LONQUIST FIELD SERVICE

July 1, 2024

From:

Nathaniel Byars, Lonquist & Co. LLC

Julie Shemeta, MEQ Geo Inc.

To:

Stephen H. Lee, Director
Louisiana Department of Natural Resources
Injection and Mining Division
617 N. 3rd Street
Baton Rouge, Louisiana 70802

Re: Update on status of the Tiltmeter and GNSS ground deformation monitoring at Sulphur Mines Salt Dome, Louisiana

Dear Mr. Lee,

The report "Plan to monitor ground deformation at Sulphur Mines Salt Dome: Precision Tiltmeter and Differential GPS Arrays" dated December 22, 2023, describes the overall plan for the deformation measurements using tiltmeters and differential GNSS arrays at Sulphur Mines salt dome. This memo updates the status of the monitoring stations and initial operation of the deformation network.

Halliburton's Pinnacle group installed the instrumentation and is responsible for data acquisition, processing and reporting (https://www.halliburton.com/en/completions/stimulation/microdeformation-monitoring). The installation of the tiltmeter and GNSS instruments started early April 2024 and the stations began collecting initial data on May 9, 2024. By June 1, 2024 the system was deemed fully operational but remains in the "learning" phase during which the accuracy of the modeled deformation will be limited but will improve over time. Figure 1 shows the location of the instrumentation and Table 1 lists the coordinates of the tiltmeter and GNSS sensors.

Figure 1. Google Earth image of Sulphur Mines salt dome with location of tiltmeters (white dots) and GNSS stations (green dots). Map includes the Cavern 7 sonar (red dots).

Table 1. Location of GNSS and Tiltmeter Stations at Sulphur Mines Salt Dome (WGS 84)

Differential GNSS Stations		
Name	**Latitude**	**Longitude**
GPS NE	30.257206	-93.413782
GPS NW	30.256713	-93.419670
GPS Cavern 7 Pad	30.253327	-93.414588
GPS SE	30.250953	-93.411739
GPS SW	30.250263	-93.418668
GPS Off-dome Reference Station	30.257750	-93.426649

Precision Tiltmeter Sites		
Name	**Latitude**	**Longitude**
TILT_01	30.256207	-93.422543
TILT_02	30.256705	-93.419624
TILT_03	30.256947	-93.413727
TILT_04	30.255402	-93.415087
TILT_05	30.254365	-93.416418
TILT_06	30.253489	-93.416695
TILT_07	30.254456	-93.413924
TILT_08	30.253295	-93.414595
TILT_09	30.252288	-93.416215
TILT_10	30.252987	-93.422714
TILT_11	30.253043	-93.419765
TILT_12	30.251485	-93.418691
TILT_13	30.251674	-93.415624
TILT_14	30.253120	-93.411511
TILT_15	30.252891	-93.413320
TILT_16	30.249195	-93.418437
TILT_17	30.249687	-93.414899
TILT_18	30.250951	-93.411754
TILT_19	30.250140	-93.421087
TILT_20	30.255485	-93.411405

Tiltmeter Installation. The tiltmeters at Sulphur Mines dome were installed in 35-foot deep boreholes (Figure 2). The tiltmeters are placed in cemented PVC pipe with dry sand inside the pipe (Figure 3).

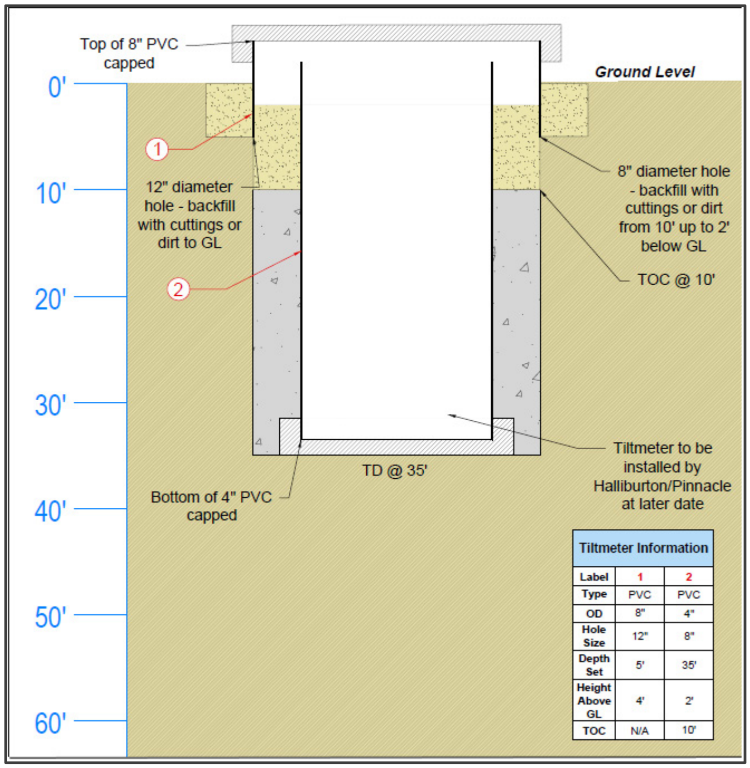

Figure 2. Schematic showing a tiltmeter installation diagram used for the tiltmeters at Sulphur Mines.

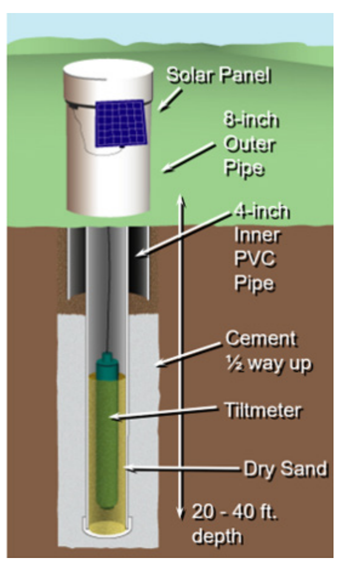

Figure 3. Figure from Halliburton showing an example tiltmeter construction illustration.

GNSS Installation. The GNSS stations were installed on 4-inch carbon steel casing which was grouted into approximately 34-foot deep 12" drill holes (Figure 4). Two stabilizing fins at 180 degrees were installed on the outside of the steel casing. The GNSS antenna was attached to a welded rod on the top of the 4" casing.

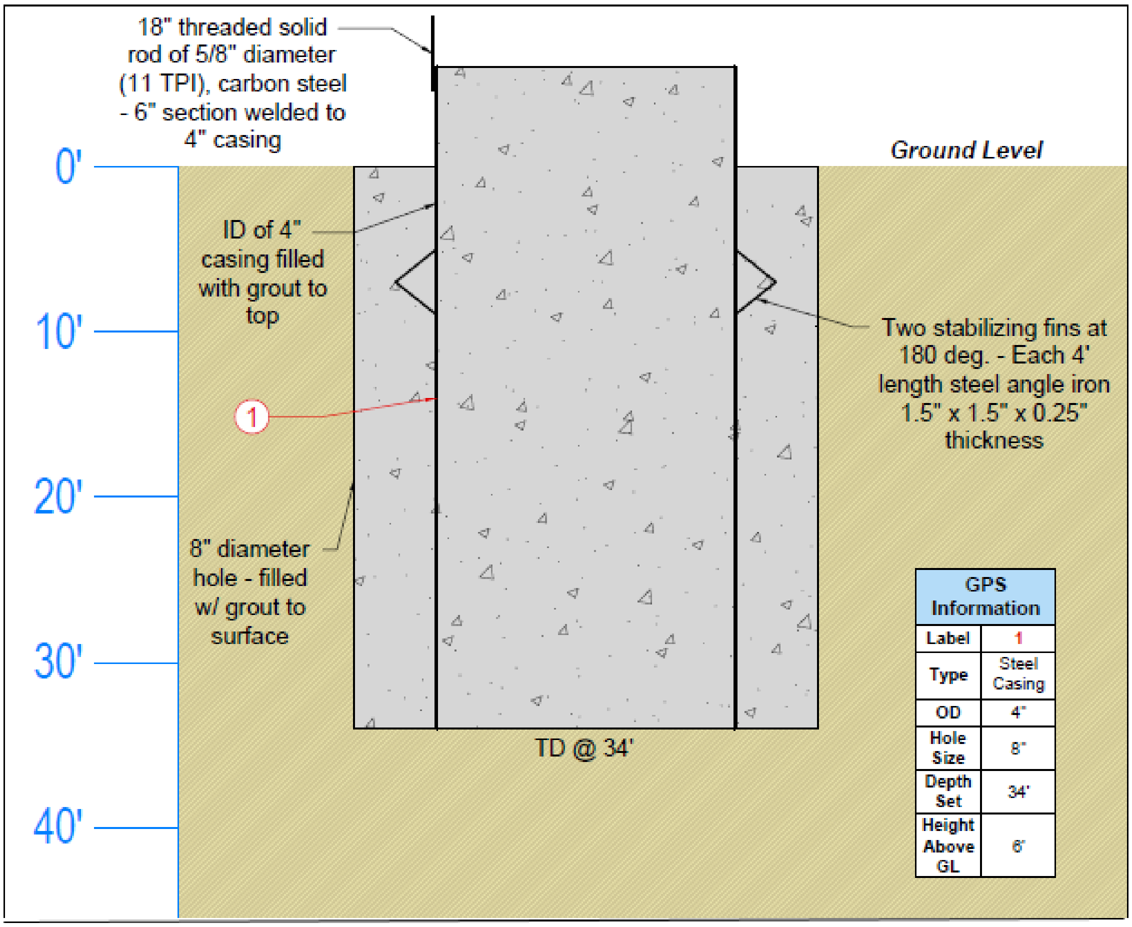

Figure 4. Schematic of GNSS Station build at Sulphur Mines.

Deformation Reporting. The deformation measurements will be reviewed for both short-term (minutes to hours) and long-term (days to weeks) trends in the data to attempt to understand the surface deformation patterns and how they might relate to the subsurface processes at Sulphur Mines.

A monthly report will be provided approximately 2 weeks after the month's end that summarizes the deformation measurements observed during the monitoring period. The deformation measurements are captured in near real-time and can be reviewed by Lonquist and Westlake during any unusual activity observed in the dome area. We propose to modify the current InSAR reporting and combine the InSAR results with Tiltmeter and GNSS array deformation observations into a single monthly surface deformation report.

As additional surface deformation information is collected, the plan is to develop a multi-level "Deformation Alert System" with defined deformation thresholds indicating normal, warning and crisis alert levels, depending on the short-term movement trends observed on the various monitoring systems. The deformation alert system will define a reporting frequency based on the alert level, where the reporting frequency will increase with each higher level of concern. Longer-term movements and trends will be reported monthly. The tiltmeter/GNSS network is still in the learning phase to understand "background" movement and what movement might indicate anomalous subsurface movement and cause for increased concern and vigilance. We anticipate about three months of observations will be needed to define reasonable thresholds for the tiltmeter/GNSS responses. During the leaning phase, the deformation shall be reviewed and reported in a timely manner to IMD if clearly anomalous behavior is observed. The deformation results will be additionally reviewed during anomalous cavern pressure sequences or when anomalous microseismic activity triggers the proposed Microseismic Alert System to a level above the 'green' Normal level.

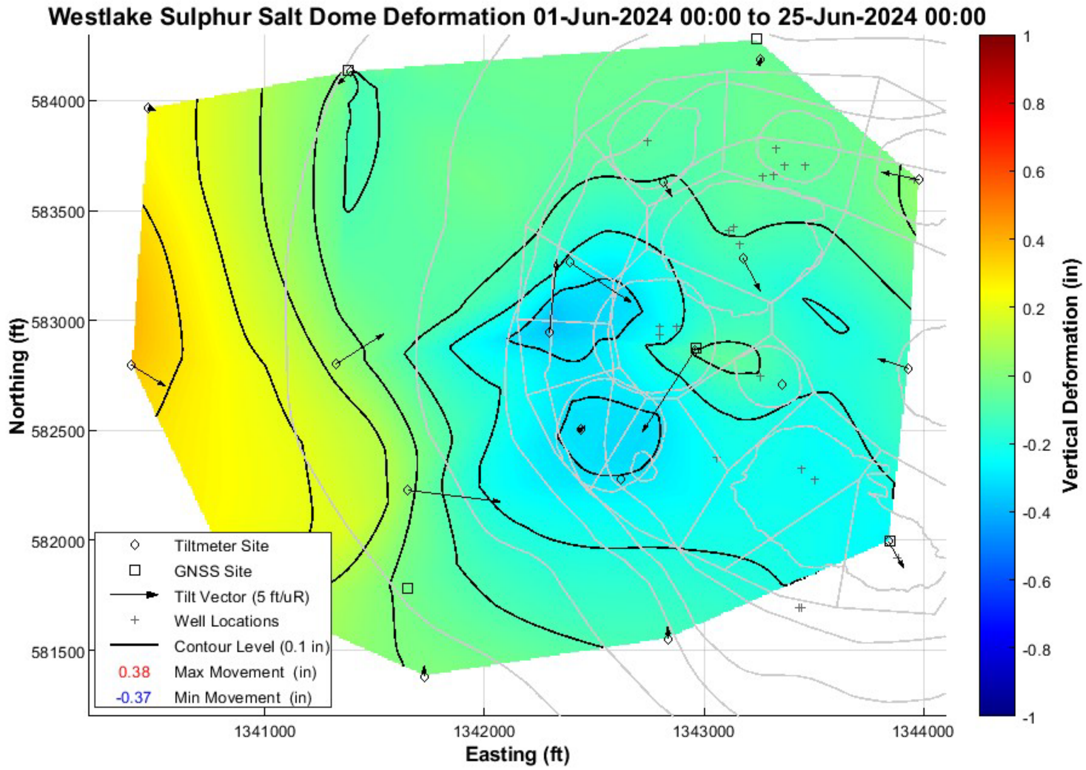

Figure 5. Sample deformation trend map from tiltmeter/GNSS array at Sulphur Mines, measured from June 1 to June 25, 2024. The salt dome contours, InSAR AOI's and cavern outlines are shown for reference.

An example of a tiltmeter deformation map for the period between June 1 and June 25, 2024, is shown in Figure 5. The area within the downward vertical deformation pattern observed in the center of the array has been declining with a consistent linear movement trend throughout the monitoring period. An apparent uplift at the periphery of this map likely indicates that the subsidence extends beyond the mapped area and the calibration of these results is required and will be performed by utilizing GNSS data.

During the commissioning phase, when all the subsystems are integrated, we may observe inconsistent signals. This is normal, as the recently installed monitoring systems need time to settle in place, which usually takes several months. Each deformation monitoring subsystem has its advantages and disadvantages. InSAR provides high spatial resolution but low temporal resolution, and its vertical precision is better than horizontal. GNSS has high temporal resolution but low spatial resolution, and its horizontal precision is better than vertical. Tiltmeters, similar to GNSS, provide low spatial resolution but high temporal resolution data, achieving very high measurement precision of tilt angle; however, they are not connected to the absolute reference frame and do not produce the desired three-dimensional measurements of deformation. By combining these three subsystems, we can observe and describe deformation processes in this region with a higher degree of certainty and minimal delay. After collecting initial data, we will estimate the standard deviation and define a normal (safe) variability; any deformation measurements exceeding this safe variability will trigger an alert. We can increase the temporal frequency of GNSS and tiltmeter monitoring so that in the case of an emergency, data can be analyzed every few minutes. Certain infrequent weather conditions and events (e.g., hurricanes, and tectonic earthquakes) may trigger an unwarranted alert. The system will be improved as we experience such events and learn from them.

Westlake has assembled a highly-experienced team in deformation measurements. The vendors (Pinnacle and TRE-A) and an outside expert, Dr. Sergey Samsonov, are providing a wealth of real-world deformation acquisition, processing and interpretation experience for the project.

The ongoing InSAR data evaluations have provided confidence that effective monitoring of long-term trends and deformation consistency is present over the dome and surrounding area. The now operational tiltmeter/GNSS system supplements monitoring efforts with localized continuous short-term data collection. Even though the accuracy of the deformation values reported by this system will be limited during this early phase of operation, the data will still allow for clear and prompt identification of relative changes in deformation behavior to be recognized and addressed.

Sincerely,

Nathaniel Byars
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Lonquist & Co. LLC

Julie Shemeta
MEQ Geo Inc.