Applied Two-dimension Resistivity Imaging for Detection of Subsurface Cavities in Northeastern Thailand: A Case Study at Ban Non Sa Bang, Amphoe Ban Muang, Changwat Sakon Nakhon

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ABSTRACT

The occurrence and evolution of sinkholes in the Khorat and Sakon Nakhon basins in northeastern Thailand call for scientific explanations, particularly in the areas where there is continuing pumping of brine solution for salt production. Residents near pumping areas have been living with fear of hazards due to collapse of subsurface cavities into sinkholes. Identification of subsurface cavities in sinkhole-prone areas could relieve such fear. A two-dimensional resistivity survey was conducted in areas near the sinkholes at Ban Non Sa Bang, Ban Muang District, Sakon Nakhon Province. This survey proved to be suited for detection of a cavity near the ground surface. The cavity was considered as a lateral anomaly in a homogenous medium. The anomalous zone of the cavity could be distinguished as a 0.1 to 0.5 ohm-meter low resistivity zone surrounded by a higher background resistivity. The survey results indicated that a two-dimensional resistivity survey can be used as a basic tool for identifying a near-surface cavity in sinkhole-prone areas in the Khorat and Sakon Nakorn basins.

KEYWORDS: sinkhole, rock salt, resistivity survey, Maha Sarakham Formation, hazard in northeastern Thailand

INTRODUCTION

The collapse of a near-ground surface cavity into a sinkhole is one of hazards in the Khorat and Sakon Nakorn basins in northeastern Thailand (Figures 1 and 2). Small sinkholes with diameters of a few centimeters to tens of meters (Figure 2) and large sinkholes with diameters of hundreds to thousands of meters have been found in these two basins. The occurrence of large sinkholes found at Nong Harn Lake in Sakon Nakorn Province and Nong Han Kumpawapee Lake in Udon Thane Province is believed to be a result of collapse of near-surface salt domes when the salt domes were dissolved (Rau and Supajanya, 1985). These two large lakes were documented as the Legend of Pha Dang Nang Ai (Mukhunthet, 2003). According to the legend, many people were killed due to a rapid collapse of the ground and the ancient cities were buried underneath the bottom of the lakes. However, fundamental problems associated with the occurrence and evolution of the small sinkholes (Figure 2) still remain.
Typically, small sinkholes have been found in areas where large volumes of brine solution were pumped from wells for salt production. Residents near these pumping areas have lived with fear of loss of life and property for more than a decade (Hinthong and Charoenprawat, 1990). In view of this, there have been a few investigations into the occurrence of small sinkholes (Hinthong and Charoenprawat, 1990; Solgosoom and others, 1999; Satarugsa and others, 2001). Loss of water from reservoirs overnight being due to the collapse of the ground into sinkholes in Ban Non Sa Bang, Ban Bo Dang, and Ban Jam Pla Dong in Sakon Nakorn Province, and Ban Wang in Nakonrajasima Province was documented (Hinthong and Charoenprawat, 1990; Solgosoom and others, 1999). Currently, the collapse of cavities into small sinkholes has generated more serious consequences than previously thought. Thus, for prevention of possible and significant damage from subsurface cavity collapse, a thorough explanation of its occurrence and evolution in sink hole-prone areas is necessary.

Two-dimension resistivity imaging is a powerful method for mapping subsurface complex structures, such as a cavity/sinkhole (Loke, 1999; van Schoor, 2002), salt-water intrusion (Abdul and others, 2000), sub-surface resistive dikes (Batayneh, 2001), industrial waste deposits (Ogilvy and others, 1999), and fractured crystalline rock (Seaton and Burbey, 2002). Loke (1999) and van Schoor (2002) used two-dimension resistivity data to detect a subsurface cavity in karst regions where a cavity was distinguished on the basis of a higher resistivity anomaly than the background. Collection of two-dimension...
resistivity data needs more time than for one-dimension resistivity data. However, a study from Dahlin and Loke (1998) showed that the results acquired by using the one-dimension resistivity survey were misleading in subsurface complex structures. Therefore, a two-dimension resistivity survey was used to determine complex subsurface structures, i.e., cavities, in the Khorat and Sakon Nakhon basins.

Two-dimension resistivity survey data were acquired at Ban Non Sa Bang, Ban Muang District, Sakon Nakhon Province (Figure 1). This set of data is a part of research on rock salt exploration and exploitation in northeastern Thailand. Objectives of this research were to (1) determine subsurface cavities, (2) identify a combination of other geophysical techniques that could be used for rapid and accurate detection of subsurface cavities, and (3) evaluate the possibility of using geophysical techniques for monitoring subsurface cavity expansion. The first objective is the focus of this paper. The second and third objectives were addressed separately.

**GEOLOGICAL SETTING**

The study areas are located nearly in the middle of the Sakon Nakorn basin (Figure 1). Surface geology of the study areas is characterised by Quaternary soil composed of sand, silt, and clay which is 0.5 to 10 meters thick (Satarugs and others, 2001). Underlying the Quaternary soil is the Cretaceous Maha Sarakham Formation. This formation is

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**Figure 2.**
Photographs of surface collapsed into sinkholes and their radial surface cracks, (a) a sinkhole with diameter of 6 meters, (b) a sinkhole with diameter of 13 meters, (c) a sinkhole with diameter of 8 meters, (d) partial radial surface cracks. The date when each photograph was taken is indicated at the right corner.
composed of claystone, shale, siltstone, sandstone, anhydrite, gypsum, potash, and rock salt (Japakasetr, 1985; Suwanich, 1986). An unconformity separates the Maha Sarakham Formation and Quaternary soil. The Maha Sarakham Formation is underlain by sandstone and siltstone of the Khok Krut Formation. The contact between the Maha Sarakam and Khok Krut Formations is also an unconformity. However, this contact is parallel at the center of the basin and angular at the edge of the basin (Satayaruk, 1985; Figure 6b in Satarugsa and others, 2000). A complete sequence from the bottom to the top of the Maha Sarakham Formation comprises a basal anhydrite, lower salt, potash zone, colour-banded salt, lower anhydrite, lower clastic rocks, middle salt, middle anhydrite, middle clastic rocks, upper salt, and upper anhydrite (Suwanich, 1986). However, the complete stratigraphy can be implied to the areas nearby and in the middle of the basins only because of the unconformity between the Maha Sarakham and Khok Krut Formations. Furthermore, seismic sections acquired by petroleum companies show spreading of salt domes with varying widths and thicknesses. The depth to salt domes also varies, from approximately 10 to 20 meters to 500 to 1,000 meters (Satayaruk and others, 1987). Seismic sections along the roads from Ban Non Sa Bang to Ban Nong Kwang and Ban Non Sa Bang to Ban Nong Pla Mad and near Ban Nong Bo Dang (Figure 1) show that the depth to rock salt varies from 23 to 145 meters and that salt thickness varies from 75 to 90 meters. Claystone overlies the rock salt and is 20 to 144 meters thick (Satarugsa and others, 2001; Satarugsa and others, 2002).

**ASSUMPTION AND DEFINITION OF GEOPHYSICAL ANOMALY**

The seismic section in the study area shows that there is only one rock salt layer and that it is quite shallow. Accordingly, Ban Non Sa Bang and other nearby areas are located on a shallow salt dome. This rock salt layer probably is the Lower Salt Member and the associated clay and claystone probably are the Lower Clastic Member, as described by Suwanich (1986). Thus, in this study area, the natural cavity-prone area probably is the Lower Clastic Member and the Lower Salt Member. There is little doubt that a small or large natural subsurface cavity should occur easily by dissolving the anhydrite, gypsum, potash, and rock salt of the Lower Salt Member rather than by dissolving the claystone of the Lower Clastic Member (Figure 3). However, current and paleosurface and subsurface drainage systems likely also produced a cavity in the claystone. In addition, highly fractured zones in claystone, deformed as a result of salt diapir tectonics, probably promote cavities in the claystone.

Generalized subsurface lithology and geophysical properties of the study area are shown in Figure 3. Geophysical contrast properties (Figure 3) indicate that a cavity either inside claystone or at the interface between claystone and rock salt and filled with either brine or air should be distinguishable on the basis of resistivity. Thus, geoelectrical responses were expected to produce changes in electrical resistivity of a medium (Figure 3). The claystone and rock salt were considered to be geophysical background whereas a cavity was considered to be a geophysical anomaly. Therefore, lateral changes of resistivity due to a cavity should be distinguishable from background resistivity.
METHOD

Apparent resistivity data that were used were synthetic data generated from a synthetic earth model and from collected field data. The synthetic earth model contained horizontal structures with varying resistivities similar to the lithology described in Figure 3. Synthetic apparent resistivities were generated with the forward modeling program RES2DMOD of Loke (1999). A Syscal R1 Plus resistivity meter was used for measuring field apparent resistivities. Current was injected into the ground through a pair of current electrodes and potential differences were measured using a pair of potential electrodes. The survey lines were measured repeatedly by a certain type of electrode arrays with dipole-dipole and Wenner arrays. Station spacing was 10 meters. Electrode spacing was kept constant for each measurement but was progressively increased from one measurement to another until the maximum spacing was reached. Investigation depths were about 30 to 50 meters. The apparent resistivities were inverted into earth models by using a two-dimension resistivity inversion program, RES2DIV, of Loke (1999), with L1 norm smooth constrained. Three resistivity survey lines were collected as line locations shown in Figure 4. Lines 1 and 2, perpendicular to line 3, were conducted near the sinkholes shown in Figures 2a and 2b. Line 3 passed over a core-drilling test well, Ban Nong Kwang12, and two abandoned brine wells. The three lines were located near several brine wells that have been pumped since 1984.

<table>
<thead>
<tr>
<th>Thickness (m)</th>
<th>Geologic Units</th>
<th>Resistivity (Ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>~0-10</td>
<td>Sand, silt, and clay</td>
<td>100-8 x 10² (1)</td>
</tr>
<tr>
<td>~10-90</td>
<td>Claystone</td>
<td>1-100 (wet) (1)</td>
</tr>
<tr>
<td>~0-10</td>
<td>Anhydrite/Gypsum</td>
<td>10³ (1)</td>
</tr>
<tr>
<td>~500-1500</td>
<td>Rock Salt</td>
<td>30-10³ (1)</td>
</tr>
<tr>
<td>~1-6</td>
<td>Anhydrite/Gypsum</td>
<td>10³ (1)</td>
</tr>
<tr>
<td>-</td>
<td>Sandstone, Silicate</td>
<td>1-6.4 x 10¹ (1)</td>
</tr>
</tbody>
</table>

Note: Resistivity of saline water (brine): 20% = 0.05 Ohm-m (1)
Source: (1) Telford, et al. (1990); (2) Sataraya, et al. (2001); (3) Swamich, (1986).

**Figure 3.**

Schematic geologic lithology of the studied area and its physical properties.
RESULTS AND INTERPRETATION

Synthetic Apparent Resistivity Data

Figures 5 and 6 show inversion results from synthetic apparent resistivities generated by a forward three-layer earth model with dipole-dipole and Wenner arrays. The forward three-layer earth model that was used to input to the forward modeling program RES2DMOD consisted of unconsolidated soil, with a resistivity of 100 ohm-meters, claystone, with a resistivity of 5 ohm-meters, and rock salt, with a resistivity of 100,000 ohm-meters. Thicknesses of 5 and 15 meters were assigned to the unconsolidated soil and claystone, respectively. The inverted synthetic resistivity earth models (Figures 5c and 6c) clearly display three different zones corresponding to unconsolidated soil, claystone, and rock salt. Synthetic apparent resistivities from the dipole-dipole array (Figure 5) vary from a low value of 9.2 ohm-meters to a high value of 43.0 ohm-meters. Synthetic apparent resistivities from the Wenner array (Figure 6) vary from a low value of 6.2 ohm-meters to a high value of 57.1 ohm-meters. Transitional resistivity zones occur between unconsolidated soil and claystone and between claystone and rock salt. Depth to the transition zone between unconsolidated soil and claystone, shown in Figures 5c and 6c, is approximately the same as the forward three-layer earth model used for generating the data. However, the depth to the transition between claystone and rock salt, also shown in Figures 5c and 6c, is deeper than the forward earth model.

Figure 4.
A map of location of three survey lines acquired over the active sinkholes' area at Ban Non Sa Bang.
The dipole-dipole model (Figure 5c) shows the depth to the transition zone between claystone and rock salt to be closer to the forward resistivity earth model than does the Wenner model (Figure 6c).

**Figure 5.**
(a) Dipole-Dipole observed apparent resistivity, (b) predicted apparent resistivity, (c) inverted resistivity earth model together with the forward three-layer earth model used as input to the forward modeling in the generation of the Dipole-Dipole observed apparent resistivity in a.

**Figure 6.**
(a) Wenner observed apparent resistivity, (b) predicted apparent resistivity, (c) inverted resistivity earth model together with the forward three-layer earth model used as input to the forward modeling for generating the Wenner observed apparent resistivity in a.
Field Apparent Resistivity Data

Figures 7 to 12 show measured and predicted apparent resistivity data and the inverted resistivity earth model for the three survey lines acquired with both dipole-dipole and Wenner arrays.

Figure 7 is the result of dipole-dipole resistivity profile line 1. The profile is located along a diameter of radial surface cracks (Figure 4). A cluster of sinkholes inside the radial surface cracks had been filled with unconsolidated soil before the resistivity data were collected. The subsurface cavity that collapsed into a sinkhole in this area was first reported in 1992 (Satarugsa and others, 2002). The surface collapse had a diameter of 5 meters. The resulting sinkhole was later filled with soil. Four years later, a subsurface cavity collapsed into a sinkhole again at the same location. The diameter of this sinkhole is 15 meters and the sinkhole was also later filled with soil. Hundreds tons of soil have been brought several times from nearby areas to fill the sinkholes. At the time of the resistivity survey, the radius of surface cracks was 60 meters and the sinkholes had been filled with soil.

In Figure 7c, the radial surface cracks were mapped at locations between 130 and 190 meters. Horizontal and vertical resistivity variations in Figure 7 are totally different from those in Figure 5, these indicating complex subsurface structures. There were two low resistivity zones, 0.1 to 0.5 ohm-meter, at locations 140 to 165 meters and 100 to 120 meters. These two zones are interpreted to be the result of highly porous zones filled with brine. Results from Figure 5 suggest homogenous lateral resistivity variation in the unconsolidated soil, claystone, and rock salt if subsurface structures are not highly deformed. However, Figure 7 results show very high lateral and vertical resistivity variations beneath the radial surface cracks. These high resistivity variations imply highly deformed structures in this zone that are associated with surface collapses that were later filled with soil.

Figure 8 is the result of the Wenner resistivity profile acquired at the same locations as the profile shown in Figure 7. Three different zones were distinguished from the inverted earth resistivity model (Figure 8c). Gradual increases in resistivity values displayed at the left bottom of the profile had a similar feature displayed in Figure 6c and, thus, this feature suggests a rock salt body. High lateral resistivity variation beneath the radial surface cracks at the near-surface is, thus, associated with filled soil. A low resistivity zone of 0.1 to 0.5 ohm-meter occurs at locations of 150 to 170 meters beneath the radial surface cracks. This low resistivity zone is interpreted to be a highly porous zone filled with brine and is located within claystone.
Figures 9 and 10 show the results of resistivity profile line 2 acquired along a laterite road with both dipole-dipole and Wenner arrays. The survey was conducted across the sinkhole.
identified in Figure 2b. Radial surface cracks of this sinkhole are shown in Figure 2d. This sinkhole occurred in 2003 and had a diameter of 13 meters. It was later filled with soil. However, the soil filling has been removed as a result of groundwater flow and the diameter of the hole was progressively expanded. At the time the resistivity data were collected in February 2004, its maximum diameter was about 30 meters and the sinkhole was again filled with soil. Figure 9c shows dipole-dipole array data. The lowest resistivity zone is 0.1 to 0.5 ohm-meter and occurs at locations of 60 to 190 meters along the profile. This low resistivity zone is interpreted to be a highly porous zone of highly fractured or deformed claystone that is filled with brine. The length of this zone is larger than the diameter of the surface collapse and suggests the continuing expansion of a larger area of surface collapse.

Figure 10c shows Wenner array data that have a low resistivity zone of 0.1 to 0.5 ohm-meter at locations of 110 to 140 meters. This low resistivity zone is smaller than the low resistivity zone of Figure 9c, but it occurs at nearly the same locations, being beneath the surface collapse. Thus, the results shown in Figures 9 and 10 suggest that there is a large, highly fractured claystone filled with brine located beneath the sinkhole locations. This large and highly fractured zone shows the potential to collapse if brine solution, filled in fractures, is overdrawn from the zone.

Results of resistivity profile line 3 acquired with dipole-dipole and Wenner arrays are shown in Figures 11 and 12. This line passed over the core-drilling test well, Ban Nong Kwang-12, at a location of 190 meters and over the two abandoned brine wells at locations of 110 and 130 meters. At locations of 170 and 220 meters, line 3 intersected the location of 230 meters of profile line 1 and the location of 160 meters of profile line 2. In Figure 11c, a low resistivity zone occurs at the locations of 90 to 270 meters and at depths 10 to 40 meters. In the Ban Nong Kwang-12 well, unconsolidated laterite soil occurs from the surface down to 4 meters, claystone occurs from 4 to 52 meters, and rock salt occurs from 52 to 100 meters. The claystone between 4 and 37 meters had an average core recovery of 34 percent and between 37 and 52 meters an average core recovery of 10 percent. Thus, the low resistivity zone of 0.1 to 0.5 ohm-meter in the Ban Nong Kwang-12 well appears to be the result of highly deformed claystone filled with brine.

In Figure 12c, two low resistivity zones occur at locations of 120 to 170 meters and 210 to 300 meters. These two low resistivity zones have smaller areas than the low resistivity zone of Figure 11c. This means that the low resistivity zone of Figure 11c could be subdivided into the two low resistivity zones shown in Figure 12c. The resistivity of the claystone in the Ban Nong Kwang-12 well was 0.8 ohm-meter. It was not the lowest resistivity zone along the profile, the lowest being 0.1 ohm-meter (Figure 12). Gradual increases in resistivities due to a rock salt body at a depth of 50 meters below the surface at the Ban Nong Kwang-12 well location in Figures 11c and 12c closely match the drilling result and resistivity imaging. Figure 12c shows irregular depths to rock salt along the profile.
Figure 9.
Pseudosection of Dipole-Dipole resistivity Line 2, (a) measured apparent resistivity data, (b) predicted apparent resistivity data, (c) inverted resistivity earth model result from the inversion of the measured data shown in a.

Figure 10.
Pseudosection of Wenner resistivity Line 2, (a) measured apparent resistivity data, (b) predicted apparent resistivity data, (c) inverted resistivity earth model result from the inversion of the measured data shown in a.
Figure 11.
Pseudosection of Dipole-Dipole resistivity Line 3, (a) measured apparent resistivity data, (b) predicted apparent resistivity data, (c) inverted resistivity earth model result from the inversion of the measured data shown in a.

Figure 12.
Pseudosection of Wenner resistivity Line 3, (a) measured apparent resistivity data, (b) predicted apparent resistivity data, (c) inverted resistivity earth model result from the inversion of the measured data shown in a.
DISCUSSIONS

Inverted Earth Resistivity Models

Four inverted resistivity earth models (Figures 7c to 10c) had well-defined low resistivity zones beneath the sinkholes although the observed and predicted resistivities appeared to have rather high absolute errors, these being 25.2 percent in Figure 7c, 17.3 percent in Figure 8c, 15.8 percent in Figure 9c, and 20.9 percent in Figure 10c. These absolute errors could have been reduced if less constraint had been put on the subsurface geology. However, this was not attempted. Moreover, there is no unique solution in inverse modeling. Many models can be generated that produce satisfactory fits to the observed data. The final inverted resistivity earth models were selected based on close matches with subsurface geology and drilling results. The absolute errors had minimal influence in selecting the final inverted resistivity earth models. Noise appeared to dominate significantly observed data as reflected by tiny high or low values in Figures 7a to 10a. This produced high absolute errors. The absolute errors shown in Figures 11c and 12c are quite small, just 7.2 percent in Figure 11c and 6.2 percent in Figure 12c. Because this profile collected data in a low heterogeneous area, especially at the near-ground surface, that there was no alien soil brought to fill the land similar to the areas along the profiles shown in figures 7c to 10c.

Geology and Physical Anomaly Assumption

Figure 3 shows a large range of the rock salt resistivity and that it is similar to the resistivity of claystone. Thus, resistivity alone cannot distinguish between claystone and rock salt. The brine has a resistivity of 0.05 ohm-meter (Telford and others, 1990). In the study area there are many brine wells. Thus, if a cavity occurs, it will fill with brine. If the resistivity zone is less than 1 ohm-meter in claystone, it should imply that highly porous fractured or deformed claystone is filled with brine (Figure 3).

The lowest resistivity of claystone in the six profiles is 0.1 to 0.5 ohm-meter. However, typically claystone resistivities range from 1 to 1,000 ohm-meters. Assuming the lowest claystone resistivity is 1 ohm-meter, the claystone would have to be highly fractured and its porosity would have to be filled with brine to cause such a low resistivity. This interpretation is unlikely to be a coincidence because all profiles have similar features. Moreover, the low resistivity zones were located beneath subsurface cavities that had collapsed into sinkholes. The low resistivity zones along the three profiles indicate that collapse of the overburden could occur if brine solution in the zone is overdrawn. Qualitative comparison between Figures 7a and 7b, Figures 8a and 8b, Figures 9a and 9b, and Figures 10a and 10b reasonably match regarding major structures.

The resistivity of a cavity within rock salt filled with brine could not be determined because the rock salt body along the resistivity profiles was deeper than the detected low resistivity zone. Results from line 3 have a close correspondence to drilling results and resistivity imaging of a rock salt body. This suggests that two-dimension resistivity techniques can be used for mapping a rock salt body. Since the resistivity imaging along profile line 3 (Figure 12c) shows low resistivity zones, subsurface cavities may exist and could collapse into sinkholes sometime in the future. Residents who live near these low resistivity zones should be moved before such collapse occurs because prevention of accidents is better than restoration afterwards.
The Occurrence and Evolution of a Cavity

Cavities in claystone are not a natural occurrence, however desirable it is to have a valid explanation of the occurrence and evolution of subsurface collapse into sinkholes. A man-made cavity is an obvious answer for the sinkhole along lines 1 and 2 (Figures 2a and 2b). At least two abandoned brine wells were known to be located where the surface had collapsed where lines 1 and 2 passed. The casings of these wells had been pulled out sometime in the past. Doing this likely caused the eventual collapse of the surface around the wells by subjecting the claystone in the wells to high stress and causing it to be highly deformed. Thus, the collapses shown in Figures 2a and 2b probably resulted from removal of this highly deformed claystone by groundwater flow.

The natural occurrence of a cavity in a highly fractured claystone zone can be caused by rock salt being dissolved by groundwater to form brine at the interface between the rock salt and the overlying fractured claystone (Figure 2c). When this brine is later pumped out, a cavity can be created at the interface of the fractured zone. The size of the cavity would increase as the claystone gradually erodes and collapses, eventually collapsing enough to create a sinkhole. Before collapse into a sinkhole occurs, the claystone likely was much fractured. The highly porous zone inside the claystone shown in Figures 11c and 12c should have been present before collapse took place. In addition, removing the brine from the highly porous zone is believed to be the main influence for the surface collapse in the study area. The fractures have been induced to form much larger porous zones by pumping brine for salt production. However, further investigation should be undertaken to provide more reasonable explanations or to confirm this observation.

The presence and future development of small sinkholes in northeast Thailand is not the only sinkhole hazard for the region. According to Satayaruk and others (1987), many cities in the Khorat and Sakon Nakon basins are underlain by salt domes. Therefore, the loss of a city and people overnight and/or the turning of a city into a swampy area might occur in the future if large sinkholes form as a result of the dissolution of these underlying salt domes. This should be a major concern. Therefore, the Khorat and Sakon Nakon basins need a large-scale regional investigation that maps and identifies sinkhole-prone areas.

CONCLUSIONS

Results from three profiles show that (1) the inversion of Wenner data displays an earth resistivity model that has more homogenous low and high resistivity zones of smaller size than that of dipole-dipole data, that (2) a low resistivity zone in claystone appears to be associated with a highly fractured porous zone filled with brine, and that (3) a two-dimension resistivity survey can detect a highly porous zone filled with brine near the ground surface. Results of this study suggest that two-dimension resistivity imaging can be used for mapping sinkhole-prone areas in the Khorat and Sakon Nakorn basins. Unconsolidated soil, claystone, and rock salt can be considered as a lateral homogenous resistivity although many physical properties influence the apparent resistivities. This geoelectrical anomaly assumption is valid. Very low, 0.1 to 0.5 ohm-meter, resistivity structures surrounded by higher resistivities are suggestive of highly porous zones filled with brine. Overdrawing brine from a low resistivity zone can trigger overburden collapse. The nature
of the sinkhole process and evolution remains to be resolved with more quantitative and intensive studies. Both natural and man-made processes can contribute to sinkhole occurrence.

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