A Brief Introduction to Land Subsidence Monitoring in Houston, Texas, USA

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Abstract

This paper has summarized the techniques and methods used for subsidence monitoring in the greater Houston, Texas, region from the 1900s to the 2010s. The primary methods include spirit leveling, extensometer, tide gauge, Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), and Light Detection and Ranging (LiDAR). The subsidence monitoring experience learned in the Houston region is expected to be transferable to other areas suffering from land subsidence.

Introduction

For over 100 years, the greater Houston region has been adversely impacted by land subsidence associated with excessive underground-fluid (primarily groundwater) withdrawals. The Houston region, as the term is here used, comprises an area of approximately 22,500 km^2 (150 km by 150 km) and encompasses nine counties in the Texas Gulf Coast plain with a population of over seven million people at the 2020 census estimates (Fig. 1), covering the regulatory areas of the Harris-Galveston Subsidence District (HGSD), Fort Bend Subsidence District (FBSD), Lone Star Groundwater Conservation District (LSGCD), and Brazoria County Groundwater Conservation District (BCGCD). The earliest subsidence was observed in the Goose Creek oil field in the early 1920s, about 40 km east of downtown. From the 1940s through the 1970s, rapid subsidence at several centimeters per year occurred in southeast Houston, including downtown Houston and areas along the Houston Ship Channel and Galveston Bay. In the 1990s, subsidence rates began to increase further inland as the rapid population growth continued in the region. Subsidence caused frequent damage to infrastructure (such as buildings, roadways, bridges, underground utility lines, and levees) and contributed to flooding, ultimately adding financial burdens on local residents and business owners. In order to tackle the problem of subsidence, the U.S. Geological Survey (USGS), National Geodetic Survey (NGS), HGSD, and many other local entities have been conducting subsidence monitoring since the 1900s. This article aims to summarize the tools and methods used for subsidence monitoring in Houston.

Land Surface Elevation Monitoring

Elevation or elevation-change measurements are fundamental to tracking land subsidence over time. Prior to the 1990s, subsidence within the Houston region was primarily measured using spirit-leveling surveys and extensometers. Global Positioning System (GPS) has gradually replaced the conventional leveling surveying and has become the primary tool for subsidence monitoring since the 1990s. Interferometric Synthetic Aperture Radar (InSAR) and Light Detection and Ranging (LiDAR) techniques have been applied to subsidence studies in the Houston region since the 2000s, which provide spatially dense measurements.

Spirit Leveling

NGS and its predecessor agency, United States Coast and Geodetic Survey, had established extensive networks of first- and second-order level lines covering most of the Houston region since the 1900s. The first spirit leveling survey was the first-order level line from Smithville to Galveston, which was run in 1905 and 1906. Since the first leveling survey, this first-order line was resurveyed several times in the following decades, and more first-order and second-order survey lines were added and repeatedly surveyed from the 1940s to 1970s. The subsidence results derived from these leveling surveys were published in USGS reports.

Extensometer

USGS has been operating 13 deep borehole extensometers at 11 sites in Houston since the 1970s and the early 1980s. Several piezometers were installed at each extensometer site for simultaneously monitoring groundwater levels at different depths. A new borehole extensometer was established in Katy, Fort Bend County, in 2017. As of the 2020s, there are 14 borehole extensometers at 12 sites within the Houston region (Fig. 1). Extensometers measure the compaction within the sediments from the land surface to the bottom of the extensometer borehole. USGS publishes the extensometer data to the public annually. These extensometers face the problem of aging equipment after being continuously operated for about half a century. HGSD and the University of Houston (UH) are working together to install permanent GPS stations at extensometer sites to preserve the continuity of subsidence monitoring. As of 2022, seven of these 12 extensometer sites have co-located GPS stations.

Tide Gauge

Tide gauges or stream gages had been used for land subsidence monitoring along the Houston Ship Channel and Galveston Bay areas during the 1960s and 1970s. As of 2022, the Center for Operational Oceanographic Products and Services (CO-OPS) at National Oceanic and Atmospheric Administration (NOAA) operates about 30 tide gauges within the Galveston Bay area (Fig. 1). Most of these stations were installed in the 2010s. The one-century tide gauge data (1904-2021) at the Galveston Pier 21 have been frequently used to delineate natural subsidence in the coastal area. All tide gauge data are available at NOAA (https://tidesandcurrents.noaa.gov).

GPS

Houston is one of the earliest urban areas that employed GPS for land subsidence monitoring. Campaign GPS surveys were employed in subsidence monitoring at benchmarks in Houston in the late 1980s, before the complement of the GPS satellite constellation in 1993. HGSD started to install GPS stations in the early 1990s. The early permanent GPS stations, known as Port-A-Measure (PAM), were designed for periodic surveys rather than continuous surveys, to overcome the high costs of GPS equipment at that time. As of 2021, the PAM network has expanded to over 110 permanent stations. UH has been building a permanent GPS network for urban geological hazards monitoring since 2013 (Wang et al., 2015). As of 2021, the UH GPS network comprises 70 permanent stations. The Texas Department of Transportation (TxDOT), SmartNet, the City of Houston, and several other agencies operate approximately 50 continuous GPS stations in the Houston region. Altogether, there are approximately 230 active permanent GPS stations in the Houston region as of 2021, which is called HoustonNet. Ongoing patterns of subsidence in the Houston region are carefully monitored by HGSD and UH using GPS data from the HoustonNet. The detailed methods for HoustonNet data processing are presented in a recent publication (Wang et al., 2022).

InSAR

InSAR has become a powerful tool for remotely mapping land-surface deformation (e.g., landslide, subsidence, faulting) over time and space. In contrast to benchmark and GPS measurements, the InSAR techniques have the ability to map ground deformation over large areas with a high spatial resolution at a low cost. Numerous researchers from USGS, HGSD, and universities have used InSAR for delineating subsidence in the Houston region since the early 2000s.

Airborne LiDAR

LiDAR mapping has become a powerful tool for obtaining bare-earth digital elevation models (DEMs) for monitoring landslides, volcanos, shoreline erosion, and land subsidence. In October 2001, the Tropical Storm Allison Recovery Project (TSARP) collected airborne LiDAR data over the entire Harris County. The USGS used the 2001 LiDAR data to produce the land subsidence map between the 1915-17 to 2001 in the Harris County (Kasmarek et al., 2009). The map was constructed using geographic information system (GIS) techniques that subtracted 1915–17 land-surface (topographic map) elevations from the 2001 LiDAR-derived DEM. This map provided the high-resolution (5 m by 5 m) subsidence estimates over the entire Harris County for the first time. Multiple airborne LiDAR datasets have been collected since the 2000s within the greater Houston region.

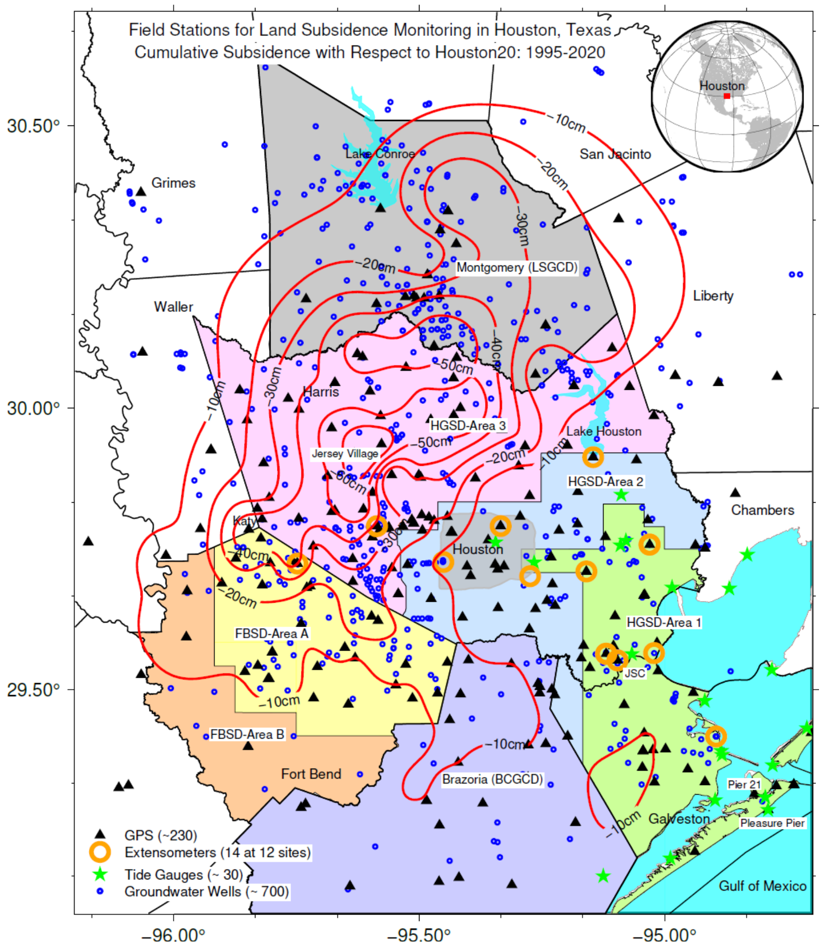

Figure 1 Map showing the current field stations (GPS, Extensometers, Tide Gauges, Groundwater Wells) in the Houston region for land subsidence monitoring. The contour lines depict cumulative land subsidence during the GPS age from 1995 to 2020. The cumulative subsidence measures are estimated according to the observations at approximately 200 permanent GPS sites and 12 extensometer sites. Most GPS stations started after 2000. For those sites that do not have GPS data in the early years or recent years (decommissioned), the subsidence spanning the gap is projected according to its adjacent 3-year-average subsidence rate. The vertical displacements are aligned to the Stable Houston Reference Frame

(Houston20) (Agudelo et al., 2020). A contour map depicting the cumulative subsidence from 1906 to 2000 was presented in Gabrysch and Neighbors (2005), and a contour map depicting the cumulative subsidence from 1978 to 2020 was presented in Greuter et al. (2021).

Groundwater-Level Monitoring

The City of Houston was founded in 1837, and groundwater was the primary source of water resources in its early history. The first well for groundwater pumping was drilled in 1886 to a depth of 43 m in the downtown area. The groundwater was reported as free-flowing. In general, the groundwater levels in the Chicot and Evangeline aquifers were higher than the land surface in the Houston region before the early 1910s. Industrial pumping began after the opening of the Houston Ship Channel in 1915. The USGS began to monitor groundwater levels in the Houston region in the early 1910s. As of the 2020s, USGS routinely measures groundwater levels in over 700 wells in the Houston region for subsidence study and groundwater resource management. The locations of these active wells are plotted in Fig. 1. USGS began to publish an annual report documenting the short-term and long-term groundwater level changes in the Houston region in 1977.

Summary

The rapidly growing population in the Houston region means that groundwater resources must be carefully managed, and subsidence must be vigilantly monitored. High costs for leveling surveys and building extensometers have prohibited frequent releveling and adding more extensometers. GPS techniques have become the primary monitoring tools in the Houston region since the 1990s. Since the late 2010s, HGSD and FBSD have been working towards integrating remote sensing technologies (InSAR, LiDAR) into their routine subsidence monitoring. HGSD and FBSD have developed sophisticated protocols and methods for subsidence monitoring and mitigation. The subsidence monitoring experience learned in Houston is expected to be transferable to other regions suffering from land subsidence.

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