Ground Subsidence: Infrastructure Impact, Investigations, Solutions and Monitoring

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“Subsidence causes permanent inundation of land, aggravates flooding, changes topographic gradients, ruptures the land surface, and reduces the capacity of aquifers to store water” (T.L. Holzer and D.L. Galloway, 2005)
Ground Subsidence – Infrastructure Impacts

Impact infrastructure sensitive to differential elevations & grades
- Gravity water conveyance
- sewers
- collapse of deep well casings

Extruded well casing south of Cochise, AZ

Irrigation canal grade change, west of Glendale, AZ

Rail spur grade change south of Cochise, AZ

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Ground Subsidence – Floodplain Impacts

Relative ground elevation changes lead to floodplain changes –
- Luke AFB closed 3 days in 1992; flooding caused by 18 ft differential subsidence & reversal of Dysart Drain
- Wenden AZ 2010 flooding influenced by subsidence

Images from ADWR, 2010
Basic Subsidence mechanisms

SUBSIDENCE PROFILE

GEOLOGIC PROFILE

Predevelopment water table

Intermittent desert river

Land surface

Earth fissure

Q Upper Alluvial Unit - open basin

QTs Middle Fine-Grained Unit
closed basin playa, alluvial fan

Present water table

Tp Lower Conglomerate Unit
including sandstone and siltstone

Crystalline Rocks: Schist, gniess, quartile, metavolcanic rocks
Subsidence can lead to another class of problem – Earth Fissures
Earth Fissures can Impact Linear Infrastructure such as Canals, Highways & Flood Control Structures.
Typical Sequence of Earth Fissuring
Shallow Impacts

Adapted from Bell, 1981

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Example Earth Fissure Problem –
Mine Dewatering in Northern Nevada

Waterline break -
developed overnight

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Detecting & Monitoring Subsidence

Satellite-based *Interferometry* by *Synthetic Aperture Radar* (InSAR)

Repeat GPS & Level Surveys
Example - 2010 InSAR Sinkhole Study Quantified
2005-2006 Underground Mining Subsidence

Carlsbad, NM area InSAR 7/2005 to 3/2006
InSAR image is ~60 miles (~100 km) across
(AMEC, 2010)
Recent InSAR for Willcox AZ area

Where archived data is available, InSAR data exists as far back as 1992.

Results of GPS monitoring at Power plant ash pond facility 1996 – 2008, part of continuing APP monitoring work

### Relative Settlements (feet) & Apparent Strains Between GPS Survey Monuments/Benchmarks - October 1996 to December 2008

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10/1996 – 12/2008

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Subsidence and Earth Fissuring are Dynamic, Time-related Phenomena

Earth fissure gully development
North of Dragoon Rd,
Cochise County, AZ

2003

2004

2006
post-flood

2008 – with trash
Meanwhile, at Dragoon Road –
Local Mitigation to Prevent Catastrophic Failure

Earth fissure crossed Dragoon Road & Cochise Stronghold Road –
Crossing reinforced to prevent piping failure
(2004)
In 2004, Subsidence Magnitude was Unknown - Maintenance Continues to this Day

Crossing survived massive summer flood events in 2006 without failure

Adjacent to Cochise Stronghold Road:
Dec 2009 gas line broken  Oct 2010 Piping holes on shoulder

By 2010, multiple leveling patches
Not all Large Cracks are Earth Fissures – Giant Desiccation Cracks may Look Similar...

Desiccation crack exposed in deep test trench

But, cracking mechanisms and engineering implications may be very different

Dragoon Road ~1 mile east of earth fissure, 2010

Upstream of Magma Dam near Florence, AZ, 2007

East bound I-10 west of San Simon, AZ, 2006

Looking West

Looking East
Keys to Understanding Subsidence: Geometry, Material Properties, Pore Pressure Change

Note extensive InSAR subsidence signatures correlating to low resistivities (<10 ohm-m)

East Salt River Valley CAP deep basin well data & corresponding InSAR 1992-2000

Basin Alluvium Characterization Based on Deep Well Geophysical Results

Short Normal (SN) Resistivity, ohm-m
Caliper (cal) and gamma density (G-G) results at SG-6 are relative

- SG-18 Short Normal
- SG-1 Short Normal
- SG-2 Short Normal
- SG-21 Short Normal
- SG-4 Short Normal
- SG-6 relative density
- SG-10 Short Normal
- SG-12 Short Normal
- Bedrock
- low-perm clay
- hi-perm alluvium

- approx water table (1978)

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CASE STUDY – Characterization, Remediation, and Monitoring of a Subsidence-Impacted Dam: McMicken Dam, Arizona

Earth fissures were originally identified nearby in 1980 and were found to be threatening the dam in 2002.

Subsidence up to ~5 ft at dam from groundwater withdrawal.

Mitigated southern end

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Period of rapid groundwater decline with associated rapid subsidence
Followed by
Period of groundwater stability / rise with associated reduced subsidence

Figure 8 - Water Level Data Trends near Sarival Ave. and Northern Ave. With Measured Subsidence along Reems Road at Peoria Ave. and Olive Ave.
General Subsidence History in West Salt River Valley -

Subsidence 1957 – 1991 (Schumann, 1992)

Percent Fines Above 700 ft. and Earth Fissures
Stulik and Twenter, 1964 and AZGS

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Earth Fissure Threatening McMicken Dam – Initial Earth Fissure Tracing Effort (2002)
Earth Fissure Features Traced Using Conventional Seismic Refraction
Gravity Survey (bedrock depth) & InSAR (alluvium lithology)

There were no logged deep wells in the area to provide useful data for depth to bedrock or subsurface characterization.
ReMi uses surface waves (Rayleigh waves) to investigate and interpret a vertical 1-D s-wave profile to depths potentially greater than 100 meters.

Equipment here included a 12 channel seismograph, 240-m cable, 4.5 Hertz low frequency geophones.

Energy source is typically ambient noise; at quiet site, a vehicle driven alongside or beyond the array was energy source.
Confirmed presence & approximate depth to extensive localized clay bodies with resistivity < 1,000 ohm-cm (<10 ohm-m), whose presence was inferred by InSAR subsidence bowls

4-point Wenner array method with electrode spacings of 5, 10, 20, 50, 100, 200, 333, 500, 750 and 1000 ft was used.
For model development purposes, a representative ‘clay body’ with significant time-delay consolidation behavior was assumed to be present and scale in thickness to the magnitude of local subsidence as inferred from InSAR.
Synthesis of Geophysical Results into Coherent Geologic and Finite Element Model Profiles

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A 2-D linked seepage and elastic Finite Element model was developed that incorporated and honored these parameters -

- Measured Ground Subsidence
- InSAR Data to Further Quantify Actual Subsidence
- Realistic Bedrock Geometry
- Characterization of Fine Sediments
- Actual Well Hydrographs
- Internal Pore Pressure Distributions
- Calibration of Input Parameters
- Prediction

Earth fissure risk

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Based on the results of the full geotechnical investigation, including InSAR and finite element model results, fissure risk zonation was accomplished.

The dam section in the high risk zone was abandoned. A relocated dam section was designed and constructed.
Going Forward: Monitoring

- Visual Inspection
- Aerial Imagery
- InSAR
- Groundwater Trends
- Vertical Survey
- Horizontal (GPS) Survey
- Experimental TDR (Time-Domain Reflectometry) abandoned
- Tape Extensometer
- Experimental Rod Extensometer
90-foot sections located in areas of modeled and anticipated ground strain along new alignment, existing alignment, and within the earth fissure field.
Recent & Current InSAR Images as Part of Continuing Monitoring Program

November 2002 to October 2005
November 2002 to January 2006
October 2003 to September 2007

InSAR provided by Arizona Department of Water Resources
Proto-type Rod Extensometer
GPS – Horizontal & Vertical Measurement
Case Study - Some Lessons Learned

- Washes often remove cemented soil horizons that are good for dam foundation
- Previous investigation disturbs ground, making visual inspection and any subsequent investigations difficult
- TDR system is very sensitive – numerous breaks due to curing of CLSM material it is encased in.
- Redundancy is necessary
- All instrumentation requires armor against vandalization
- Telemetric warning system was a challenge from the start. Sensitivity of the TDR system rendered it essentially useless
- Survey costs quickly become unsustainable
- We still have much to learn – whole system needs to be re-evaluated for effectiveness
Closure

“…public agencies that formerly were trying to stop subsidence are now adopting policies that promote it. Subsidence is returning…”

(B.E. Lofgren, 1998)

Available Resources in Arizona include ADWR for Subsidence, and AzGS for Earth Fissure Maps
Questions?

Thank You for Your Attention!

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