Louisiana Transportation Research Center

Final Report 610

CORS 911: Continuously Operating Reference Stations for the Bayou Corne Sinkhole

by

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16. Abstract

The sinkhole associated with the Napoleonville salt dome in Assumption Parish, Louisiana, near Bayou Corne, threatened the stability of Highway 70–a state-maintained route. In order to mitigate any potential damaging effects to the highway and address issues of public safety, a program of monitoring, decision support, and research was implemented to provide continuous, long-term observation and measurements of the surface stability using continuously operating GPS reference stations (CORS). Five CORS911 Sentinel sites were installed in the vicinity of the sinkhole to measure the horizontal and vertical displacements of each site relative to each other and to a fixed location outside the study area. Differential motions measured by integrity monitoring software were automatically summarized within a report and uploaded to an FTP server on a daily basis. An email system was also implemented to notify decision makers of anomalous movements measured by the CORS911 sentinels. This report presents the positional measurements collected and discusses the implementation experience and findings.

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ABSTRACT

The sinkhole associated with the Napoleonville salt dome in Assumption Parish, Louisiana, threatened the stability of Highway 70–a state-maintained route. In order to mitigate any potential damaging effects to the highway and address issues of public safety, a program of monitoring, decision support, and research was implemented to provide continuous, long-term observation and measurements of the surface stability using continuously operating GPS reference stations (CORS). Five CORS911 sentinels were installed in the vicinity of the sinkhole to measure the horizontal and vertical displacements of each site relative to each other and a fixed location outside the study area. Differential motions measured by integrity monitoring software were automatically summarized within a report and uploaded to an FTP server on a daily basis. An email system was also implemented to notify decision makers of anomalous movements measured by the CORS911 sentinels. This report presents the positional measurements collected to date and discusses the implementation experience and findings. DOTD reduced the threat level from emergency to monitoring, and then to closed this project at the end of September 2018. The CORS stations will be recommissioned to other areas of the state by DOTD (location and survey).

ACKNOWLEDGMENTS

The investigators acknowledge the support from the project manager, Joey Tureau (DOTD District 61), for his assistance and leadership while coordinating our field installations - we congratulate him on his recent retirement. We also acknowledge the invaluable contributions of the District 61 personnel whose quick work during site preparation made for the timely deployment of the monitoring sites. Furthermore, this project greatly benefitted from the support of John Boudreaux, the Director of the Assumption Parish Office of Homeland Security and Emergency Preparedness. The authors wish to acknowledge the distinguished efforts of C4G personnel who worked together to meet the challenges of this project successfully. Larry Dunaway custom-designed, fabricated and deployed the innovative CORS911 sentinels, and C4G network administrator, Randy Osborne worked many long hours to ensure that the CORS system continued to perform as expected. We also note the unfortunate passing of Josh Kent during this project. He was 47 years old and is survived by his wife and four daughters.

IMPLEMENTATION STATEMENT

This report summarizes the implementation of the CORS911 monitoring and reporting system implemented along a corridor of Highway 70 made vulnerable by the Bayou Corne sinkhole in Assumption Parish, Louisiana. Initiated in April 2013, the project was extended through September 2018. This document includes an overview of the real-time monitoring system composed of five custom-designed continuously operating GPS reference stations (CORS), the sentinels. The CORS911 system directly supported the Louisiana Department of Transportation and Development (DOTD) goals to ensure the safe use of the roadway and bridges nearest the sinkhole hazard. The deliverables of this project include the geodetic analysis of the CORS sites. Findings derived from the data and the analysis performed provide insight into the degree to which the phenomenon has affected the highway. The results also provide a baseline from which continued observations can be assessed. These data produced by this study were made available to the DOTD staff via Internet FTP services. The system also provided real-time alerts for the DOTD Emergency Operations section.

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INTRODUCTION

A sinkhole formed in the wetlands near Bayou Corne in Assumption Parish, Louisiana, on August 3, 2012. The sinkhole was centered approximately 1,500 ft. (~460 meters) south of Louisiana Highway 70, a state-maintained route (Figure 1 and Figure 2). The event triggered numerous hazards across the affected area, including surface instability, horizontal displacement, subsidence, and seismic events. These had "the potential to threaten lives, the environment, property and operations, sites and facilities"(LADNR, 2012). For this reason, the Louisiana Department of Transportation and Development (DOTD) immediately commissioned multiple monitoring solutions for the continued and safe use of the portion of highway considered to be vulnerable to the sinkhole. In April 2013, the Center for GeoInformatics at Louisiana State University (LSU) was selected to design, deploy, operate, and maintain five continuously operating reference stations (CORS) installed at designated locations along the route. This report details the program objectives, implementation strategies, and operational status of this custom solution for DOTD. Finally, an overview of geodetic analysis the recorded measurements has been summarized and presented with a discussion.

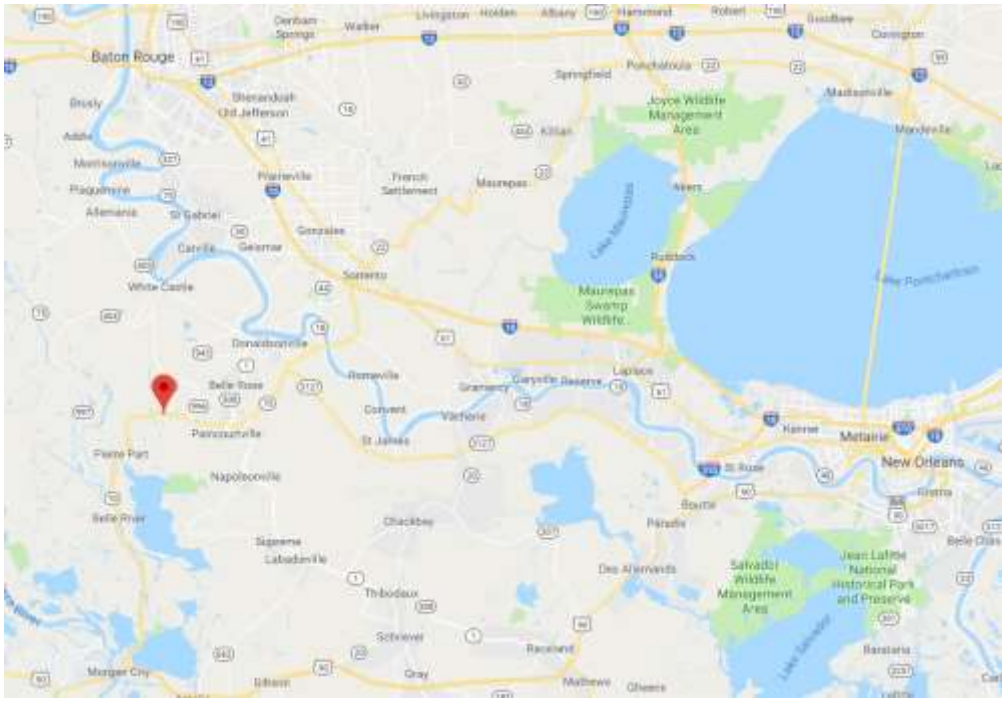

Figure 1
Bayou Corne vicinity map

Figure 2
Bayou Corne, Assumption Parish, LA

OBJECTIVE

The goal of this project was to implement a monitoring and reporting solution capable of providing situational awareness of the portion of Highway 70 at risk of damage from the Bayou Corne sinkhole. The system was designed to help mitigate sinkhole related hazards and ensure the continued and safe use of the affected highway. The project requires a continuously operating, insitu monitoring solution that can detect and record any movement of the roadway and bridges within the affected corridor. The proposed solution had to support real-time situational awareness that was capable of notifying key personnel of abnormal activity near the highway infrastructure. Finally, measurements recorded at each site had to provide decision makers with a synoptic understanding of the physical processes acting on the roadway. Accordingly, the following objectives were defined:

a) Design, install, and maintain multiple, continuously operating sensor platforms capable of monitoring and recording surface motions of the Highway 70 roadway and bridges made vulnerable by the sinkhole.

b) Provide real-time access to sensor telemetry for response personnel and decision makers tasked with ensuring the safe use of the roadway.

c) Provide regularly updated reports detailing surface motions recorded at each sensor platform.

d) Provide notification services to alert key personnel should movement exceed a pre-defined threshold.

e) Provide instructional and operational support for designated clients accessing these services.

f) Perform geodetic analysis of the telemetry for long-term subsidence analysis and decision-making.

The project received funding and was initiated in April 2013. The program was extended additional years, to ensure continued safety to Highway 70, with an end date of September 2018.

SCOPE

The portion of Highway 70 vulnerable to the sinkhole hazards is located in Assumption Parish, Louisiana, District 61, Control Section 232-01 (see Figure 1 & Figure 2). The corridor stretches nearly 10,000 ft. (1.9 miles, or 3.05 kilometers) and includes three bridges that cross relatively narrow bayous. The highway serves as an emergency evacuation route for the surrounding rural communities and businesses and, if closed, would result in an hour-and-a-half-long detour around the site.

Situational awareness of the highway stability is an essential component for mitigating potential hazards and minimizing losses associated with the sinkhole. Developing a highway monitoring solution capable of detecting motions in real-time included several functional, operational, and technical requirements. In this context, functional requirements represent what the monitoring solution will do. Operational requirements identify how the solution will work. Technical requirements define the criteria for successful operation. These requirements are presented relative to the defined project objectives outlined in the previous section.

Design, Install, and Maintain Multiple Continuously Operating Sensor Platforms

Various functional and technical design characteristics are required for this monitoring system. The sensor platform chosen for this project relied on global navigation satellite systems (GNSS) technologies, which includes global positioning systems (GPS). This technology was selected for its ability to detect and record high and low-frequency movement (i.e., rapid and slow displacements) along the affected corridor. To ensure continuous operation under any condition, each CORS911 Sentinel, had to be autonomous and fault tolerant – capable of uninterrupted operation with or without electrical utility or telecommunication services. Sentinel electronics received electrical power from either a utility service or solar panels and batteries, which can meet the electrical needs in the event of power outages. Cellular modems can provide the communication network. In the event of communication outages, receivers had to have sufficient internal memory to store measurements. Upon restoration, the receivers had to have a mechanism to upload the data to a designated server. The required servers provided a centralized hub from which the CORS sentinels could be managed and the source for all real-time monitoring functionality.

Site selection and installation criteria included several operational requirements. Functionally, sites are identified according to their proximity to the vulnerable infrastructure (i.e., roads and bridges). Given the geographic extent, the solution required no fewer than four GNSS sentinels. Operationally, the arrangement of CORS was based on two factors: an ability to measure the

motion of the road surfaces, and the geometric arrangement of the sentinels (i.e., topology). Furthermore, site selection favored but was not limited to, installations within highway right-of-way, which established the necessary coupling of the sensors to vulnerable road surfaces. DOTD assumed responsibility for arranging servitude and access rights to any non-public lands selected for installation. Technical requirements of GNSS antennas necessitated clear views of the sky with minimal physical obstructions or electromagnetic interference. When necessary, District 61 personnel agreed to clear foliage and overhanging vegetation. Regarding installation, District personnel also agreed to support miscellaneous construction tasks, as needed. Finally, site security requirements were identified for both personnel and sensor assets.

Maintenance of the CORS required both remote and physical access to each station. Remote access was facilitated by the telecommunications requirements mentioned earlier. Remote access criteria are presented in the next section. Physical maintenance and repairs included regularly scheduled, on-site visits by C4G personnel.

Real-Time Access to Sensor Telemetry

Effective situational awareness of the highway surface necessitated real-time access to the monitoring solutions. In addition to the functional and technical specifications outlined above, each sensor platform had to support network communications and protocols for remotely accessing a Sentinel's telemetry. Cellular communication was identified as the best networking infrastructure for the region. Each Sentinel required a cellular modem with the capacity to operate with both utility and solar electrical service. Site selection process also includes assessments of cellular signal strength to configure each Sentinel with appropriate electronics (e.g., modem, antenna, booster, etc.). Remote access services necessitated a network management software capable of monitoring and administering recorded measurements.

Regular Reporting

In addition to network management software, recording the measurements from each CORS required a data storage repository. The system required a data management solution and a configurable reporting tool to provide customizable summaries for any one or all sites. Criteria for the tool included automatic and manual report generation, customizable report criteria (e.g., time, scale, labeling, format, etc.), and the ability to distribute and administer access to the report documents (e.g., both secure and open access).

LSU C4G made available daily reports to LTRC and DOTD via a digital file server. The daily reports along with raw data are presented to LTRC and DOTD on self-contained electronic media.

Notification Services

Because of the unpredictable nature of the sinkhole and related hazards, the proposed solution necessitated a configurable notification service capable of alerting DOTD designated contacts. Accordingly, the notification services were configured such that it would only notify contacts when sudden position changes exceeded a pre-determined threshold.

Instructional Training and Operational Support

The utility of this system is predicated on its ability to deliver meaningful information. The operational personnel designated by DOTD developed a working understanding of the system tools. Accordingly, instructions and support must be made available for clients accessing the administrative console and services.

Geodetic Analysis

Since the CORS sentinels were coupled to the highway, the system provided a unique opportunity to assess the geodetic characteristics of the Highway 70 corridor. Synoptic understanding of surface motions within the affected area can support decision-making. For example, long-term positional trends relative to one or many constrained reference points outside of the study areas may reveal information that may otherwise be hidden from short-term monitoring.

Horizontal and vertical velocities measured at each CORS Sentinel can be acquired using precise point positioning techniques capable of producing daily solutions for each CORS Sentinel. The technique relies on several geophysical and technological parameters that must be uniquely calibrated for each CORS.

METHODOLOGY

Following consultation among DOTD and response stakeholders, the monitoring solution implemented for this project included five CORS sentinels comprised of GNSS receivers and antennas. The project identified locations along the portion of the Highway 70 corridor at risk of potentially hazardous consequences attributable to the Bayou Corne sinkhole. The LSU Center for GeoInformatics (C4G) executed this project following a work plan composed of seven tasks. These included (1) site assessments, (2) CORS fabrication, (3) deployment, (4) implementation, (5) utilization and client support, (6) administration and maintenance, and (7) reporting.

Tasks 1-4 were completed at the beginning of the project. Tasks 5-7 were ongoing until September 2018. Description of the tasks, including anticipated deliverables, reports, and data processing details are described in the following text.

Task 1: Site Assessment

As noted earlier, deployment of a GNSS Sentinel had to satisfy numerous environmental and technological criteria. Examples include, but are not limited to a clear line of sight to open sky with minimal electromagnetic interference, electrical power, continuous communications, and more. Following the functional and non-functional requirements noted in the previous section, site assessments were conducted at select locations within the corridor.

These assessments were coordinated with several DOTD sections, including, Location and Survey, Geotechnical Exploration and Engineering, Emergency Operations, and District 61 personnel. Initially, four locations along Highway 70 were identified and selected for monitoring. The locations include the three bridges crossing Bayou Corne, Grand Bayou, and Bayou Choupique. The fourth site was identified on Highway 70 at Texas Brine driveway. A fifth CORS was prepared and held in reserve should it be needed, i.e., in the event of damage to any of the original sentinels. By December 2014, the decision to deploy the fifth CORS was coordinated with DOTD. It was located on Gumbo Street near Sauce Piquante Lane, in the same neighborhood but offset northerly from the line of the first four receivers along Highway 70.

Task 2: CORS Fabrication

A CORS Sentinel incorporates GNSS hardware (antenna, antenna mast, and data collector); communications and networking (via cellular modem); and mounting hardware (e.g., antenna mast) and equipment enclosures affixed to a sturdy foundation. Accordingly, each station

required a concrete foundation; electrical power (via local utilities or via solar panel and battery pack); reliable access to a cellular network; and environmentally robust hardware (e.g., stainless steel, heat, and humidity tolerant). Accordingly, each CORS Sentinel was custom designed and fabricated in accordance with the site assessments.

The following steps were executed to accomplish this task.

- Assessment: Site assessment results were compiled and analyzed to support design processes.
- Design: CORS Sentinel design and installations were customized according to the specifications defined by the site assessments.
- Hardware Acquisition: Hardware needed to complete the design specifications was acquired. Due to the emergency nature of this event, the acquisitions were expedited. Acquisitions included, but were not limited to equipment enclosures and mounting hardware, wires, cables, and surge arresters, batteries and mounting hardware, solar panels and mounting hardware, communication receivers (modems), antennas, wires, routers, and mounting hardware.
- Assembly: CORS sentinels were fabricated and assembled prior to installation.
- Testing and Inspection: Prior to deployment, all equipment was configured, tested, and inspected to ensure nominal functionality.

Task 3: CORS911 Sentinel Deployment

The location of each CORS911 Sentinel was selected based on probable risk to the roadway. The vulnerable corridor of Highway 70 includes three bridges. The consequence of surface instability and differential motion between the road and bridge surfaces could inhibit the safe utilization of the Highway. DOTD requested a Sentinel at each bridge structure: Bayou Corne, Grand Bayou, and Bayou Choupique (see Figure 2). The sentinels were installed on concrete slabs located near each structure, to measure differential movement between the bridge foundation and the road surface, ensuring that the CORS Sentinel was mechanically coupled to the surface, not the bridge. The site selection criteria for the remaining two sentinels included choosing a location along the highway nearest the sinkhole, and locating a site that could optimize network geometry. Topologic distribution of the CORS was necessary for minimizing bias when determining differential motions between sentinels.

The following text outlines the various steps necessary to execute the task:

- Site Coordination: Staff from LSU C4G and DOTD coordinated site selection, acquisition, and preparation, for each installation.
- Site-Specific Configurations: Before becoming operational, each station demonstrated sufficient capabilities for:
    - *Site Resources, Access, and Security* – All sites had to be accessible during the installation. Traffic control measures were used whenever needed.
        - *Access Rights* – DOTD was responsible for reasonably ensuring security and obtaining permission/servitude to use and operate the sites.
        - *Mount Foundations* – DOTD District 61 personnel assumed responsibility for the construction of concrete foundations (pads) at each site. Size and dimension specifications were coordinated with C4G.
            - Utilities – Sites required electrical power. When necessary, the C4G and DOTD personnel coordinated the installation of utility service at the sites.
            - Solar Panels and battery storage at each site were provided by the C4G.
        - *Communications* – The CORS sentinels required Internet connectivity. The C4G provided and installed wireless communications services via cellular modem to meet the technical criteria at each site.
        - *Miscellaneous* – To ensure the continued operation of the CORS sentinels, DOTD agreed to provide the logistic support necessary for remediating any environmental issues encountered during deployment and installation. Issues include, but were not limited to:
            - Work Platforms – DOTD agreed to provide scaffolding, boom-lifts, crane, and other work platforms whenever necessary to complete the installation of a CORS Sentinel.
            - Tree/Vegetation Removal – DOTD agreed to prune or remove vegetation (e.g., trees, weeds, and brush) near a CORS installation.
            - Traffic Control – DOTD agreed to provide traffic control sufficient to ensure the safety of crews working at or near CORS stations.
            - Site Security – the DOTD and local law enforcement (e.g., sheriff) agreed to coordinate security of the staff and assets installed in the field. Such efforts could include regular patrols of sensor sites.
            - Other - Upon request, DOTD agreed to provide any reasonably requested logistical support for the successful deployment and installation of the CORS sentinels.

Task 4: Implementation

Real-time monitoring and instrument management was accomplished using the Trimble® Pivot infrastructure software operated by the C4G. For this project, the software provided a scalable operational platform to maintain the CORS Sentinel hardware and data.

Multiple steps were needed to operationalize and integrate the CORS911 sites within the Pivot management framework. The following activities were executed by C4G personnel:

- Software QA/QC: Quality control and assurance checks were performed to ensure nominal functionality and performance of the CORS within the C4Gnet management system.
- Network Integration and Assessment: Integration with the Pivot management software was configured by staff from the C4G.
- Network and Storage Reliability: Staff from the C4G evaluated telemetry for nominal CORS network performance and operations. Hardware and software adjustments were performed as needed.
- Sensor Assessment: Nominal operation and functionality were assessed. Required hardware and software adjustments to communications feeds were performed as needed.
- Final Adjustments: Staff from the C4G and DOTD collaborated to ensure that all features and functionality were working, including, but not limited to, configuring and testing email notification services, user login to the Web interface, and report generation accessibility. Adjustments were made as needed.

Following the deployment of the CORS sentinels, each station was integrated within the management software to establish network coordinates. This process required a minimum of 72 hours (3 days), which allowed the CORS site to stabilize relative to the network coordinate monitoring routines. The rationale for this step was to ensure that the network could correctly solve for the position of the CORS locations, thus ensuring accurate and precise differential motions relative to other CORS on the network.

Task 5: Utilization and Client Support

Once the nominal operation of the CORS sentinels within the network framework was achieved, horizontal and vertical measurements at each station were recorded at 1 hertz (i.e., once per second). The measurements recorded by each CORS are managed by the Pivot platform. Data are copied from the receivers onto a central data repository maintained by the C4G.

Multiple processing engines were configured to provide real-time monitoring, report generation, and notification services. Because it is difficult to differentiate instability attributable to the sinkhole from natural movement inherent to the landscape (e.g., pre-existing subsidence and tectonic motions), the software was configured to measure differential movement between the CORS sentinels and one, or many, constrained reference CORS outside the affected region. Horizontal and vertical position data transmitted from the CORS sites are used to provide comprehensive monitoring and a decision support resource that incorporates the following services.

- Real-time Network Motion and Deformation Monitoring
- Notification Services
- Report Generation
- Geodetic Analysis of Positional Time-Series

Descriptions of the services are provided here.

Real-time Network Motion and Deformation Monitoring
Each CORS Sentinel continuously monitored its horizontal and vertical positions. This data was recorded by the network management software to compute differential motions relative to each station. The measurements provide insight into surface stability and deformation of the station network.

Sentinels are referenced to one or many fixed reference locations outside the influence of the sinkhole, to ensure that any differential motions and deformations at a particular CORS are valid. The following are the monitoring solutions implemented for the CORS911 system:

- Coordinate Monitoring: Tool used to continuously monitor and record the coordinates of the CORS with a precision of 2 to 4 mm (Trimble PIVOT).
- Rapid Motion Detection: Tool used to measure high-frequency movement at a rate of 3 centimeters per second (Trimble PIVOT).
- Network Motion: Tool used to monitor changes to the position and geometry of the five CORS sites.

Notification Services
Continuously recorded telemetry monitored by the network software was configured to email alerts to designated DOTD personnel when positional displacements exceed pre-defined

threshold values selected by DOTD and C4G personnel. The system issued email notifications that (a) warned the recipient of sporadic position changes that revert to a nominal position over time, and (b) alerted the recipient of persistent position changes that exceeds a temporal threshold for an extended time. Table 1 presents the motion thresholds applied to the notification services.

Table 1
Email alert configuration parameters

STATION NAME	WARNING	ALERT
CORS1	12 cm (4.7 inches)	20 cm (7.9 inches)
CORS2	12 cm (4.7 inches)	20 cm (7.9 inches)
CORS3	12 cm (4.7 inches)	20 cm (7.9 inches)
CORS4	12 cm (4.7 inches)	20 cm (7.9 inches)
CORS5	12 cm (4.7 inches)	20 cm (7.9 inches)

Report Generation

Position information recorded for each CORS was made available to decision-makers and stakeholders in accordance with the emergency response activities initiated by the DOTD. Positional reports were available as real-time or as static documents.

- Real-time Reports: Data collected by each CORS has made accessible via secure Web services hosted by the C4G. Authorized users could generate *ad hoc*, customizable reports for any one or all CORS sentinels and any period. Security protocols for the Web site were enabled on the portal to limit access only to designated response professionals because of the scientific complexity of the information posted there.

- Static Reports: Daily reports were automatically generated by the system. These reports summarized the previous 24-hour (one-day), 72-hour (three-day), and 168-hour (seven-day) position values. These reports were made publically accessible via Internet file transfer protocol (FTP).

Task 6: Administration and Maintenance

The C4G managed and maintained the CORS sites, and the networked infrastructure used to detect road surface motions. The C4G performed regular inspections of the hardware, software, network, communications, and power. Maintenance was performed as needed.

- Inspection: Field inspections and maintenance were coordinated by the C4G and the DOTD.

- Ad Hoc Support: Upon request, DOTD provided logistic support, as indicated above.

Task 7: Reporting

Intermediate reports regarding the tasks performed for this project were submitted for the duration of this program. The C4G staff was available for meetings coordinated by DOTD.

Work Schedule

Table 2 summarizes the work schedule defined by this project. It incorporates the one-year extensions approved by the Project Review Committee and DOTD. The approximate timeline for the proposed tasks and research, including the duration of each element, has been provided herein.

Table 2
Work schedule for project tasks

TASK		MONTHS (e.g., 4/1/2013 – 9/30/2018)																																			
		2013												2014												2015-2018											
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	Site Assessment	X									X																										
2	CORS Fabrication	X									X																										
3	CORS Deployment	X	X								X	X													X	X											
4	CORS Implementation	X	X								X	X													X	X											
5	Utilization	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
6	Administration	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	Reporting	X	X	X			X				X	X	X			X						X				X					X						X

DISCUSSION OF RESULTS

The CORS 911 system has been operational since April 2013. Five CORS 911 sentinels have been operating at select locations within the Highway 70 corridor. Email notification service and report generation was functional, and GNSS analysis was performed. To date, the CORS have not detected movement that can be directly attributed to sinkhole activity. The system is sensitive enough to see movement continuously, and seasonal or weather-related changes are observed but tend to be within a non-alarming range. No email notices indicating the threshold values (Table 1) were issued. Over 5,600 reports have been generated (to 9/30/2018) and are available online.[1] Remote access to real-time results is available for authorized users.[2] The results of the GNSS analysis are available throughout this report's text, tables, and figures. Specific details of these outcomes are presented in the following text.

Installation of the CORS was coordinated with the DOTD Emergency Operations Center and District 61 personnel. Sites were designated according to their ability to provide a useful indicator of surface motion for the road and bridges near the sinkhole.

On April 10, 2013, the C4G deployed CORS1 at Bayou Corne. CORS3 at Grand Bayou was installed on April 11, 2013, and CORS4 at Bayou Choupique was installed on April 13, 2013. CORS 2 was installed on July 16, 2013, along Highway 70 at Texas Brine property. Finally, CORS5 was installed on December 11, 2015, at the intersection of Gumbo Street and Sauce Piquante Lane. CORS 2 and CORS 5 required resolution of servitude to access the property. Photos of each CORS Sentinel are presented in Figure 4.

[1] Reports from the active CORS sites are published daily and provided online at the following virtual FTP site: ftp://mimir.lsu.edu|anonymous:user@mimir.lsu.edu:2123 (link is compatible with most modern Web browsers).

[2] Real-time access to the CORS 911 monitoring and reporting tool is available for authorized users at the following Web link: http://c4gnet2.lsu.edu/.

Figure 3
Location of CORS 911 Sentinel installations

Figure 4
CORS 1-5 installations, in order from top left to bottom right

Table 3

Annual vertical displacements in meters

SENTINEL	2013	2014	2015	2016	2017	2018
CORS1	-0.005	0.023	-0.034	0.034	0.003	0.002
CORS2	-0.015	0.008	-0.008	-0.028	0.030	0.017
CORS3	-0.012	0.024	-0.014	-0.014	-0.001	-0.004
CORS4	-0.002	0.016	-0.008	-0.025	-0.008	-0.007
CORS5			-0.005	-0.021	0.002	0.006

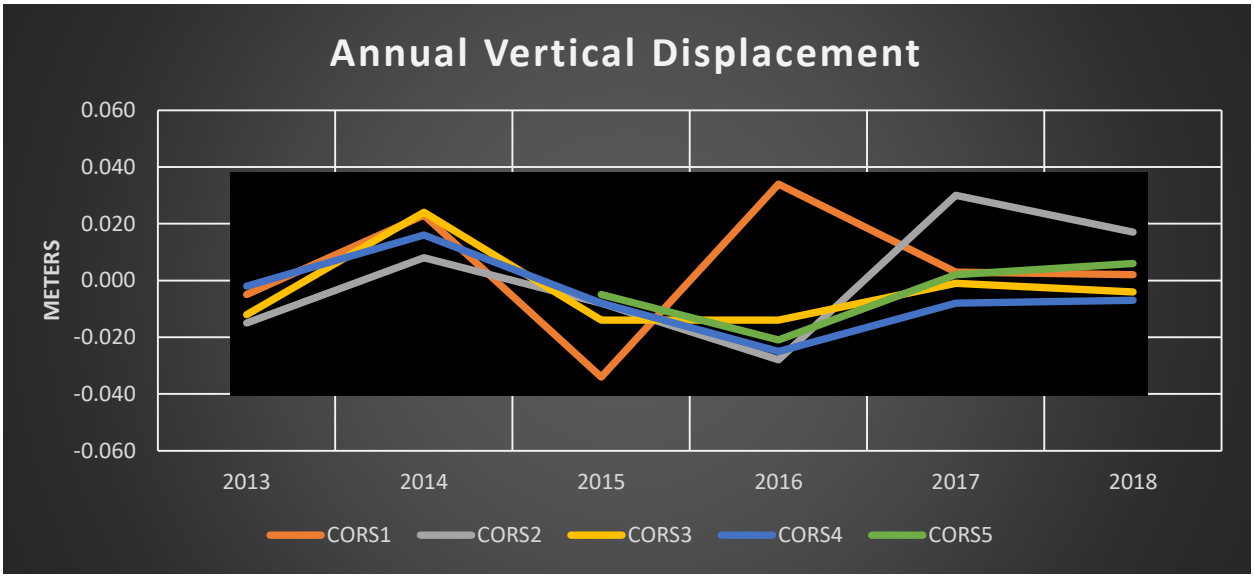

Figure 5

Annual vertical displacements

- All the CORS911 sentinels demonstrate sinusoidal patterns on the vertical axis (Figure 5), which is suggestive of hydrologic cycles observed in the region.
- The annual horizontal and vertical displacements of the stations are summarized in Table 4 through Table 8. Figure 6 through Figure 10 illustrate these horizontal and vertical displacements detected during each year of monitoring, individually. The measurements are in meters.
- Table 9 through Table 13 summarize the horizontal and vertical displacements for the final year of monitoring on a monthly basis for each CORS, individually. Figure 11 through Figure 15 illustrate these horizontal and vertical displacements for the final year of monitoring on a monthly basis for each CORS, individually. The measurements are in meters.
- Horizontal velocities calculated for CORS 1 through 5 are nominal and demonstrate a general westward or southwestward track.
    - Total movements shown in meters, though only a few millimeters, are shown in Table 14, and vectors are shown in Figure 16.

- Figure 17 shows a screenshot of the Secure Webpage utilized for real-time access to CORS 911 sentinels during operation.

Table 4

CORS 911 positional displacements for 2013 in meters

SENTINEL	EAST	NORTH	VERTICAL
CORS1	-0.007	0.006	-0.005
CORS2	-0.004	-0.004	-0.015
CORS3	-0.004	0.003	-0.012
CORS4	0.009	-0.001	-0.002

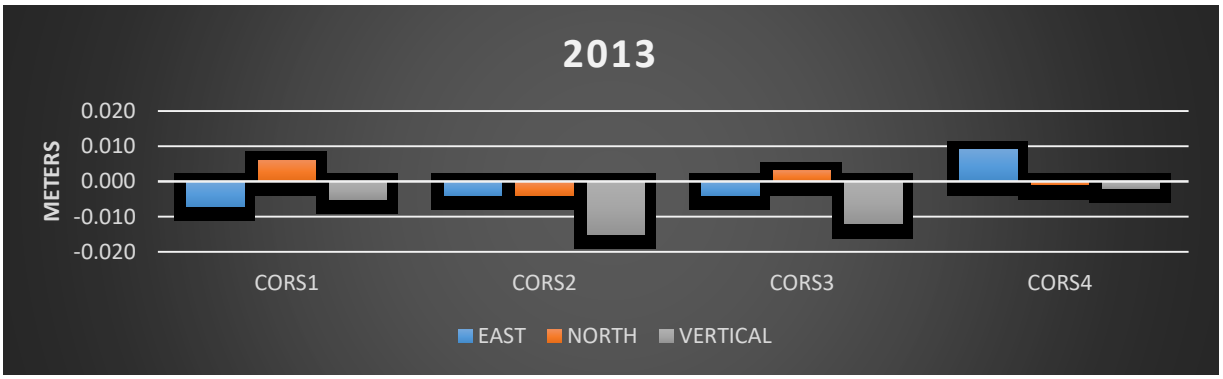

Figure 6

CORS 911 positional displacements for 2013

Table 5

CORS 911 positional displacements for 2014 in meters

SENTINEL	EAST	NORTH	VERTICAL
CORS1	-0.008	0.005	0.023
CORS2	-0.002	-0.004	0.008
CORS3	0.001	-0.004	0.024
CORS4	0.003	-0.005	0.016

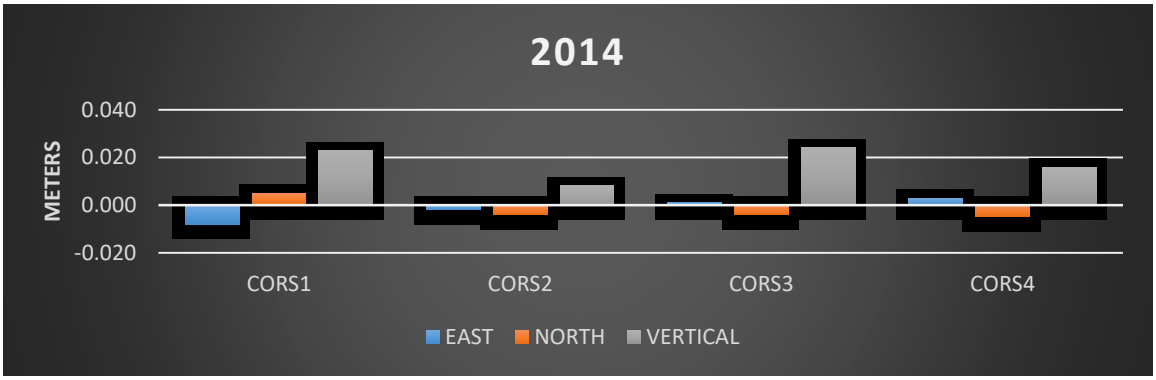

Figure 7

CORS 911 Positional Displacements for 2014

Table 6

CORS 911 positional displacements for 2015 in meters

SENTINEL	EAST	NORTH	VERTICAL
CORS1	-0.011	0.011	-0.034
CORS2	-0.010	-0.002	-0.008
CORS3	-0.007	-0.004	-0.014
CORS4	-0.002	-0.004	-0.008
CORS5	-0.020	0.022	-0.005

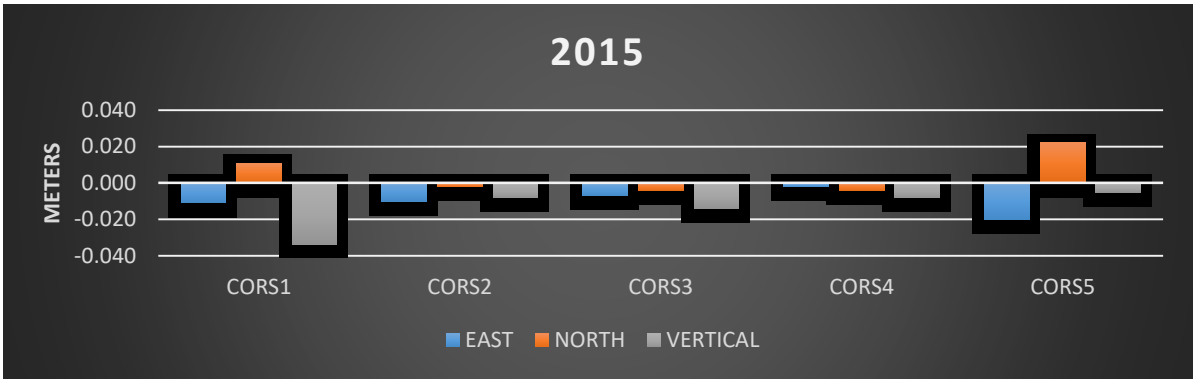

Figure 8

CORS 911 positional displacements for 2015

Table 7

CORS 911 positional displacements for 2016 in meters

SENTINEL	EAST	NORTH	VERTICAL
CORS1	0.000	0.005	0.034
CORS2	-0.010	0.003	-0.028
CORS3	-0.008	0.001	-0.014
CORS4	0.000	0.000	-0.025
CORS5	-0.008	0.014	-0.021

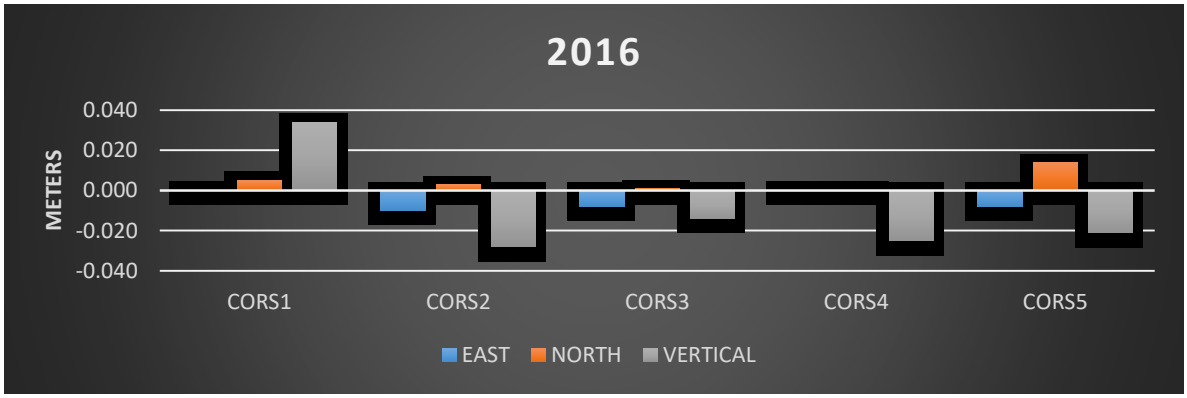

Figure 9

CORS 911 positional displacements for 2016

Table 8

CORS 911 positional displacements for 2017 in meters

SENTINEL	EAST	NORTH	VERTICAL
CORS1	0.005	0.000	0.003
CORS2	-0.002	-0.004	0.030
CORS3	-0.005	0.025	-0.001
CORS4	-0.001	0.001	-0.008
CORS5	0.004	-0.006	0.002

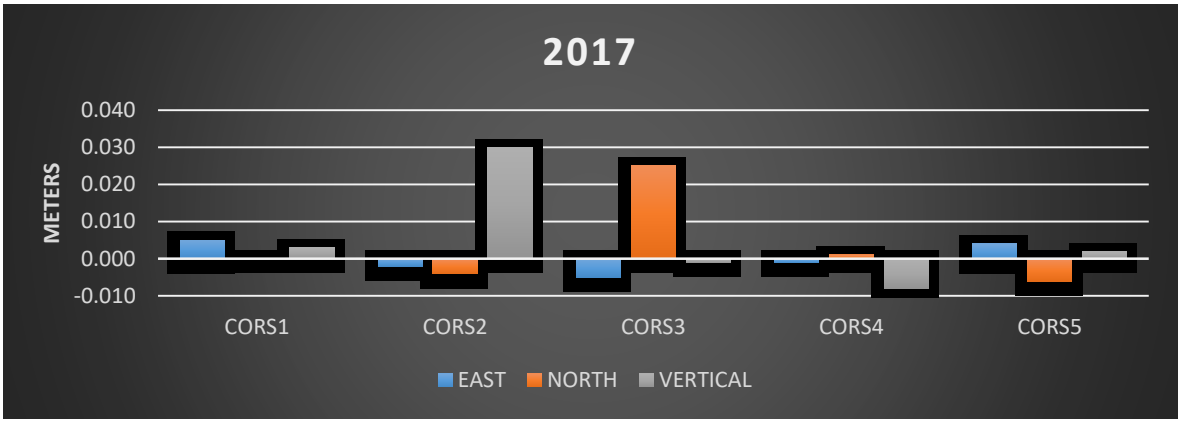

Figure 10

CORS 911 positional displacements for 2017

Table 9

C4G1 2017-2018 displacements in meters

DATE	EAST	NORTH	ELEV.
AUG-2017	0.000	0.000	0.000
SEP-2017	-0.002	0.001	-0.010
OCT-2017	0.001	0.001	-0.013
NOV-2017	0.000	0.000	0.001
DEC-2017	0.002	0.001	-0.001
JAN-2018	0.002	0.003	0.001
FEB-2018	0.003	0.006	-0.001
MAR-2018	0.004	0.008	-0.001
APR-2018	0.008	0.003	0.001
MAY-2018	0.004	0.003	0.004
JUN-2018	0.003	0.004	0.008
JUL-2018	0.005	0.000	0.003

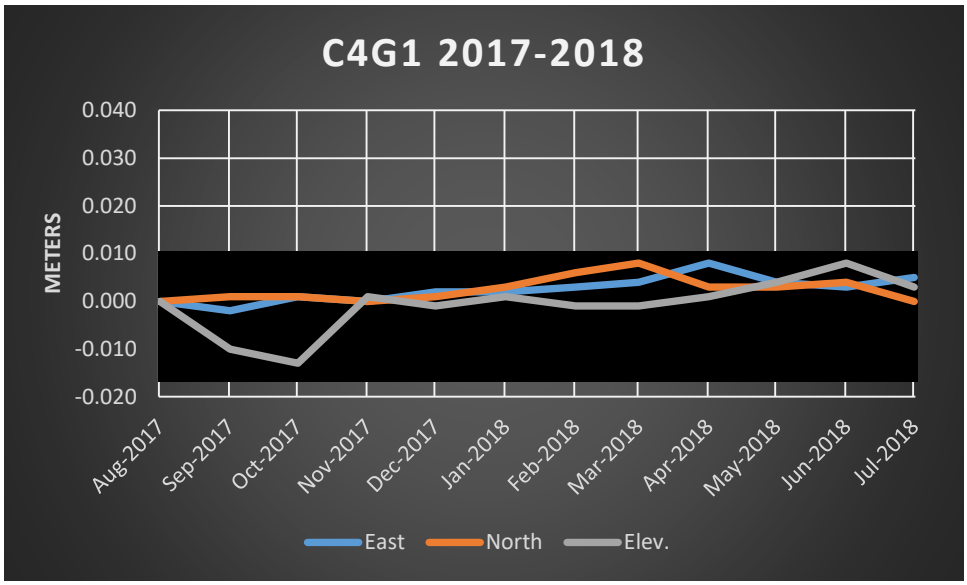

Figure 11
C4G1 2017-2018 displacements

Table 10

C4G2 2017-2018 displacements in meters

DATE	EAST	NORTH	ELEV.
AUG-2017	0.000	0.000	0.000
SEP-2017	-0.001	0.001	0.001
OCT-2017	-0.001	0.002	0.003
NOV-2017	-0.005	0.000	0.015
DEC-2017	-0.003	0.001	0.017
JAN-2018	-0.003	0.004	0.013
FEB-2018	-0.002	0.006	0.008
MAR-2018	-0.001	0.008	0.008
APR-2018	0.003	0.002	0.007
MAY-2018	-0.002	0.002	0.011
JUN-2018	-0.003	0.002	0.038
JUL-2018	-0.002	-0.004	0.030

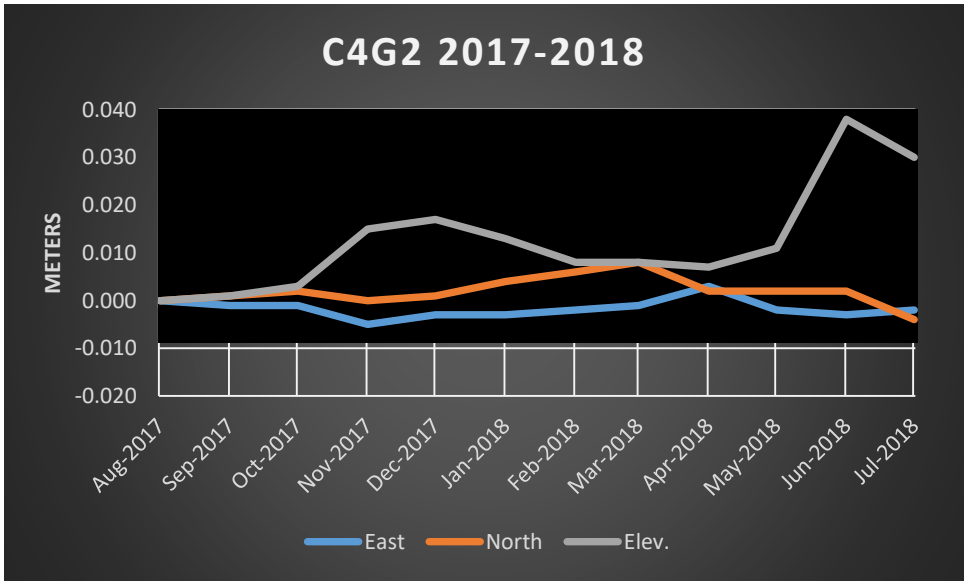

Figure 12

C4G2 2017-2018 displacements

Table 11

C4G3 2017-2018 displacements in meters

DATE	EAST	NORTH	ELEV.
AUG-2017	0.000	0.000	0.000
SEP-2017	-0.005	0.001	0.001
OCT-2017	-0.003	0.001	0.000
NOV-2017	-0.006	-0.001	0.008
DEC-2017	-0.004	0.000	0.006
JAN-2018	-0.004	0.002	0.003
FEB-2018	-0.006	0.033	-0.003
MAR-2018	-0.006	0.035	-0.002
APR-2018	-0.003	0.030	-0.006
MAY-2018	-0.008	0.030	0.003
JUN-2018	-0.008	0.030	0.011
JUL-2018	-0.005	0.025	-0.001

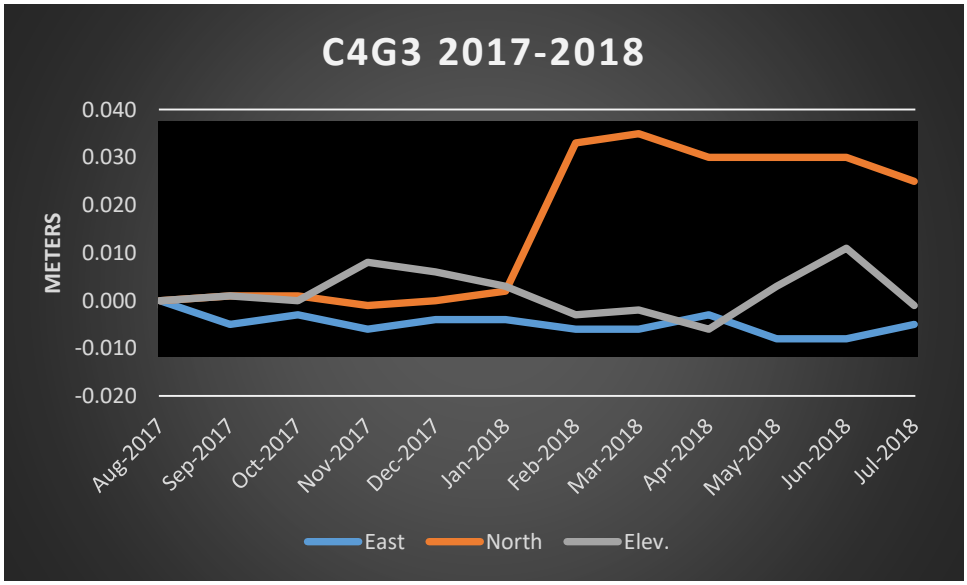

Figure 13

C4G3 2017-2018 displacements

Table 12

C4G4 2017-2018 displacements in meters

Date	East	North	Elev.
AUG-2017	0.000	0.000	0.000
SEP-2017	-0.003	0.001	-0.002
OCT-2017	-0.002	0.003	-0.006
NOV-2017	-0.006	0.000	0.006
DEC-2017	-0.005	0.002	0.001
JAN-2018	-0.004	0.006	-0.001
FEB-2018	-0.004	0.007	-0.003
MAR-2018	-0.004	0.010	-0.006
APR-2018	0.000	0.005	-0.010
MAY-2018	-0.005	0.005	0.000
JUN-2018	-0.005	0.006	0.004
JUL-2018	-0.001	0.001	-0.008

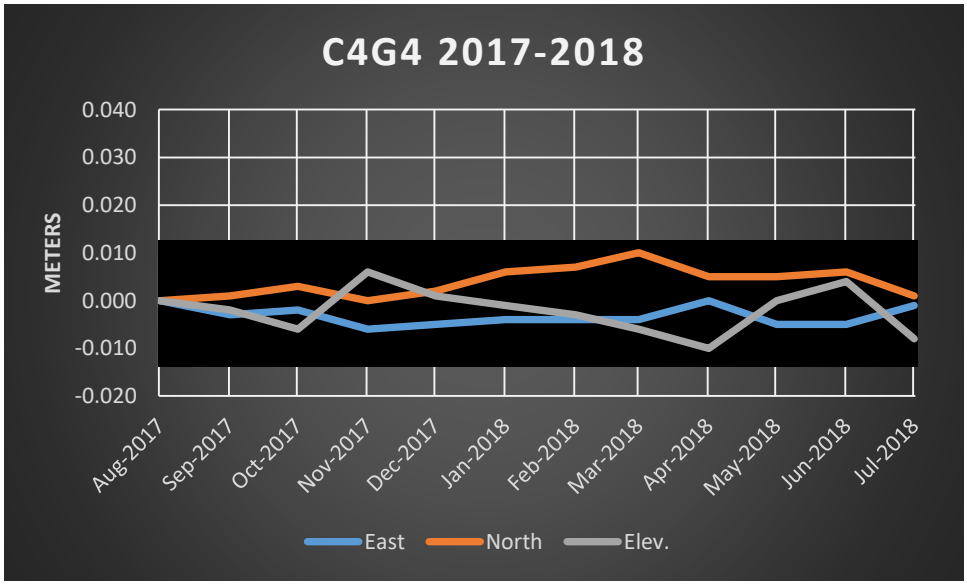

Figure 14

C4G4 2017-2018 displacements

Table 13

C4G5 2017-2018 displacements in meters

Date	East	North	Elev.
AUG-2017	0.000	0.000	0.000
SEP-2017	-0.002	0.001	-0.002
OCT-2017	-0.001	-0.004	-0.008
NOV-2017	-0.003	-0.006	-0.001
DEC-2017	-0.002	-0.003	0.002
JAN-2018	-0.003	-0.001	-0.004
FEB-2018	-0.002	0.001	-0.004
MAR-2018	0.000	0.004	-0.008
APR-2018	0.004	-0.001	-0.006
MAY-2018	0.001	-0.002	0.001
JUN-2018	0.000	-0.001	0.009
JUL-2018	0.004	-0.006	0.002

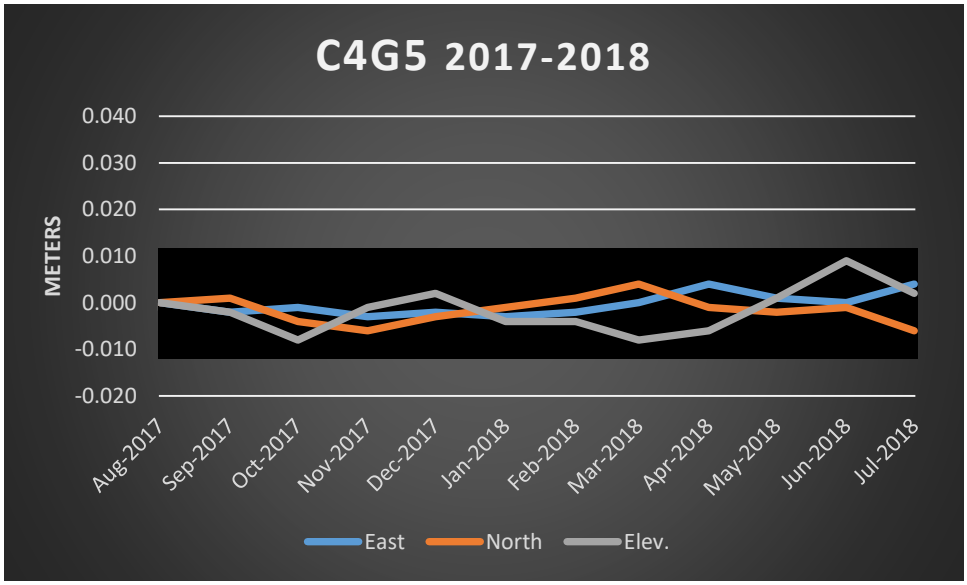

Figure 15

C4G5 2017-2018 displacements

Table 14

CORS 911 total displacements in meters

			HORIZONTAL			VERTICAL
SENTINEL	**EAST**	**NORTH**	**DISTANCE**	**BEARING**		**DISTANCE**
CORS1	-0.018	0.024	0.030	N 36.87° W		0.023
CORS2	-0.027	-0.019	0.033	S 54.87° W		0.004
CORS3	-0.024	0.044	0.050	N 28.61° W		-0.021
CORS4	0.012	-0.014	0.018	S 40.60° E		-0.034
CORS5	-0.017	0.025	0.030	N 34.22° W		-0.018

Figure 16

CORS 911 displacements vectors illustration

(arrows represent 10,000 times exaggeration: See table above)

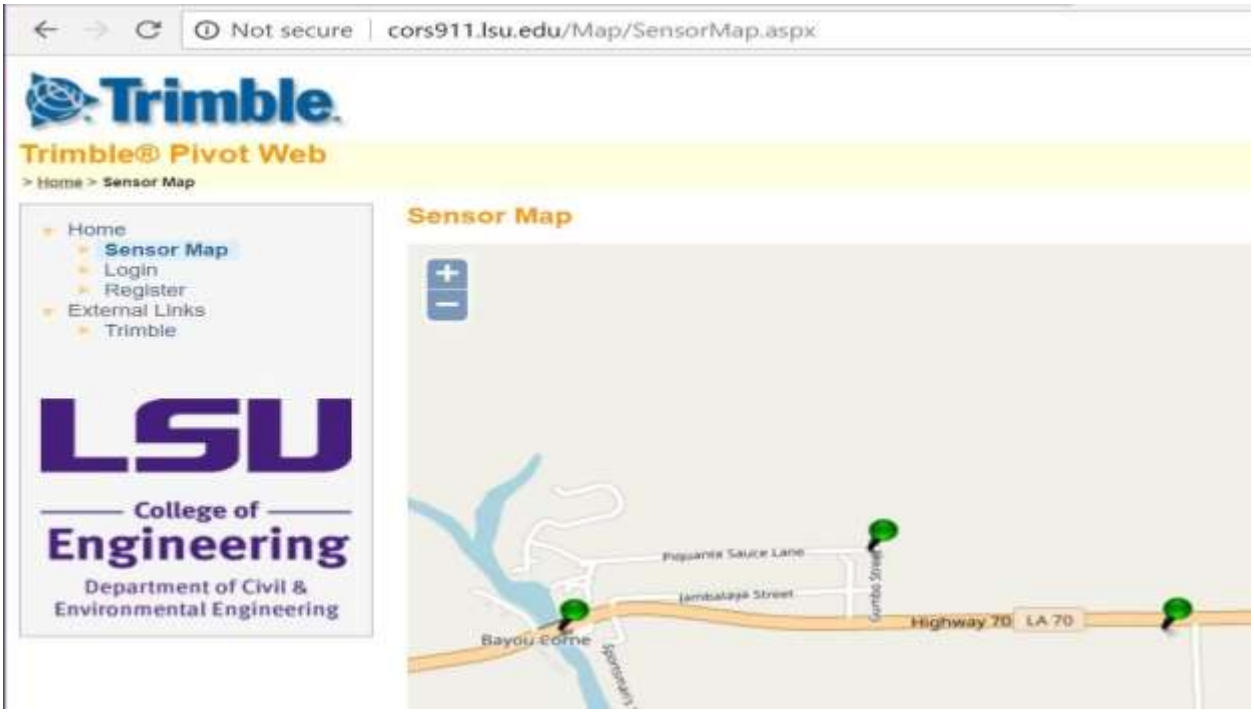

Figure 17

Secure webpage for real-time access to CORS 911 sentinels

CONCLUSIONS

The LSU Center for GeoInformatics (C4G) developed, deployed, operated, and maintained the CORS911 Sentinel system to provide continuous monitoring of the horizontal and vertical positions of the sentinels. This monitoring solution was used to establish situational awareness of surface stability, which was necessary for ensuring the safe and continued utilization of Highway 70.

RECOMMENDATIONS

The purpose of erecting and operating the CORS 911 sentinels was to observe and report to DOTD. It is our opinion that this operation worked as desired. Recommendations as to the viability of a roadway or under what conditions actions ought to occur regarding roadways is outside the scope of this project, and C4G does not presume to advise DOTD on such matters. The authors, therefore, make no roadway recommendations and because the monitoring systems operated successfully, no changes are recommended to it for similar projects in the future.

It was reasonable for DOTD to continue monitoring concerns about the proximity of the sinkholes in relationship to the roadway. With little movement experienced, that cause seems to have diminished, and so the project is concluded successfully.

No significant movement has occurred to date. DOTD reduced the threat level from Emergency to monitoring, and then to closed this project at the end of September 2018. The CORS stations employed should be recommissioned to other areas of the state by DOTD.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

C4G	Center for GeoInformatics
cm	centimeter
CORS	continuously operating reference station
EOC	emergency operations center
DOTD	Louisiana Department of Transportation and Development
ft.	feet
GNSS	global navigation satellite system
GPS	global positioning system
in.	inches
km	kilometer
LSU	Louisiana State University
mi.	mile
m	meter
mm	millimeterd
PRC	project review committee

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