A sewer sinkhole study using TEM

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On 7 September 2002, two large sinkholes opened suddenly on a major, five-lane roadway in Tucson (Arizona), USA (Figures 1 and 2). The exact cause of the sinkholes is still controversial, but the sinkholes were apparently related to failures near 90° bends in a 35-year-old, 6-m deep, 1.1-m diameter sewer line known as the outfall interceptor.

Fortunately, the collapse of the roadway and sidewalks began in the middle of the night, causing no personal injuries, but initial street repair costs were estimated at US$4.5 million, plus an additional US$2.5 million to divert sewage during repairs, and US$1 million in engineering costs. In addition, claims against the county (which operates the sewer system) were filed by numerous businesses, more than 60 nearby residents had to be relocated to hotels, and the adjacent Arizona State School for the Deaf and Blind was temporarily closed. The county was also reportedly served with at least 11 environmental violations by the Arizona Department of Environmental Quality because an estimated 25-50 million gallons of raw sewage flowed through broken storm drains and into a nearby wash. The County recently approved a consent agreement with ADEQ, settling for a US$500 000 civil penalty and agreeing to spend another US$800 000 for a supplemental environmental project.

A third, smaller sinkhole developed just a few city blocks away on the same night at another 90° bend in the same sewer interceptor line, this time at the intersection of two residential streets.

With the sudden overnight development of three sinkholes on city streets, the potential for physical harm to the public was obvious. Had the sudden subsidence under the five-lane road occurred during rush-hour traffic, for example, injuries could have ranged from minor to fatal. The City of Tucson contracted our firm to assist in rapidly evaluating other locations along the 8-km length of the sewer interceptor line. The goal was to locate other problematic sites along the sewer interceptor line before they developed into costly or possibly dangerous sinkholes. The areas around 90° bends were the highest priority, to be surveyed first, followed by a survey of the entire length of the line.

Geophysical methodology. The conditions of the survey path eliminated several geophysical methods that we might normally use to detect subsurface voids and/or unusual fluid accumulations. Since the majority of the sewer line is beneath paved roads, the galvanic methods such as resistivity and IP, which require good electrical contact with the ground, were considered too slow and difficult. (A capacitively coupled resistivity system was tested but, as expected, the low-resistivity soils limited the depth of investigation). The low-resistivity soil also limited the use of ground-penetrating radar, since the depth of investigation would not have been sufficient for the goals of the survey. Although transient electromagnetics (TEM) would not normally be our first choice for void detection, the change in resistivity from an unusual fluid accumulation should be detectable with TEM and the system can be cart-mounted for fairly rapid coverage; thus, we elected to test TEM over the third, small sinkhole to determine if it appeared anomalous relative to the surrounding, presumably good sections of the same sewer line.

TEM, or TDEM for "time domain electromagnetics," is

Figure 1. *One of two large sinkholes that opened suddenly in the early morning hours of 7 September 2002 on Speedway Avenue in Tucson, USA. The collapse closed the five-lane road for 78 days, causing millions of dollars in damage.*

Figure 2. *One of the Speedway sinkholes, after partially draining the sewage. When the sinkhole formed, raw sewage flooded the sinkhole and more than 25 million gallons of sewage flowed through a broken storm drain (center of picture, with sandbags) into the Santa Cruz River.*

Figure 3. *Assembly of the nonmetallic TEM cart during testing. The transmitter loop was 3 × 3 m, and the receiver loops were 2 × 2 m (for the Hz component) and 1 × 1 m (Hx and Hy components). The loop frames were PVC pipe, and the wheels were plastic. The large black plastic pipes on the left are part of the sewage diversion system while the sewer interceptor line was being repaired.*

a commonly used survey method for a variety of near-surface applications. In a fairly small configuration for example, a 1-m square transmitter loop, a cart-mounted version of TEM is one of the most commonly used methods for unexploded ordnance (UXO) detection. With larger loops, twenty to hundreds of meters, we often use TEM in deeper minerals and groundwater exploration.

For this TEM survey, a 50% duty cycle, time domain, square wave signal (usually 3 amps) was transmitted into the ungrounded transmitter loop of wire measuring 3×3 m (Figure 3). This square wave signal alternates between positive, zero, negative, and zero voltages, and this cycle repeats 64 times per second. The measurements are made when the transmitter is off (i.e., transmitter voltage is zero). During these times, decaying secondary magnetic fields from subsurface conductors can be measured. In this survey, these magnetic fields are detected with three orthogonal ungrounded square loops of wire, measuring 2×2 m (for the vertical component measurement) and 1×1 m (for the two horizontal measurements). The measurements are made at 31 times (or "windows") after the transmitter is turned off in order to measure the decaying response of the background earth as well as secondary fields from strong conductors (such as metallic objects) after the background earth response has decayed to near-zero values. To minimize random background noise, 32 complete cycles of the waveform are stacked and averaged, constituting one data block. Measurements are made at a rate of about 1 data block every 0.6 s, and at a slow walking pace, this results in one stacked and averaged data block approximately every 0.3-0.5 m. Measurements of all three receiver loops are made simultaneously on three separate A/D channels (i.e., no multiplexing is used) and stored in the digital memory of the receiver. A Trimble Asset Surveyor GPS system, with the antenna mounted above the center of the transmitter loop, provided positioning information.

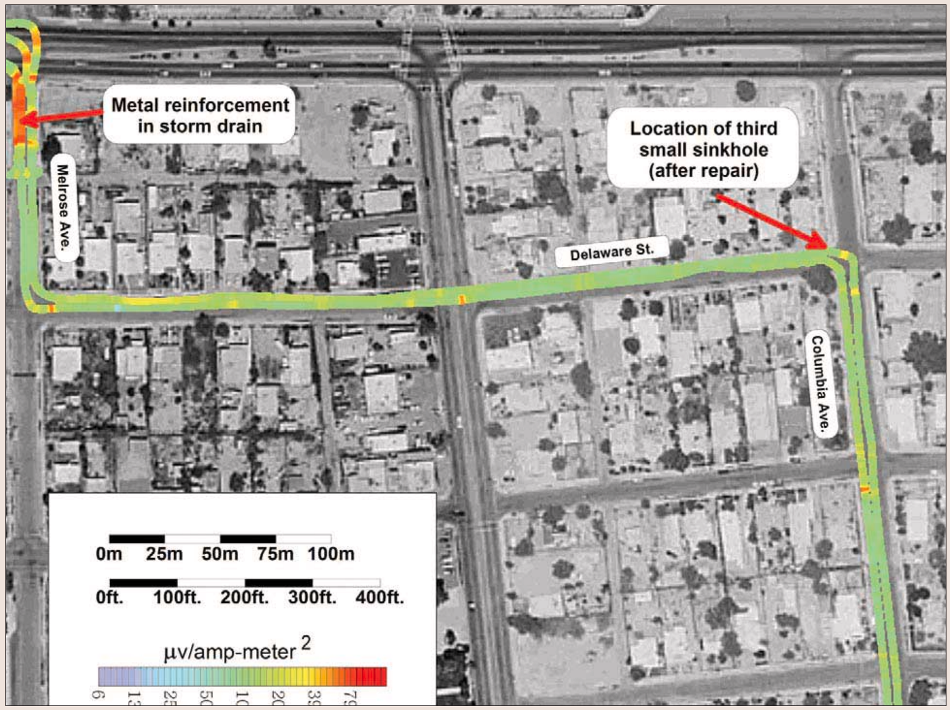

Figure 4. Plan view of the TEM data showing typical background levels which were seen along most of the sewer interceptor line. The data plotted are the vertical component magnitudes in micro-volts/amp-m^2. For comparison to an anomalous section, see Figure 5.

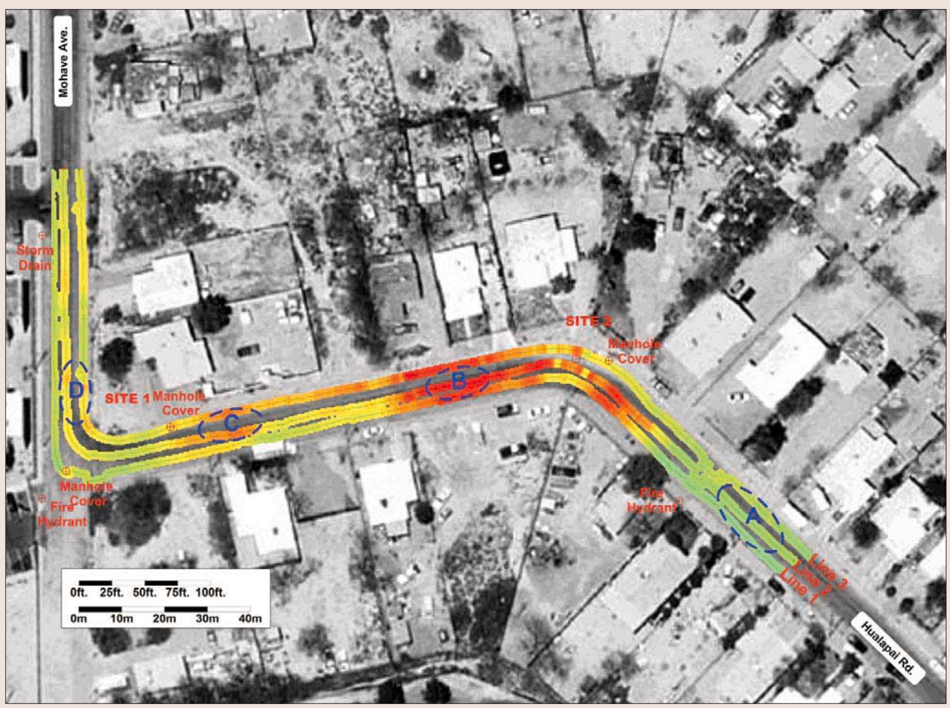

Figure 5. Plan view of the anomalous TEM data on three survey lines along Hualapai Road, using the same color scale for the data as in Figure 4. Dashed ovals labeled A, B, C, and D were areas selected for shallow borehole investigations.

Survey results. As a test of the method, and to evaluate the effects of cultural noise on the survey results, we surveyed the third, small sinkhole area relative to adjacent areas of the same sewer interceptor line. Cultural noise includes active electrical noise sources such as power lines, electrical motors, and radio frequency sources (transmitters, computers, etc.), plus "passive" cultural sources which include metallic conductors that respond to the TEM-transmitted signal (metal pipelines, metal fences, telephone lines, and large metal objects).

The sinkhole area was weakly anomalous: lower resistivity relative to nearby, presumably good sections of the sewer, probably as a result of the fluid escaping from the corroded and collapsed sewer. Since it appeared that the fluid accumulation could be distinguished from cultural noise,

Figure 6. One of the corroded sections of the 42-inch sewer interceptor line in the anomalous segment on Hualapai Road. Enough soil and dirt had fallen into the sewer to create a 2-m void above the sewer line, under the residential street.

Figure 7. A corroded section of the sewer interceptor line in the Silverbell Golf Course.

seven additional sites near sharp bends along the same sewer were surveyed. Most showed the expected cultural effects, usually consisting of sharp, strong anomalies from manhole covers and buried pipelines, and background results which were consistent with background data along streets which were not over the sewer interceptor line (Figure 4).

A strongly anomalous area with much lower resistivity than other areas was measured along a section of Hualapai Road, where the sewer interceptor line had two sharp bends in a distance of approximately 125 m (Figure 5). As a result, the survey lines in that area were repeated; background line segments and cultural features were consistent on both surveys, while the anomalous segments remained anomalous but showed a slight decrease in anomaly strength. This observation was expected since flow through the sewer had been reduced to near-zero levels. Based on this data, the city decided to drill shallow boreholes in areas A (as a background region), B, C, and D (as potential target areas) to investigate the source of the anomalous readings (Figure 5).

Upon notification of the city's plan for boreholes, the county decided to investigate this segment of the sewer interceptor line first by running a specialized video camera through the sewer line between the manholes near Site 1 and Site 2 (Figure 5). The camera, aimed upward at the top of the sewer pipe, clearly showed two 5-m segments of the pipe with the top or "crown" dissolved and completely missing. Above one segment, the video camera showed a void more than 2 m tall with a natural gas pipeline suspended in the void, just 1 m below the road pavement. The area was immediately closed off and excavated (Figure 6).

After the entire 8 km length of the sewer interceptor line had been surveyed, a long section of the line crossing the Silverbell Golf Course was found to be almost entirely anomalous, and very similar to the data on Hualapai Road. At the same time, investigations by the county with the in-pipe cameras found that stretch of the sewer line so corroded that even golf carts were not allowed to cross over the buried sewer line (Figure 7).

Conclusions and caveats. The geophysical survey clearly showed anomalous areas that were later confirmed as problematic sections of the sewer interceptor line. In the case of Hualapai Road, the geophysics may have averted the formation of a catastrophic sinkhole. Clearly any collapse (from a heavy vehicle, for example) would have broken the natural gas pipeline, with the possibility of an explosion. School buses travel this road to an elementary school two blocks away, and worst case scenarios can easily be envisioned.

However, the physical characteristics of the shallow subsurface responsible for these low-resistivity anomalies remains somewhat unverified in this case. After several legal discussions, the city eventually drilled four boreholes on Hualapai Road to determine the source of the low resistivities. As expected, moisture content was significantly higher in the anomalous areas relative to background (Area B showed an average of 10.7% moisture content by weight for the top 6.1 m of soil, measured at 0.8-m intervals, compared to 4.7% in Area A). However, the fluid did not appear to be sewage; thus, the low-resistivity anomaly could not be directly correlated with sewage escaping from the pipe. A speculative possible explanation is that hydrogen sulfide, a common sewer gas, escaped from the corroded sewer pipes and reacted with natural moisture and bacteria to form sulfuric acid, significantly lowering the resistivity of the soil. The borehole testing did not include enough fluid chemistry to determine the presence of sulfuric acid or other possible anomaly sources.

As with any event that impacts public safety, the Speedway sinkhole occurrence is not without controversy. In and around the city of Tucson, the public sewer system is owned and operated by Pima County, which is a very separate and distinct legal entity. The roads and sidewalks above the sewer are the responsibility of the City of Tucson, however, as are the water utility lines that may be buried very close to or above the county-owned sewer lines.

As the sinkhole events unfolded, the cause of the sewer interceptor failure itself was, and is, disputed. Age/condition of the sewer line is considered one possible reason for the failure. Other proposed causes for the failure include the possibility of leaking city water mains which could have prematurely weakened the sewer line.

Suggested reading. "Detection of groundwater contamination near waste disposal sites with transient electromagnetic and electrical methods" by Buselli et al. (in volume II of *Geotechnical and Environmental Geophysics*, SEG, 1990). "Broad band electromagnetic systems" by Zonge (in *Practical Geophysics II for the Exploration Geologist*, Northwest Mining Association, 1992). *Near-Surface Geophysics* (SEG, 2005). TLE

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