NCKRI REPORT OF INVESTIGATION 6

GEOPHYSICAL INVESTIGATION OF FLOOD-INDUCED SINKHOLE COLLAPSES, LAKEWOOD REGION, EDDY COUNTY, NEW MEXICO

National Cave and Karst Research Institute

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Cover photo: Lasha Asanidze examines a newly developing sinkhole next to Lakewood Road. Photo by George Veni.

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NCKRI Organization and Mission

NCKRI was created by the US Congress in 1998 in partnership with the State of New Mexico and the City of Carlsbad. Initially an institute within the National Park Service, NCKRI is now a non-profit 501(c)(3) corporation that retains its federal, state, and city partnerships. Federal and state funding for NCKRI is administered by the New Mexico Institute of Mining and Technology (aka New Mexico Tech or NMT). Funds not produced by agreements through NMT are accepted directly by NCKRI.

NCKRI's enabling legislation, the National Cave and Karst Research Institute Act of 1998, 16 USC. §4310, identifies NCKRI's mission as to:

1) further the science of speleology;
2) centralize and standardize speleological information;
3) foster interdisciplinary cooperation in cave and karst research programs;
4) promote public education;
5) promote national and international cooperation in protecting the environment for the benefit of cave and karst landforms; and
6) promote and develop environmentally sound and sustainable resource management practices.

NCKRI Report of Investigation Series

NCKRI uses this report series to publish the findings of its research projects. The reports are produced on a schedule whose frequency is determined by the timing of the investigations. This series is not limited to any topic or field of research, except that they involve caves and/or karst. To minimize environmental impact, few or no copies are printed. Electronic copies of this and previous reports are available for download at no cost from the NCKRI website at www.nckri.org.

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Executive Summary

Following flooding in September 2013, several areas near the community of Lakewood in northern Eddy County, New Mexico, were damaged by multiple sinkhole collapses. Pettigrew & Associates contracted with the National Cave and Karst Research Institute (NCKRI) to conduct electrical resistivity (ER) surveys for cavities to guide road repairs along Lake and Lakewood roads. ER surveys involve injecting an electrical current into the ground between two implanted metal electrodes and measuring the voltage drop between two additional electrodes. Given the current flow and voltage drop, the distribution of electrical resistivity in the subsurface can be measured and mapped. ER surveys are one of the most effective methods for detecting air- or water-filled caves. Interpretation of the resistivity data was informed by subsurface records from area water wells.

Electrical resistivity surveys conducted parallel to Lakewood and Lake roads attained a maximum exploration depth of 55 to 62 m (180 to 203 ft.). Subsurface stratigraphy, including clay-rich floodplain sediments, and mudstone and gypsum of the underlying Seven Rivers Formation can be identified by vertical and lateral variations in electrical resistivity. The irregular bedrock surface of the Seven Rivers Formation reflects paleotopography developed on that surface prior to its burial by floodplain sediment. Some of the negative paleotopographic features are probably filled sinkholes that may be associated with shallower karstic features not imaged on the profiles.

Two shallow high resistivity anomalies are visible on the Lake Road ER profile, and on the Lakewood Road profile east of the railroad tracks. These features most likely represent shallow subsurface cavities partially filled with unconsolidated sediment that are related to observed sinkholes and soil fractures.

No near-surface resistivity anomalies along Lakewood Road west of the railroad were observed, in spite of the presence of several shallow sinkholes along this section of the road. The small number of zones of probable subsidence found with the ER method in areas of known sinkhole collapse suggest that relatively narrow vertical channels are transmitting sediment into underlying cavities. The depth to bedrock indicated by the resistivity data demonstrates that remediation of the sinkholes is impractical by conventional methods of excavation of bedrock followed by graded back-filling. Instead, dynamic compaction may be a more effective remediation technique, with added attention in areas where sinkholes are known and the ER surveys suggest potential subsurface cavities.

Introduction

Following flooding in September 2013, several areas along Lakewood Road and Lake Road in northern Eddy County, New Mexico, were damaged by multiple sinkhole collapses. Pettigrew & Associates contracted NCKRI to conduct electrical resistivity (ER) surveys for cavities to guide road repairs. NCKRI agreed to conduct this research to assist in solving a threat to public safety in addition to collecting additional geophysical data, to include in its database for future detailed studies of ER data collection methods and analyses.

The sinkholes in the study area, cover collapse sinkholes, form by the piping of soil and alluvium into underlying karstic cavities. Their position along the two roads is the result of drainage channels along either side of each road, which have promoted groundwater recharge in these linear areas for many years. The piping of the unconsolidated materials created cavities in the alluvium that slowly stoped up toward the surface and into the soil. The flood of September 2013 focused substantially greater flow down into the soil in the channels until the cavities became sufficiently large and unstable to collapse and breach the surface. A visual survey of the area by Pettigrew and NCKRI personnel on 12 February 2014 supported this hypothesis, finding that collapse and related features appeared to diminish with distance from the roads (Figure 1). Subsequent interviews with Lakewood residents revealed additional karstic fissures and sinkholes occurring several tens of meters from the roads, but still indicating the majority were concentrated along the drainage channels.

For detailed discussion of sinkhole processes and remediation, see Sowers (1999) and Zhou and Beck (2011). Additionally, NCKRI manages the Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. This conference series began in 1984, and its proceedings are highly sought internationally as the most comprehensive set of information on the topic. Most proceedings volumes are out of print but can often be found on-line through various book sellers. NCKRI has made the most current volume (Land et al., 2013) digitally available via its website (www.nckri.org) as an open access publication.

Geologic Setting

Effective remediation of cover collapse sinkholes requires accurate characterization of piping zones and depth to bedrock. Stratigraphic units in the Lakewood area that are relevant to this investigation include a surface layer of topsoil 0 to 5 m thick, which grades into underlying clay, sand, and gravel of the Pecos River floodplain. The thickness of floodplain deposits is highly variable because of paleotopographic relief developed on the underlying bedrock. Bedrock in the study area is represented by the Seven Rivers Formation, the middle unit of the Permian-age Artesia Group, which is composed of interbedded reddish-brown mudstone, siltstone, dolomite, and gypsum. The Seven Rivers Formation is exposed along the McMillan Escarpment on the eastern margin of the Pecos River valley, where it is capped by dolomites of the Azotea Tongue.

Subsurface dissolution of gypsum within the Seven Rivers Formation and other members of the Artesia Group has caused local and regional subsidence and has profoundly influenced topography along the margins of the Pecos River Valley. The presence of these highly soluble rocks has also contributed to the formation of sinkholes and caves (Land, 2003; Stafford et al., 2008). Lake McMillan, less than one kilometer east of Lakewood, was ultimately abandoned because of loss of water through karstic conduits within the underlying Seven Rivers Formation (Cox, 1967).

Based on a survey of well records in the area, depth to the top of the Seven Rivers Formation in the vicinity of Lakewood ranges from 26 to 49 m. One well intersected a cave within the Seven Rivers Formation at a depth of aproximately 60 m.

Methods

The basic operating principle for electrical resistivity surveys involves generating a direct current between two metal electrodes implanted in the ground, while the ground voltage is measured between two additional implanted electrodes. Given the current flow and measured voltage drop between two electrodes, the subsurface resistivity between the electrodes can be determined and mapped. Resistivity profiles detect vertical and lateral variations in resistivity in the subsurface. Previous work has shown that resistivity surveys are among the most effective methods for identifying water-filled and especially air-filled voids due to their electrical contrast with the surrounding bedrock.

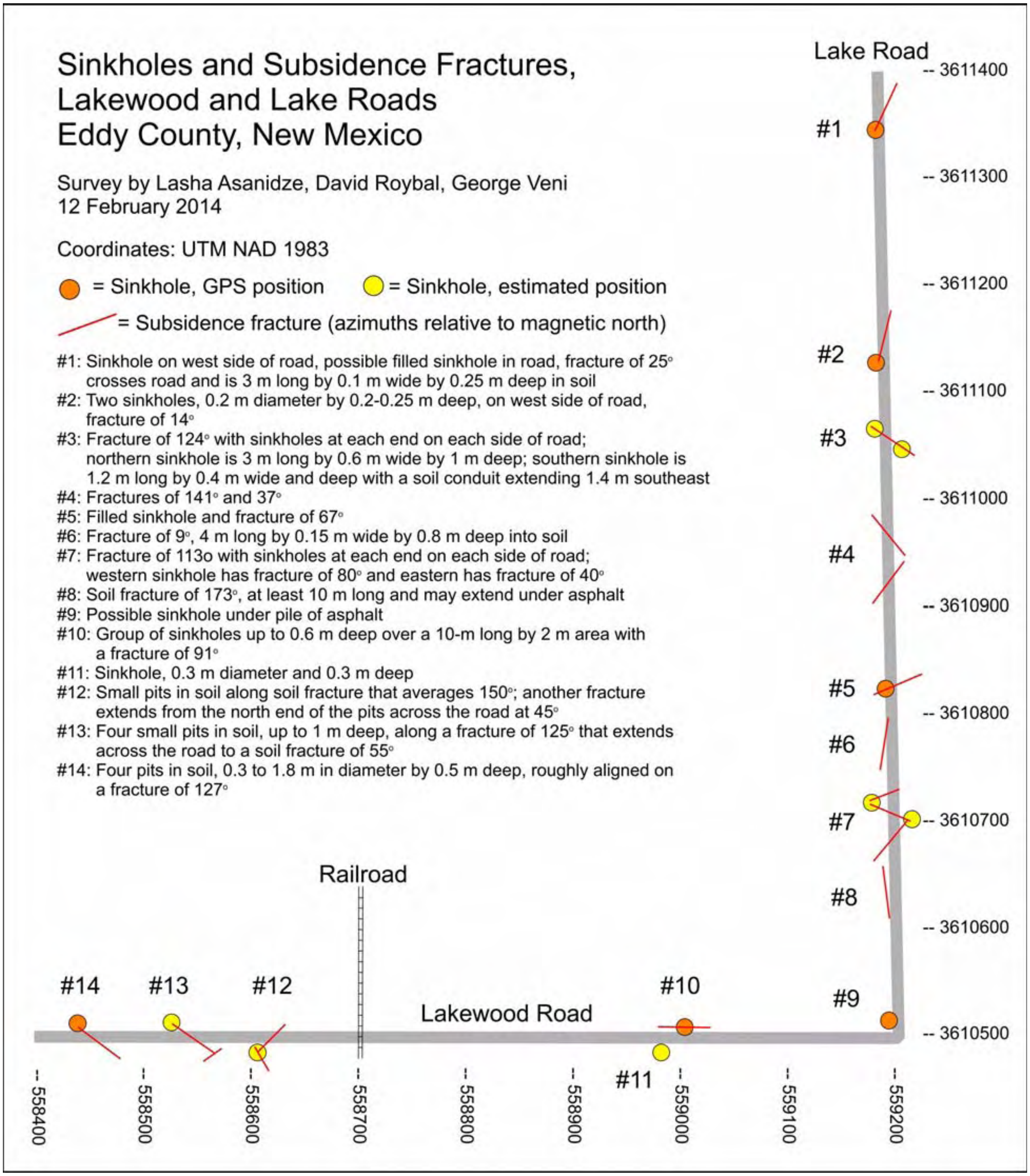

Figure 1. Reconnaissance survey of sinkholes and subsidence fissures in Lakewood area.

Figure 2. Lakewood, NM, study area. ER survey lines parallel to Lake and Lakewood roads are indicated by red and blue dots; each dot represents one electrode in the array. Yellow filled circles show locations of sinkholes and other karst features photographed during resistivity surveys (Appendix).

The depth of investigation for a typical ER survey is approximately one-fifth the length of the array of cable. NCKRI staff, assisted by personnel from Madron Services, conducted six electrical resistivity surveys parallel to Lake and Lakewood roads (Figure 2), using 112 electrode arrays at an electrode spacing of 3 m, for a maximum deployment length of 333 m per array and an anticipated depth of investigation of approximately 65 m. This spacing and target penetration depth were selected to determine if substantially larger cavities occur in the subsurface than are indicated by the size of the observed sinkholes, which should be considered in remediation of the sinkholes and repair of the roads.

Four of the surveys employed a rollalong method to increase the length of the resistivity profiles. After data were collected for each 112 electrode array, the lower half of the array was shifted forward to the far end for a 50% overlap. Although this method does not increase the depth of investigation, it permits a seamless ER profile much longer than the length of a single array. While resistivity data were collected, a survey-grade global positioning system (GPS) survey was conducted of all electrode positions for each array. The elevation data were used for advanced processing to correct for variations in topography along the survey line.

We used SuperSting R8/IP electrical resistivity equipment provided by Advanced Geosciences, Inc. (AGI) to collect the resistivity data. The data were then processed using EarthImager 2D™ software. The EarthImager software chooses a resistivity scale designed to highlight natural conditions in the subsurface; thus resistivity profiles shown in this report may not have the same resistivity scale. AGI technical staff report that, in general, it is not advisable to force the software to adhere to a specific scale, and attempts to do so may yield misleading results.

Results and Discussion

Lakewood Road, East of Railroad

Two rollalong resistivity surveys were conducted parallel to Lakewood Road, one on each shoulder, extending west from the intersection of Lake and Lakewood roads to the Burlington Northern and Santa Fe (BN&SF) railroad tracks (Figure 2). These surveys achieved a maximum depth of investigation of 62 m below ground level. Variations in electrical resistivity are influenced by subsurface stratigraphy and facies variations (Figure 3), and by the presence of subsurface cavities. Our interpretation of the resistivity data is informed by subsurface records from area water wells, including an augmentation well drilled by the New Mexico Office of the State Engineer (NM OSE) in 2006, located approximately 3.2 km southwest of the survey area.

Three distinct stratigraphic units can be identified on the resistivity profiles. A thin zone of relatively high resistivity occupies approximately the uppermost 5 m of the section and extends almost continuously across the profile from west to east. This high resistivity layer most

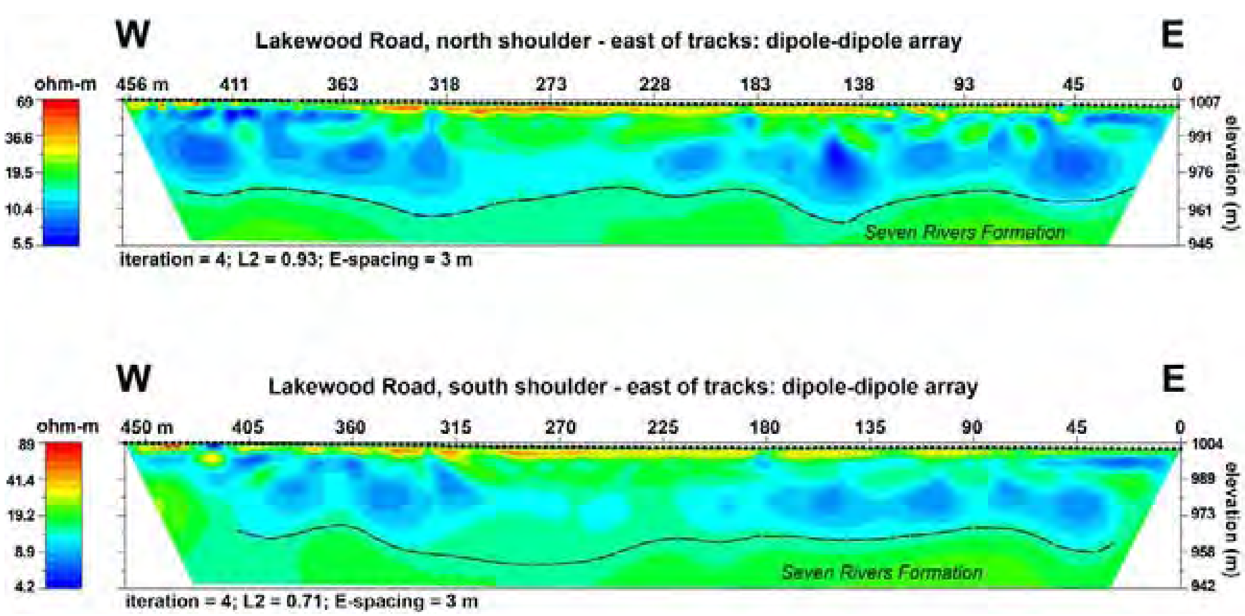

Figure 3. Electrical resistivity profiles conducted along the north and south shoulders of Lakewood Road, east of the BN&SF railroad tracks.

likely represents air-filled porosity in unsaturated soil and gravel.

Underlying this high resistivity layer is an interval approximately 30 to 50 m thick of generally lower resistivity (5 to 30 ohm-m). This layer probably represents a more clay-rich section of alluvial material of the Pecos River floodplain. Clays typically have lower resistivity than more coarse-grained sediments.

A zone of moderately high resistivity extends across the profiles approximately 40 to 50 m below ground level. Based on well records in the survey area, we interpret this interval to represent mudstone and gypsum of the Seven Rivers Formation, which crops out along the McMillan Escarpment on the opposite side of the Pecos River. Undulations in the top of the Seven Rivers Formation reflect the paleotopography of the unit prior to burial by floodplain alluvium. A prominent depression in the top of the Seven Rivers is visible on the north shoulder profile between 138 and 165 m. This feature may represent a buried sinkhole filled with more electrically conductive clay, as indicated by a pod of very low resistivity material above it.

A small, distinctive pod of relatively high resistivity occurs approximately 8 m below ground level at the west end of the south shoulder profile at 420 m, overlain by a near-surface interval of low-resistivity. A subdued reflection of this feature is also present on the north shoulder profile. Resistivity values are too low for this feature to be caused by an air-filled cave, but it may represent a shallow cavity filled with unconsolidated sediment.

Lakewood Road, West of Railraod

Because of the presence of the railroad tracks, it was not possible to conduct continuous rollalong surveys on Lakewood Road. For this reason two separate surveys were conducted on the north and south shoulders on the west side of the railway (Figure 4). These surveys achieved a maximum exploration depth of 60 m.

A thin layer of high resistivity is also present on the profiles west of the railway, reflecting air-filled pore space in sand and gravel of the soil horizon. This layer is underlain by 40 to 50 m of generally lower resistivity material of the Pecos River floodplain. However, several lenticular bodies of higher resistivity are also present within this section. One distinctive high-resistivity lens is present on the south shoulder profile between 110 and 140 m, approximately 15 m below ground level. A more laterally extensive high resistivity layer occurs beneath the west end of the north shoulder profile. Subdued reflections of both of these features are also present on the opposite shoulder profiles. Because of their geometry and their presence within the alluvial section, we interpret these features as lenticular bodies of coarse sand and gravel in the unsaturated zone; it is unlikely that they represent caves. In spite of the presence of several small sinkholes along the shoulders of Lakewood Road west of the railway, no obvious subsurface cavities are visible on the ER profiles.

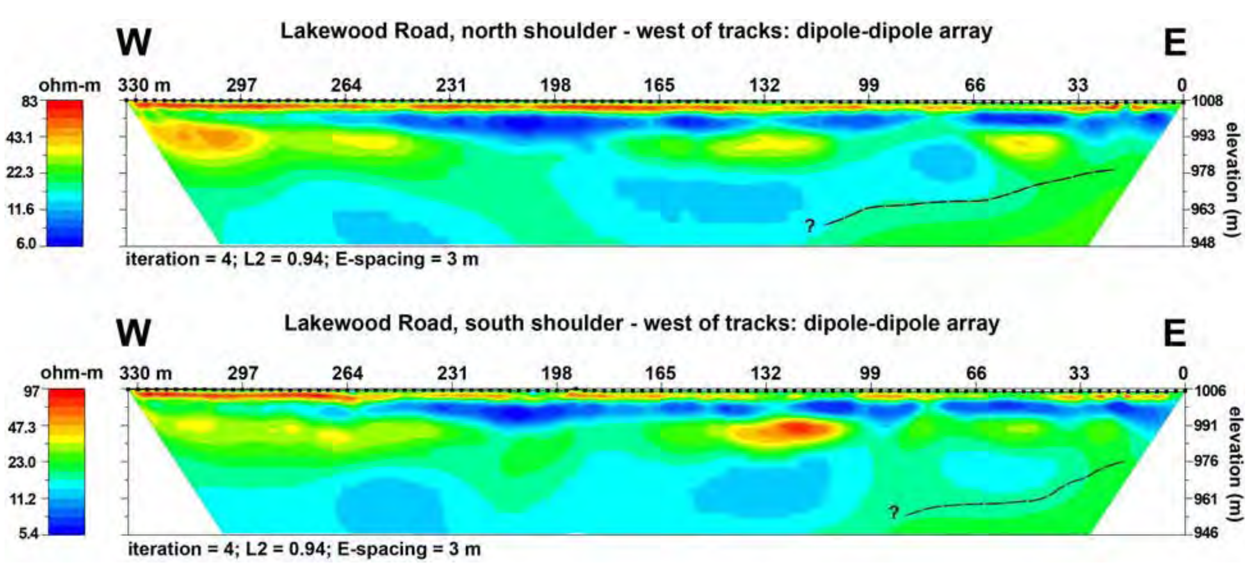

Figure 4. Electrical resistivity profiles conducted along the north and south shoulders of Lakewood Road, west of the BN&SF railroad tracks.

The top of the Seven Rivers Formation is poorly defined in the resistivity survey data collected west of the railway. It is possible that the top of the Seven Rivers exceeds our depth of investigation in this area, dipping locally to the west. Although regional dip is to the east, the topography of the Pecos Valley has been strongly influenced by local and regional subsidence due to subsurface gypsum dissolution (Bachman, 1984; Land, 2003), resulting in the presence of a number of sediment filled basins along the western margin of the river valley (Lyford, 1973).

Lake Road

Two rollalong resistivity surveys were conducted along the west and east shoulders of Lake Road, extending north about one kilometer from the intersection of Lake and Lakewood roads. Both surveys attained a maximum depth of investigation of 55 m.

The near-surface, high resistivity soil horizon is not as well defined on the Lake Road ER surveys. However, the lower resistivity, clay-rich alluvial section is clearly visible, extending along the entire length of both profiles (Figure 5). The Seven Rivers Formation is clearly defined by a high resistivity zone beneath the northern half of the profile approximately 25 m below ground level, and appears to be dipping gently to the south.

The higher resistivity section that represents the Seven Rivers Formation is interrupted in several places, reflecting the paleotopography developed on the top of the formation. One of these breaks occurs on the west shoulder profile between 600 and 650 m, where a sag in the top of the unit most likely represents a filled sinkhole. Subsidence over this feature appears to have caused a local near-surface accumulation of coarser sediment, as indicated by an overlying lenticular high resistivity zone. This feature is also visible on the east shoulder profile between approximately 630 and 670 m. Several less defined breaks in the Seven Rivers profile may also represent filled sinkholes.

A small but well defined pod of higher resistivity occurs at 305 m on the east shoulder profile, approximately 5 m below ground level. A second high resistivity pod occurs directly beneath the first at approximately 20 m below ground level. These features are likely to represent subsurface cavities partially filled with sediment, or two segments of a fissure adjacent to or extending beneath the roadway. A 4-m long soil fracture was identified near this section of the ER profile during the February, 2014, reconnaissance survey (Figure 1, number 6).

Conclusions

Electrical resistivity surveys conducted parallel to Lakewood and Lake roads near the community of Lakewood, NM, attained maximum exploration depths of 55 to 62 m. Subsurface stratigraphy, including a near-surface soil horizon, clay-rich alluvium of the Pecos Valley floodplain, and mudstone and gypsum of the Seven Rivers Formation, are indicated by vertical and lateral variations in subsurface electrical resistivity. The irregular surface of the Seven Rivers Formation on all profiles reflects paleotopography developed on that surface prior to its burial by floodplain alluvial sediment. Some of the negative paleotopographic features are almost certainly filled sinkholes, which may be associated with shallower karstic features not imaged on the profiles.

Two distinct and well defined pods of high resistivity are visible on the Lake Road east shoulder profile and near the west end of the Lakewood Road south shoulder profile, just east of the BN&SF railroad tracks. These features most likely represent shallow subsurface cavities, partially filled with unconsolidated sediment, that are related to observed sinkholes and soil fractures.

There were no observations of any near-surface resistivity anomalies indicative of karst features on the ER profiles west of the railway, in spite of the presence of several shallow sinkholes along this section of Lakewood Road. However, the absence of a well defined Seven Rivers section on these profiles may be due to a broad zone of subsidence caused by subsurface dissolution of evaporites, also accompanied by a thicker accumulation of overlying floodplain alluvium.

The few zones of probable subsidence found with the ER method in areas of known sinkhole collapse suggest the development of relatively narrow vertical piping channels to transmit sediment into underlying cavities. The clear imaging of the Seven Rivers Formation demonstrates that remediation of the sinkholes is impractical by the conventional method of excavation of bedrock followed by graded back-filling. Instead, it is recommended that dynamic compaction be considered as a remediation technique, with added attention in areas where sinkholes are known and the ER survey suggests potential subsurface cavities. Dynamic compaction has the potential to work especially well due to the clay-rich soil and alluvium present, but a geotechnical engineer experienced in sinkhole remediation should be consulted.

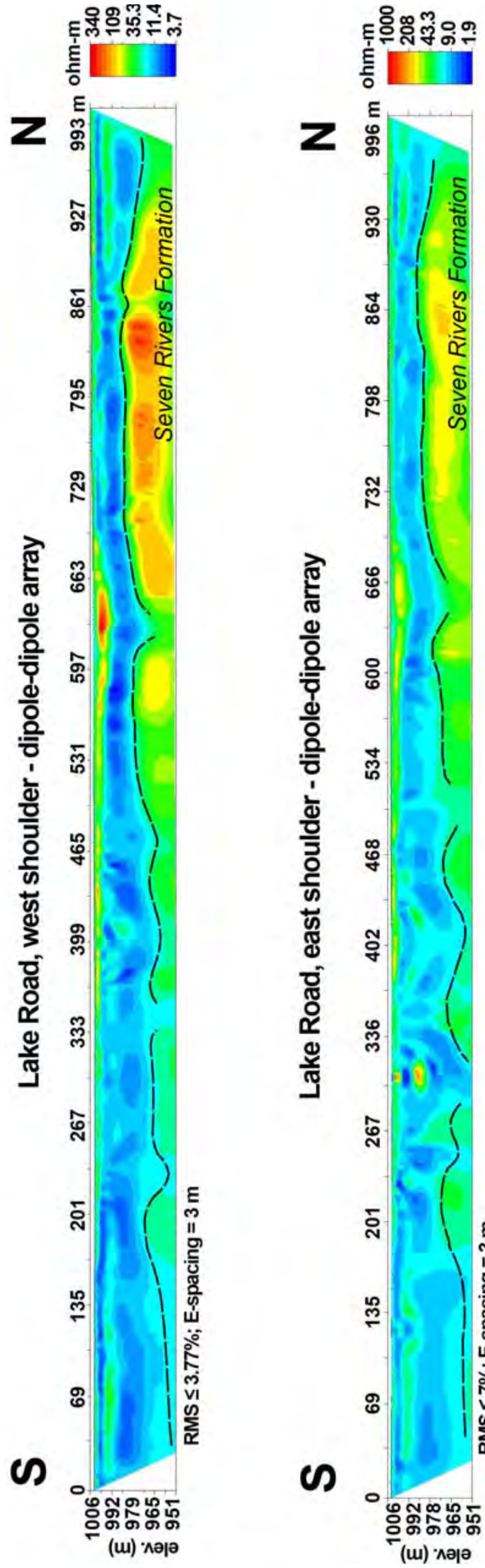

Figure 5. Electrical resistivity surveys conducted along the west and east shoulders of Lake Road.

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Appendix
Sinkholes and other karst features in the survey area

Below are photographs and summary descriptions of sinkholes and other karst features in the survey area. Figure numbers reference locations shown in Figure 2. UTM coordinates use WGS84 datum, and are listed as easting, northing, and estimated precision. Fracture azimuths are given relative to true north.

Figure A-1. Small collapse sinkhole, south side of Lakewood Road, filled with asphalt rubble; 0.46 m diameter. 559048, 3610704, 5 m.

Figure A-2. Soil fracture, north side of Lakewood Road. Length ~18 m, width 0.5 – 1.5 m, depth 0.5 – 1.0 m, azimuth 102º. 559027, 3610715, 4 m.

Figure A-3. Soil fracture mostly filled with gravel, north side of Lakewood Road. Pavement damage suggests fracture most likely extends beneath road to opposite shoulder, where asphalt slabs may cover fracture extension. Length, ~18 m (assuming fracture extends beneath road), width 1.4 m, depth where not filled 0.6 m, azimuth 20º. 559008, 3610714, 3 m.

Figure A-4. Small sinkhole, south side of Lakewood Road. Diameter, 0.4 m, depth, 0.44 m. 558997, 3610704, 3 m.

Figure A-5. Soil fracture, south side of Lakewood Road, mostly filled with gravel. Pavement damage indicates fracture extends beneath road to opposite shoulder, where a recent pile of gravel probably buries north end of feature. Length >10 m (assuming fracture extends beneath road), width 0.4 m, depth where not filled, 0.4 m, azimuth 137º. 558944, 3610701, 4 m.

Figure A-6a. First of a pair of sinkholes following a soil fracture, south side Lakewood Road. Length 0.6 m, width 0.2 m, depth 0.9 m, fracture azimuth 62º. 558449, 3610702, 2 m.

Figure A-6b. Second of a pair of sinkholes following a soil fracture, south side Lakewood Road. Length 0.83 m, width 0.41 m, depth 0.63 m, fracture azimuth 62º. 558449, 3610702, 2 m.

Figure A-7. First sinkhole in a cluster of five, north side Lakewood Road. First three sinkholes occur in a line oriented 122º. Length 3.2 m, width 1.35 m, depth 2.3 m. 558430, 3610719, 3 m.

Figure A-8. Second sinkhole in a cluster of five, north side Lakewood Road. Length 1.58 m, width 1.0 m, depth 0.85 m. 558429, 3610721, 3 m.

Figure A-9. Third sinkhole in a cluster of five, north side Lakewood Road. Length 1.7 m, width 1.52 m, depth 0.9 m. 558427, 3610724, 3 m.

Figure A-10. Fourth sinkhole in a cluster of five, north side Lakewood Road. Length 3.6 m, width 1.92 m, depth 1.0 m. 558423, 3610719, 3 m.

Figure A-11. Fifth sinkhole in a cluster of five, north side Lakewood Road. Length 0.84 m, width 0.38 m, depth 0.84 m. Sinkhole follows fracture with azimuth of 177º. 558427, 3610725, 3 m.

Figure A-12a. Line of three sinkholes, north side Lakewood Road. Line of sinkholes is oriented azimuth 146º. 558392, 3610717, 3 m.

Figure A-12b. First of three sinkholes in line, north side of Lakewood Road. Length 1.78 m, width 1.45 m, depth 0.87 m. 558392, 3610717, 3 m.

Figure A-12c. Second of three sinkholes in line, north side of Lakewood Road. Length 0.56 m, width 0.35 m, depth 0.69 m. 558392, 3610717, 3 m.

Figure A-12d. Third of three sinkholes in line, north side of Lakewood Road. Length 0.73 m, width 0.46 m, depth 0.57 m. 558392, 3610717, 3 m.

Figure A-13. Sinkhole, north side Lakewood Road. Length 2.67 m, width 1.7 m, depth 0.64 m. 558385, 3610719, 3 m.

Figure A-14. Discontinuous soil fracture, mostly concealed by dense mesquite, west side of Lake Road. Length ~20 m, maximum width 1.55 m, maximum depth 1.37 m, azimuth 97º. 559128, 3610938, 4 m.

Figure A-15a. First of two sinkholes following fracture, west side of Lake Road. Length 1.65 m, width 1.1 m, depth 0.7 – 1.6 m. Fracture azimuth 2º. 559133, 3610963, 3 m.

Figure A-15b. Second of two sinkholes following fracture, west side of Lake Road. Length 1.62 m, width 0.54 m, depth 0.7 m. Fracture azimuth 2º. 559133, 3610963, 3 m.

Figure A-16. Soil fracture, west side of Lake Road. Length 0.66 m, width 0.1 m, depth 0.4 m, azimuth 172º. 559138, 3610973, 4 m.

Figure A-17. Soil fracture, west side of Lake Road. Length 2.0 m, width 0.19 m, depth 1.8 m, azimuth 172º. 559137, 3610990, 4 m.

Figure A-18. Poorly exposed, irregular and discontinuous soil fracture extending into mesquite. Length >20 m, width ~0.5 m, depth ~0.5 m. 559133, 3611008, 4 m.

Figure A-19. Soil fracture, west side of Lake Road. Pavement damage indicates that fracture extends beneath road to opposite shoulder, where a poorly exposed fracture with the same orientation extends into mesquite. Length ~15 m (assuming fracture extends beneath road), width ~0.5 m, maximum depth 1 m, azimuth 112º. 559135, 3611177, 3 m.

Figure A-20. Sinkhole in asphalt, west shoulder of Lake Road. Length 0.33 m, width 0.2 m, depth 0.3 m. This sinkhole aligns with asphalt patches in road that are probably filled sinkholes, and another sinkhole on the opposite shoulder. Orientation of these features is azimuth 27º. 559134, 3611322, 3 m.

Figure A-21. Sinkhole, east side of Lake Road. Length 0.3 m, width 0.23 m, depth 0.43 m. This sinkhole aligns with asphalt patches in road that are most likely filled sinkholes, and another sinkhole on the opposite shoulder. Orientation of these features is azimuth 27º. 559144, 3611341, 3 m.

Figure A-22. Soil fracture extending into dense stand of mesquite, west side of Lake Road. Length ~3 – 4 m, width 0.66 m, depth 0.4 m, azimuth 22º. 559132, 3611532, 3 m.

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