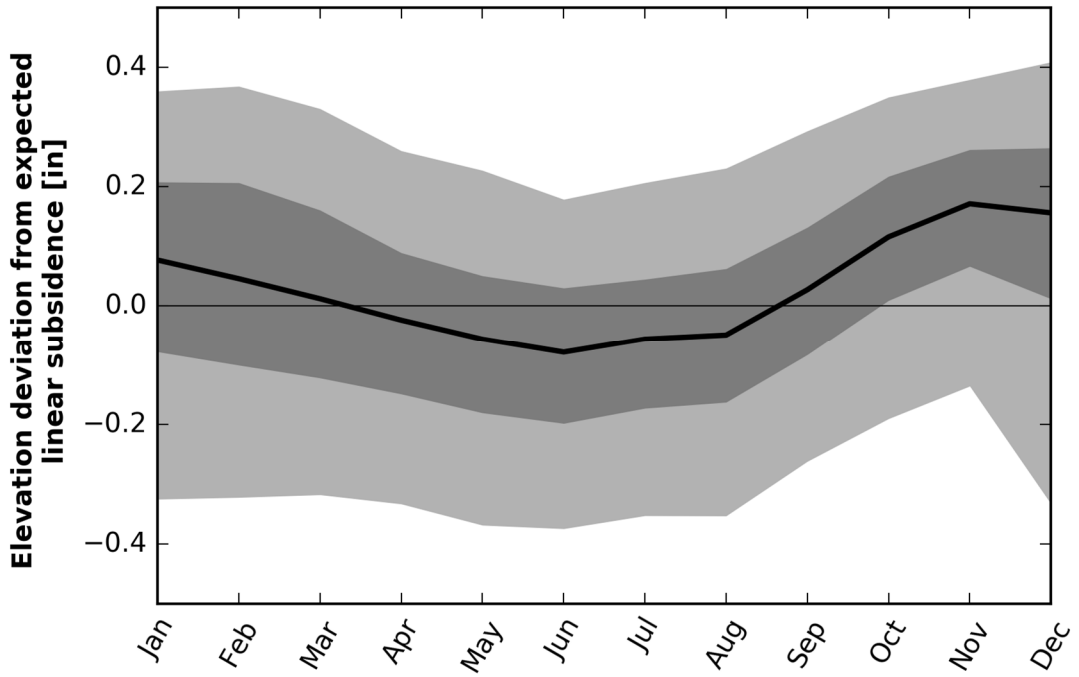


Figure 7 – GPS elevation above expected linear subsidence rate. The black line represents the median value while the darker area represents the extents of the 25th and 75th percentiles. The lighter grey area shows the extents of the 10th and 90th percentiles.

Jumps in Tiltmeter Measurements

Figure 8 shows the original tiltmeter data. It was mentioned in the main text there were missing data in May 2013 and August 2013 but there were also jumps in the data caused by resetting the instrument. Below is a list of known causes for these jumps and missing data. Since all of the jumps were human caused, and not actual subsidence events, the data presented in the main text has the jumps removed for clarity.

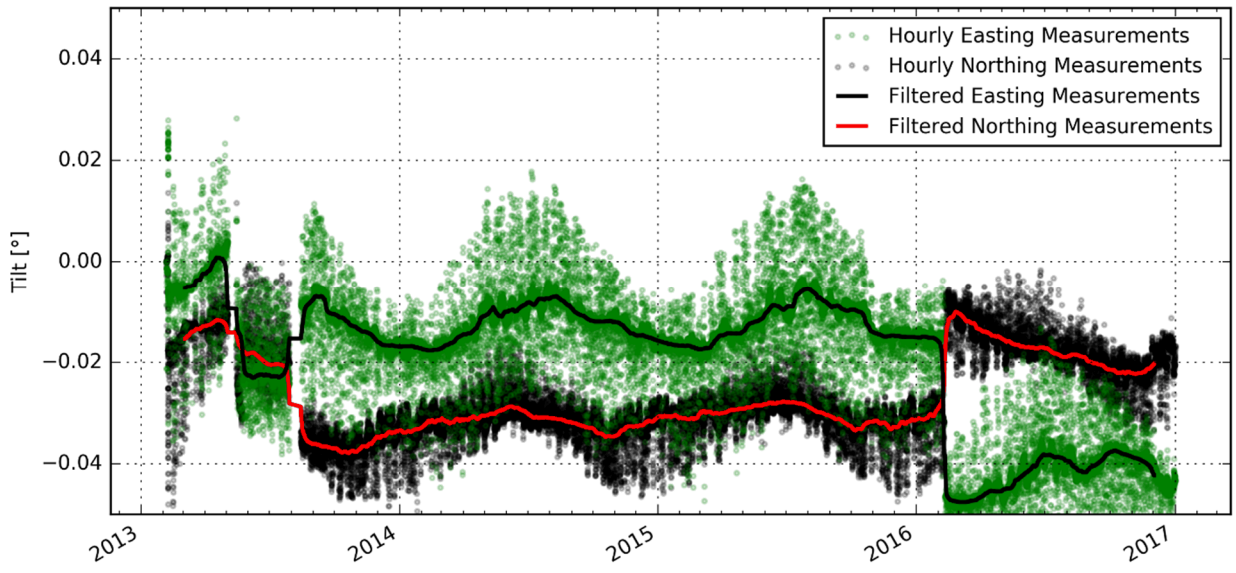


Figure 8 - Raw tiltmeter data showing raw northing (black circles) and easting (green circles) measurements. The filtered data for the northing and easting data are represented by red and black lines, respectively.

April/May 2013 – System was re-leveled and adjusted followed by instrument failure. The instrument was replaced in May 2013. During this time the tiltmeter was placed in a weather proof box and mounted to the wellhead.

August 2013 – Equipment was removed so that the electronics portion of the tiltmeter could be located at ground level for ease of access. The jump was caused by the fact the tiltmeter could not be installed in the exact same location.

February 2016 – The tiltmeter was removed for a multi-arm caliper survey. Again, the tiltmeter could not be reinstalled in the exact same location.

Negative Outliers in GPS measurements

As can be seen from Figure 5 in the main text, there is an increase of outlying measurements in winter. All of the significant outliers are in the negative direction. This phenomenon is caused by roosting birds that congregate on and around the Cavern 4 wellhead. This issue is most prevalent during the winter as the warmth radiating from the brine pond attracts large migratory buzzards. Site personnel have seen between 50 and 100 birds near and on the wellhead at any given time. The amount of birds on the instrument have even sent the GPS into alarm. In February 2016 site personnel installed plastic bird spikes to help reduce the number of birds roosting on the instrumentation.

Original Measurements

Name	Elevation [ft]	Notes
1A	10.196	
1B	10.235	
2A		Not Taken
2B		Not Taken
3		Not Taken
4A		Not Taken
4B		Not Taken
4C		Not Taken
4D		Not Taken
5		Not Taken
6A		Not Taken
7A		Not Taken
7B		Not Taken
8A		Not Taken
8B		Not Taken
9		Not Taken
10A		Not Taken
10B		Not Taken
10C		Not Taken
10D		Not Taken
11A		Not Taken
11B		Not Taken
11C		Not Taken
11D		Not Taken
12A		Not Taken
12B		Not Taken
12C		Not Taken
12D		Not Taken
13A		Not Taken
13B		Not Taken
14A		Not Taken
14B		Not Taken
15B		Not Taken
18B		Not Taken
21B		Not Taken
22B		Not Taken
25B		Not Taken
28B		Not Taken
29		Not Taken
30		Not Taken
31A		Not Taken
31B		Not Taken
32	11.193	
BC1	8.446	
BC2	8.900	
BC4	12.467	GPS
BC8A	8.251	

Name	Elevation [ft]	Notes
BC13	6.871	Elev. taken on top of stub welded to plate inside PVC (-0.67 to top of plate elevation)
BC15	13.363	
BC15A	10.598	Wellhead reset
BC17	10.461	Wellhead reset
BC17A	10.754	Wellhead reset
BC18	11.615	Wellhead reset
BC18A	11.962	Elevation taken on first flange above gate
BC19	11.381	Wellhead reset
BC19A	11.037	Wellhead reset
BC20	10.733	Wellhead reset
BC20A	11.787	Wellhead reset
BC101A	10.657	Wellhead reset
BC101B	10.653	Wellhead reset
BC102A	11.353	
WellCH10	8.283	
33		Not Taken
34		Not Taken
SMS3		
NewcoordsSMS3	8.711	
SMS4	6.920	
SMS6	4.193	
SMS7	8.936	
SMS8	9.096	
SMS9	9.395	
SMS10	5.717	
SMS11	7.840	
SMS12	4.977	
SMS13	6.973	
SMS14	7.512	
SMS15	8.849	
SMS16	10.434	
SMS17	7.019	
SMS18		N/A (DOE 21)
J-2Boardwalk		Not Accessible
N-3Boardwalk	11.924	
6ABoardwalk	12.722	
16ABoardwalk	12.774	
24Boardwalk	10.628	
25Boardwalk	7.659	
26Boardwalk	8.496	
27Boardwalk	11.031	
28Boardwalk	10.759	
J-02	8.043	
J-07	12.741	
CH-2	8.617	
J-03	14.406	
J-04	9.344	
J-08	11.237	