

# Land Subsidence, Sinkhole Collapse and Karst Subsidence

An Un-assessed Risk



# 1.0

## Introduction

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Although land subsidence, sinkhole collapse and karst subsidence all result in lowering of the ground surface, they are slightly different phenomena. They occur due to subsurface movement of earth and all have the potential to cause significant damage to building foundations, features and critical infrastructure.

These risks typically remain un-assessed and hidden because of the challenges associated with estimating their impact. In addition to the impact of land subsidence, damage to building foundations and other structures as a result of poor preparation or soil conditions such as expansive clay is a significant concern for new construction projects.

Lack of comprehensive loss data makes land subsidence, sinkhole collapse and karst subsidence challenging and an un-assessed hazards. Although the scope of this risk is global, the data available is sparse, incomplete and mostly anecdotal, which makes understanding and estimating these hazards a huge challenge. Compared to other catastrophic natural hazards, such as floods and earthquakes, the damage caused by these hazards is generally scattered and localized. The damage costs can be expensive locally, but fail to gain wider media attention or a declaration of regional disaster. The damage from these hazards can range from building foundation cracks, infrastructure damage, building collapse, damage to buried pipelines and damage to rail and highway transportation networks, dams and other critical structures. In addition, on-going maintenance, remediation and rehabilitation costs can pose significant uninsured risks.

# 2.0

## Sinkhole collapse and Karst subsidence

Sinkhole collapse and karst subsidence are similar in morphology or process and are caused by dissolution of underground soluble bedrock (soluble carbonate and evaporite rocks), voids caused by removal or washout of subterranean material or decaying buried organic material.

Carbonate stone is dissolved or weakened by acid rains or significant movement (flow and volume) of groundwater or waterways. Over time, this weakened sediment and carbonate rock formation can collapse suddenly, resulting in a sinkhole formation. These sinkholes are natural hazards but do not depend on a single extreme weather event such as a flood. A sinkhole is a collapsing cavity occurring as a result of loss of subsurface support from on-going dissolution followed by a sudden collapse of top-level soil. Sinkhole collapses generally occur without any warning or anticipation and are hard to predict without sophisticated geological instruments, such as ground penetrating radar, to detect the cavities and weakening of rock formations. Although sinkhole collapse is a natural hazard, a broken underground water pipe can wash away underground soil forming a cavity that can also lead to a collapse. Karst subsidence is sinking of land that occurs as a result of gradual dissolution of soluble surface or subterranean material on bedrock. Unlike sinkhole collapse, it is a slow and gradual process and is less likely to cause any immediate damage or loss of life. Land subsidence is also sinking of land, but it results from compaction of shrinking voids in subsurface earth layers.

The large sinkholes can span several feet in diameter and depth. Many sinkholes are round in shape due to an hour-glass shaped flow of collapsing cover material into the underground cavity or caves formed by the dissolution process. Filling large sinkholes can be challenging and requires several geological considerations.



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Although sinkhole collapse, karst subsidence and land subsidence are different in the way they occur, many times they are grouped together and not distinguished in description of incidents, media reports and damage information. This is particularly the case with interchangeable use of descriptions for sinkhole collapse and land subsidence.

Based on compilation of news media accounts and anecdotal information from 2000–2014, annual average cost of damage from sinkhole collapse and karst subsidence was estimated<sup>1</sup> in an article presented by David Weary of US Geological Survey (USGS) at the 2014 Sinkhole Conference at over \$300 million, an estimate that the author considers to be very low. Also, this estimate presumably is limited to structural damage and remediation costs and excludes damage to personal property.<sup>2</sup> According to USGS data, Florida is the most susceptible US state to sinkholes and karstic subsidence, but Alabama, Kentucky, Missouri, Pennsylvania, Tennessee and Texas are also vulnerable to karstic collapse due to their soil geology. In fact, an open file report (# 2014-1156<sup>3</sup>) from USGS estimates about 18% of ground in the US has karstic terrain and all 50 US states contain geologic formations with soluble rocks and sediments that are susceptible to sinkhole development and collapse.

Although tied to eligibility for post-disaster federal funding and mandated by the US Disaster Mitigation Act of 2000, a 2013 review of FEMA-approved State Hazard Plans indicated only 29 out of 50 states<sup>4</sup> describe karst subsidence hazard in their plans. Many states reference the subsidence hazard in their plans, but none have a comprehensive mechanism to track sinkhole and subsidence events and costs. A research paper by David Weary of USGS presented at the 14th Sinkhole Conference, provides a summary of major sinkhole incidents (2000-2014) in several states with associated cost estimates<sup>5</sup> and links to additional details. Although not an exhaustive list, it gives a fairly good idea about the nature and the scope of sinkhole collapse hazard in the US and may assist in identifying susceptible areas.

# 3.0

## Land subsidence

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Land subsidence is the gradual settling or lowering of land surface elevation due to underground changes and earth movement as a result of compaction of subterranean earth layers. Subsidence is a slow process and generally not observable visually, but the cumulative action of subsidence is potentially destructive.

Human activities are the primary causes of land subsidence, and according to USGS Circular 1182, excessive pumping of ground water is reportedly a cause in about 80% of identified land subsidence in the US. (<http://pubs.usgs.gov/circ/circ1182/>) In addition, pumping of oil and natural gas, collapse of underground mines, drainage of wetlands and organic soils, thawing of permafrost, decay of organic material and hydro compaction of clay soil are some of the other causes that contribute to land subsidence.

Land subsidence is a global problem. In the US alone, over 45 states have reported varying levels of subsidence. Swiss Re findings have reported that large swathes of France and UK and parts of Germany, Spain, Italy and Eastern Europe are vulnerable to increased risk of land subsidence.<sup>6</sup> The risk of subsidence in Mexico City is especially acute. The city is built on layers of clay and highly permeable sand and gravel that are extremely vulnerable to inelastic compaction caused by on-going pumping of groundwater to supply the ever-increasing population of Mexico City. The land has sunk about 30 feet in the last century and continues to sink at an alarming rate of one to three inches per year.<sup>7</sup> With the area's low rainfall, limited replenish rate for groundwater and excessive pumping of groundwater, Mexico City may ultimately pump the aquifer dry, which may result in a human crisis, further subsidence and significant infrastructure damage. Several other megacities<sup>8</sup>, such as Bangkok, Jakarta, Ho Chi Minh City, New Orleans and areas in Netherlands are sinking due to excessive groundwater pumping and are suffering huge flooding losses. Ocean-front and delta urban developments are particularly vulnerable.

As in Mexico City, increased pumping of subsurface ground water can be for municipal use to accommodate growth in urban areas or for agricultural uses in remote areas such as San Joaquin Valley in California. When subsidence occurs in remote areas, the damage may go unnoticed and have little immediate impact. Subsidence in urban areas or near critical infrastructure, however, can be very damaging and expensive. Principally, the cause of land subsidence is excessive pumping of groundwater. Groundwater is stored in aquifers consisting of semi-consolidated silt, sand, gravel and clay layers (aquitards) with pore spaces between the aggregates. The groundwater is stored in pores and in the inter-granular spaces. When the rate of replenishment is lower than the pumping rate over an extended period, such as in case of drought, irreversible changes may occur to the aquifer and the water table. Excessive pumping of groundwater may

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result in lowering of the water table and compaction or shrinkage of the saturated zone (clay) below it. Reduction of water pressure and compaction of compressible silt and clay layers may result in loss of support to the land surface above and may lead to land subsidence.

Land subsidence is not uniform and depends on several factors including geology and physical attributes of the aquifer, soil compressibility, water table levels, groundwater pumping rates and recharge rates. Excessive pumping of groundwater (where extraction exceeds recharge) may lead to soil compaction. This compaction of subsurface unconsolidated or semi-consolidated layers of clay and silt aquitards and inter-granular pores may result in rapid deterioration of the water storage capacity of the aquifer. This capacity depletion may be irreversible unless over-exploitation of groundwater is controlled in a timely manner.



# 4.0

## Damage from subsidence



Land subsidence can cause serious damage to buildings and structures. Long, rigid linear structures and features such as bridges, dams, roadways, rail lines, underground pipelines, storm sewers, canals, aqueducts and levees are particularly vulnerable to uneven or non-uniform subsidence of land.

In addition to structural damage, land subsidence can also change the slopes and land elevations affecting the drainage patterns in the area and may result in significantly increased flood risk. Such occurrences are evident in low lying areas in certain coastal communities where the tide water is moving into areas that were previously above high tide levels, as was seen in case of Hurricane Katrina damage in the New Orleans area. Land subsidence from years of groundwater pumping in the Houston-Galveston area has worsened the risk of flash floods to the entire area and continues to cause large scale flood damage.

Surface and subsurface water bodies are hydrologically connected over a large area. Over-exploitation of groundwater resources from deep below surface often results in lateral or horizontal movement of water and sediments. This movement can result in earth fissures that are associated with land subsidence. They initially start with small, narrow cracks, but continued movement and surface drainage through these openings lead to erosion and fissures that are wide and long. One extraordinary fissure in central Arizona is reportedly 10 miles long.

# 5.0

## Cost of over-exploitation of groundwater and land subsidence

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As indicated earlier, the direct and indirect costs associated with land subsidence particularly from over-exploitation of groundwater is thought to be huge, yet with the lack of a comprehensive database to collect, monitor and analyze these costs, understanding the magnitude of this challenge is difficult. The existing efforts to quantify total damage and remediation costs are fragmented and the data is mostly anecdotal.

For example, as reported by Stanford Woods Institute for the Environment, remediation cost for damages resulting from land subsidence in California's Santa Clara Valley is estimated to be more than \$756 million. Cumulative damage costs for San Joaquin Valley (from 1955-1972) in 2013 dollars was estimated at \$1.3 billion. No US national level estimates for subsidence damage are available.

According to a loss model jointly developed by Swiss Re and Swiss Federal Institute of Technology (ETH), property damage in Europe from drought-induced and over use of ground water has increased dramatically. Based on their review of available data for France alone, they have reported an increase of over 50% within last two decades, with an average annual cost of EUR 340 million.<sup>9</sup> Similar to the US, Europe also lacks any database to collect, monitor and analyze subsidence loss data, but efforts are underway. Swiss Re efforts are discussed in "The Hidden Risks of Climate Change: An Increase in property damage from Soil Subsidence in Europe." (A URL is provided in the references section.)

Climate change resulting in erratic rainfalls and periods of intense drought can accelerate depletion of ground water, increasing the risk of land subsidence for both new areas and areas already feeling the impact of subsidence. Although the progress is very slow, awareness of this hidden risk is growing and gives some hope for responsible and sustainable groundwater management as evidenced by California's Sustainable Groundwater Management Act of 2014: <http://www.acwa.com/content/groundwater/groundwater-sustainability>. More implementation effort is certainly needed, especially in vulnerable areas, to protect the groundwater resources.

In addition to direct and indirect physical damage to buildings and infrastructure, there are other hidden costs and impacts to consider. As the groundwater depletes and water tables continue to go deeper, the energy cost for pumping the water out from deep wells continues to increase, and can put a significant burden on power grids, particularly in hot summer months. The California Energy Commission estimates that water-related electricity use is 48 Terawatts-hours (TWh) and reportedly accounts for nearly 20%<sup>10</sup> of California's total energy consumption. Over-exploitation of groundwater can also result in degradation of groundwater quality<sup>11</sup> due to accumulation and increased concentration of agricultural fertilizers, pesticides and industrial pollutants in the aquifers. Long-term damage to the ecosystems of rivers, lakes, streams, wetlands, flora and fauna can be devastating and irreversible. In addition, groundwater pumping in coastal areas may lead to brine water infiltration, contamination of groundwater and coastal flooding from ocean water.



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In a study published in the journal *Nature* in 2014 (<http://sfpublicpress.org/news/2014-05/groundwater-depletion-is-destabilizing-the-san-andreas-fault-and-increasing-earthquake-risk>), a group of scientists posited a hypothesis that depletion of groundwater in the Central Valley of California may trigger an increase in seismic activity. They base this theory on their observation of GPS data that indicates mountains closer to the Central Valley are growing at faster-than-expected rates. Although not reviewed or confirmed by the US Geological Survey, a USGS seismologist suggests that this hypothesis is “plausible”. More research is needed to confirm or refute this theory.

There are controversial allegations of a link between hydraulic fracturing (“fracking”) in oil and gas exploration with reports of increased seismic activity in those areas. As mentioned earlier, oil and gas production is known to have an impact on land subsidence in the area, but there is no specific research that suggests potential convergence from fracking and groundwater movement, land subsidence or increased seismic activity.

#### **Subsidence damage from mining:**

Subsidence damage caused by underground mining operations is a serious concern. This can be controlled to some extent in the case of long wall mining with tailored approaches suitable for local conditions, but is essentially uncontrolled in the case of abandoned mines with poor records. Underground cavities in abandoned mines can fill up with water and can be a source of pollution to nearby drinking water resources. These abandoned underground mines can present a serious threat to people and property from collapse. There are thousands of such abandoned mines in the US and all over the world, yet there are no recordkeeping systems in place for monitoring them. An in-depth geological and engineering assessment and evaluation are strongly recommended in the case of any restoration or construction projects in the vicinity of such abandoned mines.

#### **Risk assessment and mitigation actions:**

Land subsidence is a global risk that affects many parts of the world. It is a hidden risk with serious consequences. There is no silver bullet solution, but better understanding and assessment will go a long way toward tackling this risk and will require a comprehensive, collaborative and integrated approach by all stakeholders. Ever-increasing demands on groundwater resources from growing populations and agricultural water use to feed the hungry world requires development and implementation of a sustainable water management strategy by regulators with cooperation of municipal authorities, the agriculture sector and also businesses and organizations that are heavy consumers of water.

This starts with an education program that stresses the importance of water conservation and sustainable water management. All stakeholders must understand the source of the water they consume. If the water supply is primarily from groundwater resources, the long term threat of land subsidence is probably unavoidable. That presents us with two options. The first one is a collective

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emphasis on water conservation and to reduce all negligent and wasteful use of water, but that will not be enough. That brings us to the second and probably more important option, which is adaptation to the reality of the gradual sinking of land to reduce the possibility of a catastrophic damage.

Sustainable groundwater management must understand the finite nature of groundwater resources and the need to manage the pumping rates and well locations. Land subsidence is a slow, gradual process, but periodic observations, land surveys and satellite data can provide early warnings of subsidence or an accelerating rate of subsidence. It is imperative that appropriate actions are implemented to heed these early warnings.

Businesses located in areas particularly susceptible to subsidence risk must consider a mitigation plan that includes a periodic inspection program for existing building settlement, foundation cracks, maintenance of underground pipes/utilities and infrastructure supports. Any signs of settling or subsidence require prompt repairs, maintenance and mitigation to avoid further damage. Any new construction projects should review and comply with building codes and stringent construction practices that address subsidence hazards in the area. If the location is in a susceptible area and the local building codes don't address this hazard, it is important to investigate more stringent codes and practices and go beyond local building codes.

As mentioned earlier, land subsidence can cause depression in land surface and changes drainage patterns. Businesses located in areas with significant land subsidence may also be exposed to a risk of flash floods, and should have a mitigation plan in place. Water accumulation in these shallow land depressions can also promote mosquito breeding and must be watched carefully. Businesses that pump their own water from deep wells on their property may have some unique challenges for compliance with sustainable water management regulations and legal issues to consider. An example that is often cited is the case of an international cola drink bottling operation in India that was held accountable for mismanagement and depletion of groundwater that affected local communities.

*<http://www.globalresearch.ca/coca-cola-causes-serious-depletion-of-water-resources-in-india/18305>*

# 6.0

## Measuring and monitoring subsidence

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Identifying, measuring and monitoring vulnerable areas for increased risk of land subsidence and potential damage to critical infrastructure will help our understanding of subsidence.

Historically, land surveys using levels and GPS tools established key benchmarks. Subsequent changes in these benchmarks showed evidence of subsidence. In the face of large scale subsidence, new, stable markers are needed to detect the extent of subsidence. Also, successful monitoring of subsidence requires land surveys on a regular basis.

In recent years, use of high resolution repeat-pass radar images using Interferometric Synthetic Aperture Radar (InSAR) from earth-orbiting satellites has improved our capability to measure and map spatial land-surface deformations with unprecedented accuracy and detail. This tool not only enhances mapping accuracy, it also gives us an ability to implement time-interval based monitoring programs in support of scientific studies. Integrating deformation measurements, subsidence levels and continuous water level measurements could be used in modeling aquifer storage properties and capacity for more efficient management of groundwater resources and monitoring the impact of land subsidence.



# 7.0

## Insurance and legal Issues

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Property insurance coverage for sinkhole collapse and mine subsidence may be purchased in the form of special endorsements to homeowners and business insurance policies. Insurance companies may be required to offer this coverage based on state insurance regulations, if the state has these exposures present. Without these special endorsements, the standard property policies may not cover this exposure.

Similarly, general liability insurance normally excludes land subsidence exposure. Again, some insurance companies may separately offer coverage through the purchase of a special endorsement. Many insurance companies choose to extend the land subsidence exclusion to an absolute exclusion for all land movement, including earthquake. Many courts have upheld the exclusion for subsidence, even for broad exclusionary wording in several cases. A legal review of this exclusion is strongly recommended to avoid any coverage litigation and disputes. This legal review is particularly important for construction and contractor policies dealing with completed operations for foundations or other damage/bodily injuries, as well as any earthquake-associated bodily injury or property damage.

With continued over-exploitation of groundwater, land subsidence is expected to increase, which may lead to increased litigation against those who are pumping the groundwater, such as public water works or commercial farming operations. A property owner may sue a responsible third party for damages caused by land subsidence under a variety of legal theories, including common law (right of subjacent support), negligence theories, public and private nuisance, statutory water laws and others. The success of any such litigation will depend on actual facts and circumstances of each individual case. The case law in most cases is not well developed. Any detailed discussion of potential legal issues is beyond the scope of this paper. An article by Ryley, Carlock & Applewhite (February 19, 2015 "Land Subsidence Damage Caused by Groundwater Withdrawal in Arizona: Who Pays?") provides an overview focusing on the legal landscape in Arizona. (URL Link: <http://www.rcalaw.com/land-subsidence-damage-caused-by-groundwater-withdrawals-in-arizona-who-pays>)

An old article in *Natural Resources Journal* (April 1980) provides a very good analysis of various liability issues in a decision by the Texas Supreme Court in a groundwater pumping case and resulting land subsidence damages in *Friendswood Development Co. v. Smith-Southwest Industries*, 576 S.W.2d 21 (Tex. 1978). The Plaintiff, Smith-Southwest, and owners of neighboring commercial and residential properties, brought a class action suit against Friendswood and its parent, Exxon Corp., seeking damages for subsidence of their lands located along the west bank of Galveston Bay for damages from ocean water flooding. The Court decided, based on the common law rule of absolute ownership of groundwater that insulates landowners from liability in nuisance and negligence for causing of nearby land by pumping groundwater, but prospectively recognized a cause of action in negligence for future subsidence without clarifying necessary elements of negligence (such as wasteful use) for legal action. [http://lawschool.unm.edu/nrj/volumes/20/2/12\\_reuter\\_sinking.pdf](http://lawschool.unm.edu/nrj/volumes/20/2/12_reuter_sinking.pdf)

# 8.0

## Conclusion

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Land subsidence, sinkhole collapse and karst subsidence are hidden hazards that are essentially un-assessed and often not fully understood. Sinkhole collapse and karst subsidence are natural hazards associated with local terrain and soil geology. Land subsidence, on the other hand, predominantly occurs as a result of over-exploitation of groundwater, oil and gas drilling, mining and other human actions.

The convergence of climate change, irregular rainfalls and increasing water demand from growing populations and the agriculture sector is leading to excessive pumping of groundwater and is resulting in rapid depletion of critical groundwater resources. These actions are accelerating existing land subsidence and increasing the risks in and near major urban population centers and near critical infrastructure.

The legal landscape and the case law on “who pays for the damages” are not very clear. As depletion of groundwater and land subsidence get more visibility and attention, litigation activity is likely to follow. Although soil subsidence may be an insurable risk, the insurance sector is essentially risk averse to insuring this hidden risk and primarily relies on broad exclusionary wording to exclude the risk.

The Swiss Re report mentioned earlier has some ideas and discussion on insuring soil subsidence risk, and stresses that this risk can be an insurable risk at affordable prices only if systematic prevention measures are in place. Creating an integrated and comprehensive database will go a long way toward enhancing the understanding and management of this risk, and improving the insurability of the subsidence risk. The advances in modern satellite imaging and mapping technologies will be of great help in accurately measuring and monitoring the rate of land subsidence in and around susceptible areas, and will assist in better understanding and management of this risk. It will be increasingly more important for all stakeholders to collaborate in developing innovative solutions and strategies in regional planning, construction codes, regulations and cost-effective risk management and insurance solutions.

# 9.0

## References

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<http://www.energy.ca.gov/research/iaw/water.html>
11. Stanford Woods Institute for the Environment and The Bill Lane Institute for the American West: "The Hidden Cost of Groundwater Overdraft": (Part of a series of articles exploring the use and management of California's precious resource)  
<http://waterinthewest.stanford.edu/groundwater/overdraft/>

# 10.0

## Additional Resources

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The resources (links) below provide a good discussion on recommendations and practices that may provide additional guidance to stakeholders located in areas susceptible to land subsidence.

### **Land Subsidence Losses in the United States (1991) by National Academy Press-Chapter: A Survey of Current Mitigating Mitigation Measures:**

- USGS Report Circular 1182: Land Subsidence in the US  
<http://pubs.usgs.gov/circ/circ1182/>
- USGS Factsheet 165 (December 2000): Land Subsidence in the United States  
<http://pubs.usgs.gov/fs/fs06903/pdf/fs06903.pdf>
- USGS Factsheet 069-2003 (December 2003): Measuring Human-Induced Land Subsidence from Space  
<http://pubs.usgs.gov/fs/fs06903/pdf/fs06903.pdf>
- USGS: Land Subsidence from Groundwater Pumping  
<http://geochange.er.usgs.gov/sw/changes/anthropogenic/subside/>
- Deltares – Taskforce Subsidence (Delft, The Netherlands) October 2013: Sinking Cities-An integrated Approach towards Solutions  
[http://www.circleofblue.org/waternews/wp-content/uploads/2014/12/Deltares\\_Sinking-cities.pdf](http://www.circleofblue.org/waternews/wp-content/uploads/2014/12/Deltares_Sinking-cities.pdf)
- Deltares—Enabling Delta Life: Land Subsidence-causes, impacts and adaptive measures  
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- Landmark Group: A Guide to Subsidence: Risk Assessment and Risk Management against soil Shrinkage  
<http://www.subsidenceupport.co.uk/downloads/Property%20Assure%20Guide%20to%20Subsidenf>

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