Time-lapse gravity monitoring of an aquifer storage recovery project in Leyden, Colorado

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Summary

We present a case study on using time-lapse micro-gravity surveying to monitor an aquifer storage recovery project. An abandoned coal mine is being developed into an underground water reservoir in Leyden, Colorado. Excess water from surface sources is poured into the reservoir during winter and then retrieved for use in the summer. Efficient operation of the storage-recovery process requires knowledge of water concentration and movement within the mine shafts as well as well in the hosting geologic units. Three micro-gravity surveys were carried out to monitor the process over the course of ten months during the initial water injection stage. We will present the survey design, data acquisition, and preliminary results of the monitoring experiment.

Introduction

The Colorado Front Range has history of repeated draught conditions. Water storage and retrieval has become an increasing concern in the region since there is a large amount of excess water in the winter months while increased consumption strains the water supply in the summer. The aquifer storage recovery process offers an attractive means to manage the water supply in this region, since it utilizes an underground reservoir and surface space is not needed. Instead of further straining naturally occurring aquifers, the City of Arvada has turned to abandoned coal mines as a solution to water storage. This alternative solution is advantageous because abandoned coal mines have large storage capacity their subsurface conditions are better known. Filling coal mines with water has previously been done locally in Colorado Springs for subsidence prevention, and such experiments have proven the feasibility of using these old mines as underground water reservoir. As in any storage-recovery process, however, there are many uncertainties. In particular, water distribution and concentration in the subsurface are unknown. Although observations in well provide spot information, monitoring using geophysical methods is necessary to provide a larger-scale characterization.

We investigate the feasibility of using time-lapse micro-gravity surveys to monitor the water distribution in the mine. Three gravity surveys were taken over a ten-month period. The gravity surveys have observed stable anomalies over the period and the time-lapse data are consistent with the known geology and projected water distribution.

Background

The Leyden mine is located near Leyden, a suburb of Arvada, Colorado. This was an active coal mine with two coal seams. The mine operated until 1950. Subsequently, the mine was used for natural-gas storage by a local utility company. The City of Arvada retained rights in 2003 and began using it as a subsurface water reservoir in 2004. The initial injection of water will be for two years, after which the storage-recovery cycle will begin. During this stage, water injection will also help in removal of residual natural gas stored in the mine.

The mine is approximately 300 meters in depth and has a lateral extent of 16 square kilometers encompassing two coal seams (Figure 1). The extensive mined rooms serve as the primary storage space. The coal seams are contained within the lower Laramie formation. Figure 2 shows a simplified geologic cross section. Directly below the mine is the Fox Hills sandstone, which is a natural aquifer. The Pierre shale is a thick impermeable layer directly below the Fox Hills. The lower Laramie formation was deposited in a fluvial environment and is a mix of sandstone and clay. The overall permeability of the Laramie is poor, so this provides a good location for water storage. The mine has slight dip of less than 5 degrees.

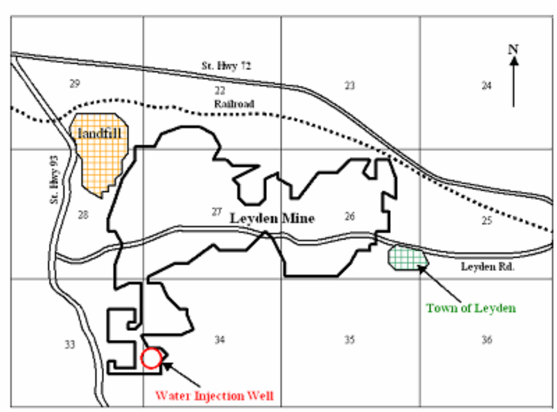

Figure 1. Each box on the map represents a section (one square mile in area). The outline of the Leyden mine is given by the thick black line. Water is being poured in the well shown in red in section 34.

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Abandoned coal mines generally do not remain as large open voids. Normally, over time, the roof collapses and the region above the mine dilates or is 'stoped' to some height above the workings (Figure 3). In some areas, this causes problems when the rubble zone reaches the surface causing damage to structures and utilities. The Leyden mine is at 300 meters depth and its stoping does not get near the surface. However, stoping will reach some height, so the storage water filling the voids can reach considerable height above the actual mine level. The water can also infiltrate these zones before the voids are filled. The extent and precise nature of these rubble zones are unknown, and constitute the largest variability in factors that control movement of water.

In order to effectively use Leyden mine for water storage and recovery, details on water distribution and concentration are critical. Rubble zones in the mine will create higher permeability zones through which water can flow. In order to extract a substantial amount of water, these zones should be identified for potential placement of wells. Any information about leakage out of the mined area is also significant, as the recovery efficiency (percentage of injected water that can be recovered) is critical in any storage-recovery project.

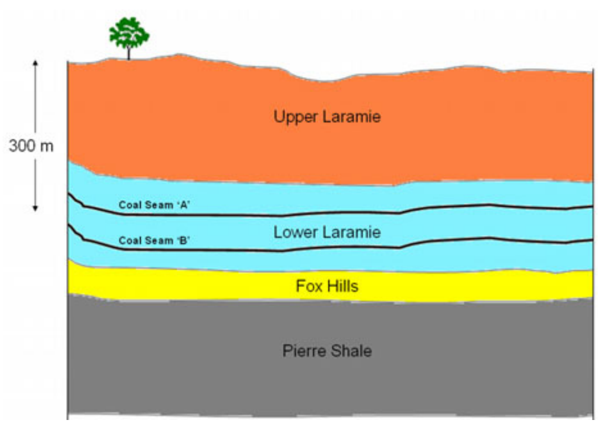

Figure 2. A vertically exaggerated, simplified geologic cross section of the Leyden coal mine, located in the lower Laramie. The coal seams are located approximately 300 meters below the surface.

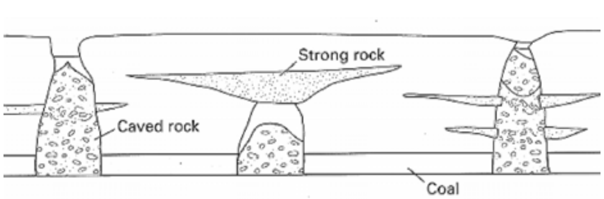

Figure 3. Illustration of types of collapse above mine workings and the formation of rubble zones (Dunrud, 1998).

Time-lapse gravity survey

Survey Design. Having no prior information of the activity of the water in the subsurface, we choose to use a 300-m station spacing for gravity survey. Originally, there were 107 gravity stations; however, due to time, terrain, and inclement weather, only 61 stations were used consistently throughout three surveys. These stations surround the area over the mine into which water is being poured. The stations were marked with a 12" steel bar so that both location and elevation of each gravity station can be repeated accurately over time. The steel bar also allowed the stations be found with a metal detector and enabled the survey locations to be permanent, even after a wild fire in the survey area. Black x's represent stations in Figures 4 through 6 that display the result of gravity survey. For reference, the black circle corresponds to the location the well in which water is introduced.

Four background stations were placed at least one half mile away from the known boundaries of the mine. These locations were also used as quality control stations in order to ensure the accuracy of each individual measurement. Quality control was maintained through the use of absolute gravity measurements. Three measurements were taken in three important locations: the water location, the middle of coal seam 'B', and a background location a mile away from the mine.

One background station is treated as a reference station where the gravity value is assumed to be constant over time. The gravity differences of the other background stations are observed for quality control purposes. Three data sets are processed accordingly. During the survey, the background stations varied less than 5 μGals, which is the accuracy of the gravimeter.

Instrumentation. The first two gravity surveys were performed with a Scintrex CG-3 relative gravimeter. These surveys were taken in April and October of 2004. The CG-3 has an accuracy to within $\pm$ 10 µgals. Measurements were recorded for 60 seconds and then an average reading was obtained. To improve accuracy, two readings were taken at each station.

The third survey was acquired with a Scintrex CG-5 relative gravimeter. This survey was taken in February of 2005. The CG-5 has an accuracy of $\pm$ 5 µgal. Measurements were also recorded for 60 seconds with two readings per station, as with the CG-3. The two readings were then averaged to obtain one reading per station for difference mapping and inversion purposes.

Both gravimeters had an automatic drift correction, seismic correction, and auto rejection of outliers. The use of these automated corrections was utilized, though base stations were repeated every 2 to 3 hours to improve the accuracy of tidal/drift corrections.

Results. Due to the nature of time-lapse gravity, only the drift/tide corrections were made to the data. Though the gravimeters had automatic drift correction, base stations were used in addition to ensure quality. Other commonly applied reductions, such as terrain and latitude corrections, were not applied to individual data sets. Since they are common to all three data sets, their effect is removed when time-lapse differences are obtained by subtracting two data sets.

Three absolute gravity stations were taken to during the first survey, two directly over the mine and one for a background measurement. The three stations will be repeated at the end of the project and compared to the amplitudes of the relative gravity for quality control.

Three difference maps were generated from the data sets. The difference between the first and second, second and third, and first and third surveys are shown in Figures 4, 5, and 6, respectively. Figure 4 indicates the change in water distribution from April to October of 2004. Figure 5 shows the change in water distribution from October 2004 to February 2005. Figure 6 reflects the total change in water mass from April 2004 until February 2005.

Quantitative analysis through modeling and inversion is being carried out. However, much information can already be obtained from visual inspection of the difference maps. The major positive anomaly occurs near the injection well, reflecting the increased water mass in the vicinity. A major rubble zone may be present just northwest of the well, as a clearly defined anomaly is present in the first difference map (Figure 4) and also is visible in the second difference map (Figure 5). This leads us to believe that the rubble zone may be filled with water to a large extent. The total amplitude of the rubble zone is about 250 μGals.

Secondary rubble zones may now be filling as indicated by the difference map between the second and third surveys. The size may be comparable to the major anomaly from the first difference map, however we will not know until the same amount of time has elapsed. The amplitude change in three months is comparable to the major anomaly at about 130 μGals. The background measurements confirmed accurate results as there is no difference over the course of all three surveys.

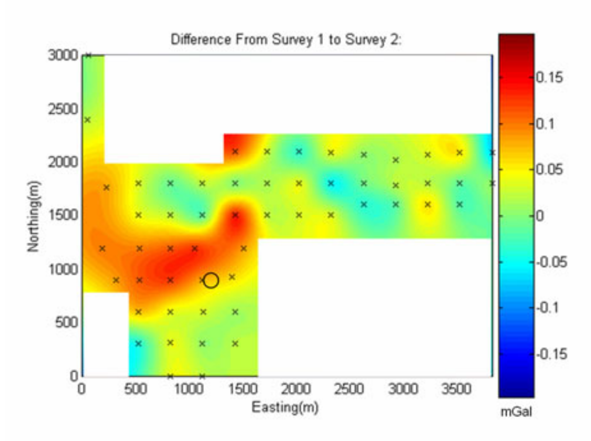

Figure 4. The difference map in of water mass between April and October 2004. The center of the black circle indicates where water injection is occurring.

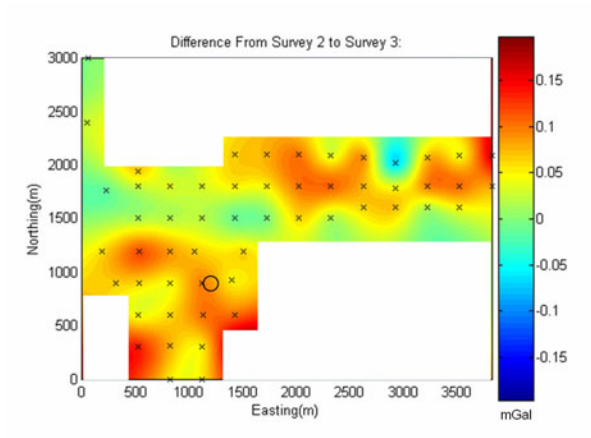

Figure 5. The difference map in of water mass between October 2004 and February 2005. The center of the black circle indicates where water injection is occurring.

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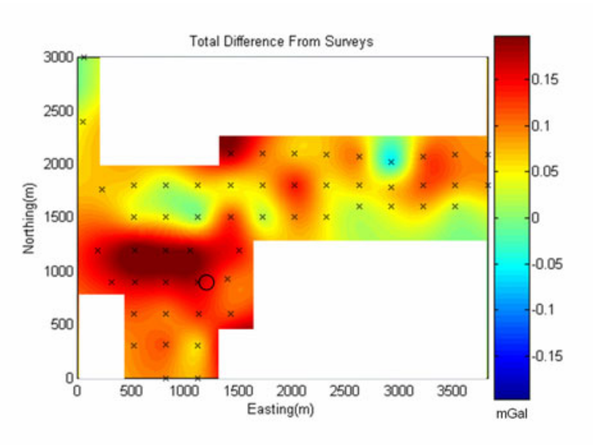

Figure 6. The total difference from April 2004 to February 2005. The black circle represents the location of water injection.

Discussion

The City of Arvada engineers speculate that there is a presence of rubble zones in the mine that may extend up to 100 meters above the mine. The results from the time-lapse surveys confirm the presence of rubble zones, but preliminary interpretation cannot constrain the size. The positive anomalies can be correlated to rubble zones due to the excess mass of the water present and the knowledge of the impermeable intact rocks surrounding the mine since the rubble zone would be much more permeable and allow for water movement.

Several aspects of this project require further work. Inversion of the data will take place and a model of the difference maps will be created. The inversion will help city engineers to decide if they need to drill another well in order to extract the water in a time of need.

In addition, a DC resistivity survey was performed in order to better understand the subsurface behavior and compliment the gravity data. The Schlumberger sounding was performed the same day as the second gravity survey was taken.

Acknowledgements

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EDITED REFERENCES

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