Coastal zones are among the most challenging locations to juggle the delicate balance of infrastructure development, consideration for the environment, and economic requirements related to the collection and analysis of data necessary for hazard assessments and mitigation during design. This consideration is not limited to sustainability of the environment (such as the local ecosystems) but also resiliency. Geological conditions are often a critical factor in resilient infrastructure development along the coast, yet they are frequently difficult to study. The geological conditions that present hazards to infrastructure are known as geohazards, which in the coastal zone may include examples such as nearshore earthquakes, unstable ground and inundation.

With the number of existing as well as new projects planned within coastal zones, the need for properly identifying geohazards associated with a given project site becomes critical for cost-effective construction and sustained operation throughout their designed life. The cohesive integration of these techniques—bathymetry, imagery, geophysics and geotechnics—play an integral role in the evaluation of marine geohazards affecting the design, construction and long-term reliability of coastal infrastructure.

Here, we describe a modern approach to geohazard investigations in the coastal environment that incorporates technology developed recently, which has revolutionized some aspects of data collection and provide solutions that are now within the economic reach of coastal infrastructure projects. We will focus on investigations that are below the water surface, including both the seafloor and seafloor sub-bottom, and briefly touching on mobile laser scanning.

**Seafloor Surface Investigation**

Many geohazards are visible on the seafloor surface due to their geomorphic expression. These surface expressions can be viewed using sonar imaging and/or multibeam
tions to increase the sounding data density. An increase in data density provides higher resolution of the seafloor, which helps identify features such as fault scarps, landslides, fluid expulsion features, sunken vessels, exposed utilities and obstructions.

**Mobile Laser Scanning.** Mobile laser scanning from a vessel uses rapidly fired laser pulses to map above the water surface, effectively extending the multibeam survey. Mobile laser scanning provides highly detailed and more accurate data than multibeam, principally due to reduced uncertainties related to the speed of the laser and the reduced uncertainty of the medium (air versus water).

When used in combination with multibeam, an integrated point cloud data set can be developed to create a comprehensive model of the Earth’s surface above and below the water line. This can extend the investigation of the site to include identification of coastal hazards, such as landslide and rock-fall prone areas along sea cliffs.

**Sonar Imaging.** Commonly referred to as side scan sonar (SSS) due to the conventional method of utilizing side-looking sonar transducers, this technique captures the backscatter (reflection) intensity of sonar pulses from the seafloor to create monochromatic imagery. The sensor can be a dedicated imaging device or can be a captured attribute (backscatter) of an MBES sensor.

Sonar imagery can play an important role in providing visual and contextual information of the seafloor, particularly in identifying objects, changes in seafloor surface material types and/or ecology. The level of detail (resolution) required dictates the appropriate sensor: higher frequencies have shorter range limitations and dedicated SSS sensors will provide superior imagery data to MBES systems capturing backscatter data.

**Seaﬂoor Subsurface Investigation**

Although many geohazards can be identified through their surface expressions, the nearshore seafloor environment is highly dynamic, and thus active erosion and sediment transport can rapidly remove or cover surficial geomorphic evidence. Geophysical techniques that allow imaging below the seafloor can be essential for mapping these hidden features. Geotechnical drilling and core sampling is typically integrated with the geophysical data for calibration and verification.

**Offshore Geophysical Surveys.** Many geophysical survey projects conducted for infrastructure are performed in relatively shallow water—often in the presence of vessel traffic and/or in confined spaces. Small survey areas also require frequent turns of the vessel creative line plans to provide adequate data coverage. In addition, infrastructure engineering projects typically require high-fidelity investigations of the shallow subsurface, rather than the deep-penetration systems typical of most seismic exploration programs.

echosounders (MBES). Multibeam sensors are used to map the 3D bathymetric surface of the seafloor. Sonar imaging captures the sonar reflection (backscatter) of the seafloor to produce monochromatic imagery.

**Multibeam Echosounding.** Multibeam bathymetric echosounding relies upon sonar (sound) pulses, which travel through water to map the seafloor. There are different types of sensors that are optimized for different environmental or data acquisition scenarios. Each sensor offers a different level of precision and accuracy, observations per pass, wider or steerable fields of view, and many also capture backscatter imagery of the seafloor.

Multibeam surveys require the sensor to be fully submerged in the water below the hull of the boat; therefore the water must typically be at least 1.5 to 2 meters in depth to allow a seagoing vessel and sensor to operate. A multibeam sensor is typically pointed downward (or at a 30 degree angle from nadir) and collects a swath four to eight times the water depth below the sensor. The edge data from wider field-of-view sensors are less reliable and require more data cleaning/editing but are more efficient for field work.

The steerable beam sensors represent a new generation of multibeam systems. This ability allows the surveyor to change the beam separation, swath width or beam direction to increase the sounding data density. An increase in data density provides higher resolution of the seafloor, which helps identify features such as fault scarps, landslides, fluid expulsion features, sunken vessels, exposed utilities and obstructions.

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The advent of ultra-high-resolution digital multichannel systems, such as the GeoEel (2D) and P-Cable (3D) systems built by Geometrics (San Jose, California), has revolutionized seismic reflection techniques for marine engineering and construction applications. These systems are among the highest-resolution and utilize the highest-fidelity offshore hydrophones available and offer immense flexibility for use in shallow-water environments and small areas of interest. The cables are smaller than previous generations of digital streamers, so they can be deployed from smaller vessels with shallower drafts that have lower operating costs. The exceptional signal-to-noise ratio also maximizes data quality when there are limits imposed on the maximum source signal power (such as in California).

Seismic reflection data is not a direct observation of the physical subsurface, but rather a measurement of the two-way travel time of seismic energy to distinct acoustic impedances. Interpretation software is used to map out these horizons of significantly different acoustic properties (which correspond to different material types) to create a 3D geological model that represents the bounds of different soil layers. To calculate the actual vertical positions (depths) of stratigraphic changes, this model must be calibrated, typically using geotechnical borings, cone penetration testing (CPT) and velocity profiling.

**Geotechnical Exploration.** Geotechnical exploration provides essential information for engineering analyses (e.g., slope stability, sediment transport and scour, etc.), constraining geophysical data interpretation, developing geologic models and providing samples for testing. Geotechnical investigations are typically conducted from floating barges, jack-ups, lift boats or drilling ships. Exploration typically involves drilling or in-situ testing (e.g., CPT). Drilling using marine techniques offers many advantages over land-based drilling techniques (i.e., using a truck-mounted drill rig on a barge and drilling using rod-based techniques). Marine drilling techniques utilize wireline systems that collect higher quality data and are much faster than rod-based, land techniques.

**Assessment in GIS**

Integration and interpretation of the various data types are often managed within the GIS environment. A GIS database is populated with the “layers” of information collected during the various site investigation techniques. The datasets can be integrated, allowing the development of a 3D ground surface and subsurface model. This 3D model can be used to conduct comprehensive hazard and risk assessments. Various interpretations of faults, slope instability features, sediment transport features (e.g., sand wave fields), fluid escape and environmentally sensitive areas are cataloged and incorporated into the GIS database. Relatively recent developments have demonstrated significantly improved efficiencies in site condition assessments when GIS has been employed to this effect.

For surface data, bathymetric and topographic terrain data may be fused to produce the topmost layer in a 3D model. The imagery data (sonar backscatter/reflectance or aerial imagery) and geophysical data are incorporated to produce models. Geophysical data is too vast to import and manipulate directly in a GIS environment. Instead, it is generally interpreted in specialized software packages (such as Kingdom Suite). However, after layer stratata are identified, representation and further analysis in GIS is typically ideal. This is due to the ability to integrate data from other sources and the presentation capabilities through planimetric maps, cross sections and oblique scenes. The 3D subsurface model is imported into Esri’s (Redlands, California) ArcGIS as multiple gridded surfaces representing the boundary between each soil layer. However, once again the seismic reflection data do not provide a true spatial representation. To calculate the actual vertical positions (depths) of stratigraphic changes, the acoustic properties of each layer of material must be known and the model calibrated. ArcGIS can be used to import geotechnical log data, which are then matched to the interpreted seismic surfaces. The GIS analyst works with the geophysicist to correct the subsurface model by fitting the interpreted layers to the borings data.

Once calibrated, the 3D subsurface model is added to the surface model to produce a harmonized model that captures both surface and subsurface data. This model can be analyzed through review of any of the surfaces and soil units or it can be sliced across any plane or cross-section. These 3D ground models are principally used by engineers to support design engineering and identification of geohazards. The flexibility of GIS to present the data in a variety of formats—from paper plans to 3D renderings—is frequently the key to a successful project.

**The Project**

The Choctawhatchee Bay bridge and causeway system represents a 19,000-foot-long major transportation structure that also serves as a hurricane evacuation route in the panhandle region of Florida. Sections of the bridge-causeway system have been experiencing severe performance issues and require a major remediation effort to stabilize the system in order to live out its designed life expectancy. In addition to the remediation work, a second bridge-causeway system will be constructed to meet hurricane evacuation route capacity needs.
The remediation work and new bridge construction will be conducted as part of a design-build project. During the proposal stage of the pursuit, a small budget was appropriated for site investigation work that did not allow for both geotechnical exploration and geophysical surveying. It was decided by the team that the existing geotechnical data did not provide an adequate understanding of the subsurface conditions and that the limited number of geotechnical explorations planned during the proposal stage would likely not be able to provide the necessary insight. It was noted that the water depth along most of the investigation area ranged from 5 to 15 feet and only reached 20 feet in the navigation channel. Due to its cost effectiveness related to its ability to be deployed from a small, shallow draft vessel, high resolution and fidelity, and ability to mitigate water bottom multiple effects inherent to single-channel surveys, an eight-channel, Geometrics GeoEel mini-streamer (1.56-meter group interval) was selected for a seismic reflection survey. Side scan sonar, magnetometer, and multibeam systems were also applied to the site investigation.

The survey revealed complex geologic conditions inferred to be contributing to the poor performance of the existing bridge-causeway system. Survey data revealed a slope failure complex along a section of the causeway likely being induced by scouring of toe support material during tidal flushing; horizontal separation of sheet-pile walls along sections of the causeway soil retention system due to creep or lateral spreading; sheet-pile walls being overtopped by mass-wasting; and large buried palaeochannel features infilled with soft, highly compressible soils. Existing geotechnical data did not previously document the geometry of the large buried palaeochannels, which were considered to be one of the most important observations derived from the survey. The multichannel seismic data were used to illuminate the channel features. The 3D ground model graphic included in this article shows one of the major buried channels illuminated by the seismic reflection data that was related to unexpected conditions encountered during previous bridge construction activities.

The survey represents an example of how new technology and integration of geophysical and geotechnical data (both new and existing) can provide cost-effective means for collecting high-quality data in challenging environments within limited budgets.

Conclusion

Globally, we have constructed much of our infrastructure near ocean coasts. Although we continue to build infrastructure that is more critical or involves more inherent risks—such as nuclear power generation stations, immense bridges, LNG terminals and taller buildings—we often have not fully explored the exposure of this infrastructure to marine geohazards. When tolerances and design criteria may be insufficiently constrained, it becomes critical to better understand these risks.

The use of several data collection systems are now being successfully integrated in a GIS environment. GIS is also exceptionally well-suited to presenting these disparate data sets in a number of formats to meet the needs of each stakeholder. This enables engineers and geologists to identify and study offshore faults, weak geotechnical conditions and other offshore hazards that may threaten some of this critical infrastructure. The use of both surface and subsurface data sets enables investigation of specific aspects of these hazards to improve understanding of their potential impacts on our coastal infrastructure.

References

For a list of references, contact Todd Mitchell at tmitchell@fugro.com.

Todd Mitchell is the remote sensing manager for Fugro in Ventura, California. With more than 12 years of experience, he consults clients on applicability of various remote sensing technologies to project requirements in multiple industries. Mitchell is an ASPRS certified mapping scientist, ASCE certified floodplain manager, certified engineering technologist and certified GIS professional.

Kevin Smith is a professional geologist and an associate engineering geologist for Fugro in Norfolk, Virginia. Smith has spent the last 14 years using the integration of geotechnical and geophysical site investigations to conduct geohazard evaluations and support planning and design of coastal infrastructure projects.

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