LAND SUBSIDENCE AND EARTH FISSURES
FROM GROUNDWATER WITHDRAWAL – A GROWING WORLDWIDE PROBLEM

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We

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AGENDA

- What are land subsidence/uplift and earth fissures?
- How do we measure them?
- How do they affect infrastructures?
- What is our understanding about them?
- What can we do to mitigate negative effects of land subsidence/uplift and earth fissures?
What are land subsidence/uplift and earth fissures?

How do we measure them?

How do they affect infrastructures?
DEFINITIONS

- **Land Subsidence**
  - sinking of the ground
  - ground settlement
  - Compaction (Geologists, hydrologists, hydro-geologists)
  - Consolidation (geotechnical Engineers)

- **Uplift**
  - rising of the ground
  - ground uplift

- **Earth fissures**
  - Long, deep cracks in the ground (depths extend to groundwater elevation ??)
About 80% of land subsidence in the US is due to groundwater withdrawal [Hoffman et al. 2003]

Land subsidence is a worldwide problem (Philippines, China, Iran, India and many others)

States where subsidence has been attributed to pumping of groundwater. [USGS, 2000]
Groundwater withdrawal exceeds natural recharge

- Water table declines
- Land subsidence
- Earth fissures

Image. Courtesy Ralph Weeks
Groundwater levels have recovered in some areas from reduction in pumping and increased groundwater recharge (Leake and others, 2000).
# Subsidence for Selected Locations in Southwest US.

<table>
<thead>
<tr>
<th>State</th>
<th>Location</th>
<th>Subsidence</th>
<th>Years</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Arizona</td>
<td>Eloy</td>
<td>12.5 ft</td>
<td>1969</td>
<td>Schumann and Poland, 1969</td>
</tr>
<tr>
<td></td>
<td>Stanfield</td>
<td>11.8 ft</td>
<td>1977*</td>
<td>Laney et al., 1978</td>
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<td></td>
<td>Queen Creek</td>
<td>3 ft</td>
<td>1977*</td>
<td>ALGS**, 2007</td>
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<tr>
<td></td>
<td>Bowie</td>
<td>6 ft</td>
<td>1952-1982</td>
<td>Strange, 1983</td>
</tr>
<tr>
<td></td>
<td>Tucson</td>
<td>&lt;1 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td></td>
<td></td>
<td>0.5 ft</td>
<td>1952-1980</td>
<td>Schumann and Anderson, 1988</td>
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<tr>
<td></td>
<td></td>
<td>4.3 ft</td>
<td>1989-2005</td>
<td>Carruth, 2007</td>
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<tr>
<td></td>
<td>Northwest Avra Valley</td>
<td>1 ft</td>
<td>1948-1980</td>
<td>Schumann and Anderson, 1988</td>
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<tr>
<td></td>
<td></td>
<td>1.7 ft</td>
<td>1989-2005</td>
<td>Carruth, 2007</td>
</tr>
<tr>
<td>Nevada</td>
<td>Las Vegas</td>
<td>6 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td></td>
<td>Albuquerque</td>
<td>&lt; 1 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td></td>
<td>Mimbres Basin</td>
<td>2 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td>New Mexico</td>
<td>Lancaster</td>
<td>6 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td></td>
<td>Southwest of Mendota</td>
<td>29 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td>California</td>
<td>Davis</td>
<td>4 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
</tr>
<tr>
<td></td>
<td>Santa Clara Valley</td>
<td>12 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
</tr>
<tr>
<td></td>
<td>Ventura</td>
<td>2 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
</tr>
<tr>
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<td>Southwest of Mendota</td>
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<td></td>
<td>Ventura</td>
<td>2 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<tr>
<td></td>
<td>El Paso</td>
<td>1 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
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<td></td>
<td>Houston</td>
<td>9 ft</td>
<td>1997*</td>
<td>Leake, 1997</td>
</tr>
</tbody>
</table>

* This is the year in which the amount of subsidence was reported in the literature.
** Arizona Land Subsidence Group.
EXAMPLES OF LAND SUBSIDENCE

San Joaquin Valley southwest of Mendota, California.

South of Eloy, Arizona. Subsided more than 15 feet between 1952 – 1985

[Arizona Bureau of Geology and Mineral Technology, 1987]
MONITORING LAND SUBSIDENCE

- Land surveys
- Aerial surveys
- Lidar
- GPS

- Compaction recorder
INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)

http://www.esa.int/
SALT RIVER VALLEY
WELLS IN PART OF SALT RIVER VALLEY

Data from ADWR
LAND SUBSIDENCE IN PART OF SALT RIVER VALLEY FROM InSAR
MEASURED SUBSIDENCE USING InSAR NEAR BROWNING SUBSTATION

Subsidence bowl

Subsidence (mm)

Long. distance (m)  Lat. distance (m)
IMPACTS OF LAND SUBSIDENCE

- Enhanced Flooding
- Damage to infrastructure
- Damages to utilities
  - Electric transmission lines, gas and water pipes, cables
  - Reversal of flow in canals and irrigation systems
  - Damage to well-casings
- Land use
- Earth fissures

Flooding of Happy Road, Queen Creek, Arizona

Image: Courtesy Ray Harris
Earth fissure in an open range.

Image: Courtesy, Ray Harris

Earth fissure winding its way through farm/residential land.

Image: Courtesy, Ken Fibelkorn

Earth fissure identified during trenching near an earth dam.

Image: Courtesy, Mike Rucker, AMEC.
LAND USE

Image. Boggan, 2008

Sign warning motorists of subsidence hazard was erected after an earth fissure damaged Snyder Hill Road in Pima County, Arizona, 1981.
OPENING OF AN EARTH FISSURE FROM EROSION

Images Courtesy, Ken Fibelkorn
What is our understanding on land subsidence and earth fissures?
GROUNDWATER AND GROUND SURFACE CHANGES FROM PUMPING

- Depressed ground surface
- Original ground surface
- Original water table
- Cone of depression
- Unconfined aquifer
- Control volume

Groundwater level decreases

Equivalent stress changes transferred to the soil particles

Soil settles
Groundwater level decrease

Groundwater level declining, effective stress increasing, soil becoming denser, decreasing water storage.

Groundwater level increasing, effective stress decreasing, soil becoming looser, increasing water storage.

Subsidence

Uplift

Permanent land subsidence

Total subsidence

Uplift
STRESSES FROM GROUNDWATER DECLINE

SOIL DEFORMATION FROM GROUNDWATER DECLINE

\[ \Delta \sigma_{zB}' = \Delta \sigma_{zA}' \]

Isotropic consolidation

Simple shear on vertical planes

rotation
Components of land subsidence from groundwater pumping.

a = subsidence due to hydrostatic consolidation (compression, compaction)
b = subsidence due to consolidation settlement from simple shearing
c = subsidence due to simple shear on vertical plane
d = subsidence due rotation (when micro-rotation = macro-rotation)
\( \Delta \theta \) = change in rotation
\( \Delta \gamma \) = change in simple shear strain
RESULTS: LATERAL COMPRESSION

THE MECHANICS DO NOT SHOW THESE TENSILE STRESSES

After Bell, 1981

After Jachens and Holzer (1979 and 1982)
RESULTS: PREDICTION OF THE FORMATION OF EARTH FISSURES

- Slope of subsidence bowl is a good indication of the possible initiation of earth fissures.
- Slope must be calculated over a distance of about $\sqrt{2}$ times aquifer thickness or thickness of top cemented layer.
- EF location can be predicted by the intersection of the slopes of the subsidence bowl slope and the upper curve.

**RESULTS: SLOPES FOR INITIATION OF EARTH FISSURES: TOP CEMENTED SOIL**

- **Important finding for groundwater management**
  - Earth fissures will not form if the slope of the “subsidence bowl” is less than $8 \times 10^{-5}$ (0.008%) regardless of soil type, pumping rate and volume pumped.

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RESULTS: WHAT HAPPENS WHEN AN OUTCROP IS ENCOUNTERED?

Possible movement of soil wedge to close earth fissure

Outcrop

Earth fissure

Upper cemented alluvium

Production well

Lateral compression

Void filled by sediments from erosion of earth fissure and surface wash

Aquifer alluvium

Groundwater level at time, t

EF location at a site in Las Vegas Valley, Nevada. Data and observations made by Holzer 1984

Vertical Deformation Profile Along 202L Centerline
Based on data provided by Tatlow (2004) for the period 1992-2000

Graph: Courtesy Dr. Samtani, NCS Consultants, LLC
What can we do to mitigate negative effects of land subsidence and earth fissures?
SOME POSSIBLE SOLUTIONS

- Stop pumping groundwater
- Aquifer recharge
- Manage groundwater extraction and aquifer recharge
  - reduce negative effects of subsidence and reduce the potential for earth fissure initiation.
Water for the Future

Water use

- Colorado River: 41%
- CAP: 20%
- In-State Rivers: 15%
- Groundwater: 21%
- Reclaimed Water: 3%

Climate change

Arizona Population Projections

Population (Millions)

Year


[US Population Projections from the US Census Bureau]

Hoerling, M., 2007, Past Peak: Water in the Southwest, Southwest Hydrology, Volume 6, Number 1, January/February.
GROUND MOVEMENTS FROM TDRP

OUTAGE

AFTER 4 YEARS OF OPERATION

Displacement (mm)
-100.0 - 15.0
-15.0 - 0.0
0.0 - 5.0
5.0 - 10.0
10.0 - 15.0
15.0 - 20.0
20.0 - 25.0
25.0 - 30.0
30.0 - 40.0

Palo Verde Nuclear Generating Station

Tonopah Desert Recharge Project

Town of Tonopah

Cap Canal

Major Highway

Nov. 17, 2007 to Nov. 01, 2008 (1 yr)

Feb. 25, 2006 to Mar. 06, 2010 (4 yrs)
HOW CAN OUR ANALYSIS OF LS AND EF FORMATION BE USED FOR SUSTAINABLE GROUNDWATER MANAGEMENT?
CONCLUSIONS

- Land subsidence comprises settlement from (a) hydrostatic consolidation and (b) simple shearing and rotation.

- Earth fissures will not initiate in any soil or from any pumping regime if the slope of the subsidence bowl is less than 0.008%.
CONCLUSIONS

- Low hydraulic conductive geo-materials
  - Responsible for large ground movements
  - “Delayed” ground movements
  - Harmonic (wavy) ground movements
  - Affect flow patterns
**CONCLUSIONS**

- Ground slope is the key to managing groundwater considering land morphology.
- Remote sensing using InSAR is an excellent tool to collect the monitoring data for use with the model results.