Mapping and monitoring earth fissures in Arizona; a man-made geohazard

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Earth fissures are landscape-scale tension cracks that form in response to differential land subsidence in basin sediments. In Arizona, fissures are a clear consequence of groundwater overdraft which has led to significant land subsidence in valleys with long-term agriculture. Considerable groundwater overdraft began in the 1930s to support an expanding agricultural footprint. Groundwater level declines in excess of 500 ft and associated land subsidence of up to 20 ft has been measured in some basins. Widespread fissure formation began in the 1960s and continues today. Fissures have negative and potentially destructive impacts on property and infrastructure and have recently become the subject of state legislation requiring their presence be disclosed during real estate sales. The Arizona Geological Survey (AZGS) was tasked with creating official maps of earth fissures throughout the state. To date, AZGS has mapped and currently monitors over 185 miles of earth fissures in 27 study areas.

Groundwater use in Arizona is closely related to potential zones of earth fissure formation. AZGS works closely with the Arizona Department of Water Resources (ADWR) who monitors groundwater use and associated land subsidence throughout Arizona. Groundwater level recovery and waning land subsidence was observed following the introduction of Central Arizona Project (CAP) water for agricultural use in the 1980s. In contrast, unregulated groundwater withdrawal for expanding agriculture in Cochise County in southeastern Arizona has resulted in rapid groundwater lowering, coincident land subsidence, and continued fissure formation. Ongoing drought has led to cutbacks on available CAP water which will result in renewed groundwater withdrawal in recovering basins. The consequences of switching back to groundwater are easy to predict. The only question is how long before renewed subsidence and associated fissures reappear?

Land Subsidence in Arizona and Monitoring by the Arizona Department of Water Resources

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Land subsidence due to groundwater overdraft has been an ongoing problem in south-central and southern Arizona since the 1940s. In some areas of the State, groundwater level declines of more than 400 feet have resulted in extensive land subsidence and earth fissuring. Land subsidence in excess of 18 feet has been documented in both western metropolitan Phoenix and Eloy, Arizona. The declining groundwater levels in Arizona are both a challenge for future groundwater availability and for mitigating land subsidence.

In 1997, the Arizona Department of Water Resources (ADWR) created a land subsidence monitoring program. The program initially focused on monitoring land subsidence in the east valley of the Phoenix Metropolitan area, what is known as the Hawk Rock Area, using survey-grade Global Navigation Satellite System (GNSS) equipment. In 2002, ADWR was awarded a 3-year $1.3 million NASA grant to expand the land subsidence monitoring program to include Interferometric Synthetic Aperture Radar data (InSAR). Upon completion of the NASA grant in 2005, ADWR quickly migrated to a land subsidence monitoring program that primarily utilized InSAR data using GNSS surveying to support the program. Using InSAR data, ADWR has identified more than 26 individual land subsidence features in Arizona, collectively covering more than 3,400 square miles. In addition, the program now cooperates with 14 entities whose financial assistance allows ADWR to fund the InSAR data collection. ADWR provides land subsidence maps for download from ADWR's website. As of October 2019, 496 land subsidence maps are available for download and are used daily by geologists, hydrologists, engineers, planners, surveyors, floodplain mangers, GIS analysts, and water resources managers.

Earth fissures caused by extensive aquifer exploitation in China and the numerical simulation of Wuxi case

Shujun Ye

Abstract:

Initially observed in the semiarid basins of southwestern USA, earth fissures due to aquifer over-exploitation are presently threatening a large number of subsiding basins in various countries worldwide. Land subsidence and associated earth fissures attributed to groundwater extraction has been severe in China and is still occurring, especially in three principal regions of the North China Plain, Fenwei Basin and Yangtze Delta. Earth fissures accompanying subsidence create significant geohazards, and more than 1,000 earth fissures have been identified in the three regions mentioned above. Different mechanics have been proposed to explain the earth fissure development, such as differential compaction, horizontal movements, and fault reactivation. Numerical modeling and prediction of this major geohazard caused by overuse of groundwater resources are challenging because of two main requirements: shifting from the classical continuous to discontinuous geomechanics and incorporating two-dimensional features (the earth fissures) into large three-dimensional (3-D) modeling domain (the subsiding basin). In this work, we proposed a novel modeling approach to simulate earth fissure generation and propagation in 3-D complex geological settings. A nested two-scale approach associated with an original nonlinear elastoplastic finite element/interface element simulator allows modeling the mechanics of earth discontinuities, in terms of both sliding and opening. The model is applied on a case study in Wuxi, China, where groundwater pumping between 1985 and 2004 has caused land subsidence larger than 2 m. The model outcomes highlight that the presence of a shallow (□80 m deep) bedrock ridge crossing the Yangtze River delta is the key factor triggering the earth fissure development in this area. Bending of the alluvial deposits around the ridge tip and shear stress due to the uneven piezometric change and asymmetrical shape of the bedrock have caused the earth fissure to onset at the land surface and propagate downward to a maximum depth of about 20–30 m. Maximum sliding and opening are computed in the range of 10–40 cm, in agreement with the order of magnitude estimated in the field.

Modeling the development of ground ruptures by a FE/IE approach

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A hypothetical modeling analysis was used to investigate the relative susceptibility of various geologic configurations to rupture generation. A geomechanical Finite Element (FE) - Interface Element (IE) modeling approach is used to simulate rupture generation and propagation for three typical processes: i) reactivation of an existing fault; ii) tensile fracturing above a bedrock ridge; and iii) differential compaction due to heterogeneous thickness of aquifer/aquitard (sand/clay) layers. A sensitivity analysis was used to address various factors of the rupture processes, including the thickness of the compacting layers, their depth below the land surface, the ratio between compressibility and thickness of sand/clay layers in heterogeneous formations, and the height of the bedrock ridge with respect to the thickness of the compacting alluvial sequence. The numerical results are processed by a statistical regression analysis to provide a general methodology for a preliminary evaluation of possible ruptures development in exploited aquifer systems susceptible to aquifer-system compaction and accompanying land subsidence. A comparison with a few representative case studies in Arizona, China, and Mexico supports the study outcomes.

Continuous Monitoring of an Earth Fissure in Chino, California—A Management Tool

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Continuous measurements of deformation were made in Chino, California across an earth fissure and nearby unfissured soil during 2011 to 2013 in two buried, horizontal, 150-mm-diameter pipes that were 51 m long. The pipes were connected by sealed boxes enclosing vertical posts at mostly 6 m intervals. Horizontal displacements and normal strain were measured in one line using nine end-to-end quartz tubes that were attached to posts and spanned fissured or unfissured soil. The free ends of the tubes were supported by slings and moved relative to the attachment post of the next quartz tube. Linear variable differential transformer (LVDT) sensors measured the relative movements. Five biaxial tilt sensors were also attached to selected posts in that line. Relative vertical movement was measured at nine locations along the line in the second pipe using low-level differential pressure sensors. The second pipe was half full of water giving a free water surface along its length. Data were recorded on a Campbell CR10 using multiplexers.

The quartz-tube horizontal extensometers exhibited more than 3 mm of predominantly elastic opening and closing in response to about 32 m of seasonal drawdown and recovery, respectively, in an observation well 0.8 km to the south. The nearest production well was 1.6 km to the west. The horizontal strain was 5.9 x 10^{-5} or 30 percent of the lowest estimate of strain-at-failure for alluvium. Maximum relative vertical movement was 4.8 mm. Maximum tilt in the fissure zone was 0.09 arc degrees while tilt at a separate sensor 100 m to the east was 0.86 arc degrees, indicating a wider zone of deformation than was spanned by the instrumentation. High correlation of horizontal displacements during drawdown, and especially recovery, with change in effective stress supports differential compaction as the mechanism for earth-fissure movement. Coefficients of determination (r^2) ranged from 0.89 to 0.99.

Continuous measurements of horizontal strain coupled with water-level fluctuations and vertical borehole extensometry can provide a real-time adaptive management tool for restricting pumping if strain approaches the lower limit of strain-at-failure or a stress-strain curve deviates from the previous mostly elastic regimen.

ASU-Unesco IGCP 641
Land Subsidence and Earth Fissure Workshop

Classification of ground fractures associated to Land Subsidence in the Iztapalapa Region, Mexico City

Dora Carreón-Freyre, Mariano Cerca, Raúl Gutierrez-Calderón, Carlos Alcántara-Durán

Land subsidence has been widely studied in Mexico City during the last six decades (Nabor Carrillo, 1947, Cabral Cano, 2008). A total subsidence of 13 m has been reported at the center of the lacustrine plain in Mexico City as a consequence of a generalized consolidation state of thick clayey sequences related to deep groundwater depletion. The most of ground fractures in the fluvio lacustrine areas are non-dilatant ruptures in silts and clay sequences that may propagate through weak planes associated with lithological contacts or major structural features (Carreón-Freyre et al., 2016). Deformation features can also be related to shallow groundwater flows and, consequently, fractures may open and close seasonally. Brittle fracturing is also present in a special kind of lacustrine materials without any crystalline structure associated to ashes alteration (Carreón-Freyre et al., 2006). Because Mexico City is placed in an active seismic area fractures propagation may also be related with microtremors and have a close relation with soil-structure interactions during earthquakes within the Mexico Basin (Ovando-Shelley et al., 2012).
The Iztapalapa Municipality is located in the eastern part of Mexico City, it is one of the most populated areas of the country and since the 70´s the most of groundwater extraction was localized in this area. Furthermore, due to the high heterogeneity of geological materials in the Iztapalapa subsoil (interbedded volcanic rocks, pyroclastics, fluvial and lacustrine sediments) the differential deformation is highly determined by lithological contacts.
Ground fractures are caused by the interaction of four main factors (Carreon-Freyre et al., 2019): (1) geological preexisting discontinuities caused by variations in the depositional environment, (2) stress history determining the geometry of early fracturing, (3) variations in compressibility and permeability of geological materials, that control short-term and local-scale deformation and, (4) exhaustive exploitation of aquifers causing a decline of the pore water pressure leading to subsidence and creating vertical and horizontal tension stresses (Carrillo, 1947; Rivera and Ledoux, 1991; Holzer, 1984; Juárez-Badillo and Figueroa-Vega, 1984). Coexistence of one or several of the mentioned factors determines the mechanism of fracturing at diverse scales. We present in this work the types of fractures observed in the Iztapalapa area according with their geomechanical conditions of nucleation and propagation. This classification allowed the local government to establish specific mitigation measures to improve the Iztapalapa inhabitants housing security.

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Site Specific Characterization of an Earth Fissure impacting Infrastructure, with Prediction of Potential Future Fissuring

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Arizona has a long history of earth fissure activity resulting from groundwater pumping-induced land subsidence. Infrastructure, especially water conveyance, flood control and other embankment structures, are vulnerable to damage, and potentially to failure, from earth fissures. The author has and continues to be deeply involved in characterization, mitigation engineering and monitoring at three structures defined as dams impacted by earth fissures. In 1993, we characterized a newly discovered earth fissure at a proposed ash pond system in southeast Arizona, developed geomechanical modeling to assess ground strains associated with that earth fissuring, and provided mitigation recommendations for design that permitted the facility to be approved and constructed. We developed and implemented a monitoring system that is integral to the facility permitting, and have monitored continuing land subsidence and earth fissure behaviors at the facility on an annual basis, beginning in 1995. Investigation methods were developed or refined, including surface seismic refraction to trace incipient (not yet visible) earth fissuring, and monitoring criteria based on integration of GPS and optical survey methods, and tape extensometer measurements for both vertical and horizontal monitoring of earth fissure movements at the facility. These lessons learned, and methods and procedures developed, were ready when earth fissures impacting flood control structures (FRS) in the Phoenix area began to be identified. In early 2002, a known earth fissure system was being re-mapped in the near vicinity of McMicken Dam FRS west of Phoenix. Use of the seismic refraction method traced incipient fissuring to extend under the dam. Geophysical characterization was applied to explore the sites' relevant deep geology and geometry for effective 2-d finite element stress and strain modeling of the subsidence (measured at limited locations by survey) and earth fissuring. By that time, the earth fissure and land subsidence characterization toolkit had expanded to include satellite-based InSAR, and surface geophysical techniques including combined seismic refraction and surface wave refraction microtremor methods for incipient earth fissure detection, and deep resistivity soundings to assess compressibility of basin materials where differential subsidence could lead to earth fissuring. Successful modeling consistent with the characterization confirmed that the earth fissuring was sufficiently well understood to confidently design and implement an interim dam safety mitigation. In 2007 another incipient earth fissure was detected at the toe of Powerline Dam FRS east of Phoenix. Historic data developed for the Central Arizona Project canal, including surface and deep borehole geophysics, and repeat elevation surveys along the canal, combined with data obtained using the characterization toolkit, including InSAR, were incorporated into the subsidence and earth fissure characterization and intermediate dam safety mitigation. As interim dam safety mitigations were completed and earth fissure and subsidence monitoring programs were implemented, more complete characterization of the underlying land subsidence behaviors, and geomechanical modeling to assess potential for future earth fissuring, proceeded. These efforts were focused on long term subsidence and earth fissure risk. Results of these investigations have been incorporated into the design for rehabilitation of the system of FRSs in the greater Phoenix metropolitan area for their future 100 year design life.

Identification and Mitigation of Earth Fissures

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There are four projects for which Terracon and McDOT have identified and mitigated known and suspected earth fissures. They are as follows:

- 4th segment of Arizona State Route 303L (SR 303L) between Glendale and Peoria Avenues;
- San Tan Boulevard ½ mile east of Sossaman Road;
- Baseline and Meridian Road Intersections; and,
- Northern Parkway between Dysart Road and El Mirage Road.

In addition to the known earth fissures crossing these major roadways, several earth fissures have been mapped by the Arizona Geological Survey as unconfirmed earth fissures. A methodical approach consisting of numerous steps was performed for two of the projects to determine which earth fissures could be positively identified, and which ones should be removed from further consideration on the unconfirmed earth fissure list.

The investigative information considered in our analyses included:

a. literature review,
    i. geology maps showing subsurface stratigraphy
    ii. earth fissure maps
    iii. lineament analyses of historical aerial photographs
b. historical survey information showing subsidence in the area
c. site reconnaissance,
d. seismic p-wave and ReMi field investigation and analyses,
e. earth fissure trench field investigation,
f. discussions with ADOT personnel and MCDOT personnel to decide upon the level of risk each entity was willing to accept in design and construction of their respective roadways.

Based on the information obtained from the foregoing efforts, those unconfirmed fissures not showing any substantial evidence for their existence were eliminated from the list of unconfirmed earth fissures. For earth fissures for which positive identification or substantial evidence for their possible existence was obtained, measures to mitigate their potential effects to the roadways were modeled by finite element analyses.

The results of the finite element analyses indicated that a high modulus material is needed to distribute the strain caused by the potential differential movement that could impact the roadway embankments constructed across the location of the earth fissure. A five foot high zone of material having a Young's modulus of at least 10,000 psi constructed below the embankments will spread 6-inches of potential differential movement occurring over 7 feet beneath the embankment at the fissure locations, to over 30 feet at the pavement surface. This governed the design of the mitigative measures developed for two of the projects. For the other two projects, mitigative measures consisted of high modulus materials along with cut-off walls.

Quantitative Analysis of InSAR Subsidence Magnitude and Pattern at a Single Pumping Well

Danielle Smilovsky

Satellite-based InSAR (Interferometry by Synthetic Aperture Radar) technology has provided land subsidence documentation across the Salt River Valley (SRV) for over a quarter century. InSAR results have been essential to developing quantitative understanding of differential subsidence and earth fissure behaviors and risks on an engineering scale. Among its applications, quantitative risk assessment, risk mitigation, and rehabilitation design for major flood control infrastructure, including flood retention structures (FRS), have benefitted using characterization knowledge gained from InSAR. Detailed InSAR information has supported focused engineering solutions to these hazards. Historic InSAR coverage has been dependent on the duration of satellite missions, and includes time periods of 1992 to 2000, 2003 to 2010, and 2010 to the present.

Major subsidence in the SRV was driven by groundwater pumping for agriculture prior to completion of the Central Arizona Project (CAP) in the mid-1980s; as CAP water deliveries replaced groundwater consumption, active subsidence in the SRV had become primarily residual in nature by 1992 when InSAR data collection began. When InSAR imagery of the SRV became available in 2002 (covering a time period of 1997 to 2000), a specific conical-shaped feature with about 6-inches of subsidence (the image covered a time period of 1997 to 2000) and a 1- to 2-mile radius, was noted in the west valley. As additional InSAR results became available, a more complete history of this feature, including its disappearance as an active subsidence feature after 2003, was compiled.

Review of available ADWR records provided identification of a specific municipal water supply well centered in the subsidence feature. ADWR records also provided a history of construction and annual pumping quantities at this well. Concepts and methods to model local subsidence at an aquifer stress point, such as a large pumping well, including lateral propagation of subsidence over time around that stress point, had been developed to assess subsidence histories and future subsidence potential at FRS's. This municipal supply well with pumping records and InSAR documentation of subsidence magnitude and lateral propagation pattern from start of pumping provided a case-study to test the subsidence modeling concepts and methods independently from the FRS-derived subsidence information. Modeling results using the pumping history provided by ADWR documentation were consistent with the measured subsidence derived from InSAR results.

Danielle Smilovsky, ASU & Wood Plc., has a master's degree in geographic information science and 10 years of industry experience in remote sensing sciences and GIS for engineering applications. She has applied her expertise to projects involving landslides, subsidence, earth fissuring, transportation infrastructure, mining, sinkholes, flood control dams, plant densities, building infrastructure, and material/water volumetrics, among others. She is highly skilled at transforming large, complex datasets into something others can easily understand. A winner of the 2017 xyHt Top 40 Under 40 Remarkable Geospatial Professionals, Danielle is currently a Ph.D. student at ASU's School of Earth and Space Exploration and plans to continue her research interests using remote sensing and GIS to help establish a better understanding of our environmental issues in the Southwest.

Earth Fissures and Infrastructure: A Case History at the Siphon Draw Detention Basin, Apache Junction, Arizona

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Land subsidence can severely impact infrastructure and alter existing floodplain designations by changing the ground elevation, ground slope (gradient), and sometimes through the development of ground cracks known as earth fissures that can erode into large gullies. Due to the alteration of surface water flow, ground elevation, and ground cracking that can undermine foundations, subsidence poses a particularly high risk to water conveyance, flood control, and other linear infrastructure.

The Siphon Draw Detention Basin (SDDB) in Apache Junction, Arizona provides a unique opportunity to observe the impact of an actively propagating earth fissure. Earth fissures were first identified in the area in the 1990s. In the mid-2000s, plans were developed to construct a basin to provide flood control along Siphon Draw. A series of land subsidence and earth fissure investigations were performed as part of the design process for the SDDB. During investigations, the Southeastern Earth Fissure (SEF) extended over 200 feet overnight following a rain event. Later during the investigation a trench located at the termination of the fissure extension was flooded by another rain event.

The SEF extension terminated just upstream of the boundary of the basin. It was determined that the consequence of failure of the basin due to the earth fissure was low enough that avoidance wasn't necessary. However, it was decided to implement some mitigation. Mitigation strategies included constructing 2 slurry, cutoff walls along the fissure extension, placing an embankment over the fissure extension, and a placing geotextile liner in part of the basin. SDDB construction was completed in 2010. An annual monitoring program has been implemented that includes evaluation of satellite-based interferometric synthetic-aperture radar (InSAR), real-time kinematic GPS survey, analysis of high-resolution aerial imagery, and annual ground inspection.

"Investigating Highway Structures near the Willcox Playa, Arizona"

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Abstract:

Highway overpass approaches and a three barrel reinforced concrete box culvert located on US Highway 191 about milepost 63 are showing signs of differential movement as evidenced by the transverse cracking of the barrel walls and roof across all of the barrels. Additionally, the highway embankments on the bridge approaches have a history of roadway deformation. These structures are located in a geologic area of known aquifer over-drafting, earth subsidence and subsequent continued development of earth fissures and giant desiccation cracks. This presentation discusses those geologic conditions and includes photographs of the damage to the 1939 bridge approach embankments and to the culvert that was built in 1942, which were constructed prior to the accelerated regional earth subsidence due to groundwater withdrawal. Recently additional geotechnical investigations were conducted and are shared in this presentation.

Water Availability and Land Subsidence in California's San Joaquin Valley

Michelle Sneed and Claudia Faunt

The San Joaquin Valley covers about 26,000 km^2 and is one of the most productive agricultural regions in California. Surface and groundwater are used conjunctively in the valley, but the contributions of each can vary substantially from year to year. Two recent droughts: 2007–09 and 2012–16, coupled with recent land-use changes and surface-water restrictions, put the valley's groundwater system under considerable strain. Groundwater pumpage caused significant and extensive drawdowns, resulting in land subsidence at rates up to 0.3 meters per year. These conditions prompted legislation aimed at managing groundwater in a sustainable way. California's Sustainable Groundwater Management Act of 2014 (SGMA) provides a framework to comprehensively measure and manage groundwater and empowers local agencies to assess hydrologic conditions that can cause "undesirable results." Land subsidence, resulting from compaction of unconsolidated aquifer systems caused by groundwater extraction, is listed as one of SGMA's "undesirable results." Subsidence generally is gradual and widespread, such that the occurrence often goes undetected for decades until revealed by repeated elevation surveys or infrastructure damage. Subsidence monitoring can result in early detection, provides a measure of water-resources sustainability within relevant planning horizons, and produces data and information needed for subsidence management. Therefore, consideration of subsidence, and if necessary, subsidence monitoring and management, is required for inclusion in Groundwater Sustainability Plans.

The location, extent, and magnitude of land subsidence from the 1920s to 2019 have been examined using geodetic survey (spirit leveling and Global Positioning System surveys), extensometer, continuous Global Positioning System (CGPS), and Interferometric Synthetic Aperture Radar (InSAR) data. Complementary spatially and temporally dense data types are needed to understand the mechanisms that underlie the spatial subsidence patterns and improve subsidence simulations. Geodetic survey, extensometer, and CGPS measurements show monthly, seasonal, and (or) inter-annual variations in subsidence rates at specific locations. Since InSAR data became available in 1992, the comprehensive spatial coverage it provided has allowed the delineation of the spatial extent of subsidence. Spirit-leveling surveys between the 1920s and 1970 indicated that more than half of the valley was affected by at least 0.3 m of subsidence, which locally exceeded 8 m. Data from extensometers, combined with other data sources, indicated that beginning around 1970, when surface-water delivery systems were mostly in place, subsidence during the remainder of the 20^{th} century occurred largely during drought periods. However, subsequent data from InSAR, geodetic surveys, extensometers, and CGPS showed subsidence patterns have changed, and in some circumstances, subsidence occurred irrespective of climatic conditions and was tied to land-use changes. Data from extensometers, combined with geodetic survey or CGPS data, indicated that compaction of sediments below the Corcoran Clay confining unit was the primary cause of subsidence.

Planning for the effects of subsidence in the San Joaquin Valley is important for water managers. As land use and surface-water availability continue to vary, long-term groundwater-level and subsidence monitoring, analysis, and modeling are critical to understand the dynamics of historical and continued groundwater use that cause water-level and groundwater-storage changes, and associated subsidence. Modeling tools, such as the USGS Central Valley Hydrologic Model, are useful to evaluate management strategies to mitigate adverse impacts due to subsidence while also optimizing water availability. This knowledge is critical for successful implementation of Groundwater Sustainability Plans.