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Subsidence Monitoring and Analysis Final Report

Red Lodge, Montana

Prepared for:

Montana Department of Environmental Quality
Remediation Division
Abandoned Mine Lands Section
PO Box 200901, Helena, Montana 59620

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EXECUTIVE SUMMARY

This Subsidence Monitoring and Analysis Report (SMAR) is a continuation of the Red Lodge Subsidence Drilling Investigation which was presented in the *Final Data Summary and Analysis Report, Subsidence Drilling Investigation, Red Lodge, Montana, 2015* (DSAR). This project was initiated by the Montana Department of Environmental Quality in response to several residents within the City who expressed concerns over whether collapse of underground mines could lead to surface subsidence and threaten their homes, property, or personal safety.

Work presented in the DSAR included a literature review of past subsidence analyses and historic mining documents, completion of a detailed drilling investigation, and engineering analyses assessing the potential for mine-related subsidence within the study area. Conclusions within the report stated a potential for mine subsidence exists, but any such movement and associated surface settlement would occur over a relative long period of time and very little risk exists of rapid “sinkhole” type subsidence caused by mine collapse. The subsidence monitoring program discussed herein was designed to collect information to help in the assessment of potential mine subsidence by measuring ground surface elevations over time.

Survey monitoring started in January 2014, prior to the Subsidence Drilling Investigation, and continued quarterly through 2015. The survey monitoring area was located in the area surrounding the drilling investigation, approximately bounded by Adams Avenue on the west, Haggin Avenue on the east, 11th St. on the north, and 19th St. to the south. A total of eight quarterly monitoring (QM) events were conducted during this period. The monitoring program began with 57 monitoring points and eight crack gages attached to three specific homes (501 S. Broadway, 505 Platt, and 404 S. Broadway). Later in 2014, additional survey points were added (bringing the total to 90) and a crack gage installed on the fourth home (207 S. Hauser). These 90 survey points were installed to detect movements in the vicinity of these four specific residences. Measurements completed during this time frame were analyzed and showed a subtle downward trend ranging from a rate of 0.01 to 0.14 inches per year.

Following review of the existing survey data and the DSAR, the monitoring program was expanded during the first quarter of 2016 to cover a larger geographic area and incorporated a more extensive survey method to increase the overall accuracy of the survey data. The study area boundary was expanded north to 10th Street and additional points were added to the network, bringing the total number of survey points to 125. This updated program allowed for a more rigorous statistical analysis of data than did the pre-2016 methodology, and therefore greater confidence in the estimated movements.

The additional survey monuments were installed and partially surveyed during January 2016, as part of Quarterly Monitoring event 9 (QM9). The revised monitoring program was fully implemented in April 2016, as part of the QM10 event. QM11 was conducted in September 2016 and QM12 in April 2017. The data and discussion presented in this report focuses on these last three survey events.

The data collected during this study, and specifically the last three survey events, is a short-term snap shot of potential mine subsidence. Mine subsidence can be a long-term process that occurs over several decades or even hundreds of years. From a measurement and monitoring standpoint, the implications of monitoring such a process are dual:

- Detectable movements may be near the limitations of current technology; therefore the resulting measurements have some associated margin of error that describes the potential variability of the value, and

- Estimated surface displacements measured over a single year show what was occurring during that time. Future or past displacements may be greater or less in other areas above the workings.

Regarding the residences of interest, as listed in the DSAR, numerous non-mining factors and conditions may cause distress to a structure or surface displacements. Many of the residences of interest may have multiple factors causing problems:

- Insufficient structural support due to antiquated or inadequate foundation systems.
- Structural weakening and deterioration due to age, environmental conditions, original construction practices or faulty maintenance.
- Insufficient structural connection between additions and original structures.
- Susceptibility to frost action (cyclic freezing and thawing) due to shallow foundations.
- Soils settlement caused by loose or poorly compacted fill, poor drainage or other factors.

Over the 12-month measurement period (QM10 to QM12), elevation estimates across much of the survey area showed small downward movements, many of which have a 95% confidence interval where the entire range is downward. The following items summarize principal findings and conclusions:

- Estimated movements range between 0.005 inches (upward) to 0.40 inches (downward), with an average of 0.16 inches (downward) over the 1-year measurement interval (April 2016 through May 2017).

- Estimated movements are near the theoretical estimates presented in the DSAR; 3 to 7 inches of subsidence over a 50 to 100-year time frame, or approximately 0.03 to 0.14 inches/year.

- While downward movement was measured at some locations, the magnitude of movement measured in this study is relatively small and, based on the fact that the average movement correlates fairly closely to the rate predicted in the DSAR, further confirms that the overall potential subsidence predicted in that report is most likely a worst-case scenario.

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1 Introduction

This Subsidence Monitoring and Analysis Report (SMAR) describes the data collected during the Red Lodge Subsidence survey monitoring project and presents the engineering analyses conducted based on that data. This work is a continuation of the Red Lodge Subsidence Drilling Investigation which was presented in the *Final Data Summary and Analysis Report, Subsidence Drilling Investigation, Red Lodge, Montana, 2015* (DSAR) (Pioneer Technical Services, Inc., 2015). The primary objective of this effort was to gather and evaluate survey data for the study area to determine if any measurable subsidence is occurring on the ground surface. Of special interest was movement potential near residences in the study area.

Survey monitoring started in January 2014, prior to the Subsidence Drilling Investigation, with the installation of 57 survey monuments and 8 crack gages. This network was expanded in the spring of 2014 to include 90 survey points and an additional crack gage. The preliminary survey network was set up to monitor for vertical ground movement in the study area. Survey monitoring was initially conducted on a quarterly basis through 2015 (2 years). As a result of the data and engineering analyses submitted in the DSAR, the survey network was expanded to cover a greater geographic area and included a total of 125 monitoring points. The expanded network was surveyed four times between January 2016 and May 2017.

1.1 Project Location

The City of Red Lodge is located in south-central Montana, approximately 60 miles southwest of Billings. Figure 1-1 shows the study area location. Survey monitoring was completed in the area surrounding the drilling investigation, approximately bounded by Adams Ave. on the west, Haggin Ave. on the east, 11th St. on the north, and 19th St. to the south.

1.2 Project Background and Site History

Prior to the Red Lodge Subsidence Drilling Investigation, several residents within the town expressed concern over whether collapse of underground mines could lead to surface subsidence, which might present a current or future threat to their homes, property, and personal safety. The Subsidence Drilling Investigation concluded November 4, 2014 and the DSAR was submitted May 15, 2015. The primary objective of this effort was to gather information to evaluate subsurface conditions and assess the condition of abandoned underground coal mine tunnels and pillars in the vicinity of several homes within the City of Red Lodge, Montana. As many as seven coal seams underlying this part of Red Lodge were mined in the early 20th century. The coal seams are located in sandstone and claystone bedrock, which is overlain by 14 to 111 feet of alluvial gravel and boulders. The seams vary in depth and condition, with depths below ground surface ranging from 50 feet to over 700 feet. The seams are numbered from 1 to 5: number 1 being nearest the ground surface. Each of the coal seams dips at an angle of approximately 18 degrees, so that the seams reach deeper towards the south end of town.

Eight boreholes were drilled, field logged, and sampled. The information gathered from the boreholes was utilized to assess the potential of mine-induced subsidence. A plan view showing the general location of documented mine workings, the initial residences of interest, and the bore hole locations from the drilling investigation is shown in Figure 1-2.

For each bore hole, the condition of the bedrock, coal seams encountered, and any remaining mine void were noted. The historic method of mining left pillars of coal in place next to mined-out rooms; if the coal seam encountered in this study's drilling was intact, it means that either a pillar was found or that part of the seam was not mined. Bedrock core was collected continuously and observations were made regarding the strength and condition of this rock, especially in the region immediately above or below a coal seam.

Other exploratory work included:

- Excavation of a test pit near the intersection of Platt Avenue and 17th Street to assess surface soils in an area showing an apparent surface depression.
- Excavation of two shallow hand auger holes to assess surface soils at 505 Platt Avenue.
- Coring concrete and excavation of six hand auger holes to investigate floor subsidence at the Police Station shop.

Extensive research was conducted regarding the mining history, mine locations and conditions, subsidence of underground coal mines in other locales, and previous studies in the Red Lodge area.

An engineering analysis of the data collected from the drilling investigation was performed to determine the likelihood and magnitude of past, present, and future ground surface movement caused by the underground coal mine workings. Ground surface displacements from failure of room and pillar mines can occur through the following mechanisms:

- Pothole Subsidence; and
- Trough Subsidence.

Pothole, or sinkhole, subsidence occurs in areas overlying underground mines which are relatively close to the surface. Pothole subsidence is fairly localized and can express as a steep-sided pothole or shallow-sided pothole formation on the surface. Steep-sided potholes are the most familiar and damaging to structures.

Trough subsidence occurs over abandoned mines when the overlying soils (or overburden) sags downward due to the failure of remnant mine pillars or by punching of the pillars into a soft mine floor. The resultant surface effect is a large, shallow, and broad depression of the ground surface.

The following items summarize principal findings and conclusions of the DSAR investigation and analyses:

- **Structures of Interest:**
    a. 207 South Hauser Ave. – Reported observation of a subsidence feature combined with drilling observations was cause for continued monitoring and possible additional investigation.
    b. 501 South Broadway Ave. – No definitive evidence of mine-related subsidence was found.
    c. 505 South Platt Ave. – No definitive evidence of mine-related subsidence was found; however, the observed surface depression located parallel to Platt Avenue warranted continued monitoring and possible additional investigation.
    d. 404 South Broadway Ave. – Observation of an undocumented opening in conjunction with disruption of the borehole casing and the resident's reported subsidence observations warranted continued monitoring and possible additional investigation.
    e. Police Station – No evidence was found that floor subsidence was caused by mining-related activities.

- **Extent of Mining:**
  Historic documentation of the abandoned mines is fairly well preserved with the exception of seam No. 2. The absence of mine data for seam No. 2 greatly inhibited the interpretation of potential subsidence features in the southeast section of the study area.

- **Existing Mine Conditions:**
  The mine conditions were observed to range between fully open (6 feet of void in BH06) to completely closed. Mine workings that are not totally collapsed may continue to slowly deteriorate such that further collapse ensues. Based on the fact that the mining occurred over 100 years ago, any further collapse would likely occur over a long period.

- **Overburden Materials:**
  Natural conditions within the overburden materials that are able to cause surface subsidence were not observed. Although a thin veneer of non-native fill material was observed in hand auger holes and test pits in the Finn Park area, this material, if improperly constructed upon, could be responsible for structural settlements but would not likely cause surface subsidence features.

- **Pothole Subsidence:**
  Most of the workings are at depths where chimney failures, which can lead to pothole subsidence, are likely to self-arrest before reaching the upper limit of the bedrock. Pothole subsidence is possible in locations of the city where bedrock thicknesses are less than approximately 150 feet. Hazardous, steep-sided pothole subsidence (i.e. sinkholes) are considered highly unlikely anywhere. Shallow-sided pothole subsidence may be possible in areas of lesser bedrock thickness. The likelihood of a future pothole of this

nature to affect any one resident is very low, considering only two are suspected to have developed over the past 75 years.

- **Trough-type Subsidence:**
  Potential vertical settlement is estimated to be on the order of 3 to 7 inches, depending on the size of mine room collapse. Considering the abandoned mines below Red Lodge have likely been slowly degrading and collapsing for the past 75 years and within this time frame no significant observations regarding subsidence have been made, future trough-type subsidence are likely to remain slow and may accumulate over the next 50 to 100 years. Building damage resulting from this slow deterioration is estimated to be localized and structural damage may be on the order of slight to appreciable. Building size and orientation with respect to the collapse feature are key factors affecting the amount of potential structural impacts.

One of the goals of this survey monitoring effort was to gather information to verify or refute the theoretical estimates with measured values.

2 Survey Monitoring

2.1 Monitoring Locations

Two main groups of monitoring points were established during the subsidence investigation program. The first group was installed during the fall of 2014, prior to initiating the subsidence drilling program. These monitoring points were established in the vicinity surrounding the four houses of interest, shown in Figure 2-1. The general area was bounded by Hauser Avenue on the west, Haggin Avenue on the east, 13th Street on the north, and 17th Street to the south. Monitoring points included a combination of one National Geodetic Survey (NGS) benchmark, fire hydrants, 36-inch long #6 rebar pounded into the ground (MP), bench ties installed in house foundations, and "MAG" nails installed in concrete flat work. National Geodetic Survey Monument PID: QW0296 (benchmark), located in Fountain Park was used as the control point.

Measurements were completed using a leveling survey, which is a standard method used when accurate elevation measurements are required (Moffitt, 1975). Accuracy of a leveling survey is directly related to the number of measurements recorded; more accuracy requires more measurements and more labor. To balance accuracy and cost, since potential subsidence rates were not well understood, a basic leveling circuit from the benchmark to each house of interest was established.

Survey monitoring with this method was conducted on a quarterly basis from January 2014 through 2015. Measurements were made with a Trimble DINI 0.3 Digital Level and TD 24 Staff. An interim data summary, Draft Quarterly Monitoring Report QM9, presents the data collected between QM1 through QM9, and is included in **Error! Reference source not found.**. Measurements from this time frame showed signs of downward movement at some monitoring points. However, in order to verify overall trends, a longer period of monitoring, with more data, was deemed necessary.

Following the completion of the Subsidence Drilling Investigation DSAR, theoretical subsidence estimates and survey monitoring data collected up to that point in time were analyzed; both suggested potential subsidence could be very slow, with rates near 0.14 inches per year (7 inches/50 years), or 0.01 feet/year. In order to capture this very small rate of elevation change, the quarterly survey monitoring would need to be able to detect changes of one fourth this annual rate, or approximately 0.0025 feet (0.04 inches). This theoretical rate estimate was not known prior to starting the survey monitoring work. An analysis of the initial survey method showed that it would not produce the required accuracy. At the beginning of the study the level of accuracy was thought to be sufficient; however, the need to capture potentially smaller changes in elevation led to the conclusion that the survey methodology would need to be refined.

A revised plan was developed that included an expanded study area and a more accurate survey method. The more accurate method was based on methodologies discussed in the *U.S. Army Corps of Engineers, Structural Deformation Surveying, Engineering and Design Manual* (ACOE, 2002). The manual presents techniques for planning and processing deformation surveys when more extensive leveling procedures, such as least squares processing, may be necessary. The same digital level equipment was used, but other changes were implemented that added rigor to both the field collection and processing of the data that would insure more accurate results. The plan was implemented in January 2016. The primary changes to the methodology were as follows:

- Expand the study area to include both a larger portion of Red Lodge and more survey monitoring points.
- Tie the survey to a benchmark north of the northern extent of mine workings and include areas that are not undermined.
- Performed pre-survey analysis (ACOE, 2002).
- Use a Survey Network (least squares processing) with redundant measurements and designed to collect data with sufficient accuracies to detect the theoretical values.
- Increase monitoring interval from quarterly to semi-annually.

The study area boundary was increased to encompass the portion of Red Lodge bounded by 10th Street on the north. This expansion included additional under-mined areas within the City and an area north of 13th Street, which is not under-mined, based on historical records. The expanded network consisted of the original monitoring points and incorporated several additional points, for a total of 125 monitoring locations. The new survey was tied to two control points; the original NGS monument (PID QW0296) that is located in Fountain Park and monument PID QW0299 that is located at the northeast corner of the intersection of North Broadway Ave. and 10th Street. Similar to the original survey, the additional monitoring points included a combination of fire hydrants, 36-inch long #6 rebar pounded into the ground (MP), and an extensometer (installed during drilling). Major monitoring points (except bench ties) are shown on Figure 2-1. Focus Areas A, B, C, and D show higher density monitoring points near the residences of interest: 207 S. Hauser Ave., 404 S. Broadway Ave., 501 S. Broadway Ave., and 505 S. Platt Ave., respectively. Focus Area E covers the block immediately east of 505 S. Platt

Ave. and Focus Area F shows the northern survey extent. Focus areas A through E are shown in greater detail in Figure 2-2 through Figure 2-6.

Table 2-1 lists the chronology of tasks completed as part of this work.

Table 2-1: Chronology of Survey Monitoring Work Completed

Quarterly Trip	Date	Point/ Gage Install	Elevation Level Survey	Horizontal GPS Survey	Crack Gage Readings	Notes
1	1/20/14	X	X	X		Install and survey monitoring points and crack gauges at 501 S. Broadway Ave. and 505 S. Platt Ave.
2	4/28/14	X	X		X	Install additional survey monitoring points and crack gauges at 404 S. Broadway Ave.
3	7/30/14	X	X		X	Install additional monitoring points and a crack gauge at 207 S. Hauser Ave.
4	11/19/14		X	X	X	Survey the borehole (BH) locations from the recently completed drilling investigation.
5	1/13/15		X		X	
6	4/8/15		X		X	
7	8/5/15	X	X	X	X	Install two monitoring points near Civic Center
8	10/26/15		X	X	X	
9	1/29/16		X		X	Interim survey expansion to include Fire Hydrants.
10	4/27/16	X	X	X	X	Replace disturbed monitoring points and expand survey network per Red Lodge Monument Survey Work Plan.
11	9/26/16		X		X	
12	5/2/17		X		X	

The *Red Lodge Monument Survey Draft Work Plan*, developed in January and approved in April 2016, and an example calculation are included in Appendix B to describe the expanded network and methodology. Using this methodology, it was expected that a level of accuracy could be attained that would capture the magnitude of potential movement predicted by the engineering analysis and subtly observed with the basic leveling circuit.

Considering these improvements, the expanded survey contains more complete information about potential changes in the monitoring point elevations. Consequently, the data and analyses presented herein refer to that information collected in the three monitoring events from 2016 to 2017 (QM10 through QM12).

2.2 Elevation Measurements and Analysis

Monument elevations were measured using a survey network that uses a least squares regression analysis as opposed to the basic leveling circuit. Appendix B provides a simple surveying example that demonstrates how a network survey provides better elevation estimates than a basic leveling circuit. The example calculation estimates the theoretical precision of a basic leveling circuit and compares it to the theoretical precision of two network surveys. Each of the three calculations were performed for the same 28 hypothetical survey points.

In general, the network survey achieved a precision two times better than the basic leveling circuit for this example. The amount of increased precision is directly related to the number of redundant measurements. The basic leveling circuit uses 28 measurements to estimate the 28 point elevations, thus no redundancy The first network survey example uses 44 measurements to estimate the 28 point elevations, thus 16 redundant measurements. The second network survey example uses 76 measurements to estimate the 28 point elevations, thus 48 redundant measurements. Table 2-1 shows the change in standard deviation and the number of redundant measurements for each scheme.

Similar to the method shown in Appendix B, a pre-analysis was performed for the actual survey. After selection of the expanded survey area and monitoring point locations, simulations were completed to model the precision of various survey measurement schemes. The schemes were adjusted until the necessary precision was acquired. The scheme with the best precision balanced with cost was selected.

Table 2-2: Survey Precision (Standard Deviation) vs. Measurement Redundancy

	Basic Level Circuit	Network Survey 1	Network Survey 2
Total Number of Survey Points	28	28	28
Number of Measurements	28	44	76
Number of Redundant Measurements	0	16	48
Point 8, Standard Deviation	1.4×10^{-4}	1.0×10^{-4}	0.7×10^{-4}
Point 20, Standard Deviation	1.6×10^{-4}	1.2×10^{-4}	0.8×10^{-4}

The mathematical methods used to calculate the point elevations and survey precision (Standard Deviation) were calculated using two Network Analysis Methods: Weighted Least Squares Method (L2-norm), as described by Strang and Borre (1997), Borre (2001); and Least Absolute Error Method (L1-norm) as described by Strang (1986). Weighted Least Squares Method was used to calculate elevation estimates. Least Absolute Error Method, along with standardized residuals (part of L2-norm), were used to identify outliers, gross measurement errors, or disturbed monuments. Detected errors were removed from the data before calculating the final elevation estimates.

A total of 125 monitoring points were measured and of these monitoring points, 45 points were duplicated. Measurements were made with a Trimble DINI 0.3 Digital Level and TD 24 Staff.

Of the 125 locations, 10 monuments have shown erratic measurements and were possibly disturbed. The follow list describes the points with erratic measurements and their resolution:

- Points 601, 605, and 616 were damaged and have been replaced with new monuments - 824, 818, and 817, respectively.
- Points 404-2, 404-3, 404-7, 501-9, and 609 were damaged and have been permanently removed from the network.
- Point 404-9, a well cap located in Area B, showed an inconsistent elevation increase during the QM12 survey and may have been disturbed.
- Point 510 (NGS monument) will continue to be measured; however, the monument is located in a wall and the reference cap is set vertically, which results in less precise readings.

To evaluate elevation changes in the remaining 118 monitoring points, data for each monitoring point recorded during successive surveys (QM11 and 12) were subtracted from the initial elevation measurement (QM10). Figure 2-7 shows the estimated elevation change and standard deviation at monitoring points 628, 615, 701, 506, 617, and 505-7, one near each area of interest (A, B, C, D, E, and F). In general, most monitoring points show a similar, subtle trend of slightly decreasing elevation through time.

The revised survey was fully implemented in April 2016 (QM10). Surveys QM11 and QM12 were completed September 2016 and May 2017. The time span between monitoring periods QM10 and QM12 is approximately one year. Elevation differences are easiest to discern between these two measurement periods. Estimated elevation changes and 95% confidence intervals (error bars) for each monitoring point are shown in Figure 2-8 through Figure 2-11. A 95% confidence level is usually accepted for the assessment of deformation measurements pertaining to embankment and concrete structures, where a 99% confidence level is accepted in practice as certainty (ACOE, 2002).

To explain these error bars, it is helpful to understand the statistical term “95% confidence interval”. The confidence interval is comprised of the elevation estimate (the most likely value) and a margin of error around that estimate. The margin of error indicates the amount of uncertainty that surrounds the elevation estimate. The term "95% confident" means if we went through this process many times (i.e. if we could go back in time and re-collect the data over and over again), 95% of the resulting “95% confidence intervals” would capture the true value. That is, the method used to estimate the upper and lower bounds would fail to capture the true value 5% of the time. The 95% confidence interval is a standard statistical measure of the precision of an estimate, the percentage; in this case 95% is the confidence level.

The six largest downward movements were measured at the monitoring points shown in Table 2-3. Along with movement estimates, the table includes the upper and lower measurement ranges [confidence interval (C.I.)]. For example, monitoring point 609 is measured to have moved 0.40 inches downward between April 27, 2016 and May 2, 2017. The upper bound for downward movement measured at this point is 0.48 inches downward and the lower bound for downward movement is 0.32.

Table 2-3: Monitoring Points with the largest movement (QM10-QM12)

Point ID	Location	Movement	Movement 95% Lower C.I.	Movement 95% Upper C.I.	Monument Type
609	603 Platt Ave. S. – on 17th St. E.	-0.033 ft (-0.40 inches)	-0.020 ft (0.324 inches)	-0.046 ft (-0.48 inches)	(MP, 3-foot rebar with aluminum cap)
618	Haggin Ave. S. – Near 17th St. E.	-0.022 ft (-0.26 inches)	-0.009ft (-0.18 inches)	-0.035 ft (-0.35 inches)	(MP, 3-foot rebar with aluminum cap)
625	Back yard – 505 Platt Ave. S.	-0.022 ft (-0.26 inches)	-0.009 ft (-0.18 inches)	-0.035 ft (-0.35inches)	(MP, 3-foot rebar with aluminum cap)
701	NW Corner Civic Center	-0.036 ft (-0.42 inches)	-0.025 ft (-0.37 inches)	-0.047 ft (-0.50 inches)	(MP, 3-foot rebar with aluminum cap)
703	NW Corner – 114 14th St. E.	-0.027 ft (-0.32 inches)	-0.014 ft (-0.25 inches)	-0.040 ft (-0.40 inches)	(MP, 3-foot rebar with aluminum cap)
404-8	NE Corner Garage behind 404 Broadway Ave S.	-0.020 ft (-0.25 inches)	-0.008 ft (-0.17 inches)	-0.033 ft (-0.31 inches)	(MAG, Nails installed in Concrete Flatwork)

Monitoring points with a 95% confidence interval that include downward (negative) movement at both upper and lower bounds have likely experienced some downward movement within that range. Figure 2-12 shows the distribution of all measured differences, where the highest values shown in the table are on the left side of the bar chart.

Figure 2-13 shows a displacement map created from the survey data. The map includes city streets and the location of known workings. Displacement shown in Figure 2-13 should be cautiously interpreted in light of measurement accuracies and the relatively short period included in the monitoring program; for example, just because a small negative displacement shows on the map, the monitoring point may not have moved down. The 95% Confidence intervals shown in Figure 2-8 through Figure 2-11 should be considered to assess the amount of uncertainty associated with each individual monitoring point. Furthermore, while every effort was made to filter measurement errors and disturbed monuments, unanticipated and uncontrollable monument disturbances (vehicle and pedestrian traffic, poor drainage, and unstable surface materials) may appear as movement and not actually be associated with mine subsidence.

3 Crack Monitoring Gages

Eight crack gages (CG) were installed at the following addresses:

- 501 S. Broadway Ave. (CG1, CG2, and CG3). Note CG3 is abandoned.
- 505 S. Platt Ave. (CG4 and CG5).
- 404 S. Broadway Ave. (CG6 and CG7).
- 207 S. Hauser Ave. (CG8).

The purpose of the gages was to monitor existing cracks on the house foundations to see if there was noticeable change over time. The gages are rigidly attached to both sides of the crack on the house foundations. The gage measures the relative movement across the crack. Pioneer monitored movement by photographing each gage and then comparing that picture to the initial monitoring trip pictures. Crack gage measurements are listed in Table 3-1. The movements are also shown in Figure 3-1. The results show some recordable movement, with a magnitude of 1 millimeter (mm) or less, was observed on all the crack gages. Gages installed at 501 South Broadway showed the most movement and are discussed below.

Three gages were installed at 501 South Broadway and two remain; the third gage was damaged early on in the study. The two remaining gages (CG1 and CG2) are located on the south side of the house near the east and west ends. Both registered small amounts of movement. As shown in Table 3-1, CG1 indicated horizontal and vertical movement of -0.5 mm, and CG2 measured horizontal movement of 1 mm, both left and right, and vertical movement of -0.5 mm.

Because the movement is in multiple directions, and is less than 1mm, it likely indicates slight shifting of the foundation caused by freeze-thaw or wetting/drying of subsoils. It is unlikely that this type of movement could be caused by collapse of mine workings beneath the structure.

The initial and final crack gage photographs are included in Appendix C.

Table 3- 1. Crack Gage Measurements

		QM1		QM2		QM3		QM4		QM5		QM6	
		1/20/2014		4/28/2014		7/30/2014		11/19/2014		1/5/2015		4/8/2015	
Resident	Crack Gage	V*	H**	V*	H**	V*	H**	V*	H**	V*	H**	V*	H**
404 Broadway Ave	CG6	-	-	Install	Install	NA	NA	0.0	0.5	0.0	0.0	0.0	0.0
404 Broadway Ave	CG7	-	-	Install	Install	NA	NA	0.5	0.0	NA	NA	0.5	0.0
501 Broadway Ave	CG1	Install	Install	0.0	0.0	NA	NA	0.0	-0.5	NA	NA	NA	NA
501 Broadway Ave	CG2	Install	Install	-0.5	0.0	NA	NA	-0.5	0.0	-0.5	1.0	-0.5	0.0
505 Platt Ave	CG4	Install	Install	NA	NA	NA	NA	0.0	0.5	NA	NA	0.0	0.0
505 Platt Ave	CG5	Install	Install	0.0	0.0	0.0	0.0	0.0	0.3	NA	NA	0.0	0.0
		QM7		QM8		QM9		QM10		QM11		QM12	
		8/5/2015		10/26/2015		1/29/2016		4/27/2016		8/26/2016		5/2/2017	
Resident	Crack Gage	V*	H**	V*	H**	V*	H**	V*	H**	V*	H**	V*	H**
404 Broadway Ave	CG6	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	NA	NA	0.0	0.0
404 Broadway Ave	CG7	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0	0.5	0.0
501 Broadway Ave	CG1	-0.5	-0.5	-0.5	-0.5	-0.5	0.0	-0.5	0.0	-0.5	-0.5	-0.25	-0.25
501 Broadway Ave	CG2	0	-1.0	0.0	-1.0	-0.25	-0.25	-0.25	-0.25	NA	NA	-0.25	-0.25
505 Platt Ave	CG4	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
505 Platt Ave	CG5	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

* Vertical (+) indicates right-side "up" (-) indicates right-side "down"
** Horizontal (+) indicates right-side "right" (-) indicates right-side "left"

4 EXTENSOMETER

A Slope Indicator rod extensometer was installed at a depth of 124 feet (19 feet below top of bedrock) in borehole BH-02. An extensometer is a device that measures and records vertical movement of subsurface material. A VW-displacement sensor (Slope Indicator) and VW Mini Logger (Slope Indicator) were installed to measure and record movements of the extensometer. The VW Mini Logger recorded daily measurements.

Due to problems and damage caused by freezing water, the electronic monitoring device was removed during the QM10 (April 2016) monitoring trip. The extensometer rod remains in place and was incorporated into the survey network starting with the QM10 trip as point 823. Within the accuracy of the extensometer device, the measured data do not show any abnormal deviations or changes that would imply a change in elevation.

5 SUMMARY AND CONCLUSIONS

Over the year spanning April 2016 to May 2017, measured movements at all locations ranged between 0.0 to -0.036 feet (-0.43 inches), with an average of -0.0135 feet (-0.16 inches). This provides good correlation to the calculations presented in the DSAR, which estimated maximum potential subsidence values of 3 to 7 inches over the next 50 to100 years, equating to an average rate of -0.0025 to -0.012 feet/year (-0.03 to -0.144 inches/year).

As illustrated in Figure 2-13, some locations within the study area exhibited a greater amount of elevation change than others. However, no monuments surveyed had movement which would cause a concern for any kind of rapid subsidence occurring, further verifying the DSAR prediction of a relatively slow rate of movement over a long period of time. Degradation of mine workings is a slow process with many complicating factors; in the end, surface subsidence is the accumulation of many very small episodic events that accumulate as the mines slowly close in on themselves. The magnitude of movement measured in this study is relatively small and, based on the fact that the average movement correlates fairly closely to the rate predicted in the DSAR, further confirms that the overall potential subsidence predicted in that report is most likely a worst-case scenario.

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