SINKHOLES (36)

I Main Topics
A Sinkhole settings
B Recognition of sinkhole hazards (Case histories)
C Characteristics of subsidence bowls and sinkholes/pit craters
D Characterization methods
Urban sinkhole, China

https://www.youtube.com/watch?v=R_B1PkgA3kA
II Sinkhole Settings

A Above broken pipes and drains (e.g., Guatemala City)
B Carbonate terrains (e.g., China, Florida)
C Over coal mines (e.g., Wyoming, Pennsylvania)
D Over salt (e.g., New Mexico, Texas, Kansas)
E Volcanic pit craters (e.g., Hawaii)
Sinkhole above broken pipes and drains
Guatemala City

https://www.youtube.com/watch?v=Nni68iqI7WA
Guatemala City

- May 27, 2010: Pacaya volcano erupts
- May 30, 2010: Tropical Storm Agatha makes landfall, washes ash into sewers
- Fluid from a sewer eroded uncremented volcanic ash and other pyroclastic deposits
- Sinkhole forms
- 15(+) killed
- ~20 m across
- ~30 m deep
- Steep-walled

B  Sinkholes in Carbonate Rock

1 Sinkholes in Carbonate Rock: China

- >45,000 sinkholes
- Primarily in karst (limestone)
- > 30 metropolitan areas and large cites affected including Guangzhou, Wuhan, Guiyang, Kunming, Tangshan, Hangzhou, and Guilin
- 14,000 km highways and 9,000 km railways were at risk of sinkhole collapses.
- > 40 mines, 25 railways, and hundreds of dams severely impacted
- >75% of sinkholes triggered by human activities, primarily by drastic water level fluctuations in karst aquifers.

Sinkhole distribution in China 1950-2012

From Lollino et al., 2014
1 Sinkholes in Carbonate Rock: Guangzhou, China

https://www.youtube.com/watch?v=3i6l17Zc0pk
2 Sinkholes in Carbonate Rock: Florida

The type, location, and frequency of sinkhole subsidence in the Southwest Florida Management District of west-central Florida have been related to the type and thickness of overburden materials.

New sinkholes in the coastal region are small and numerous. The buried limestone surface is intensely karstified, and the thin sandy overburden materials constantly settle into the buried voids and cavities. Recent urban development in this region increases the observation and occurrence of sinkhole activity.

<table>
<thead>
<tr>
<th>TYPE AND THICKNESS OF OVERBURDEN</th>
<th>FREQUENCY OF SINKHOLES</th>
<th>TYPE OF SINKHOLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin, highly permeable</td>
<td>Generally few</td>
<td>Dissolution cover-subside, cover-collapse</td>
</tr>
<tr>
<td>30 to 200 feet thick; permeable sands are dominant</td>
<td>Numerous</td>
<td>Cover-collapse-occur slowly; cover-collapse-usually induced</td>
</tr>
<tr>
<td>30 to 200 feet thick; more clays</td>
<td>Very numerous</td>
<td>Cover-collapse-occur abruptly</td>
</tr>
<tr>
<td>Greater than 200 feet</td>
<td>Few</td>
<td>Cover-collapse-large diameter and deep</td>
</tr>
</tbody>
</table>

Reported sinkholes from 1960 to 1991
(Generally, sinkhole occurrence is under-reported in remote areas; urban areas often appear to have higher sinkhole occurrence due to good reporting.)

Winter Park

Seffner
2 Sinkholes in Florida
Winterhaven sinkhole

https://www.youtube.com/watch?v=0WawQhmNrm4
Sinkholes in Carbonate Rock

Dissolution of the limestone or dolomite is most intensive where the water first contacts the rock surface. Aggressive dissolution also occurs where flow is focussed in pre-existing openings in the rock, such as along joints, fractures, and bedding planes, and in the zone of water-table fluctuation where ground water is in contact with the atmosphere.

Rainfall and surface water percolate through joints in the limestone. Dissolved carbonate rock is carried away from the surface and a small depression gradually forms.

On exposed carbonate surfaces, a depression may focus surface drainage, accelerating the dissolution process. Debris carried into the developing sinkhole may plug the outflow, ponding water and creating wetlands.

Gently rolling hills and shallow depressions caused by solution sinkholes are common topographic features throughout much of Florida.

\[
\text{CaCO}_3 + \text{H}_2\text{CO}_3 \rightarrow \text{Ca}^{2+} + 2 \text{HCO}_3^- \]

From USGS Circular 1182
Sinkholes in Carbonate Rock

**Cover-subsidence** sinkholes tend to develop gradually where the covering sediments are permeable and contain sand.

- Granular sediments spall into secondary openings in the underlying carbonate rocks.
- A column of overlying sediments settles into the vacated spaces (a process termed “piping”).
- Dissolution and infilling continue, forming a noticable depression in the land surface.
- The slow downward erosion eventually forms small surface depressions 1 inch to several feet in depth and diameter.

In areas where cover material is thicker or sediments contain more clay, cover-subsidence sinkholes are relatively uncommon, are smaller, and may go undetected for long periods.

From USGS Circular 1182
Sinkholes in Carbonate Rock

**Cover-collapse** sinkholes may develop abruptly (over a period of hours) and cause catastrophic damages. They occur where the covering sediments contain a significant amount of clay.

Sediments spall into a cavity. As spalling continues, the cohesive covering sediments form a structural arch. The cavity migrates upward by progressive roof collapse. The cavity eventually breaches the ground surface, creating sudden and dramatic sinkholes.

Over time, surface drainage, erosion, and deposition of sediment transform the steep-walled sinkhole into a shallower bowl-shaped depression.

From USGS Circular 1182
Sinkholes in Carbonate Rock

• Sinkhole at pump sites are not uncommon

• Inferences
  – In some cases water supports the roof of a growing sinkhole
  – Water withdrawal removes roof support

Drill rig in sinkhole

From USGS Circular 1182
C Sinkholes over Coal Mines

U.S. Geological Survey Professional Paper 1164
Sinkholes over a Coal Mine
Near Sheridan, Wyoming

U.S. Geological Survey Professional Paper 1164
Subsidence over a Coal Mine Near Sheridan, Wyoming

U.S. Geological Survey Professional Paper 1164
Sinkholes over a Coal Mine Near Sheridan, Wyoming

U.S. Geological Survey Professional Paper 1164
Sinkholes over a Coal Mine

Collapse over rooms in room and pillar mines
Sinkholes over a Coal Mine Near Sheridan, Wyoming

U.S. Geological Survey Professional Paper 1164
Sinkholes over a Coal Mine Near Sheridan, Wyoming
Subterranean Coal Seam Fires

• Estimated to represent 3% of the world's annual CO₂ emissions
• U.S.
  > 100 fires in nine states, mostly in Colorado, Kentucky, Pennsylvania, Utah and West Virginia
  Cost: > $1 billion
• India
  68 fires were burning beneath Jharia coalfield
• Germany
  Two fires have burned for more than 300 years
• China
  Fires estimated to consume 10-200 million tons of coal annually

• Sources
  • http://content.time.com/time/health/article/0,8599,2006195,00.html
  • http://en.wikipedia.org/wiki/Coal_seam_fire
D Sinkholes over Salt

Map showing locations of sinkholes over salt in the Southwest United States.
Sinkholes over salt: Wink 1 and Wink 2, Texas

Wink 1

Formed 6/3/1980
~100m across in 2004 photo
Hole encircles a 780m-deep oil well

http://www.beg.utexas.edu/nso/winksink.php

Wink 2

Formed 5/21/2002
~100m mean radius in 2004 photo
Hole encircles a 1km-deep water well
Sinkholes over salt: Stratigraphy at Wink sinkholes

http://www.beg.utexas.edu/nso/winksink.php
Sinkholes over salt: Daisetta, Texas

- Formed 5/7/2008
- Nicknamed “Sinkhole de Mayo”
- Hole encircles several oil and gas wells
- Less than 300m above top of Hull salt dome
- No more than 0.5km from residences, businesses, and a school

View north across Daisetta sinkhole. Debris and crude oil float on water in the sinkhole.

From Paine et al., 2012
E Pit Craters

Pit craters of Kilauea

View to north across Devil’s Throat pit crater

48m mean radius, 50m depth

From Okubo and Martel, 1998
E Pit Craters

Faults and Opening Mode Fractures Near Devil's Throat Pit Crater

From Okubo and Martel, 1998
E Pit Craters

Inferred Sequence of Formation

From Okubo and Martel, 1998
## III Common Characteristics of Subsidence Bowls and Sinkholes/Pit Craters

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Subsidence Bowls</th>
<th>Sinkholes and Pit Craters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface deformation</td>
<td>Continuous</td>
<td>Discontinuous (ring fault)</td>
</tr>
<tr>
<td>Radius (R)</td>
<td>&gt; 1 km</td>
<td>1m – 100m</td>
</tr>
<tr>
<td>Surface depression (D)</td>
<td>&lt; 20m</td>
<td>5m – 100m⁺</td>
</tr>
<tr>
<td>D/R</td>
<td>~ 0.01</td>
<td>~ 1</td>
</tr>
<tr>
<td>Map view shape</td>
<td>Circular</td>
<td>Circular or in chains</td>
</tr>
<tr>
<td>Boundary inclination</td>
<td>Boundary ill-defined</td>
<td>Steep</td>
</tr>
<tr>
<td>Development time</td>
<td>Years</td>
<td>Final collapse is abrupt</td>
</tr>
<tr>
<td>Inferred cause</td>
<td>Fluid withdrawal</td>
<td>Collapse into a void</td>
</tr>
<tr>
<td>Depth of volume loss</td>
<td>~ 1 km</td>
<td>&gt; Surface depression</td>
</tr>
<tr>
<td>Shape of volume loss region</td>
<td>Spherical or disk shaped</td>
<td>Disk or tabular</td>
</tr>
<tr>
<td>Nature of host</td>
<td>Porous sedimentary</td>
<td>Layered</td>
</tr>
</tbody>
</table>
IV Characterization methods

A Characterization of surface
1 Conventional surveying
2 GPS surveys
3 Interferometric Synthetic Aperture Radar (InSAR)
4 LIDAR
5 Fracture mapping

B Characterization of subsurface
1 Boreholes
2 Geophysical surveys
   a Seismic methods
   b Ground penetrating radar
   c Electrical resistivity
   d InSAR
   e Gravity measurements
III Characterization methods

B Characterization of subsurface

1 Boreholes

2 Geophysical surveys
   a Seismic methods
   b Ground penetrating radar
   c Electrical resistivity
Imaging Sinkholes: Seismic Reflection

Oblique aerial photo looking southwest shows the large sinkhole off north Key Largo

Seismic profile across sinkhole. Opaque character of sinkhole sediments reflects gas-saturated sediments.

From USGS Professional Paper 1751
Sketch of sinkholes along I-70, Kansas
Sinkholes above Hutchinson Salt

From Miller and Steeples, 2008
Imaging Sinkholes: Seismic Reflection Images of I-70 Sinkholes

- Prominent reflector at 260 ms is the 900’-deep Stone Corral Anhydrite.
- Top of salt is at about 340 ms and is ~1200 ft below ground surface.

Sinkholes at stations 1340 and 1500.

From Miller and Steeples, 2008
Ground Penetrating Radar (GPR)

1. Physical principles parallel those in seismology

2. Uses high-frequency (usually polarized) radio waves, usually 10 MHz to 1 GHz

3. Where transmitted radar encounters a change in dielectric constant, the signal may be reflected or refracted

4. Receiving antenna records the variations in the return signal

5. Technique sensitive to subsurface electrical properties

6. Good for detecting salt water

\[ v = \frac{c}{\sqrt{u_r \varepsilon_r}} \]

- \( c = 3 \cdot 10^8 \text{ m/s} \) (speed of EM waves in free space)
- \( u_r = u/u_r \) is the relative magnetic permeability of medium
- For rock, \( u_r \approx 1 \)
- \( \varepsilon_r = \varepsilon/\varepsilon_r \) is the ratio of the dielectric permittivity of the medium to the dielectric permittivity of free space
- Radar velocity is primarily controlled by \( \varepsilon_r \).
Imaging Sinkholes: Ground Penetrating Radar, Jordan

Location map of site. Dead Sea is at bend in strike—slip fault.

Ground Penetrating Radar Profile over a known filled sinkhole, 100 MHz

Betayneh et al., 2002
Electrical Resistivity

- Penetration depth increases with electrode spacing
- Voltage drop measured at several places
- Current flows perpendicular to equipotential curves
- Surface voltage measurements allow resistivity structure to be evaluated at depth
- Greater penetration depth than GPR

Images of Sinkholes: Electrical Resistivity

400 MHz Ground Penetrating Radar Reflection Profile

b

ERT profile

B Marsh deposits

C Sinkhole

A Aeolian dunes

Electrical Resistivity Tomographic Profile

Sinkhole marked by low resistivity (high conductivity)

From Margiotta et al., 2012
Images of Sinkholes: InSAR and gravity measurements

InSAR interferogram for the Wink sinkhole area

Residual gravity anomalies
Negative values $\rightarrow$ Mass deficit

From Paine et al., 2012
Images of Subsidence: InSAR map of Las Vegas

This InSAR-derived surface-deformation map shows subsidence in the Las Vegas Valley between April 1992 and December 1997. It was obtained by summing three time-sequential interferograms. The subsidence is caused by aquifer-system compaction and controlled in part by the surface faults, which have also been the focal point of earth-fissure formation (Amelung and others, 1999).

The northeast subsidence bowl is bounded on the southeast by the Eglington fault.

This central subsidence zone follows the general trend of several surface faults.

http://pubs.usgs.gov/fs/fs-051-00/images/fig4.jpeg
References
Sinkholes

Oil shale sinkholes

• http://www.ene.ttu.ee/maeinstituut/poster/rez.html

Winter Park Florida sinkhole

• https://www.youtube.com/watch?v=DPL4guf4BV4

Wikipedia web site

• http://en.wikipedia.org/wiki/Sinkhole

Devil’s Throat Pit Crater


Sinkhole video (52:50)

• https://www.youtube.com/watch?v=9fznZ1d_2mQ

Sinkholes and sewer line breaks

• http://www.sewerhistory.org/grfx/misc/disaster.htm

Sinkholes in New Mexico

• Land, L., 2013, Geophysical records of anthropogenic sinkhole formation in the Delaware Basin region, Southeast New Mexico and West Texas, USA: Carbonates and Evaporites, v. 28, Issue 1-2, p. 183-190.

Sinkholes in Texas

References
Sinkholes

General geophysical methods for sinkhole detection