# Salt Cavern Monitoring System for Early Warning of Sinkhole Formation

***Bill Shefchik***
***Reynold Tomes***
***Riccardo Belli***

## Introduction

The city of Hutchinson is located in Reno County, Kansas. Hutchinson is on the route of the trans-continental, high-speed mainline of one of the nation's largest railroads. The railway passes near a former salt mine well field, where mining was carried out in the early part of the twentieth century. The salt mining was performed at depths of over 400 feet by drilling wells through the shale bedrock into the thick underground salt beds, and then pumping fresh water into the salt, dissolving the salt to be brought back to the surface as brine, for processing and sale. This solution mining process resulted in the presence of multiple, large underground voids and caverns, which have been reported to be up to 300 feet tall and over 100 feet in diameter. In places, the shale roof rock over some of these old mine voids has collapsed, forming crater-like sinkholes that can be over 100 feet in diameter and 50 feet deep at the surface. The collapse and sinkhole formation can occur very rapidly, over a period of hours to days. Figure 1 is a photograph of a sinkhole that opened up virtually overnight at this site in 2005, by collapse of a salt cavern that was last mined in 1929. The potential rapid formation of sinkholes by collapse of old mine caverns clearly represents an issue for ground stability and a non-negligible safety risk for surface infrastructure, including the railway.

## Monitoring Solution

An area on the site containing old, potentially unstable salt caverns adjacent to sensitive surface infrastructure was identified with the aim of establishing an effective monitoring system in order to provide early stage detection, continuous monitoring, and automatic telemetry. Arrangements were made for alerting via cell phone and email, in case of ground deformation (strain) that may be the early signs of sinkhole formation.

The distributed fiber-optic (FO) monitoring system (Inaudi and Glisic, 2007) was selected in large part because it provides thousands of monitored points using a single fiber-optic sensing cable, all measured at the same time, in a single scan. This is well-suited to defining a monitored perimeter where the exact location of where a sinkhole might form is not known precisely. In addition, this monitoring system was selected because of the ease of installation by burial in a shallow trench.

In a geotechnical project like this, the selection of the sensing cable represents a key aspect, and at the same time, a big challenge: the sensing cable needs to be capable of withstanding hostile environmental conditions, such as wide temperature variations and burial in the ground, as well as being resistant to burrowing rodents. At the same time the cable needs to be sensitive enough to provide early and reliable displacement detection of settlement of approximately 10 mm in magnitude, according to soil type and characteristics. It must also be capable of optimizing the transfer of forces from the ground to the fiber, even through the various cable protective layers, which in this case includes a steel ribbon wrapping to resist gnawing by rodents.

The sensing cable is directly buried at a depth of approximately 1.4 meters, (4 ft), over a potential sinkhole area above and around salt caverns over a path with a total length of over 4 km, (13,000 ft) – see Figure 2.

After digging the trench, the silty soil was mechanically compacted, and the sensing cable laid on the compacted soft ground before the trench was backfilled. The sensing cable was installed in several segments in order to provide easier handling during installation, and

*Figure 1. Sinkhole formed rapidly in 2005, at Old Brine Well at the Hutchinson site.*

*Figure 2. Trench preparation.*

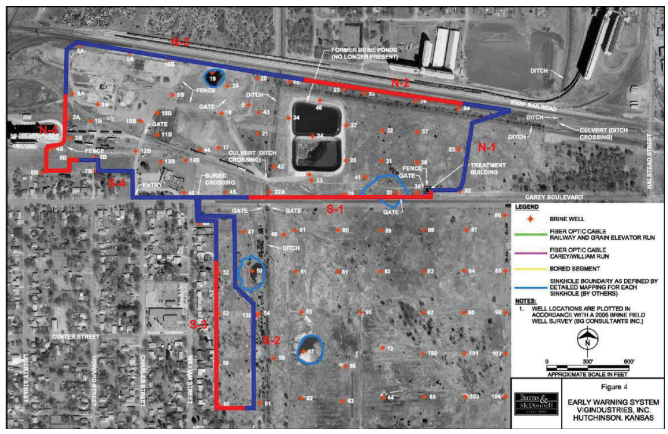



*Figure 3. Sensing cable layout.*

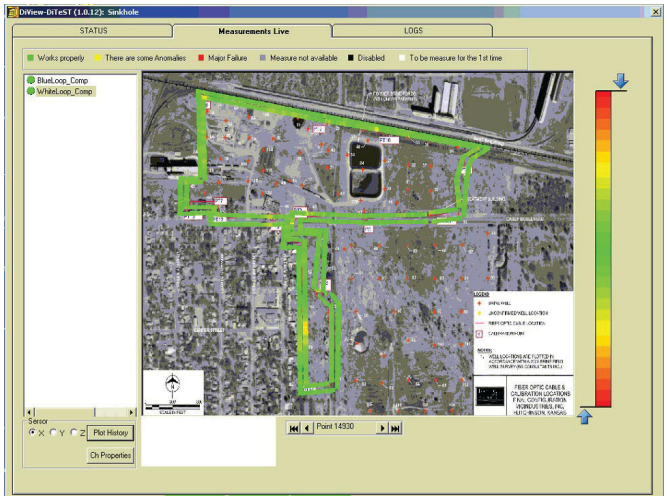



*Figure 4. Software for sinkhole project: Direct, real-time read-out of ground strain along the cable.*

to adapt to the site by running the cable through several short, horizontally bored segments beneath a large drainage ditch, multiple road crossings, and other obstacles at the surface. All cable segments were later linked together, to form a single sensing loop, by fiber-optic fusion splicing. The splices between segments, as well as some extra lengths of non-buried cable, are stored in dedicated, above-ground junction boxes, that can be accessed for maintenance as well as for re-routing segments of cable in case a break were to be caused by the formation of a sinkhole.

The final layout of the FO cable is shown in Figure 3, the different colours, with labels, are used to identify the different cable sections spliced together.

After finishing the cable installation and completing all the necessary quality/functionality tests on the sensing cable itself such as sensor integrity test by mean of visual fault locator, sensor attenuation test by means of OTDR measurements, Optical Time Domain Reflectometry, quality of the FO splices, the system was ready for commissioning and final handover. The system commissioning mainly consisted of:

- Sensor parameterization to optimize system performances in terms of strain resolution. In this phase using the FO system managing software it is possible to set the length of the sensor, the spatial resolution, the measurement time and a series of instrument parameters that influence the final system performance in terms of strain resolution and accuracy.
- Establishment and surveying of a coordinate system to relate lengths along the cable to specific marked locations on the ground: a key aspect in a distributed monitoring project is an established coordinate system that will allow the precise position of an alarm triggered by ground strain to be shown on a computerized map. At a point where ground strain is detected by the cable, the software reports the exact location along the cable, in meters of distance from the end of the cable, (essentially at location of the computer). Luminous high-visibility signs were posted at the site along the cable route, indicating lengths from the end of the cable, so that responders in the field can quickly and accurately proceed to whatever location the alarm indicates. The coordinate system also allows the definition of several specific alarms zones, according to the client's requirements, which will be automatically handled by the software.
- System functionality check: simulation of ground settlement by artificial imposition of external force. Tests were run in the field, along temporarily un-buried segments of

*Figure 5. Site pull test.*

the cable, by displacing the cable in simulation of ground strain or by putting the cable in tension, to gauge and record the response of the system.

## Software

The final step for achieving a fully automatic surveillance system is the Distributed Data Management and Analysis Software, designed for data storage, processing, representation, and analysis, as well as for the control of single or multiple reading units.

The main functions of the software are automatic data acquisition, map and graphical visualization of the real-time strain data along the entire cable length, and triggering of warnings of significant ground displacement on the display, as shown in Figure 4. The software stores all information related to a sensor in a single data-base structure. Multiple users can access the software simultaneously from different PCs (locally or remotely over a modem or LAN).

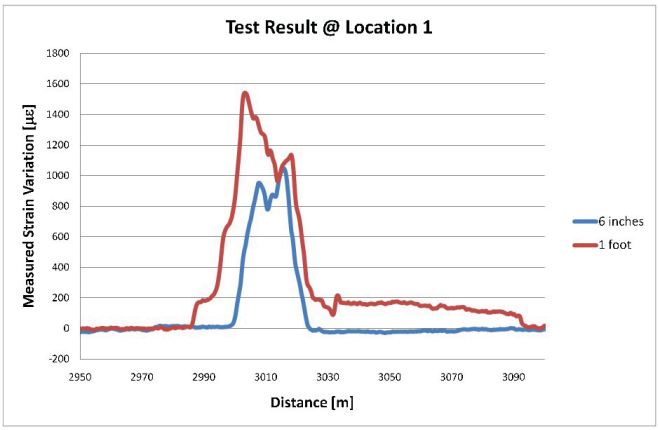
The algorithm that supports the software is particularly robust against false alarms caused by outlier values or noisy measurements. Moreover it allows the whole system, reading unit, and distributed temperature sensing cable, to be insensitive to environmental influences and variations. Seasonal variations in temperature can be screened out, so that they do not impact the validity and reliability of the measurements.

Besides all these capabilities, the software is specifically developed to send alerts in case ground deformation exceeds a designated threshold level. In this project, if a threshold is exceeded, an alert is triggered by both e-mail and text message to a selected list of recipients who will respond to the received warning by proceeding to the site to assess whether a sinkhole may be forming, and then take corrective action. The recipients include key project management, the client's consultant, and local first responders, in this case the Hutchinson Fire Department. In case the warning is not acknowledged the software automatically sends a reminder to the same recipients.

The software structure offers a certain level of self-diagnostic capability, and provides data and information to the users in an easy and fully understandable format.

## Site Pulling Tests

In order to assess system capabilities in terms of ground deformation detection and alert triggering, some site pulling tests were carried out. These tests are aimed to evaluate and confirm the performances of the whole final system intended as sensor, reading unit and data management software working together. The idea was to apply an external force to segments of the cable in portions of the trench that had not yet been backfilled, in order to induce strain and simulate the symptoms of ground deformation.



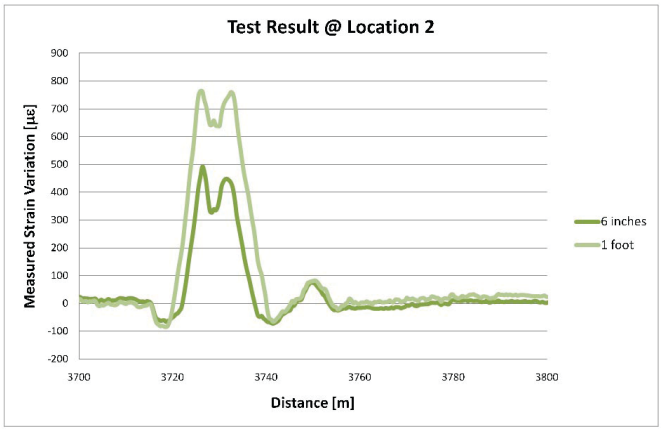




*Figure 6 a & b. Examples of results of the on-site pulling tests.*

For one test, a vertical force was applied on a cable section by raising the cable to different heights above the floor of the trench in order to simulate a highly localized ground deformation event – see Figure 5.

Different forces were applied to the cable during the test, to simulate different levels of ground displacement, with cable displacements of 15 cm, (6 in.), 30 cm, (1 ft), 61 cm (2 ft), and 1.2 m. The test was repeated at several different locations to evaluate the capability of the system for reliably determining the exact location of ground strain events. The system proved capable of sub-meter accuracy, at multiple test locations along the 4 km-long cable. All the tests demonstrated the proper functioning of the system, both in terms of ground deformation detection and alert triggering with exact locations.

The recorded results and graphs showed how the different amounts of deformation of the cable can influence the strain distribution along the sensing cable. The data showed a coherent behaviour of the system at all of the test locations – see Figures 6a and 6b.

## Challenges Encountered and Overcome, and Lessons Learned

Some of the biggest challenges in the development of an FO distributed project can be field issues during installation of the sensing cable. Despite the overall relative ease of the installation by conventional trenching and horizontal boring, inconveniences that can occur over such a wide area, with a 4 km perimeter, must be considered, including the need to divert around buried obstacles; to modify the cable path to avoid third party properties; and to cross beneath roads and surface water drainage features using lined, horizontal borings. These issues can usually be overcome because FO sensing cables are relatively easy to handle, when installed by trained personnel, and, if necessary the cable can be cut and spliced to facilitate the installation. The capability to splice provided the opportunity to install the cable in several sections, greatly simplifying the field modifications needed to install the cable and bypass or overcome obstacles. A challenge that had to be met and overcome on the Hutchinson project was the presence of a particular type of rodent (pocket gopher) that, in their feeding habit of burrowing through the ground to eat plant roots, were found to be damaging the cable. Although the cable was being installed inside a woven fiberglass sleeve to deter such rodents, damage was still being done. Fortunately the damage was discovered by continuous and scrupulous quality checking that was on-going during installation. A new, more robust, armored cable was quickly designed, tested, and produced at the factory. The new cable was required to not only be rodent-proof, but to still be sufficiently flexible to serve the detection sensitivity specifications of the project. The first prototypes from the factory included a precisely wrapped, flexible steel ribbon-armored layer, plus a larger cable diameter designed to exceed the effective jaw spread of the rodents. Prototypes of the new cable were tested under laboratory conditions for suitability of its mechanical and optical characteristics before the subsequent full production run, which then produced all of the cable needed for the project. The re-designed cable has overcome the rodent issue.

## Conclusions

Monitoring of the ground for the earliest possible warning of incipient or actual formation of a sinkhole due to collapse of underground mine caverns involves challenges that are uniquely addressed by a fiber-optic system. Since sinkhole formation resulting from mine cavern collapse can occur very rapidly, and possibly with little or no prior warning, a monitoring system that can run virtually continuously is essential if an effective, earliest possible warning is to be provided. For the project discussed in this article, the caverns are widespread across a significant area, are near significant infrastructure (including rail), and will lead to sensitive ground strain variation if their collapse is imminent. A distributed FO system offers significant advantages compared to any other possible monitoring approach in addressing all of these factors, and is very well suited to this complex task.

The entire system was developed to provide fully automatic and self diagnostic capabilities, no operator required; to dispatch alerts via telemetry through both email and cell phone sms; and to provide for remote control of the system to increase troubleshooting effectiveness and system maintenance. The ultimate value of the system is its ability to allow a rapid and effective response and intervention to the consequences of potential rapid sinkhole formation due to collapse of a cavern.

## Reference

D.Inaudi, B.Glisic "Distributed Fiber-optic Sensors: Novel Tools for the Monitoring of Large Structures" GIN September 2007, pp 31-35. www.geotechnicalnews.com/pdf/GeoTechNews/2007/GIN_sept_2007.pdf

*Bill Shefchik, Burns & McDonnell, 9400 Ward Parkway, Kansas City, MO 64114 USA,*
*email: bshefch@burnsmcd.com*

*Reynold Tomes, Burns & McDonnell, 9400 Ward Parkway, Kansas City, MO 64114 USA,*
*email: rtomes@burnsmcd.com*

*Riccardo Belli, SMARTEC SA, Roctest Group, Via Pobiette 11, 6928 Manno – Switzerland, Tel: +41 91 610 18 00,*
*email: riccardo.belli@smartec.ch*