Protecting Secure Facilities From Underground Intrusion Using Seismic/Acoustic Sensor Arrays

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The necessity to detect tunnels that penetrate secure facilities such as detention centers, government offices, borders, or forward operating bases (FOBs) has developed from the need to deter or counter underground exploitation along the southern United States border, Iraq, and other facilities. The United States Army has been in the tunnel detection business for many years, to include providing support to other government agencies in locating tunnels along our southwest border. Iraq became an issue with the nearly successful escape from a tunnel constructed over several months by detainees in an Iraqi center.[1] A team of researchers was sent to Iraq to investigate the utility of several technologies that perhaps could detect voids as small as 1 meter in diameter. A third technology investigated was a passive seismic/acoustic array. The team built a 7-meter-deep tunnel at the same depth as the escape tunnel.[2] The array was tested around the camp to garner the seismic and acoustic characteristics of the typical vehicles and machinery and their interactions with the soil and each other. The in-tunnel tests were conducted using typical digging tools available to the detainees. All of these signals were then used to "train" the computer algorithms. Plans were laid for a larger study and more detailed sediment and mineral studies. There is a definite requirement to thoroughly understand the interactions between sound propagation and the local geology and geochemistry of the sediments.

Site Geology

Distribution of mineral composition, grain size, and moisture content of soils are known to affect attenuation of electromagnetic and other geophysical sensor signals.[3, 4] The geologic setting of an area determines the suitability of a given technique for locating visually obscured features such as tunnels in the shallow subsurface.

In the area surrounding the test tunnel, the upper 6 meters of sediments were deposited as part of a delta during a time of higher sea level, when low-gradient rivers carried fine-grained sediments into a shallow sea. The resulting sediments vary in thickness, density, moisture content, and color—both horizontally and vertically. These sediments are now overlain by fine-grained, windblown material. Subsequent natural and man-caused processes have changed much of the original sedimentary layering.

The upper sediments can be cemented with either calcium carbonate (calcite) or calcium sulfate (gypsum) to a depth of about 30 centimeters and are difficult to dig through. In the upper layer, the gypsum forms veinlets some 5 millimeters in diameter and spaced quite closely throughout the layer. Crystals of gypsum up to 3 centimeters in length are present in the upper layers. The lower sediment layers are typically devoid of visible gypsum crystals. These veinlets are hard, making digging difficult and producing definite signatures that can be picked up with the sensors (see Figure 1).

Figure 1: Typical strata sequence in the study area. Subtle vertical color changes represent varying geochemical characteristics of the sedimentary environment.

At some locations in the study area near the surface, there are substantial areas of white cemented sand that is locally called "gatch" (see Figure 2, page 73). Gatch forms when carbonate or sulfate minerals (calcite, gypsum, or both) are deposited by movement and evaporation of water in the pore space of previously deposited sand.[5] When water is mixed with a 50-50 mixture of gatch and other surficial material, an extremely hard block is formed. This local geochemical phenomenon has significant impact on potential tunnel

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Figure 2. A layer of gatch about 20 centimeters below the surface. This layer was about 10 centimeters thick.

construction. The top some 20 centimeters of fine windblown sand is loose, but below that, the sand is cemented. This layer is strong enough to support pedestrian traffic and even heavy equipment. Thus, even in highly disturbed sediments and sands, stabilized shallow tunnels are possible after just a short time.

On the FOB, a thick sequence of unconsolidated sand occurs at about 7 meters. This coarse sand is composed of angular grains of quartz (particles 2 millimeters in diameter) and extends at least 1 meter below the tunnel floor. Digging in the sand layer is easy. This sand is distinctly different from the other sediments on the FOB and, if observed on the surface, is a telltale sign of digging. Understanding the geology of an area will provide good intelligence signs of digging in any location. Use of imaging technologies can be key to detecting digging in many locations.

Within the lower sand layer and the silt just above it, black concretions appear as very hard clusters of sand grains cemented in a star-burst pattern by a black mineral up to 3 centimeters in diameter (see Figure 3). Digging through these mineral clots makes a distinct high-pitched sound when they are struck with an entrenching tool or chisel.

Figure 3. Black mineral concretions at the tunnel face. Striking these minerals makes a distinctive noise.

The extraordinary lateral and vertical variability of the sediments in the upper several meters of soil at the site caused the failure of traditional geophysical techniques to locate tunnels or voids. The presence of fine-grained minerals and soluble salts increased the conductivity of the soil and precluded downward propagation of signals from methods such as ground-penetrating radar and electromagnetic surveys. These unfavorable geologic factors prompted the team to develop passive seismic-acoustic technologies to detect tunneling activity rather than the tunnels themselves.

Initial Experiments

The initial project centered on data collection from a tunnel the team dug at the interface of the compacted silt layers and the unconsolidated coarse sand layer. The sensor array was placed at right angles to the tunnel and data collected over several days.[6] This data was used to populate the computer algorithms and train the users. During data collection, the rainy season began. This 36-hour rain event provided an excellent opportunity to compare the effect of soil moisture on the propagation and receipt of signals by the array.[7] The rain event allowed the team to quantify the signal changes from the full range of mechanical and other sources on a secure facility. The most significant impact was the increase in amplitude; nearly all signals were detected from greater distances through moist soil than had been observed during the dry season (see Figure 4).

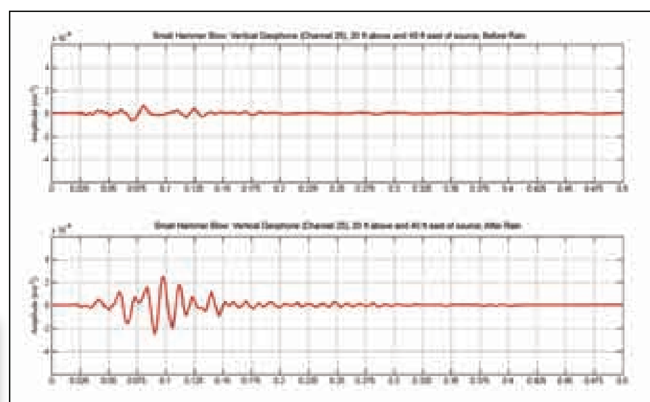

Figure 4. Ambient acoustic noise field before and after 36 hours of steady precipitation.

Beetles, insects, and rodents burrow within the sediments and can dig large galleries. With extended reach of the data collection array in a wet environment, some of these signals could be identified as human digging without proper analysis.

During the 2008 sampling season, detailed soil samples were collected. Long trenches were dug to a depth over 2 meters and a small block of one wall was selected for sampling. Ten centimeters deep, drive cylinders were used to collect *in situ* samples. The soil around the cylinders was carefully removed and saved for further analysis (see Figure 5). The collection process continued to a depth of about 2 meters.

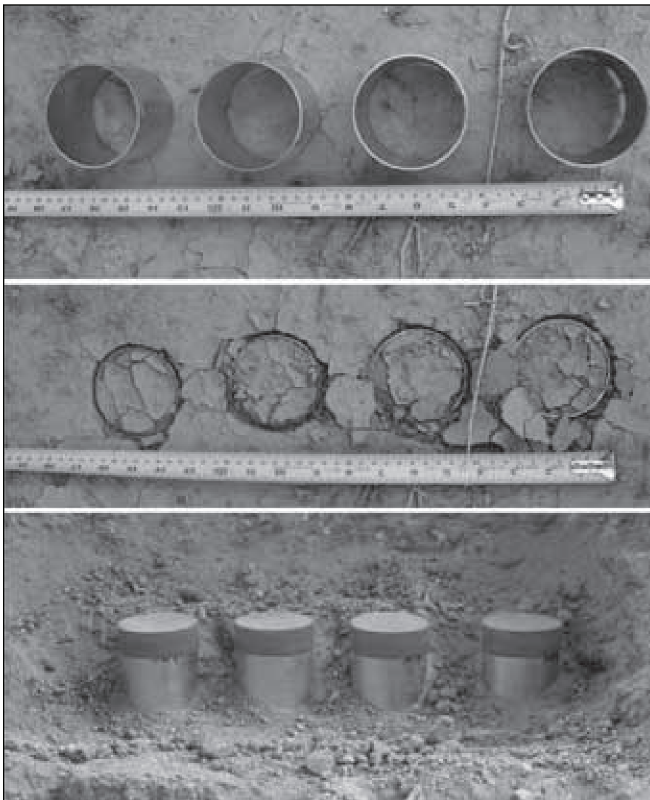

Figure 5. The top panel shows the drive cylinders before emplacement. The middle panel shows the emplaced cylinders. The bottom panel shows the cylinders just before being removed from the sample layer.

Array Around the Camp

The physical tests and the soil analysis indicated that a seismic and acoustic array could be installed around a facility. Automated processes could be used to filter out the vast majority of the energy sources while still differentiating the signals of interest that were likely tunnels being constructed or tunnels being used.

Commercial off-the-shelf geophones were emplaced around compounds where tunnels had been found. Sensors were placed in pairs (one deep and one shallow) at regular intervals covering the entire perimeter. The geophones were connected to a buried cable that circled the compound. Installation of the sensors and associated cabling required a significant effort because the compound infrastructure was already in place. Detection systems need to be integrated into the construction design and installed with initial construction when possible.

Placing the geophones in pairs was crucial to discriminating between deep and shallow energy sources. Acoustic sensors were placed at regular intervals to help filter out the huge amount of surface background noise from sources that included vehicles, generators, rotary wing aircraft, explosions, and conversations.

After the signal was digitized, it went through an outside the continental United States (OCONUS) filter to determine which signals have characteristics similar to the signals of interest. An initial statistical analysis of these signals was computed to reduce the amount of data sent to the Continental United States (CONUS) via a satellite uplink. The data CONUS received went through a set of sophisticated algorithms which again reduced the data the analyst needed to review. The signals that remained were generally of interest to the analyst. The filtering processes significantly reduced the amount of data that needed to be reviewed by a human, but still the most important part of the system was a human analyst. Each area of interest was reviewed by a trained analyst to determine what kind of energy source produced the signal, whether the signal was generated by threat activity (such as digging with a hand tool—scraping of tools against wall or floor) or clutter activity (such as construction, vehicle traffic, or generators). This was completed by looking and listening to sections of the digitized signal since the human eyes and ears comprise one of the best pattern-recognition systems. The analyst was able to identify these signals by comparing them to signals from the Tunnel Activity Detection System (TADS) signal library. This library included both types of signals—threat activity and clutter.

After an analyst identified an area with threat activity (see Figure 6), he sent a notification to the appropriate authority at the secure facility. These notifications were vetted to determine if they were actually threats. The results of this process produced great success and were added to the signal library to further expand our knowledge of the threat.

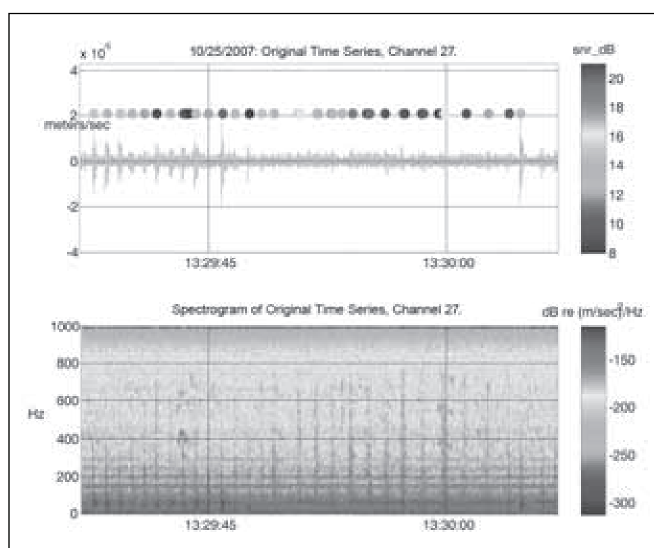

Figure 6. An example of threat activity. The lines in the lower graph (between 10 hertz and 400 hertz) are impacts with a hand tool. The dots above top graph indicate detections made by the TADS algorithm.

Recent Threats

After a unit received a tip that something strange was going on there, a young lieutenant led his patrol to a bakery where two men were sitting. The quiet street in Mosul quickly became a hub of activity. The patrol noted that there was no bread or even flour in the bakery, just shovels and piles of dirt. The patrol discovered the tunnel entrance, and a check of the database showed that the two men had been arrested earlier on suspicion of being al-Qaeda supporters. A tunnel went about 50 feet from the bakery toward a secure governmental facility. The plan seems to have been to set a large amount of explosives in a gallery under the facility to inflict as much damage as possible.[8] The tunnel appeared to be constructed in compacted sediments with only a few rocks. The sediment seemed relatively strong and did not appear to require a lot of shoring to provide short-term use of the structure.

On 2 September 2008, another tunnel was discovered on our southwest border, with its origins in a house in Mexicali, Mexico, heading toward Calexico in the United States (see Figure 7). The tunnel—about 1.5 meters wide by 2 meters high and about 5 to 6 meters below the surface, with lights, piped air, and rails—appeared to have been dug with hand tools through compacted sediments. The soil was competent enough to hold its shape, allowing the builders to use minimal supports.

Conclusions

Tunnels remain a persistent threat to U. S. security, both at home and abroad. Due to the highly local and variable nature of the near surface, imaging techniques to discover tunnels has met with many challenges. The most promising technology was passive seismic/acoustic arrays. Through the second deployment, the team constructed an array around a secure facility. The initial data were added to the more extensive subsequent data and used to "train" the algorithm.

The installation, validation, and transition of this system were an overwhelming success, advancing from a field test in 2005 to a fully operational system in a combat zone in one generation. Over the first three months of operation and experience, the analyst tasks were reduced by an order of magnitude and the signal-processing algorithms were continually improved.

A systematic geologic and geochemical investigation of the impacts of soil properties on seismic/acoustic wave propagation could benefit further refinement of the algorithm. The geologic and geochemical aspects of the physical environment will impact the ability to detect active tunneling or tunnel use, as well as the actual construction of a tunnel. Understanding this physical environment will have effects on the design and construction of secure facilities and the construction materials used. Knowledge of the subsurface soils will provide clues to tunneling activities by direct and indirect observation on and away from a secure facility. The use of tunnels to penetrate or breach secure facilities has been used for thousands of years (with sappers and mining engineers leading the way). The current struggles in Southwest Asia are no exception to the threat of subterranean intrusion (tunneling). Engineers with geology/geochemical/geophysics expertise could make technical assessments throughout the planning and execution phases of these projects. The engineers and military police must work together to mitigate this threat and continue to protect our secure facilities from subterranean intrusion.

Figure 7. Discovered tunnel leads from Mexicali toward the United States.

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Endnotes

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("Modularity," continued from page 71)

Sharing Lessons Learned

The Engineer Regiment's transition to a modular force is now more than 90 percent complete. That means that we are beginning to see adjustments that need to be made in our organizations, as well as changes that need to be made to the tactics, techniques, and procedures we use when employing these forces. It is essential that lessons learned from the employment of our engineer forces are captured and shared so that best practices can be incorporated into the way we train and fight.

Current doctrine is being revised to address the engineer force structure at all levels to ensure that emerging lessons learned from Iraq and Afghanistan are incorporated into our doctrine. The doctrine for employment at the BCT is published, and the doctrine for echelons above the BCT is close to being published. Engineer organizations will continue to incorporate these lessons learned while still addressing the full spectrum of engineer tasks and support to enduring operations.

There are still changes being worked for the Engineer Regiment. The prime power company and battalion have been restructured to better use prime power assets. The topographic company has been restructured to provide a required capability at all levels of the fight. There is an initiative to add a geospatial warrant officer to each of the BCTs as was done for the Stryker BCT. The MRBC is being considered for review to bring its organization in line with the other baseline company structures. The clearance company is now under consideration for a force design update incorporating lessons learned from Operations Iraqi Freedom and Enduring Freedom. There is also considerable effort at this point to restructure engineer forces within the BCTs to provide a wider range of engineer capability to BCT commanders.

There will continue to be force structure adjustments to the Engineer Regiment in the coming years. Each of these efforts will be attuned to keeping it relevant to the fight while providing the commander with the best-trained, best-organized, and best-equipped force feasible.

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