Case Studies in Integrated Autonomous Remote Monitoring

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ABSTRACT: This paper will describe the technology that enables autonomous collection and Internet display of measurements from a wide variety of geotechnical sensors. In order for continuous monitoring to be economical, data must be collected without travel to the site, and ideally with no human intervention. Northwestern University's Infrastructure Technology Institute (ITI) has developed and deployed several techniques for the effective continuous remote monitoring of geotechnical facilities, all of which employ the same Internet display. These techniques include systems for control, data acquisition, and power management of instruments in the field as well as methods for data distribution and display. These technologies are readily adapted and scaled to sites ranging from a single-family home to projects covering entire city blocks. The case studies described herein include monitoring sinkhole-like subsidence on a Florida highway, monitoring soil movement adjacent to deep excavations in downtown areas of two major cities, and monitoring the effects of mine blasting vibration on a house in Kentucky.

INTRODUCTION

Monitoring and evaluation are parts of all engineering projects. Traditionally, monitoring has entailed periodic visits to the facility in question to take measurements. With the advent of rugged computerized dataloggers, it has become practical to make engineering measurements continuously without human intervention. This paper will describe the procedures employed in the continuous remote monitoring of several distinct types of facilities. These include a state highway disrupted by sinkhole-like subsidence, an excavation in an urban center where the effects of soil movement on nearby buildings were of concern, another excavation in an urban center where the effects of soil movement on adjacent utility tunnels were of concern, and finally the monitoring of the effects of mine blasting on a nearby residence. Each scenario presented different site geometry, communication link, and data display conditions.

Data Acquisition and Communication

The first step in establishing a remote monitoring installation is to identify the engineering quantities that can best provide insight into the aspect of facility performance to be measured. This is likely the most difficult step in establishing a remote monitoring installation and is beyond the scope of this paper. Once the quantities to be measured have been identified, a wide variety of sensors and data acquisition systems may be employed to take measurements. These data must then be communicated to the office or lab for analysis; telephone modems, high-speed Internet connections, and point-to-point radio links are some of the technologies that have been used for communication with remote sites.

The Common Web Interface

Field measurements are much less useful if not readily available for interpretation in near-real time. Each of the monitoring installations described in the following case studies uses an instance of the common Web interface for engineering data developed at ITI. This interface provides access to a relational database in which all the data are stored. Data are autonomously plotted and made available to stakeholders in near-real time. This autonomous operation frees users from the time-consuming tasks associated with manually collecting, downloading, parsing, and plotting new data from the field. The password-protected Web site allows users to view the latest data, search historical data for comparisons, and set alarm thresholds for e-mail alerts based on incoming data. (Kosnik, 2006). Figure 1 shows a typical page from a remote monitoring Web site.

CASE STUDY 1: SINKHOLE-LIKE ACTIVITY ON FLORIDA SR-66

In early 2001, subsidence similar to a sinkhole formed directly under State Route 66 near the city of Sebring in Highlands County, Florida. A land bridge was built over the subsided area and the road was reopened to traffic. A monitoring system was installed because of the unusual nature of the subsidence (O'Connor, 2001). The layout of the site is shown in Figure 2.

Instrumentation

Time-domain reflectometry (TDR) instruments and tiltmeters were installed to measure possible future subsidence. A commercial Campbell Scientific CR-10X datalogger powered by a solar panel and battery was used to read the instruments (Dussud, 2002). For the first eighteen months of monitoring, an operator visited the site periodically to download data from the datalogger directly to a laptop computer. By October 2002, a remote communication system was added to autonomously download data on a daily basis.

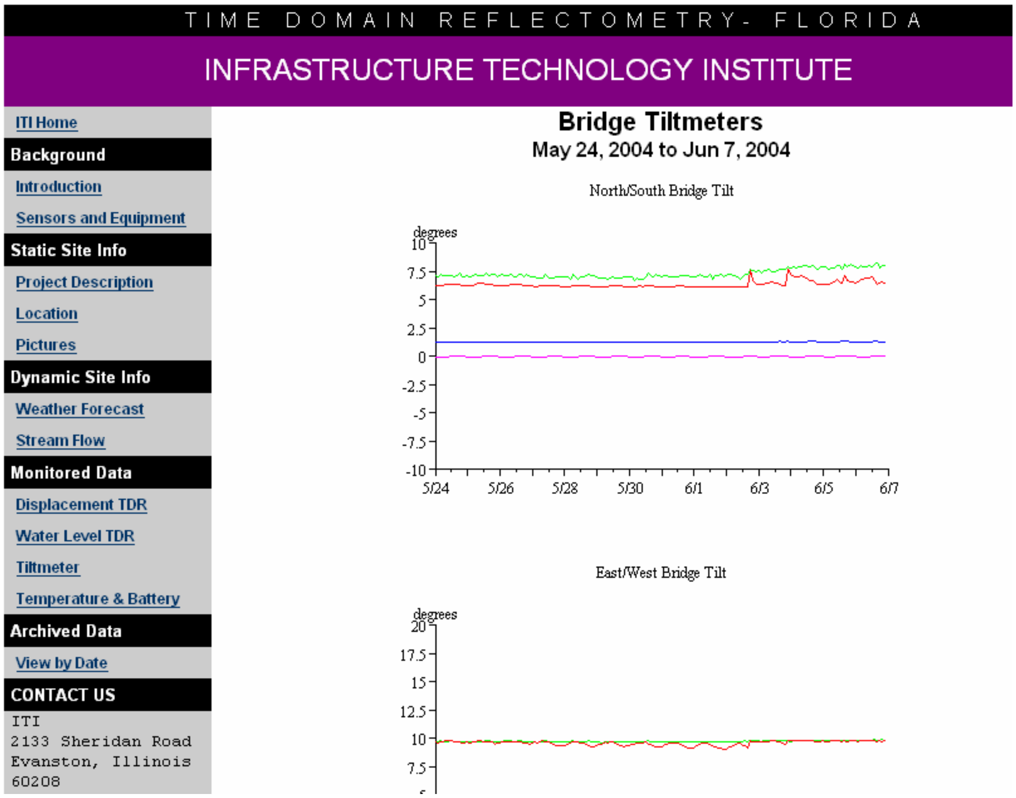

FIG. 1. Typical page from remote monitoring Web site.

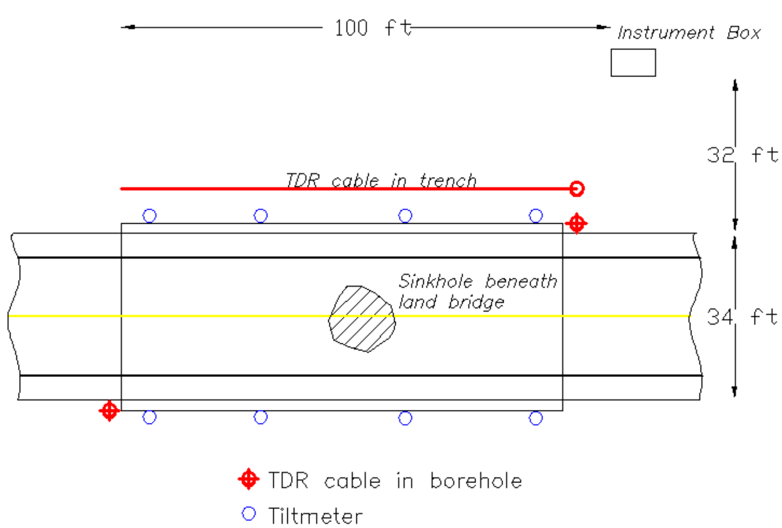

FIG. 2. FL-66 site (after O'Connor, 2001 and Dussud, 2002)

Communication Link

No telephone line was available at the site, and cellular coverage was found to be unreliable. A point-to-point radio link was established to connect the instruments to a modem mounted on the nearest telephone pole, slightly over half a mile away. Software and hardware were developed to power-on the communication link for only a brief window each day in order to save power (Kosnik, 2005).

Florida SR-66 Web Site

From October 2001 through April 2005, TDR and tiltmeter readings from the remote installation were automatically downloaded from the site every night. Custom software was then autonomously invoked to enter the data into a relational database for archiving and to produce plots for distribution via a password-protected Web site. The Web site provides access to both the manually- and autonomously-acquired data.

CASE STUDY 2: URBAN EXCAVATION MONITORING WITH AN AUTOMATED SURVEY STATION

During the summer and fall of 2006, ITI engineers installed an automated survey station and a remotely-controlled camera to monitor the effects of a deep excavation on surrounding structures, including a 50-story office building and a 15-story hotel. Figure 3 is a plan view of the excavation and surroundings.

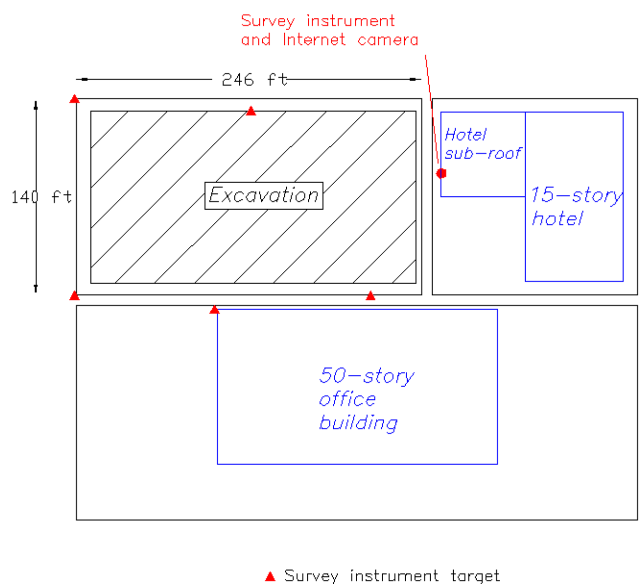

FIG. 3. Plan view of excavation monitored by automated survey station

Instrumentation

A Leica Total Station automated survey instrument was installed on the third-floor sub-roof of a 15-story hotel immediately adjacent to the excavation. A custom-built mount fastened the survey instrument to the hotel roof parapet. The survey instrument was programmed to automatically take measurements several times daily. An Internet-accessible pan-tilt-zoom camera was installed with the survey station. This camera allowed authorized parties to view the progress of the excavation and particularly to see where and when specific activities, such as installation of soil nails, were taking place. Two levels of authorization allowed some users to see the camera view and move the camera, while others were allowed only to see the camera view. The photographic record with timestamps allowed for the correlation of soil movements with construction activities, even when construction records were unavailable.

Internet Connection and Embedded Computer Control

The hotel on which the instruments were installed provided wireless Internet access for its guests through a commercial provider. An access contract was purchased to allow the instrument suite to be accessible via the Internet. A commercial 802.11 wireless-to-Ethernet network bridge and VPN router inside the instrument enclosure provided a stable, secure connection. A point-to-point radio link was established between the enclosure and a telephone modem in contractor's field office approximately one-half mile away. This data link provided a backup communication method in the event of a disruption of the wireless Internet service.

Custom software on an off-the-shelf embedded GNU/Linux computer inside the enclosure recorded data from the survey instrument several times daily. It also recorded photos from four different camera angles hourly to provide a continuous visual record of the excavation. While it would have been possible to poll the survey station and camera directly from the lab via the Internet connection, the embedded computer provided on-site data recording capability in the event of a communication disruption. Finally, a custom-built digitally-controlled power switch enabled the embedded computer to reset itself as well as the communication equipment in the event of a malfunction.

Automated Survey Station Web Site

New data from the automated survey station were posted to the project Web site nightly. Custom software converted the raw survey data into displacement from initial readings for each survey point. Manually collected data from slope inclinometers around the excavation were also posted as they became available. Data from May through August 2006 are available on the site.

CASE STUDY 3: URBAN EXCAVATION NEAR UTILITY TUNNELS

In the fall of 2006, a multi-faceted monitoring system was installed in a major city center where a skyscraper was being constructed. The building site is bounded by active subway tubes and century-old utility tunnels now used to carry fiber optic lines. A variety of instruments are employed to measure soil movement on the site, including traditional inclinometers, an experimental electronic in-place inclinometer, piezometers, and surveying instruments. A schematic instrumentation plan is shown in Figure 4.

Measurements from the piezometers and traditional inclinometers are taken manually on a weekly basis. The data are sent to ITI for entry into the monitoring database and display on the project Web site.

Instrumentation and Communication: Electronic Inclinometer

An experimental electronic inclinometer was installed in a borehole and grouted in place. An off-the-shelf embedded GNU/Linux field computer using custom software collects data from the inclinometer and uploads data to ITI three times daily. Since the instrument is located on an active construction site, it was impractical to connect it to power or communication cables. A system was developed to communicate wirelessly and run for months at a time on battery power. A commercial cellular-to-Ethernet router was employed to provide a reliable cellular data connection to the instruments. The entire system is powered by a deep-cycle marine battery. A control device was developed to power-on the inclinometer reader, field computer, and cellular connection only when measurements are to be made and reported. The inclinometer controller, cellular-to-Ethernet router, and embedded computer were placed in a watertight suitcase enclosure with appropriate bulkhead connectors for power and communication. The complete system was placed in an electrical vault at the head of the inclinometer.

Instrumentation and Communication: Utility Tunnels

An experimental system of displacement sensors was installed along construction joints in the utility tunnel itself. LVDT-type displacement transducers were affixed to the tunnel wall one month before excavation began. The instruments are distributed along a section of tunnel approximately 350 feet long. Communication is established by a land-line telephone in the basement of a building one-eighth of a mile down the tunnel from the instrumented section.

The analog-to-digital conversion of displacement data is done inside the tunnel to reduce vulnerability to electrical noise over the long cable run. Power was tapped from service to a dewatering pump at the west end of the instrumented section of tunnel. An embedded GNU/Linux field computer with custom software at the tunnel portal in the basement continuously queries the displacement sensors via the digital bus, stores data, and uploads the latest data to ITI nightly.

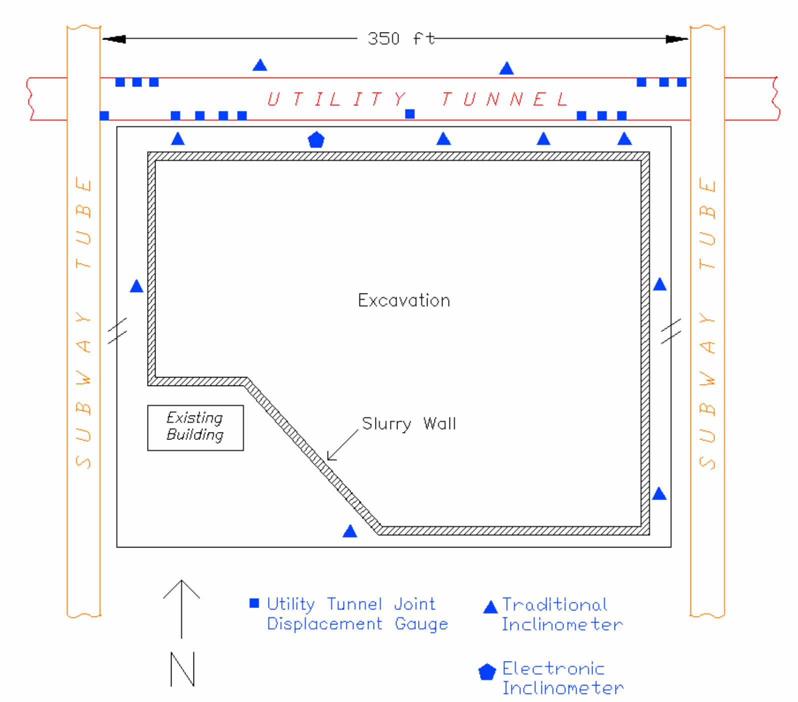

FIG. 4. Instrumentation plan for excavation near utility tunnel

Project Web Site

The Web site provides a clearinghouse for all deformation and piezometer data for the project. New data from the electronic inclinometer and tunnel displacement sensors are automatically posted on the project Web site nightly. Manually collected data from traditional inclinometers and other instruments are also posted on the site as they become available. In addition to display of new data, the site allows for the search of and comparison to historical data.

CASE STUDY 4: VIBRATION MONITORING AT A RESIDENCE NEAR AN UNDERGROUND AGGREGATE MINE

In January 2005, instrumentation was installed in a house in Frankfort, Kentucky, located near an underground aggregate mine in order to measure the effects of ground motion from mine blasting on several existing cracks in the walls of the house.

Instrumentation

The sensor suite included a buried triaxial geophone, several sets of crack displacement transducers, and indoor and outdoor temperature and humidity sensors (Waldron, 2006), as shown in Figure 5. A Somat eDaq data acquisition system was employed to record both long-term and dynamic time histories. The crack displacement, temperature, and humidity sensors were sampled hourly. When the ground motion trigger threshold was exceeded, the crack displacement sensors and geophone were sampled at 1000 Hz for three seconds, including a 500 ms pre-trigger buffer.

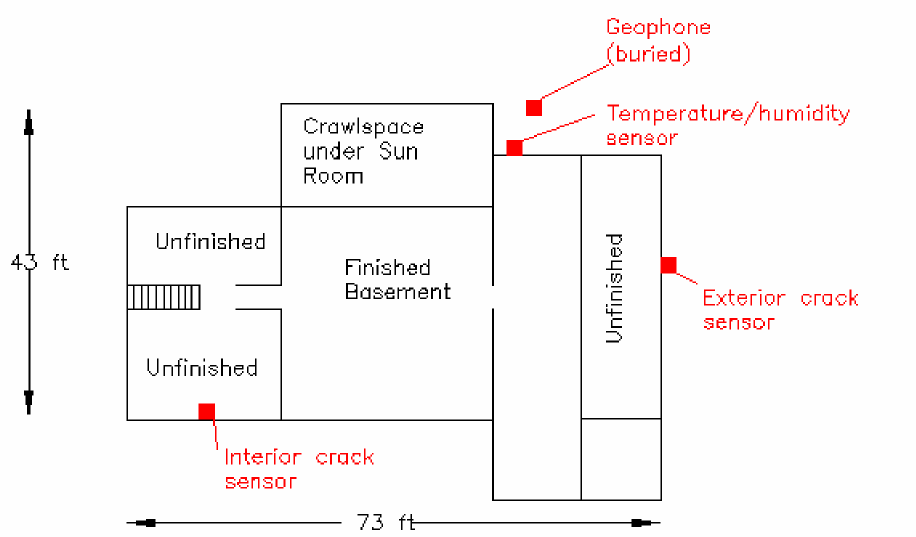

FIG. 5. Frankfort, Kentucky house (after Waldron, 2006)

Internet Connection

Data were downloaded from the data acquisition system via the house resident's cable modem. A VPN router was installed to prevent unauthorized Internet access to the data acquisition system while keeping general Internet access open and transparent to the resident.

Frankfort Web Site

Long-term crack displacement and weather data as well as dynamic crack displacement and ground motion data were downloaded from the data acquisition system and posted to the project Web site nightly. The Web interface allows for searching and display of historical data. In addition, reports on the Web site allow for the comparison of the crack displacement associated with ground motion and the crack displacement associated with normal household activity, such as slamming a door.

SITE GEOMETRY AND SCALABILITY

The preceding remote monitoring installations vary widely in terms of geometry and site conditions. Figure 6 shows plan views of all four sites using the same scale for comparison. The preferred methods of data acquisition and communication depend on the geometry and condition of the site as well as the availability of utility service. Where long cable runs are necessary, such as in the utility tunnel in Case Study 3, it is recommended that analog-to-digital conversion take place as close to the transducer as possible and that all further communication be made along a digital bus. The reduced vulnerability to electrical noise allows monitoring systems to cover a large facility without the signal degradation associated with analog signals over long cable runs.

CONCLUSIONS

In order for remote monitoring of geotechnical facilities to be effective and economical, data must be acquired and communicated autonomously. The techniques described in this paper have been successfully deployed for projects ranging in duration from several months to years. Specific challenges in power, communication, control, and data acquisition must be met with appropriate strategies and technologies. The experiences of the preceding case studies suggest that employing on-site intelligence improves the robustness of a monitoring installation. For example, the on-site embedded computers used in Case Studies 2 and 3 ensure that data continue to be collected and power properly managed even when communication is disrupted.

A common Web-based interface provides access to data for interpretation in a readily useful manner by autonomously parsing, archiving, and displaying data as it becomes available. The Web site provides a universal mechanism for handling all data that are part of a monitoring installation, whether the measurements are taken manually or automatically. This clearinghouse for all relevant data helps maximize the usefulness of remote monitoring and should be considered in future installation projects where monitoring may be useful.

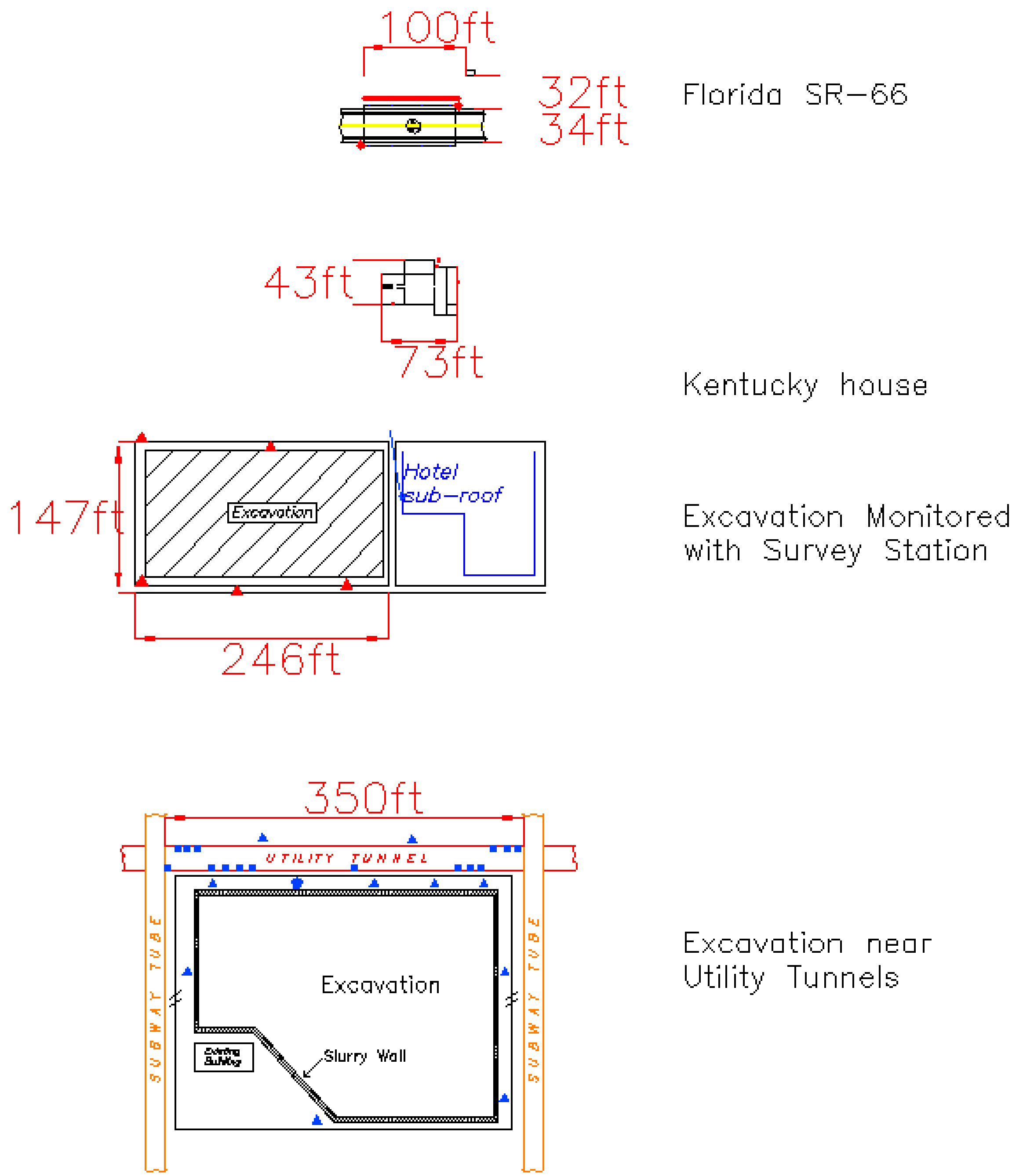

FIG. 6. Relative geometry of monitored facilities

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