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FINAL PROJECT REPORT

Impact of Drought-related Subsidence on Gas Infrastructure in California

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Gas-Related Transportation.

Impact of Drought-related Subsidence on Gas Infrastructure in California is the final report for the project Characterize Actual and Future Impact of California's Drought on Three-component Ground Deformations and their Influence on the Gas Infrastructure (PIR-16-015) conducted by the Lawrence Berkeley National Laboratory and InfraTerra Inc. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at 916-327-1551.

ABSTRACT

This project developed an approach for characterizing the risk posed by drought-related subsidence to gas infrastructure in California. Project innovations include estimating vertical and horizontal ground displacements from remote sensing data, providing guidance on the characteristics of areas in particular need of such monitoring, and developing a displacement gradient threshold to identify areas where risk to gas infrastructure merits site-specific analysis, and if necessary, remedial actions.

Geospatial analysis of historic cropping patterns revealed that the presence of high water-demand crops correlates with occurrence of subsidence, and the magnitude of subsidence correlates with the fraction of irrigation met with groundwater, well density, and well depth. Some sustainability plans for adjacent groundwater basins articulate substantially different limits to future subsidence, suggesting differential subsidence could develop at their boundary as a regulatory outcome.

Coupled ground deformation and pipeline modeling based on extrapolation of recent subsidence suggested thresholds of differential subsidence to trigger site-specific risk analysis and possible remedial action: 1.5 feet per quarter mile for horizontal differential displacement along the pipe and one foot per quarter mile for differential vertical subsidence along the pipe. Proposed vertical and horizontal ground deformation monitoring technology along with differential subsidence limits can more accurately identify areas where gas infrastructure is at risk of damage from land subsidence.

Keywords: Gas pipelines, subsidence, groundwater pumping, drought, monitoring, surface deformations, InSAR, modeling

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EXECUTIVE SUMMARY

Background

The 2011-2017 drought in California significantly increased groundwater pumping in the Central Valley of California. This extensive amount of water extraction resulted in unprecedented rates of land subsidence (downward vertical movement of the ground), which affected infrastructure, including gas transmission pipelines and aqueducts that transport water from the northern part of the state to the San Joaquin Valley and southern California. There are many areas of the San Joaquin Valley where recent groundwater levels are more than 30 meters below previous historical lows. These areas generally correspond to regions undergoing subsidence.

California currently imports about 90 percent of the gas it uses to for heating, domestic and industrial, and power generation. Safe and reliable delivery of gas is a key requirement of the current energy system in California. A fundamental understanding and evaluation of possible impacts of future drought-related subsidence on gas transmission lines are critical for risk assessment and monitoring to maintain safe and reliable gas delivery.

Monitoring of land subsidence related to groundwater use in California is conducted by the United States Geological Survey (USGS). The Central Valley Hydrologic Model is the primary tool used in the modeling of variable water supply and demand and its influence on major aquifers. The USGS modeling of regional-scale subsidence in the Central Valley Hydrologic Model uses a groundwater flow and subsidence package and evaluates vertical ground movements. However, vertical ground movements co-occur with horizontal ground movements that may be more damaging to gas pipelines. This project evaluates both the vertical ground movements and the horizontal ground movements to more accurately identify areas where natural gas infrastructure is at risk of damage from land subsidence.

Project Purpose

The team developed and demonstrated a new method to more accurately identify areas with relatively high risk of gas infrastructure damage from land subsidence and includes potential remedial actions. The team combined large-scale state-of-the-art remote sensing surveys and an advanced approach to estimate three-component (one vertical and two horizontal) ground movements to evaluate its impact on gas pipelines. The research results can guide risk-based decisions to protect critical infrastructure before it experiences damaging strains, safeguarding against abrupt failure and gas leaks. Increased safety, lower costs and greater reliability contributes to California energy security and lower costs for California ratepayers.

Project Approach

The project team consists of scientists and engineers from the Lawrence Berkeley National Laboratory (LBNL) and InfraTerra, Inc., in collaboration with the Jet Propulsion Laboratory (JPL), Pacific Gas and Electric Company (PG&E), and Natural Resources Canada. The technical approach used is based on state-of-the-art surveillance, monitoring, and modeling techniques that are integrated into a study of land subsidence impact on gas infrastructure. Specifically, the study uses groundwater pumping and geologic data, groundwater flow and land subsidence modeling, ground deformation monitoring, and infrastructure damage evaluation to demonstrate the methodology for evaluating potential future drought-related subsidence and risk of damage to infrastructure.

The team investigated and analyzed the link between agricultural activities, water demand, existing wells, and subsidence. Monitoring of vertical and horizontal ground movements was achieved by processing data from Interferometric Synthetic Aperture Radar (InSAR) images of ground deformation developed from satellite data. The ground deformations were used to simulate pipeline stresses and strains. The team used these analyses to develop and demonstrate a method to assessing the risk to gas pipelines posed by future drought-related subsidence scenarios. Using the methods developed by this research, the team calculated the risk to gas pipelines from those scenarios.

Project Results

As expected, the study showed subsidence is greater in areas where the water demand by crop type is the highest and in areas with a high density of groundwater wells. The rate of subsidence is strongly affected by the amount of local and imported surface water and by pumping of groundwater. These provide a guide to areas that should be monitored more closely for emerging subsidence. Given the link between areas of high subsidence and local water demand, areas that should be prioritized for subsidence monitoring may shift relative to results reported here.

Horizontal and vertical ground movements associated with subsidence were estimated based on InSAR data. These estimated ground movements were used as input to a pipeline structure model that identifies the types of ground movements that create the most risk of pipeline damage. The results found that it is the horizontal movements at the slope of the subsidence bowl that causes the highest risk to pipelines. However, it was also found that the monitored ground subsidence during 2015-2017 would not be sufficient to cause damage to the existing pipeline network.

The modeling results showed that more than three times the maximum observed rates of subsidence in the 2015-2017 period would have been required to cause yielding in local pipelines due to high subsidence. The maximum subsidence during 2015-2017 was about 2 feet (ft) (0.6 meters (m)) and occurred in the Southeastern part of San Joaquin Valley (Jeanne et al., 2019). However, the modeling showed that maximum stresses may not occur at locations of maximum subsidence. Instead, maximum stresses may occur on the slopes of a subsidence bowl, with maximum stresses usually at pipeline elbows and T-connections.

This study suggests that if the horizontal ground movements exceed 1.5 ft (0.46 m) per quarter mile along the pipe, site-specific analysis should take place to determine if a pipeline is at risk. If horizontal ground movement data are not available, the study suggests that one foot per quarter mile of vertical subsidence could be used as a proxy to trigger site-specific risk assessment. Site-specific investigation could include a local and more detailed forecast of the subsidence considering expected water demand and groundwater pumping and resulting impact on pipelines in the area.

Technology/Knowledge Transfer

The methodology developed within the project for assessing effects of subsidence on pipeline safety includes a method of estimating three component surface deformation from satellite

(InSAR) data, criteria for precursors to pipeline damage, and an instrument for subsurface borehole deformation measurements.

The project team developed materials that aid in making this information available to interested parties, such as project fact sheets, and a plan to make the knowledge gained, experimental results, and lessons learned available to the public and to key decision makers. The team published a journal article in Elsevier's *Journal of Hydrology*, provided a presentation at the American Society of Civil Engineers' Lifeline Conference 2021-2022, and engaged in focused discussions with investor-owned utilities (IOUs), including PG&E, as well as groundwater management regulators, including the California Department of Water Resources.

Benefits to California

This project provided methods to more accurately monitor and forecast the impact of groundwater pumping on gas infrastructure. This detailed information can provide early warning as to where site-specific pipeline damage may occur. If determined likely, action can be taken to mitigate the risk of pipeline damage before it occurs, increasing safety, lowering costs, and benefiting the environment. Avoiding pipeline damage would also contribute to California's energy security.

CHAPTER 1: Introduction

1.1 Project Background

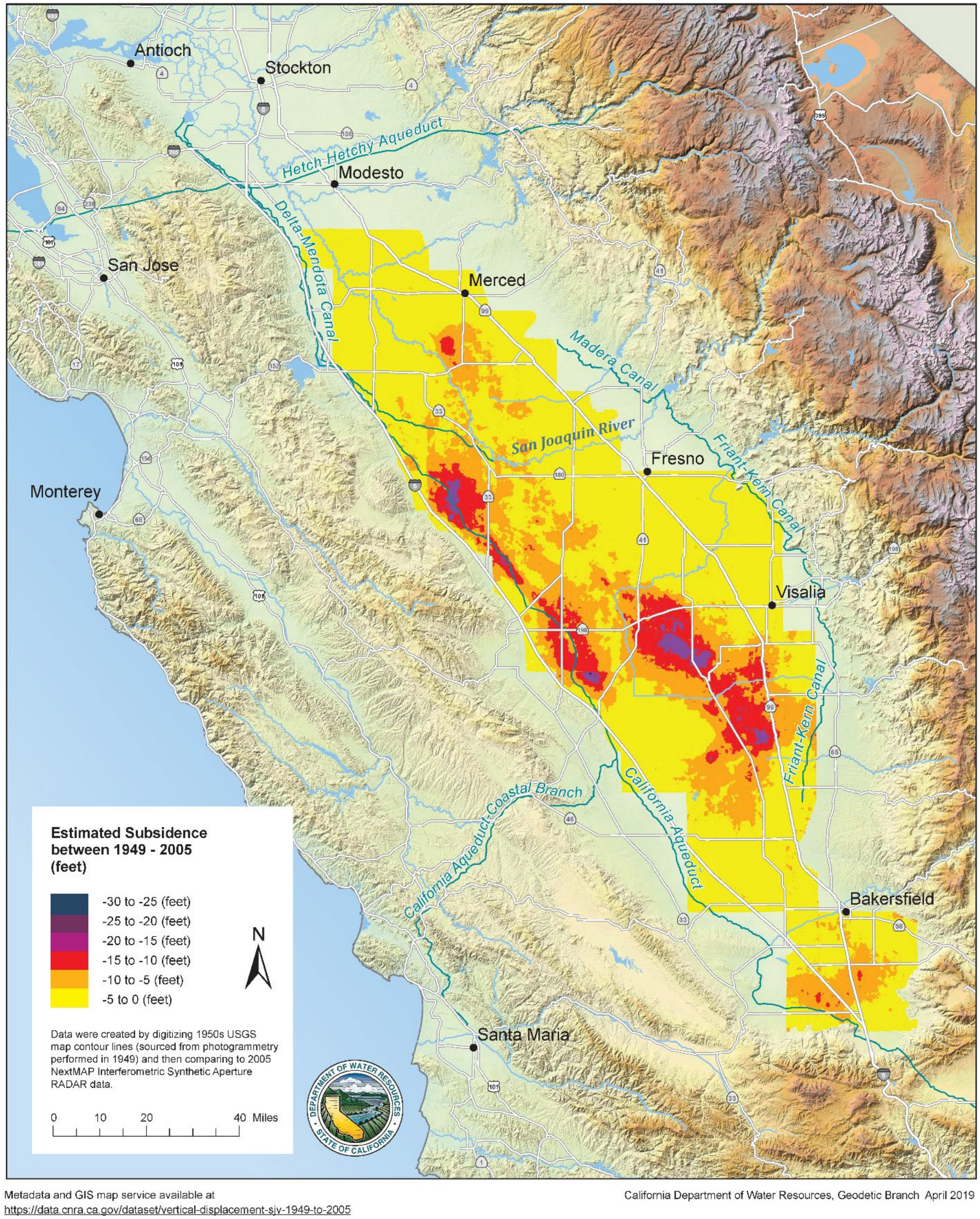
California imports about 90 percent of its fossil gas. The safe and reliable delivery of this resource is a key responsibility of state regulators and investor-owned utilities (IOUs). A fundamental understanding and evaluation of the possible impacts of natural hazards on gas transmission and distribution lines is critical for risk assessment and monitoring, which supports safe and reliable delivery. Recent safety concerns due to the acceleration of land subsidence in the Central Valley resulting from drought-driven increased groundwater pumping motivate this project. Such subsidence can potentially lead to the exhumation of, and/or damage to, gas pipelines, with serious consequences for public health and safety.

Figure 1 shows historic subsidence in the San Joaquin Valley with up to 30 feet of subsidence from 1945 to 2005. At the center are Tulare, Fresno, Merced, Kings and Madera Counties, which are among the most productive agricultural regions in the US. Because the San Joaquin Valley is semi-arid, farmers typically rely heavily on surface-water diversions to meet irrigation water demand. Periodic droughts, including during 2015-2017, have induced substantial increases in groundwater pumping to meet irrigation water demand. These variously cause increased subsidence.

Currently, the monitoring of subsidence related to groundwater use in California is conducted by the United States Geological Survey (USGS). The Central Valley Hydrologic Model is the primary tool used to model variable water supply and demand and its influence on major aquifers. The model simulates surface-water movement, groundwater flow, and the vertical component of subsidence across the entire Central Valley (Faunt et al., 2016). Declining groundwater levels, approaching or surpassing historical low levels, cause accelerated and renewed consolidation. The resulting subsidence varies in magnitude and rate due to spatial differences of the hydraulic and mechanical properties of the saturated geologic materials constituting the aquifer system and on the consolidation history.

The relation of current groundwater levels to the previous lowest water level controls whether subsidence is inelastic (permanent) or elastic (recoverable). When the water level declines below that which has occurred previously, most of the subsidence that results is inelastic. There are many areas of the San Joaquin Valley where recent groundwater levels are more than 30 meters (m) below previous historical lows. These areas generally correspond to regions undergoing subsidence (Faunt et al., 2016). One example is the El Nido area south of Merced (indicated in Figure 1 by the red area located about 10 miles south of Merced). This area has recently experienced substantial subsidence (Farr et al., 2015). Elevation decrease in this area from 2007 to 2014 is shown by the monitoring results in Figure 2.

Figure 1: Estimated Historic Subsidence in the San Joaquin Valley

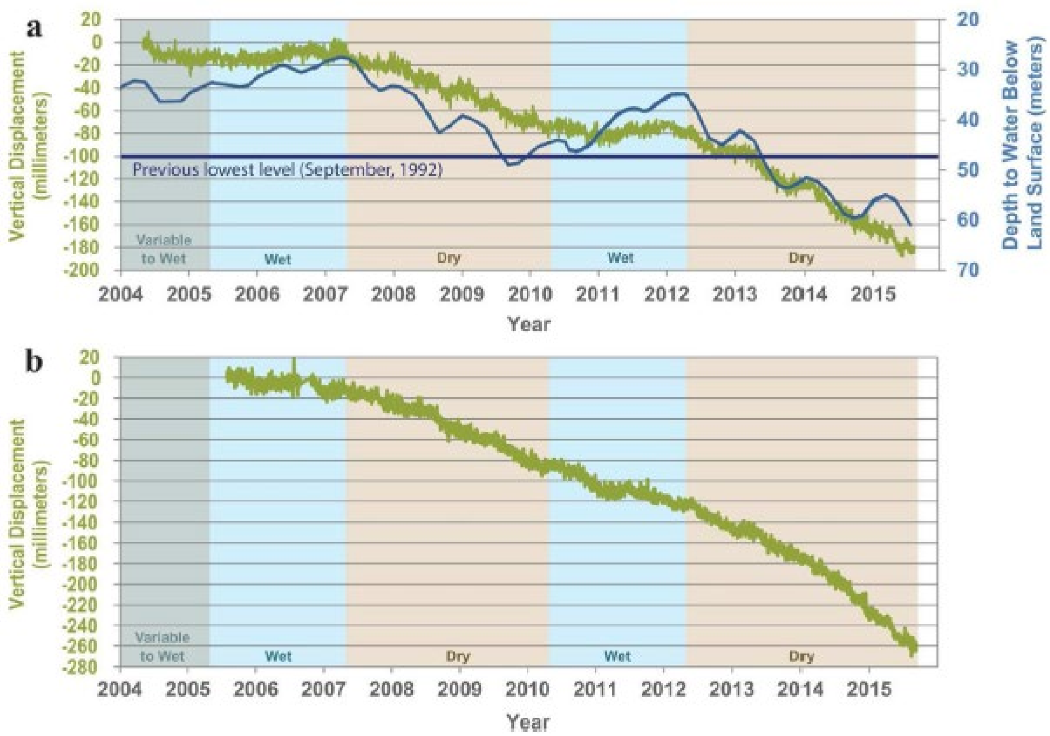


Source: DWR (2019).

Those results demonstrate the heterogeneity of subsidence. At the location where the data in Figure 2a were collected, most subsidence occurred during droughts. Little occurred between droughts when the area received surface water deliveries. Figure 2b shows at another location subsidence continued at a high rate during non-drought conditions, such as from 2010 to

2012. This may be due to the lack of surface water deliveries to the area under conditions. It could also result from residual (delayed) consolidation due to the slow equilibration of fluid pressures in relatively thick, interbedded, low-permeability fine-grained units (aquitards) in the aquifer system. Predicting drought-related subsidence may require detailed knowledge of an area, including the local geology and water use patterns.

Figure 2: Historical Subsidence at Two Locations in the El Nido Area



Graph showing water table depth and vertical displacement (subsidence) from 2004 to 2015 at two GPS stations in the El Nido area during dry and wet years.

Source: Faunt et al., (2016).

With regard to predicting pipeline damage from subsidence, differential vertical and horizontal displacements are relevant, but the horizontal component is generally responsible for the greatest damage. One reason is that differential horizontal displacements can create large compressive strains in the ground and consequently the pipeline, leading to upheaval and buckling, as shown in Figure 3. Horizontal ground displacements result from relatively deep-seated aquitard consolidation over a limited area flexing the land surface.

Currently, the full three-component displacement field is not considered in subsidence monitoring and modeling. For instance, subsidence across the Central Valley is modeled in the USGS's Central Valley Hydrologic Model using the Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW subsidence package. This modeling represents only vertical displacements. Because each cell in the model is a mile square it fundamentally is unable to characterize differential horizontal displacements that occur over a few miles such as occur between the center and edge of the El Nido area. To do so, a finer grid and more sophisticated three-dimensional model is required.

The primary need addressed in this project is characterizing the impact of current and future droughts on California's gas pipeline infrastructure, considering horizontal (lateral) as well as vertical ground displacements resulting from groundwater pumping.

Figure 3: Buckling of a Pipeline from Subsidence

An example of upheaval and buckling of gas pipelines resulting from subsidence caused by fluid extraction

Source: Pipeline Research Council International, (2009).

1.2 Project Objectives

The overarching goals of this project were to develop and demonstrate new methods for assessing subsidence, to more accurately identify areas associated with a relatively high risk of subsidence-induced damage to gas infrastructure, and to identify potential remedial actions. A multidisciplinary study was conducted with these objectives:

1. Quantify the relationship between ground water pumping, aquifer and aquitard consolidation, surface deformation, and damage to gas infrastructure (Sections 3.1, 3.2, and 3.5).
2. Develop a method for estimating all three components (horizontal as well as vertical) of surface deformation (Section 3.3).
3. Evaluate deformation monitoring techniques and suggest improvements that will help detect conditions that might lead to damage of gas infrastructure (Section 3.6).
4. Predict future drought-related subsidence (Section 3.4).
5. Estimate the risk of vertical and lateral displacements from future subsidence to gas pipelines (Section 3.5).
6. Recommend possible remedial responses with their associated costs (Section 3.7).

The results of this research inform risk-based decisions on proactive engineering actions to protect gas pipeline infrastructure before it experiences damaging strains, therefore safeguarding against abrupt failure and gas leaks.

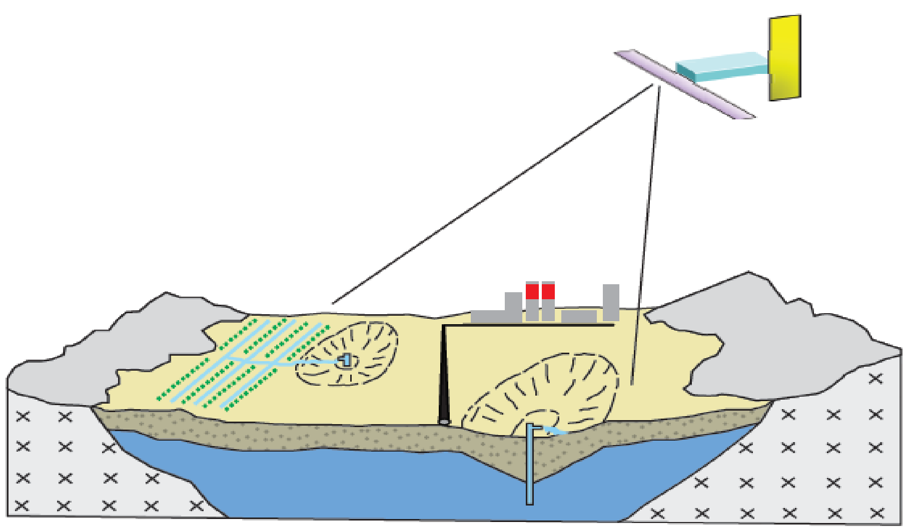
CHAPTER 2:
Project Approach

This project integrated state-of-the-art monitoring and modeling techniques to study the impact of groundwater withdrawal and the resulting land subsidence in three dimensions on gas pipeline infrastructure in California. Previous work considered only vertical subsidence without considering associated horizontal ground movements. The approach to attaining each of the project's objectives is briefly described.

The first objective to quantify the relationships between ground water pumping, surface deformation and impact on gas infrastructure was accomplished by first gathering data on crop type, and water well density and depth in the mid to latter part of last decade. Water requirements of each crop type as well as well density and depth were compared against subsidence measured during that time to assess correlations. The last step of the first objective, estimating damage to pipelines from surface deformation, was attained by the fifth objective.

The second objective to develop a method for evaluating three component ground deformation was attained by modifying an existing numerical method of estimating ground movement in three dimensions (one vertical and two horizontal) from measurements in one dimension (line-of-sight view from satellite). Specifically, the project team used satellite-based InSAR as shown conceptually in Figure 4. The change in sediment volume in the depth of groundwater extraction that could produce the line-of-sight measurements taken by InSAR was estimated. From this volume, the displacement of the ground surface in three dimensions was estimated based on geomechanical properties and relations.

Figure 4: Concepts of Basin-scale Subsidence Monitoring



A conceptual figure of monitoring of three-dimensional land surface deformations in areas with gas pipelines.

Source: Lawrence Berkeley National Laboratory, 2022

The third objective to evaluate deformation monitoring techniques was achieved by identifying and reviewing available and emerging techniques for monitoring ground deformation. Each was assessed relative to detecting displacements that could damage a gas pipeline network.

By State law, future subsidence is limited by groundwater sustainability plans recently adopted by regarding each area with historic subsidence in the San Joaquin Valley. This law is implemented by the California Department of Water Resources (DWR). The subsidence limitations in these plans were assembled into a review of the types and magnitudes of limits across plans and the differences at the boundaries between plan areas. This provided the basis for defining a future subsidence scenario in fulfillment of fourth objective related to predicting future drought-related subsidence.

For the fifth objective, to estimate the risk of damage to gas pipelines, the site (El Nido) with the largest ground displacement gradients measured by InSAR mid-to-late last decade was selected to test for pipeline damage. Hypothetical pipelines and pipeline networks were tested because the location does not have an extensive network of gas pipelines. Pipelines were tested via numerical simulations coupling geomechanical deformation of pipeline trench backfill and surrounding soil to stress and strain in the pipeline structure using the estimated three-dimensional surface deformation at the site. This deformation was amplified to match the maximum allowed by the groundwater sustainability plans. The results were assessed for pipeline damage and ground deformation thresholds for avoiding damage defined.

Various responses to ground deformation reaching these thresholds were developed to meet the sixth objective, namely, to recommend possible remedial responses with their associated costs. The advantages and disadvantages of each were identified, including estimating cost.

CHAPTER 3: Project Results

This chapter presents project results. Section 3.1 presents an investigation of the relationship between agricultural activity and land subsidence in the San Joaquin Valley, Section 3.2 presents modelling to investigate the link between groundwater pumping and ground surface deformations, while Section 3.3 discusses ground surface deformation estimation. Sections 3.4 and 3.5 explore future subsidence and its impacts on infrastructure, while Sections 3.6 and 3.7 present an overview of methods for monitoring ground deformation and a discussion of mitigation options and costs.

3.1 Subsidence from Groundwater Pumping for Agricultural Irrigation

As part of this project, the relationship between agricultural activity and land subsidence in the San Joaquin Valley was investigated and published in the Journal of Hydrology (Jeanne et al., 2019). The paper reports on how the evolution of the agricultural activity, climate variability, water supply, water level variation and groundwater well development influences the magnitude of ground subsidence.

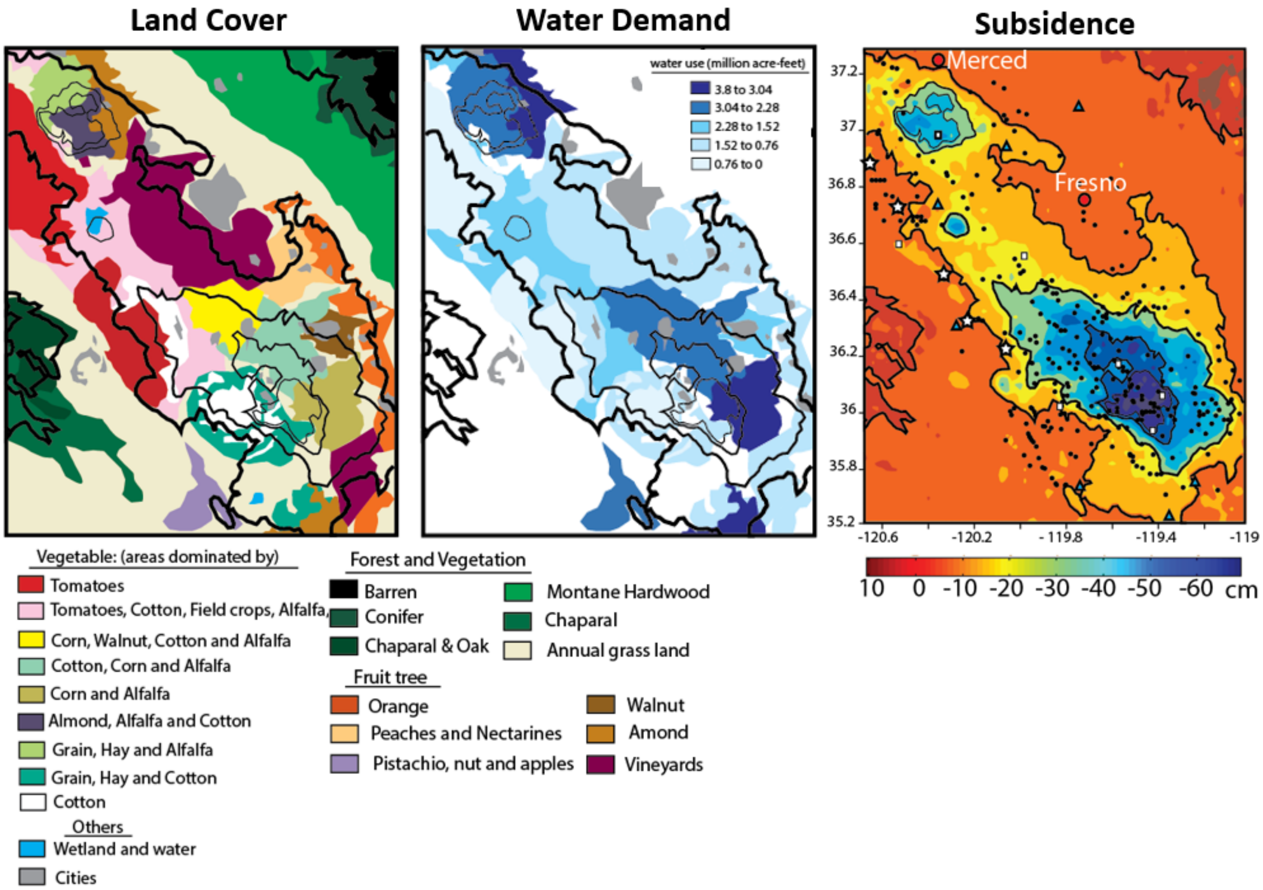
Figure 5 shows the correlation between crop type and subsidence via variations in water demand by crop type. As shown in the figure, crops with the highest water demand are approximately coincident with the greatest subsidence, particularly areas growing alfalfa and almonds. Not shown is a correlation between and the density of wells that were completed at depth below 150 meters and subsidence.

More details are given in Jeanne et al. (2019), including how crop type and consequently water demand has evolved since 1958 causing variation in subsidence location and magnitude through time. It was concluded that land subsidence in the central San Joaquin Valley is qualitatively correlated with:

- The number of active groundwater wells, which varies according to the climate and the surface water delivery,
- The water demand, which varies according to crop type and therefore according to the market price,
- Local surface water availability, which depends on the climate,
- Surface water delivery, which depends on the climate, environmental factors and system constraints, and
- Groundwater availability.

All these factors and their interactions make it difficult to predict the location, magnitude, and rate of future subsidence. However, it is clear that the location is strongly influenced by the crop type and the well locations, whereas the magnitude and rate will depend on the amount of local and imported surface water for irrigation, which affect the pumping rate.

Figure 5: Crop Type and Subsidence



A map of the land cover and agricultural crop distribution (left) estimated water demand based on land cover and farm distribution (middle), subsidence from 2015 to 2017 evaluated from satellite-based InSAR monitoring (right).

Source: Lawrence Berkeley National Laboratory, 2022

3.2 Coupled Groundwater Pumping and Subsidence Modeling

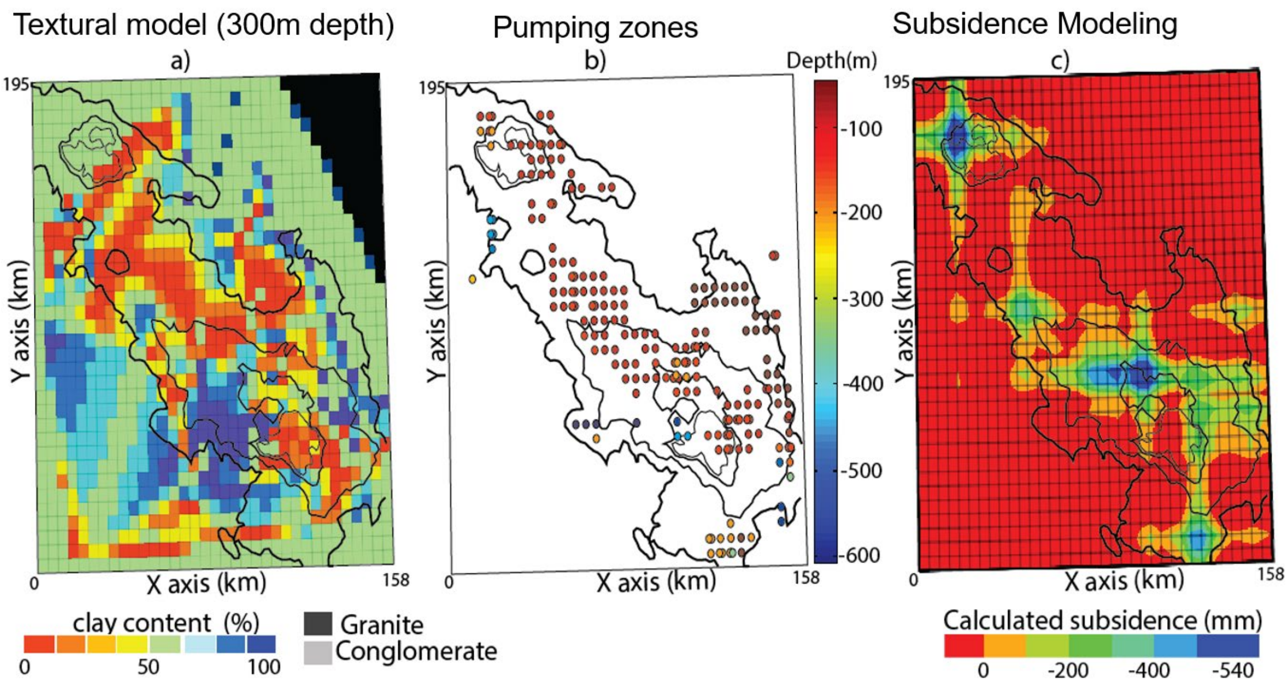
Coupled groundwater pumping and subsidence modelling of the San Joaquin Valley was conducted to investigate the link between groundwater pumping, subsidence, and three-dimensional ground surface deformations.

A soil texture model of the subsurface was developed from borehole logging data down to a depth of 700 m for 322 wells and borings held by the California Geological Energy Management Division (CALGEM, formerly the California Division of Oil, Gas, and Geothermal Resources [DOGGR]). Based on these borehole logs, a percentage of coarse-grained material was defined over 30 m intervals and textural groups were created. The model at one depth is shown for illustration on Figure 6.

The textural model was used to build a three-dimensional numerical model (35×35×19 cells) extending to a depth of 680m and laterally ~158 kilometers (km) in the eastern and 195 km in the northern direction for coupled flow and geomechanical simulation using TOUGH-FLAC (Rutqvist, 2011; 2017). Considering water wells completed deeper than 150 m, 152 well clusters were defined as the pumping zones shown on Figure 6b. The pumping rate for each well cluster was specified based on the water demand by crop types in the area, the total number of wells in the area, and the number of wells in the cluster.

Despite the coarse grid, the modeling roughly reproduced the location and magnitude of the subsidence bowls detected by InSAR from 2015 to 2017, including the El Nido area to the northwest and Corcoran area to the southeast. The modeling confirmed the correlation between subsidence location and water demand by crop type.

Figure 6: Modeling San Joaquin Groundwater Pumping and Subsidence



Map view of the textural model around 300m depth (left), locations of the 'pumping zones' (center), and calculated vertical displacement (right) after two years of simulation. The black lines are the subsidence contours from InSAR between 2015 and 2017 from Figure 5 (Jeanne et al., 2019).

Source: Modified from Jeanne et al., (2019).

3.3 Surface Deformation Estimation

Vertical and horizontal ground displacements in the San Joaquin Valley study area were estimated from 2015 to 2017 InSAR data along with geologic data. The process consisted of two steps: 1) estimating the volume change from the InSAR data, and 2) estimating the ground displacements in three dimensions from the volume change.

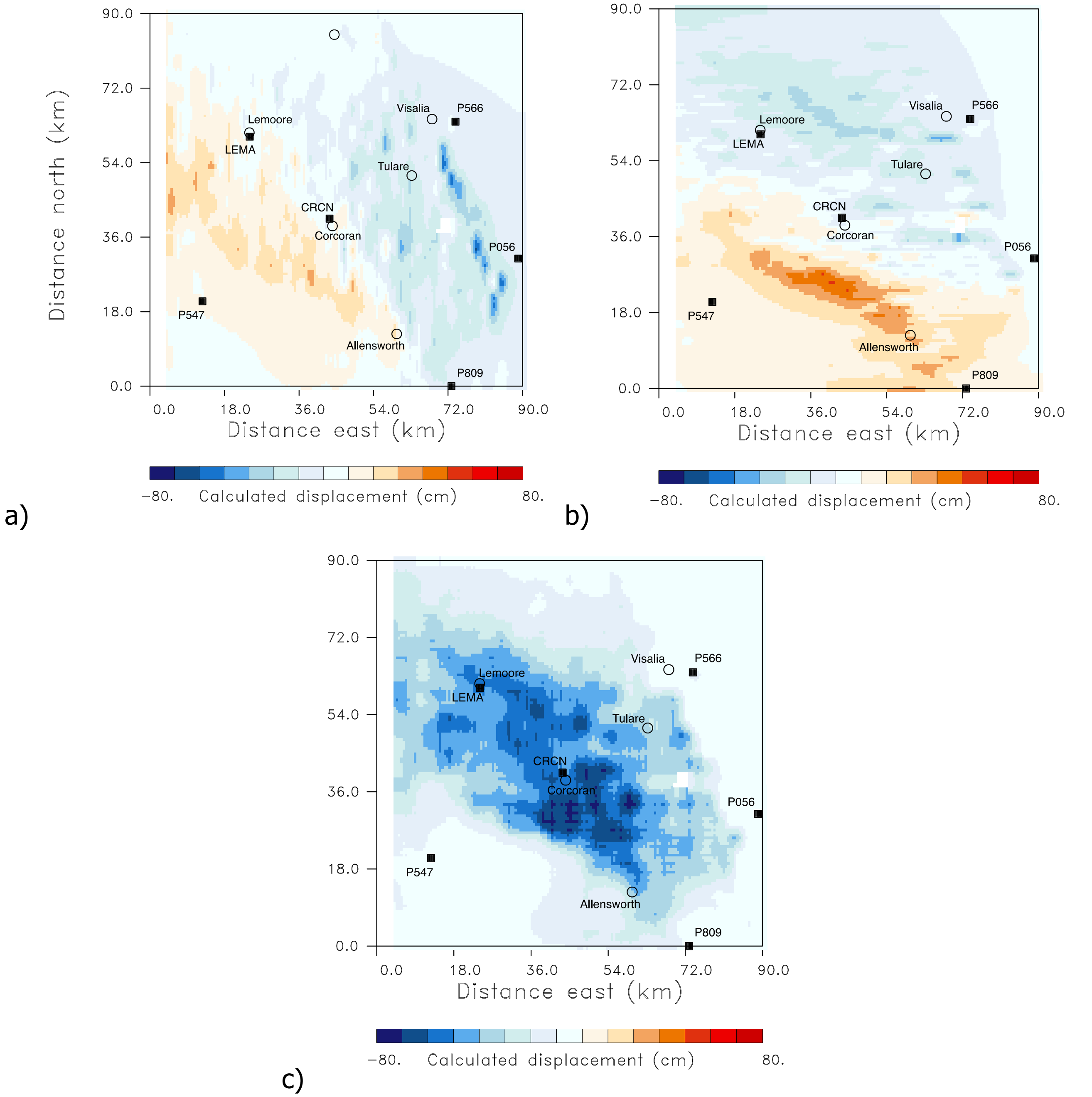
To estimate the volume change, a model of the elasticity of the sediments was constructed. Elasticities were calculated from velocity logs available for some wells. For the upper kilometer, these were correlated to depth, effective pressure and sediment texture (grain size). The sediment texture across the study area was developed from data assembled by the USGS from water well logs held by DWR (Faunt et al., 2010). The water table depth was estimated from water levels available from DWR. The correlation from well log analyses was applied to sediment texture, the effective pressure, and the sediment depth to generate the elasticity model for the upper kilometer.

For greater depths elastic properties were calculated by geologic unit. The surface of each geologic unit was developed from unit top depth picks by the USGS from oil and gas well logs held by the California Division of Geological Energy Management (Hosford Scheirer, 2007). The dynamic elasticity of each unit was estimated from sonic logs available for various wells, which was then adjusted to static elasticity. In a previous study of subsidence in an oil field, the elasticity model plus the location and amount of fluid production and injection were used to estimate subsurface volume changes that could create the InSAR line-of-site displacement patterns measured (Vasco et al., 2017). For this study, the volume of groundwater production at each well was not available because it is not required to be measured or reported. As a result, groundwater well locations from DWR locations were used to constrain where volume changes occurred.

The estimated volume changes were then used in the elastic deformation model to estimate the three ground displacement components (Vasco et al., 2017). Figure 7 shows the results for the Corcoran subsidence area.

The maximum horizontal displacements are about half the maximum vertical displacements, but not co-located. Rather, the maximum horizontal displacements occur on the sides of the subsidence bowl.

Figure 7: Estimated Ground Displacement Components in the Corcoran Area



Ground displacements estimated from 2015 to 2017 InSAR data: a) eastward displacement, b) northward displacement, c) upward displacement.

Source: Lawrence Berkeley National Laboratory, 2022

3.4 Future Subsidence

In 2014, California passed the Sustainable Groundwater Management Act (SGMA). SGMA, along with its implementing regulations, requires the creation of groundwater sustainability agencies (GSAs) in areas of historic groundwater overdraft to draft groundwater sustainability plans (GSPs). GSPs define actions the agencies must take to match groundwater demand to sustainable yield in two decades. Once drafted, the GSPs are submitted for review and approval by the California DWR.

GSPs are required to present a framework for how six undesirable results of groundwater extraction will be prevented. One of those results is ground subsidence that substantially interferes with surface uses; such uses include gas transmission and distribution infrastructure.

To avoid such subsidence, as well as each of the other five undesirable results, the GSPs set minimum thresholds (MT) and measurable objectives (MO). With regard to subsidence, the MT is the maximum subsidence that will be allowed as determined to avoid damage to surface structures and infrastructure. The MO is a more stringent target to which the groundwater extraction will be managed to assure the basin avoids undesirable results. The difference between the two provides for operational flexibility to account for short periods during which conditions vary significantly from average conditions, such as during periods of severe drought.

Because the GSPs set limits for subsidence, those limits can be used in this study. This is simpler than developing and inputting groundwater extraction scenarios during drought into hydrogeomechanical models to estimate what subsidence might occur. Because these limits have the added benefit of being legally binding, they can also be used to assess whether they protect gas pipelines.

At the start of this project, GSPs had not been drafted by GSAs, much less approved by DWR. In 2020, the GSAs covering the areas with 2015-2017 subsidence greater than 40 cm in the northern half and more than 50 cm in the southern half of the San Joaquin basin submitted their draft GSPs. These were reviewed by DWR. After the agency's comments were addressed, these GSPs were adopted and made available by DWR via a public portal.

This project's review of those GSPs found that they took various approaches to setting MTs and MOs for subsidence. These are categorized in Table 1.

"Varying" refers to the value of the criterion varying spatially over the GSA's area. "Absolute" refers to a total amount of subsidence over a period of time. Typically, the 20-year planning period defined by SGMA but some GSPs use a longer period. Some GSPs set MOs and/or MTs over the entire area covered by the plan. Others set them only at specific monitoring points within the area. The approach taken by each GSP is given on the table.

The largest MT by rate is 0.25 feet/year away from the San Luis Canal set by the Westlands Water District's GSP. Were this to occur for 20 years, the absolute subsidence would be 5 feet. The MT along the Canal is 0.1 ft (0.03 m)/yr for 2 feet (0.61 m) absolute during the 20-year period. These MTs imply differential subsidence of 3 feet over an undefined distance.

The GSP's for the two GSA's covering the Kaweah subbasin have the largest absolute MT of 15 feet over the planning period.

The Pixley Irrigation GSP defines the largest MT gradient of 0.67 feet (0.20 m)/mile.

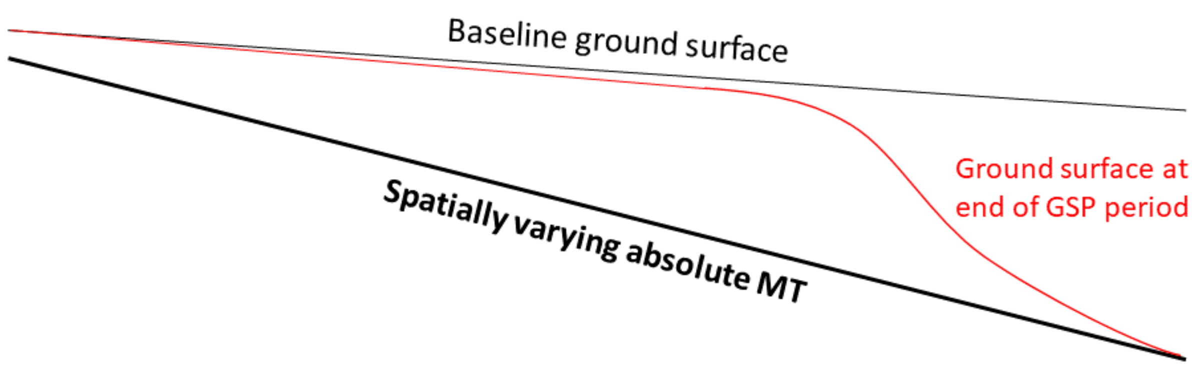
Table 1: Subsidence Measurable Objective and Minimum Threshold Approaches for San Joaquin Subsidence Areas

Subbasin	GSA	MO	(A)rea or (P)oint?	MT	(A)rea or (P)oint?
Chowchilla	Chowchilla joint	None and water level	P	Adaptive and water level	P
Madera	Madera joint	None	-	Rate	A
Westside	Westlands Water District	Rate and water level	P	Varying rate	A
Delta-Mendota	San Joaquin River Exchange Contractors	Rate	A	Impact	P
	Northern & Central Delta-Mendota	Varying rate	A	Varying rate	A
Kaweah	Greater Kaweah; Mid-Kaweah	Varying rate and absolute	A	Varying rate and absolute	A
Tule	Delano-Earlimart Irrigation; Lower Tule River Irrigation; Pixley Irrigation	Varying absolute	A	Varying absolute	A
	Tri-County Water Authority; Tulare joint	Varying absolute	P	Varying absolute	P

Source: Lawrence Berkeley National Laboratory, 2022

Even though ground displacement gradient is the phenomenon that creates risk of stresses beyond tolerance in a pipeline system, none of the GSPs set MTs based on this metric. While some of the GSPs define or imply spatially varying absolute MTs, this is not the same as defining a subsidence gradient MT. The first regards the subsidence MT varying in space. Within this it is possible for subsidence gradient to be infinite because there is no MT set for this phenomenon, as shown in Figure 8.

Figure 8: Difference Between Subsidence Gradient and Varying Absolute MT



Source: Lawrence Berkeley National Laboratory, 2022

As a result, the MTs defined in GSPs cannot be directly used to assess the risk of future ground displacement to pipeline systems. The absolute MTs do provide a means to develop displacement gradients that might occur for such assessment.

The largest absolute MT in the GSPs reviewed is 15 feet. The largest absolute MT differential between adjacent basins based on the GSPs reviewed is approximately 7 feet, occurring across a portion of the boundary between the Kaweah and Tulare subbasins.

3.5 Estimated Future Drought Related Subsidence Effects on Infrastructure

Scenarios and Simulation Inputs

Stresses and strains in gas pipelines due to subsidence were investigated via a series of scenarios simulated using the finite element code ANSYS as follows:

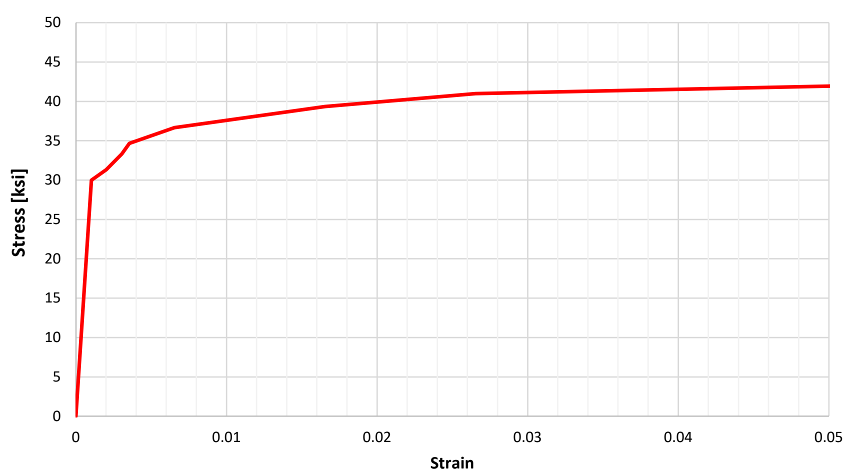
1. 2015-2017 subsidence as previously shown imposed on the gas pipeline network.
2. Portion of pipeline network displaced into the 2015-2017 El Nido subsidence feature.
3. Straight pipelines across the center of the El Nido subsidence bowl.

The gas pipeline network used in the first two simulations was based on the network in the central portion of the San Joaquin Valley (southern Madera through Fresno Counties) provided by PG&E. The data provided by PG&E consisted of vertex locations along the tops of pipelines in both plan and depth, and pipe diameters, wall thicknesses, and coatings. The elevation of the center of the pipelines was calculated by subtracting the depth and half pipe diameter at each vertex from National Elevation Data. Vertices within 5 feet of each along a pipe were consolidated and pipes within 100 feet of each other were consolidated.

Pipe diameter was consolidated to the closest of 13 values selected between 4.5 inches at the smallest and 35 inches at the largest. A uniform wall thickness based on data for pipes of each of those diameters was assigned. The longest segments were resampled to 40-foot lengths. Pipes with diameter less than four inches were not included in the pipe network abstracted for simulation.

Non-linear steel properties relating stress to strain (shown in Figure 9) were used in the simulations.

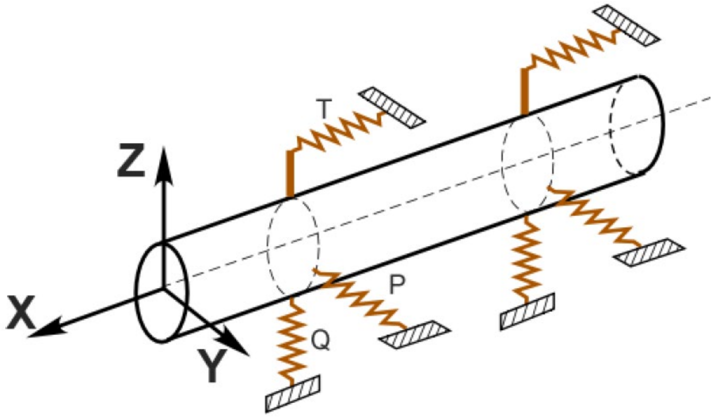
Figure 9: Steel Stress-strain Curve



Source: Lawrence Berkeley National Laboratory, 2022

Ground displacements at each simulated pipe node were imposed via three linear springs attached to each node, one along the pipe, one horizontal and perpendicular to the pipe, and one vertical to the pipe, as shown in Figure 10.

Figure 10: Springs Representing at Each Pipe Node to Represent Soil Interaction



Source: Lawrence Berkeley National Laboratory, 2022

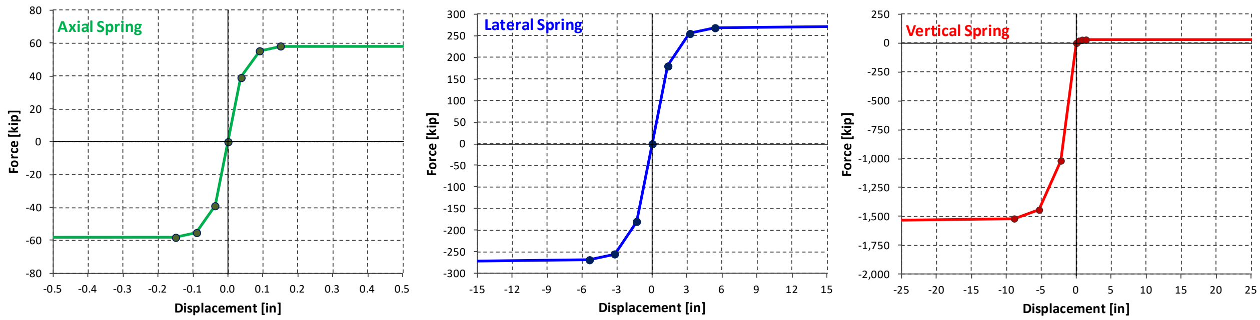
Because site-specific soil properties along each pipe in the network are not known, the constant properties (shown in Table 2) typical of sand backfill were used. The springs along and horizontal to the pipe each have one plastic force limit. The vertical spring has different plastic force limits for movement of the pipe upward and downward relative to the soil. An example of the soil force-displacement relations at a node are shown on Figure 11. In the model, the curves were represented as a series of linear relationships as shown on the figure. A unique set of springs is defined for each pipe node. Their properties are based on the pipe diameter, burial depth, coating type and soil properties.

Table 2: Properties of Soil Around Pipelines Used in Simulations

Property	Value
Density	120 pounds per cubic foot
Internal friction angle	35 degrees
Cohesion	0
Coefficient of lateral pressure	0.43

Source: Lawrence Berkeley National Laboratory, 2022

Figure 11: Example of Nonlinear Spring Properties Used in Model



Source: Lawrence Berkeley National Laboratory, 2022

Scenario 1: Subsidence Imposed on Network

The 2015-2017 subsidence field imposed on the pressurized network resulted in almost no change in stress because the stress from internal pressure dominated. To explore the risk to depressurized pipes the simulation was run again with those conditions. This resulted in a maximum stress of less than a sixth of the yield stress. Note only subsidence was imposed because horizontal displacements were not estimated across the entire basin.

The model was run with two and three times the 2015-2017 subsidence field to explore the impact of subsidence with differentials in the range of the maximum allowed by the GSPs described above. The maximum resulting stresses were approximately two and three times that of the stress occurring due to the actual subsidence, respectively. As suggested by these results, the pipes remained in the elastic domain. At three times the 2015-2017 subsidence, the maximum stress was less than half the yield stress. All of the maximum stresses were along (axial) rather than across (transverse to) the pipe.

Scenario 2: El Nido Subsidence Imposed on a Network Portion

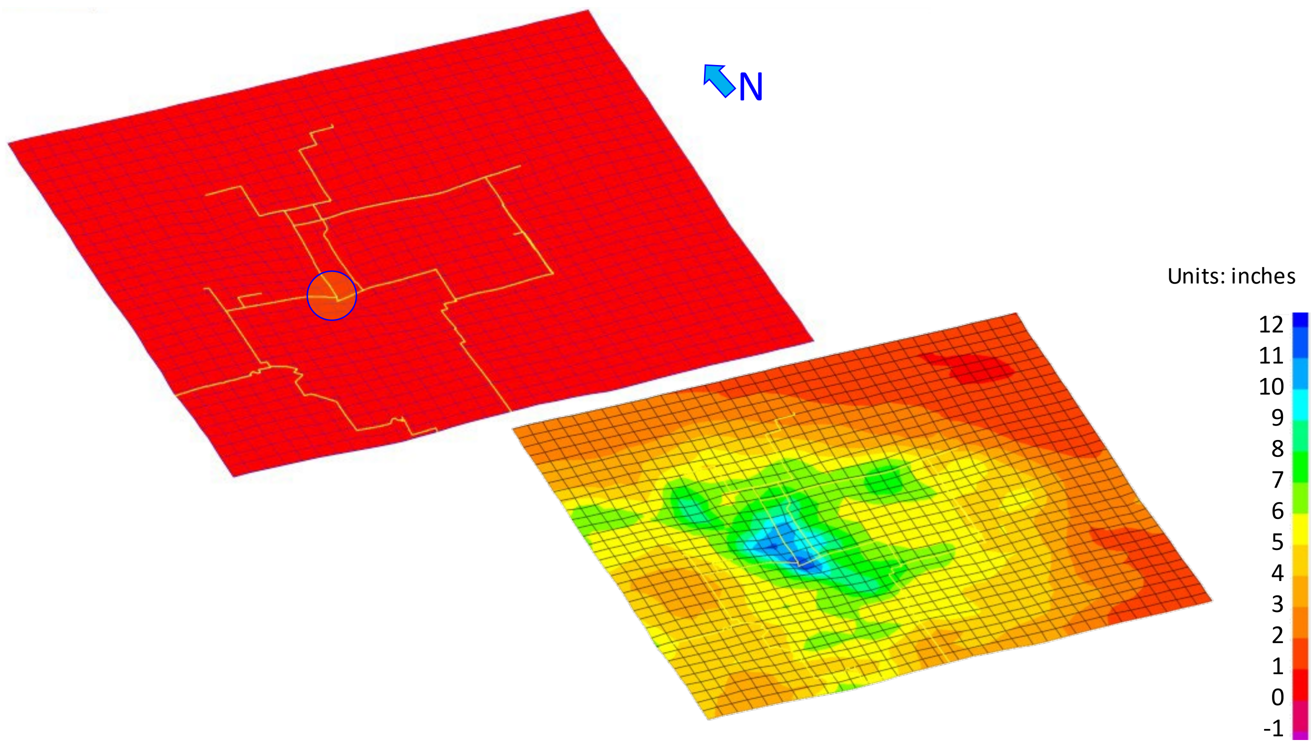
By happenstance, the existing network simulated in scenario 1 is not co-located with the areas of maximum subsidence from 2015-2017. To explore risk to a pipeline network if it were so co-located, a portion of the existing network was shifted so various features were located at the center of the 2015 to 2017 El Nido subsidence field, which is south of Merced, multiplied by ten to represent the observed subsidence linearly extrapolated to a decade. As such, the maximum subsidence considered was about 12 feet. This was selected to match the maximum differential subsidence that could result from the MTs set in the GSPs covering the recent subsidence areas.

Three different portions of the network with different topology were located at the point of greatest subsidence in the El Nido feature. In each case, the maximum stress in the network occurred at the location of maximum subsidence. In two of the cases, the maximum stress was slightly more than two-thirds of the yield stress. In neither of these did the network include a pipe running straight or nearly so across the entire subsidence feature.

Figure 12 shows the network as located in the El Nido feature for the third case. As shown on Figure 13 the maximum stress occurred at the location of maximum subsidence. This stress was slightly greater than the yield stress, but the plastic strain was limited. The network topology at the location consisted of a T-connection with a 90-degree elbow close by on the straight-through segment. The maximum stress occurred on the longer portion of the segment through the T-connection.

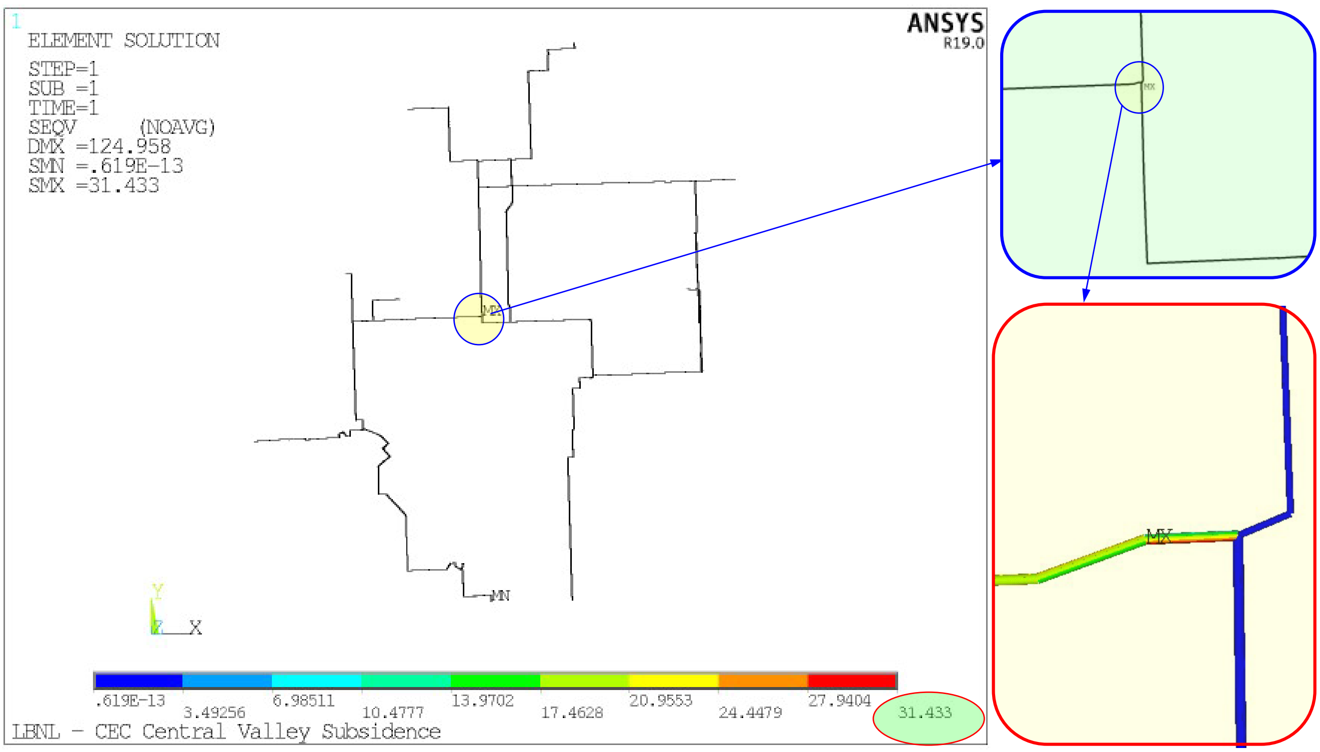
As a parametric study, the horizontal and vertical displacement fields were imposed individually on the network to gain insight into the contribution of each to stress. The horizontal field resulted in maximum stress in the same location as the full displacement field. The stress was in the plastic domain and was almost identical to the stress from the total displacements. The vertical field resulted in maximum stress less than a sixth of yield located on the slope of the El Nido feature. These results suggest that differential horizontal displacement creates most of the failure probability for a pipeline network.

Figure 12: Third Case of Pipeline Network in the El Nido Area



Source: InfraTerra, 2022

Figure 13: Pipeline Stress Resulting From the El Nido Area Case



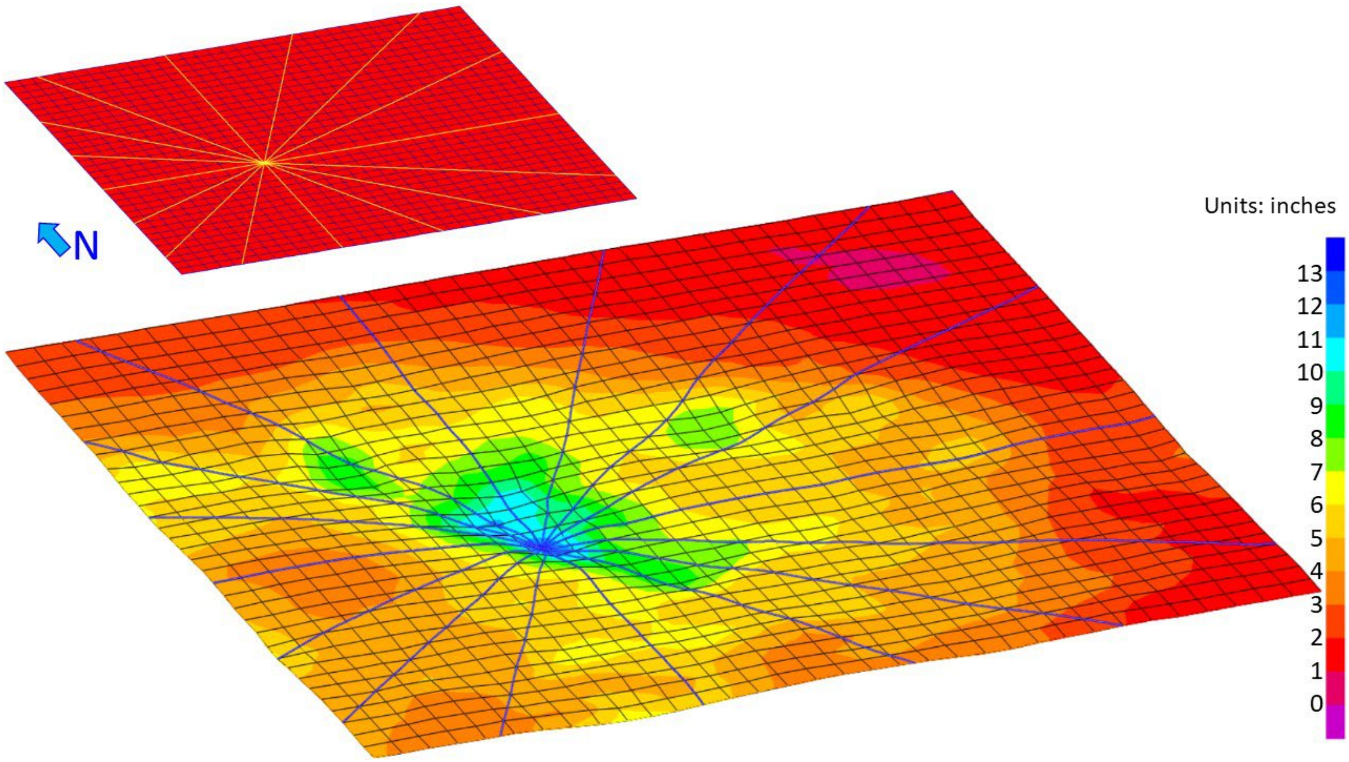
The 2015-2017 subsidence is used to calculate the pipeline stress.

Source: InfraTerra, 2022

Scenario 3: El Nido Subsidence Imposed on Straight Pipes

To further illuminate the impact of displacement gradients, simulations of single pipelines passing through the center of the El Nido subsidence feature as shown in Figure 14 were conducted. Each simulation regarded a pipeline with a different orientation (22.5-degree increments, specifically requiring 360/22.5 = 16 simulation cases). A 36-inch diameter pipe with half inch wall and 200 psi internal pressure was simulated.

Figure 14: Simulated Straight Pipelines at Various Orientations



These simulations are through the center of the 2015-2017 El Nido subsidence (inches) feature.

Source: InfraTerra, 2022

The east-west pipeline experienced the largest maximum stress. This orientation also had the maximum horizontal displacement and subsidence gradients. The maximum stress occurred at the location of maximum subsidence and within the area of maximum horizontal displacement gradient. The stress was just over yield. As such, the plastic strain was limited.

The horizontal displacements along the pipe (axial) varied by 2.5 ft (0.76 m) in a quarter mile, suggesting that is a threshold gradient for risk. The associated maximum strain was 0.22 percent in compression and 0.13 percent in tension. Generally, well-built welded steel pipeline can withstand strains as high as 2 percent (Pipeline Research Council International, 2009). This indicates that the simulated pipeline in scenario 3 would not have ruptured even with a decade of extrapolated displacement at El Nido.

To further characterize the contribution of differential horizontal and vertical displacement, those were simulated separately for the same pipe. The horizontal displacement field resulted in almost identical maximum stress occurring at the same location as the maximum stress resulting from the full displacement field. The maximum stress from the vertical displacement field was a small fraction of that from each of the full and horizontal displacement fields.

A larger suite of straight pipeline orientations, 16- as well as 36-inch diameters, and 4- as well as 8-foot depths across the 2015-2017 El Nido feature extrapolated out to a decade of displacements were also simulated by Dr. James Hart of SSD, Inc., using his proprietary PIPLIN code. The maximum strains in tension were 0.05 percent and in compression 0.12 percent. These are about half the strains from the ANSYS analysis.

Pipeline yield starting at horizontal displacement gradient of 2.5 feet per quarter mile suggests a response threshold of 1.5 feet per quarter mile. This provides time to respond before damage commences. One possible response is site-specific risk analysis to forecast if damage will occur. The length of pipe analyzed should include the entire subsidence area because maximum stresses may not occur at the location of the maximum ground deformation gradient.

While horizontal differential displacement appears to be the source of maximum stress in a pipeline and pipeline network, measuring horizontal displacements is more complicated than measuring subsidence (vertical displacement) at this time. As such, they were compared along the east-west pipeline to determine if differential subsidence could be a proxy for differential horizontal displacement. The maximum subsidence gradient was about six feet per mile, or 1.5 feet per quarter mile. This indicates a subsidence gradient of one foot per mile along a pipeline as a proxy threshold for triggering site-specific risk analysis.

3.6 Monitoring of Ground Surface Deformations

Various ground-based, remotely sensed and borehole methods are used to measure, monitor, and map subsidence. Usually, ground-based methods track changes in the position of the land surface relative to a spatial position considered stable. Borehole-based methods track the sediments compaction at depth with extensometers. Each of the techniques most commonly used to quantify surface and underground deformation is discussed, followed by discussion of technologies to improve continuous measurements of land subsidence.

Leveling

Along with triangulation measurements, observations of vertical displacements obtained from leveling surveys are one of the oldest sources of geodetic data. In principle, the technology is simple. A calibrated graduated staff or stadia rod is situated at a fixed distance from the observation point. In optical leveling, a precision telescope is used to determine the vertical distance to the base of the rod relative to a horizontal line of sight. The local horizontal plane at the measurement point is defined with respect to the gravity vector. Reoccupying the telescope and stadia rod location allows repeat measurement to determine if the elevation of the positions has changed relative to each other. Measurement of multiple stadia rod locations along a transect provides a leveling survey. Moving the telescope to occupy one of the stadia rod locations allows the rod to occupy positions further along extending transect distance.

Due to ease of access and ability to establish markers for repeat occupation, leveling is typically conducted on roadways and engineered surface water conveyances traversing an area. For these reasons it is not generally difficult to apply in undeveloped regions. For this reason, it has largely been supplanted in such areas by geodetic observations based upon Global Navigational Satellite Systems.

Leveling is still a common technique for measuring surface deformation along linear engineered structures on the ground surface and provides an important link with earlier deformation studies. As a ground-based technique, leveling avoids much of the atmospheric variability that impacts remote-sensing methods, although it must still account for variations in light refraction.

Triangulation and Trilateration

Triangulation involves accurately measuring the distance between two points and then using two angular observations to determine the geographic location of a third point that completes the triangle. It is a classic technique in geodesy that often takes advantage of unobstructed views from hills and mountain tops.

With the advent of laser ranging and other electronic distance measuring techniques, triangulation has largely been supplanted by trilateration, whereby the lengths of the three sides of a triangle are measured with great accuracy. Repeat trilateration allows measuring horizontal deformation in a given region.

The technology was improved with the use of multiple wavelengths, allowing for corrections that account for atmospheric effects. Trilateration is most useful in rugged areas with well separated topographic high points for sighting, such as in northern California. For instance, at The Geysers geothermal field (Prescott and Yu, 1986).

Tilt

Measuring tilt relative to a baseline condition is another geodetic technique with a rather long history. The earliest method used a long-length stationary pendulum. Currently, the most common approaches rely on the fact that the surface of a fluid remains normal to the direction of gravity, the principle of the bubble level. This approach has been implemented in pipes containing fluid to increase sensitivity while maintaining portability (Eaton, 1959) and, more compactly, using a conducting fluid such a mercury and resistivity changes to sense minute changes in the bubble position (Westphal et al., 1983). Due to daily thermal effects and Earth tides, the most accurate tilt measurements are made in boreholes, generally ten or more meters in depth (Wright, 1998).

Borehole extensometers

Vertical borehole extensometers continuously measure the change in distance between the land surface and the bottom of the borehole, which can be several tens to hundreds of meters deep. It is the only approach that provides measurements across the entire depth from aquifer and land surface.

To use a permanent extensometer, a borehole is first drilled deep enough either to reach below the depth of the fine-grained layers expected to consolidate due to water level/pressure changes and generate subsidence. In the most common approach, the sensor, which is measuring the land vertical movement, is set at the surface. It usually is a one-dimensional measurement of the relative displacement between the top an inner rigid pipe considered fixed at the bottom of the hole and a concrete slab which is resting on the land surface around the borehole head. Current resolution of this approach depends on the specific devices and on the in-situ setting but can be on the order of 0.01 mm to 0.1 mm.

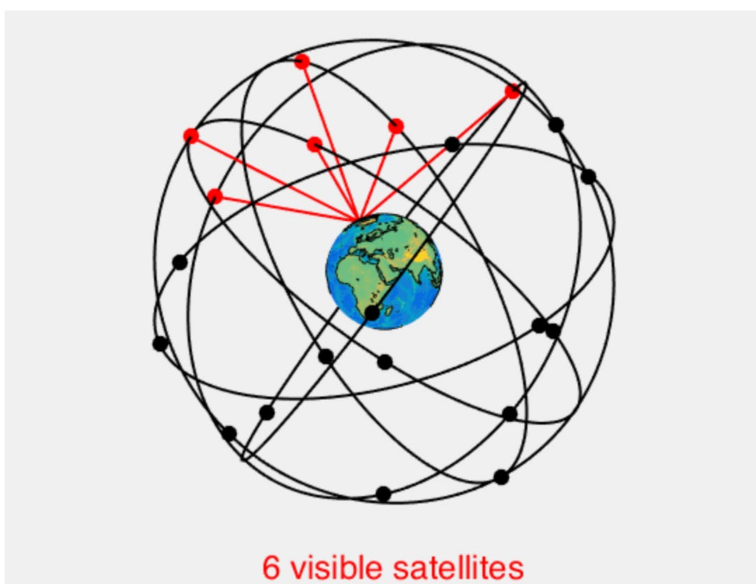
Multiple position borehole extensometers incorporate magnetic markers clamped to the borehole casing. Repeated logging with a magnetic probe allows measuring the variations of several tens of markers' position in a single borehole at measurement resolutions of 1-2 mm over depths of several hundred meters. Although of lower resolution than the vertical borehole extensometers, the multiple borehole position extensometers techniques can devolve total ground displacement to individual aquifers/aquitards when more than one is contributing.

Global Navigational Satellite Systems

Global Navigational Satellite Systems (GNSS), of which the Global Positioning System (GPS) is probably the most well-known example, provide a form of dynamic, three-dimensional trilateration (Dixon, 1991; Teunissen and Kleusberg, 1998; Hofmann-Wellenhof et al., 2007). That is, a network of closely tracked satellites send signals to receivers on the Earth's surface and the signals are post-processed to get accurate arrival times for trilateration as shown by Figure 15.

GNSS such as GPS have seen extensive applications in the Earth sciences since their development in the 1980's (Bürgmann and Thatcher, 2013; Bock and Melgar, 2016), with specific applications to the study of deformation due to groundwater withdrawal, and hydrothermal and geothermal fields. Key advantages of the approach are almost continuous temporal resolution and the availability of all three components of the displacement vector. Due to this capability, there is an extensive system of GPS stations in the Central Valley of California, including more than 100 in the portion of the San Joaquin Valley studied as shown in Figure 16. The disadvantages of measurements by GNSS are the expense of deploying the receivers and that measurements are only available at one point per receiver at an instant.

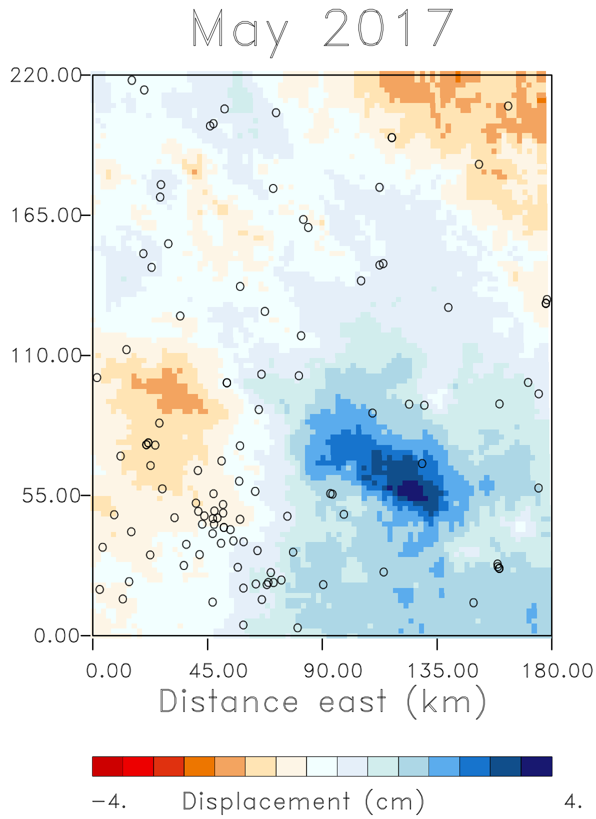
Figure 15: GNSS Satellite Configuration



Schematic of GNSS satellite configuration used for trilateration to find the precise location of a receiver on the Earth's surface.

Source: Lawrence Berkeley National Laboratory, 2022

Figure 16: Location of GPS Stations in the Central San Joaquin Valley



The open circles denote the location of GPS stations for the area studied. The background color scale denoted the line-of-sight displacement field recorded by InSAR satellite observations. The area shown encompasses the El Nido subsidence area near the northwest corner and Corcoran subsidence are in the southeastern portion.

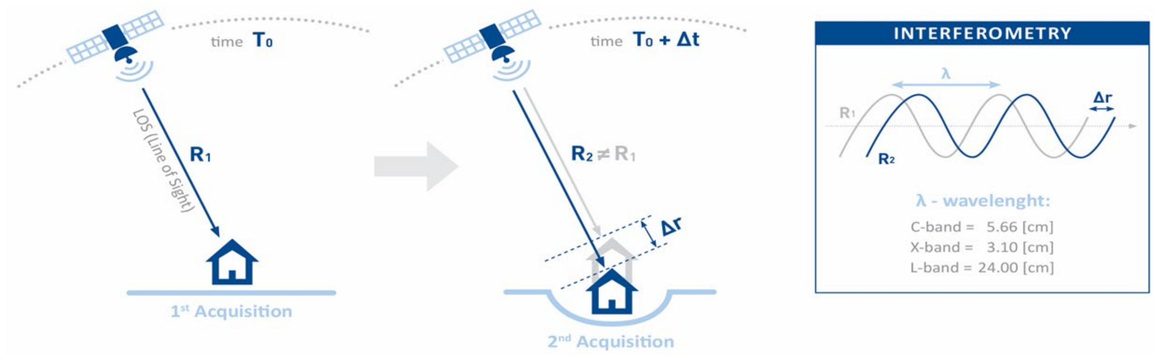
Source: Lawrence Berkeley National Laboratory, 2022

Interferometric Synthetic Aperture Radar

InSAR utilizes data from microwave signals through time propagated to a surface where it is reflected from various scattering points. These data are most often collected by satellite for scattering points on the Earth's surface. Several stages of processing result in very accurate estimates of changes in the effective signal phase for these points (Ferretti, 2014). The resulting interferograms that are then mapped into range change, the movement of the object in the line-of-sight direction as shown in Figure 17. While the technology and processing associated with estimates of surface deformation are sophisticated (Gabriel et al., 1989, Massonnet and Feigl, 1998; Bürgmann and Thatcher, 2013; Ferretti, 2014), the underlying principle is similar to that of echo location. An up-to-date overview of radar interferometry by Ming et al. (2020) covers the many approaches in more detail.

InSAR is now used more often in the study of subsidence and general surface deformation. The characteristics that contribute to its appeal are the fact that it is a cost-effective remote sensing technique that samples areas with high spatial resolution, while satellite revisit times are months to weeks. It is used when the temporal sampling from a satellite's passage overhead is adequate, a single displacement component suffices, and there is a sufficient spatial density of repeat reflectors.

Figure 17: Principles of InSAR



Principles underlying InSAR. Acquisitions at different times provide time series of microwave reflections from points on the Earth. If the surface characteristics do not change substantially, the phase shifts between the time series can be related to the change in line length, the range.

Source: Lawrence Berkeley National Laboratory, 2022

Synthetic aperture radar observations obtained from one orbital geometry simply measures surface displacement along the line-of-sight from the satellite to a reflection point on the Earth's surface (Massonnet and Feigl 1998; Bürgmann et al., 2000; Wright et al. 2004), as shown on Figure 17. It is feasible to combine observations obtained from both ascending (satellite moving northward) and descending (satellite moving southward) orbits to approximate quasi-vertical and quasi-east-west components of motion.

If the angle between the satellite and the ground surface at the scatterer is not close to vertical, the ascending geometry provides a different view of the ground displacement vector in three dimensions than the descending orbit. Horizontal displacement perpendicular to the orbit can be estimated from these views. Horizontal displacement parallel to the orbit cannot be estimated. The addition of even one more displacement component to the standard vertical component would provide improved ground deformation over wide areas for continuous updating of risk to gas pipelines.

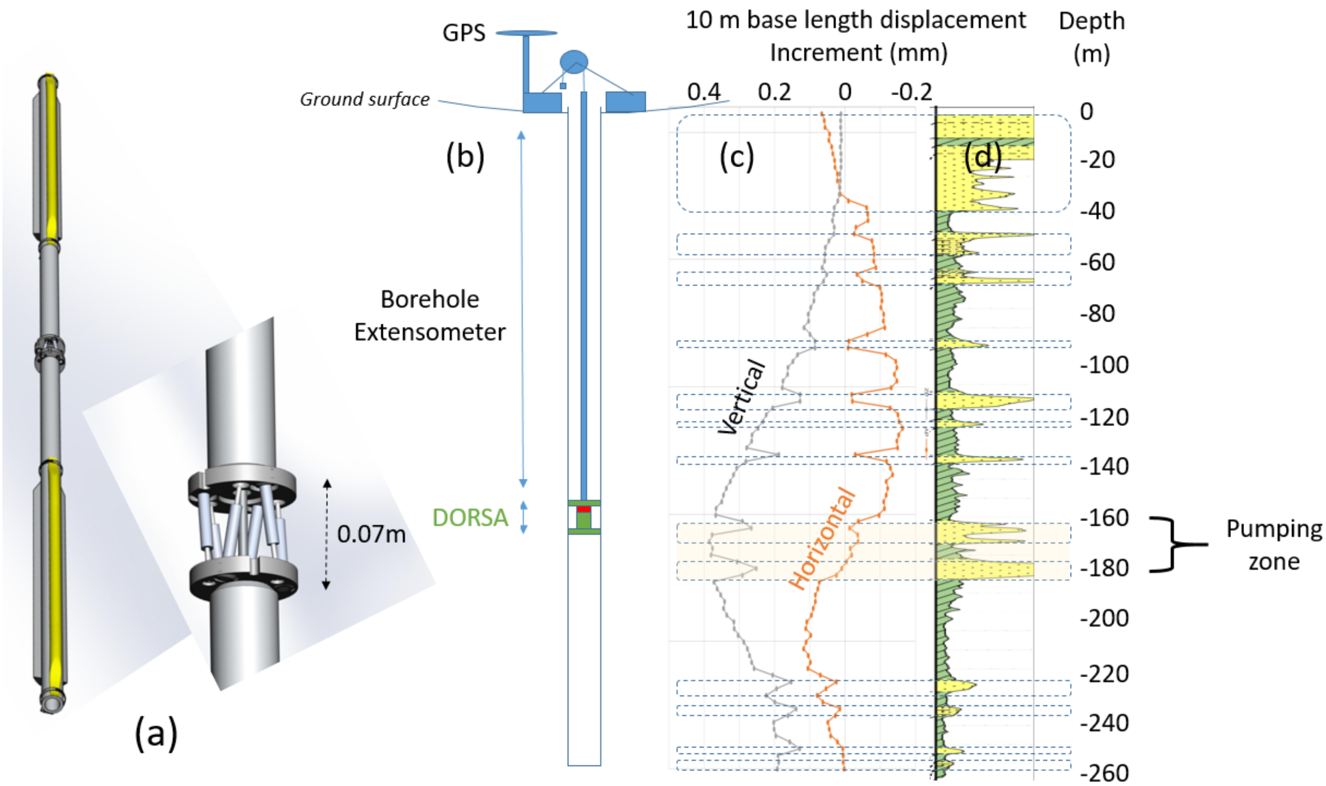
Light Detection and Ranging

Light Detection and Ranging (LiDAR) is an emerging technique for measuring deformation using laser ranging from a stationary or moving source to points on the ground surface (Eitel et al. 2016). The technology is developing and has not yet been applied in a differential mode to determine surface deformation. However, airborne systems could provide useful displacement data associated with ground subsidence. LiDAR data has been gathered over potential geothermal sites in the Pacific northwest by the State of Oregon.

A New Type of Three-dimensional Borehole Extensometer

A new borehole displacement sensor was developed in this project: the downhole robotic stress analyzer (DORSA). The DORSA-ɑ prototype is made of two anchoring zones connected to each other by a stiff carbon fiber extension tube and the three-dimensional sensor as shown on Figure 18. The three-dimensional sensor is a six degrees of freedom displacement sensor. The position and orientation of the upper anchor relative to the lower anchor is calculated from the leg length variation. There are different solutions for the anchoring zones depending on how long the instrument is supposed to stay in the borehole.

Figure 18: DORSA for Subsidence Monitoring



(a) DORSA instrument (left) with a detailed view of the displacement sensor (right). (b) Schematic of DORSA- in boring deployed with an extensometer above. (c) Potential distribution of relative displacements between the two ends of a 10 m long DORSA induced by pumping groundwater from 160 to 180 m deep. (d) Example of the lithostratigraphic column of the Madera basin where a DORSA deployment could help characterize differential compaction in the multi-layered clay-sand series.

Source: Lawrence Berkeley National Laboratory, 2022

Two DORSA prototypes were designed and tested in well-constrained field experiments conducted at LBNL and at the Mt-Terri underground research laboratory in Switzerland. The DORSA system fulfilled the expectations of these experiments.

- Logistically easy and low cost to deploy,
- Reliable over the duration of the experiments,
- High sensitivity to three dimensional micro-displacements and to rotations, and
- Ability to measure over a broad displacement range of 10^{-6} to 10^{-2} m.

Subsidence monitoring via DORSA can be enhanced by two approaches.

- Combine a DORSA with a borehole extensometer as shown in Figure 18b. The DORSA would be deployed at depth, across or at the top of the aquifer pumped to best characterize the consolidation in or close to the source zone. Then, the upper DORSA anchor could be connected to the surface with a borehole extensometer tube to monitor the vertical displacement above. A GPS could be added at the surface to increase the accuracy of the vertical displacement, and to provide correlation with INSAR and other satellite measurements.

- Use a string of DORSA at different borehole depths. This would allow characterizing the displacement rates at the top of the pumping zone and in the overlying sedimentary column. In particular, this would monitor shear in fine-grained zones and their interfaces with coarse-grained zones where shear that results in horizontal ground displacements is most likely to occur.

3.7 Mitigation Options and Costs

If site-specific analysis following an exceedance of the displacement gradient criteria determines a pipeline is at risk, action to mitigate the risk should be undertaken.

One response considered was unburying the pipeline for some distance beyond the segment subject to displacement gradients creating risk. This relieves the stress in the pipe by allowing it to shift relative to the soil, spreading the spreading the ground displacement over a longer segment.

This option was discussed with PG&E. The utility responded that due to the risk and cost of unburying a live pipe or the disruption of taking it out of service for such activity, PG&E would rather replace the pipe. PG&E relayed a rough cost of about $5 million to $10 million per mile of new pipeline based on experience for a range of settings from rural to urbanized locations. This is a full project cost estimate including planning, design, permitting, and construction. This estimate would need to be adjusted for inflation if used for future cost projections. Previous results indicate high horizontal displacement gradients occurred over a distance of about a mile from 2015 to 2017. If this is indicative of high horizontal displacement gradients generally, it suggests the cost of remediation of pipeline damage per incidence of damage from subsidence would be the cost for one mile of replacement or less.

If effectively implemented, SGMA <u>precludes</u> a utility from needing to replace a pipeline damaged by subsidence. Rather, when horizontal displacement gradients exceed the suggested trigger threshold the GSA for the area should be notified and participate in the subsequent site-specific study. If that study finds unacceptable risk developing, it is the legal responsibility of the GSA to change groundwater use to ameliorate continued ground displacement sufficiently to reduce the risk of pipe damage occurring to an acceptable level. As this likely would involve shifting the location of or actually ending groundwater extraction, there would be an associated cost. From a cost perspective, taking this action versus repairing the pipeline should be compared. Estimating the cost of shifting or ending groundwater extraction in an area sufficient to reduce pipe damage risk acceptably is beyond the scope of this project. From a legal perspective, whatever approach is taken the cost appears to be the GSA’s to bear.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

The project team at LBNL developed materials to aid technology transfer, such as project fact sheets, and a plan to make the knowledge gained, experimental results, and lessons learned available to the public and key decision makers. The technology transfer plan will include efforts focused on IOU as key stakeholders, for instance partnering with PG&E. Other market actors to be targeted are oil and gas companies through presentations and publications. Presentation materials have been developed to aid in project result dissemination.

4.1 Technology Transfer

The methodology developed within the project for assessing effects of subsidence on pipeline safety includes a method of estimating three component surface deformation from satellite (InSAR) data, criteria for precursors to pipeline damage, and an instrument for subsurface borehole deformation measurements.

- Estimation method for three-component surface deformation: This method has been fully described in Vasco et al. (2017) and could be applied at the state level, meaning that a state agency could engage a contractor to estimate the three-component surface deformation from InSAR data across all groundwater basins with historic subsidence. The estimation technique is also applicable to oil and gas production and for monitoring subsurface gas storage facilities.
- Ground deformation criteria for precursors to pipeline damage developed in this project are applicable not only to groundwater pumping in California, but universally to ground deformations induced by subsurface activities, such as hydrocarbon extraction or mining. The displacement gradient criterion has been communicated to PG&E, has been presented at the American Society of Civil Engineers Lifeline Conference (Nisar et al., 2022) and will also be described in a journal publication (Jordan et al., 2022). PG&E has already adjusted internal procedures regarding management of pipeline risks in areas of subsidence to incorporate these findings and ground deformation criteria. The publication will be shared with the GSAs whose GSPs were considered in the project and with DWR.
- The subsurface borehole deformation tool, DORSA, provides a new method that has been tested and demonstrated in the subsurface for long-term three component strain measurements. PG&E has been contacted for potential deployment of this tool at a fault near a gas pipeline in California. The tool itself was developed as part of other projects for similar applications but has in this project been tested and demonstrated for monitoring long-term strain changes in a borehole that would be relevant for linking subsurface deformations to ground surface deformations.

4.2 Knowledge Transfer

The broader knowledge developed within the project relating crop type and associated groundwater demands, well density and completion depth, to subsidence are important for the stakeholders involved in both water and energy management.

- The knowledge gained regarding the relation of crop type water to demand based on literature data and new coupled flow and geomechanical modeling characterizing the resulting subsidence was published in the Journal of Hydrology (Jeanne et al., 2019). As of July 2022, the paper had already been cited 36 times according to Google Scholar.
- The knowledge gained from the review of GSPs submitted by GSA to the DWR and the subsidence risk threshold for California's gas pipeline network, will be published in a journal article (Jordan et al., 2022).

4.3 Market Transfer

The technology and knowledge gained from this project is published in the open literature and will be available to anyone, except for the DORSA that will be the subject of a patent application and ground deformation estimation software that will have to be released for licensing to entities external to LBNL. These tools have been or will be published in peer-reviewed journal publications and conference presentations related to a variety of subsurface engineering activities subject to ground deformation impacts.

CHAPTER 5: Conclusions/Recommendations

The main conclusions from this project are:

- Land subsidence in California's San Joaquin Valley typically occurs in areas with the highest water demand crops and greatest density of groundwater wells, while the rate of subsidence is strongly affected by the amount and availability of groundwater extracted.
- Uncertainties regarding future drought-induced subsidence are substantially reduced by state law mandating the establishment of limits on subsidence due to groundwater extraction (assuming compliance with state law).
- GSPs for areas of substantial historic subsidence in the San Joaquin Valley set maximum limits on subsidence or minimum water levels in order to limit subsidence.
- The GSPs do not establish limits on differential ground displacement, which is the movement associated with the highest risk of damage to pipelines. Rather the GSPs as a group allow up to 15 feet of subsidence in some locations, which would result in displacement gradients whose size depends upon the size of the feature. The GSPs also set subsidence limits that are as much as 7 feet different at a shared border.
- Coupled geomechanical-pipe structure simulations indicate that risk to gas pipelines is typically due to horizontal rather than vertical ground displacement gradients resulting from subsidence.
- The risk for pipeline damage will be the highest in areas with the highest gradient of horizontal displacement, for example when the horizontal ground deformation exceeds a certain limit of feet of subsidence per mile along a pipeline. Simulations suggested this limit is 2.5 ft (0.76 m) per quarter mile. This gradient occurred in the vicinity of the maximum subsidence gradient in the simulations, which was one foot per quarter mile.

Based on research findings, the following recommendations are suggested as a means of protecting infrastructure from subsidence-associated damage:

- Using techniques developed and demonstrated in this project, horizontal displacements estimated from InSAR data should be quantified and monitored where historic subsidence has occurred, where there are substantial local contrasts between crop demand met by groundwater pumping, where different subsidence limits are adopted by GSAs that are adjacent, or where soils are subject to inelastic consolidation in response to groundwater pressure decreases.
- Wherever a horizontal displacement gradient is greater than 1.5 feet per quarter mile occurs, a site-specific engineering analysis should be conducted over the entire subsidence area to assess whether infrastructure is at risk.

- Subsidence monitoring should move towards providing measurements of horizontal displacement gradients. Until such monitoring is in operation, subsidence gradients based on InSAR data should be monitored and the proxy limit from our study applied.
- Wherever a subsidence gradient greater than one foot per quarter mile occurs, a site-specific engineering analysis is recommended to assess the risk to infrastructure. The analysis should encompass the area of the specific gradient as well as the surrounding area.
- If site-specific analysis finds gas pipelines at risk, the GSA covering the area should modify groundwater utilization to reduce the risk to an acceptable level. Or, depending on the cost and likely effectiveness of this action, plans to replace the identified segment(s) of pipeline should be made and executed. GSP regulations should be updated to require limits on differential ground displacement with specific consideration of impacts to infrastructure present, such as pipelines. The regulations should require the differential and absolute ground displacement limits between GSPs to be the same at their shared border.
- GSP criteria can be best informed and representative of the broad range of stakeholders by specific involvement by the variety of stakeholders that can be impacted. Information developed by the LBNL/Infraterra study provides a useful science-based framework to compare and discuss competing interests and potential alternatives.
- Pipeline impact assessments for the LBNL/Infraterra study are based on numerical models. These models would benefit from a comparison with empirical performance observations that also can provide calibration data. Some potential targets for collecting empirical data include companies/utilities that own and operate pipeline networks in regions of significant historic subsidence that were not part of the study, and including water, gas, and oil extraction networks. Important data potentially could also be collected outside of California. For example, Arizona has a well-documented history of subsidence and ground deformation associated with groundwater extraction around and west of Phoenix.

CHAPTER 6:
Benefits to Ratepayers

The project found that GSPs in the areas of greatest historic and recent subsidence have not been formulated to limit differential subsidence. Correcting this in the first update of those GSPs will decrease the risk of pipeline damage due to subsidence.

The project resulted in a methodology that provides the capability to more accurately forecast the impact of water use on gas infrastructure through analysis of three-component ground deformations imaged by satellite-based land surface monitoring.

The project demonstrated a method for monitoring differential ground surface deformation continuously over a wide area. The project developed conservative displacement gradient thresholds that can be applied to the monitoring results to identify areas at risk of causing pipeline damage and recommends that if such areas occur site-specific analysis of risk be undertaken and actions to reduce that risk be implemented if the risk is determined unacceptably high. As such, project results could provide a basis for:

- Increased safety: The project provides an approach for developing an early warning system of subsidence that puts gas infrastructure at risk. This can inform risk-based decisions on preventative engineering actions to protect the infrastructure before it experiences damaging surface strains, therefore providing safeguarding against abrupt failure and gas leaks.
- Lower costs: The quantitative predictive methodology developed by the proposed project could enable early preventative engineering measures to be taken to prevent failure, thus significantly lowering mitigation costs.
- Environmental benefits: Early risk-based failure prevention could help to minimize methane leaks and hence reduced emissions of greenhouse gases.
- Greater reliability: Improving gas pipeline integrity and preventing gas line failure could provide greater reliability for the gas supply.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
Aquifer	An underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials
Aquitard	A geologic formation or stratum that lies adjacent to an aquifer and that allows only a small amount of liquid to pass
GPS	Global Positioning System
GNSS	Global Navigational Satellite Systems
GSP	Groundwater Sustainability Plan
GSA	Ground Water Sustainability Agencies
DORSA	Downhole Robotic Stress Analyzer
DWR	Department of Water Resources
IOU	Investor-Owned Utility
InSAR	Interferometric Synthetic Aperture Radar
JPL	Jet Propulsion Laboratory
LBNL	Lawrence Berkeley National Laboratory
LiDAR	Light Detection and Ranging
Lithostatic stress	The component of confining pressure derived from the weight of the column of rock above a specified level.
MO	Measurable Objectives
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MT	Minimum Threshold
PG&E	Pacific Gas and Electric Company
Range change	Ground-surface displacement measured long the line-of-sight from a Satellite between the two time periods
SGMA	Sustainable Groundwater Management Act
Subsidence	Downward vertical movement of the ground
USGS	United States Geological Survey

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