Investigations of Marine Geohazards in Coastal Zones

Todd Mitchell, CMS, Daniel Ebuna, MSc
Fugro Pelagos, Inc.
4820 McGrath Street, Suite 100
Ventura, CA
tmitchell@fugro.com; debuna@fugro.com

Kevin Smith, P.G.
Fugro Consultants, Inc.
World Trade Center, Suite 350
101 West Main Street
Norfolk, VA
ksmith@fugro.com

***Abstract*—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 the geology. Geological conditions are often a critical factor in resilient infrastructure development at the coast, yet they are frequently difficult to study. The geological conditions that present hazards to infrastructure are known as geohazards. Studies of geohazards look to identify geologic, geospatial, and environmental hazards with the potential to impede or hinder construction of or that threaten existing infrastructure. Coastal geohazards may include examples such as nearshore earthquakes, tsunamis, unstable ground, and inundation due to storms or sea level rise.**

Heightened awareness of the impacts of these coastal processes and episodic natural disasters has brought attention to the threats to coastal infrastructure and the millions of people residing in coastal zones globally. The devastating earthquakes in Japan (2011), Chile (2010), and Haiti (2010) are just a few recent examples of these events. The concern for our coastal infrastructure has likely never been greater.

With such a significant amount of this infrastructure existing as well as new projects planned within coastal zones, the need for properly identifying the geospatial and geological hazards 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. GIS has become an effective means for integrating the various types of information, facilitating interpretation and communicating the results that are often complex and technical. This paper describes the current 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 within the economic reach of coastal infrastructure projects.

Keywords—geohazard, coastal hazard, offshore fault, offshore geophysical, seismic ground motion

I. Introduction

Nearly every year an episodic geological event takes lives and causes significant damage to infrastructure. Typically, the hazards associated with such an event were poorly understood.

One of the most critical episodic threats to coastal infrastructure is through seismic activity. Events such as the devastating earthquakes in Tohoku, Japan (2011), Maule, Chile (2010), Léogâne, Haiti (2010), Chincha Alta, Peru (2008), and Sumatra–Andaman, Indian Ocean (2004) are some recent examples that received global attention. They have greatly increased the awareness on critical infrastructure projects exposed to earthquake geohazards. In particular, the Tohoku earthquake was monitored globally as the impacts of the earthquake and tsunami devastated the Fukushima Dai-ichi nuclear power plant.

Geohazard studies are those that look to identify geologic and geospatial hazards with the potential to hinder the construction of or that threaten existing infrastructure (see Fig. 1 below). Characterization of coastal geohazards may include conducting topographic and/or bathymetric surveys to consider terrain impacts (such as slope stability or liquefaction) as well as geophysical surveys that explore the subsurface, below the seafloor, for hazards (such as seismic ground motion or sediment processes). This data can also be used for inundation modeling caused by storm events and sea level rise.

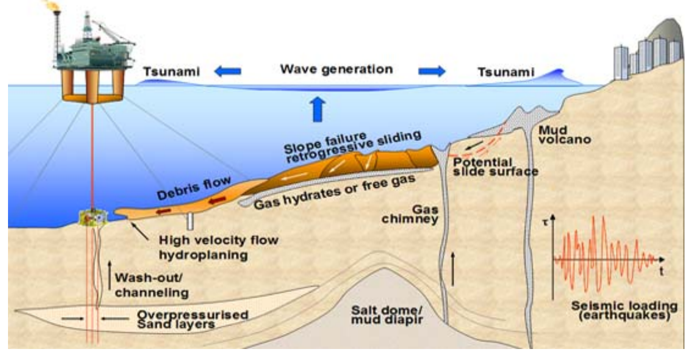

Fig. 1. Schematic diagram showing examples of marine geohazards [1]

New technologies and methods have improved our ability to detect and evaluate fault hazards. Offshore geophysical investigations using seismic reflection exploration techniques have achieved a new level of resolution and fidelity. In recent

978-0-933957-40-4 ©2013 MTS

years, these methods have been refined and have demonstrated unparalleled ability to characterize coastal geohazards.

II. Seafloor Surface Investigation

Many geohazards may be visible on the seafloor surface due to their geomorphic expression. These surface expressions can be viewed using sonar imaging and/or multibeam echo sounders. Multibeam sensors observe the 3-dimensional bathymetric surface of the seafloor (in the same way topography is the above-ground surface). Sonar imaging captures data on the reflectivity of the seafloor to produce monochromatic images of the seafloor.

A. Multibeam Echosounding

Multibeam bathymetric echosounding relies upon sonar (sound) pulses, which travel through water to map the underwater seafloor (see Fig. 2). There are different types of sensors which 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 intensity (back-scatter) imagery of the seafloor.

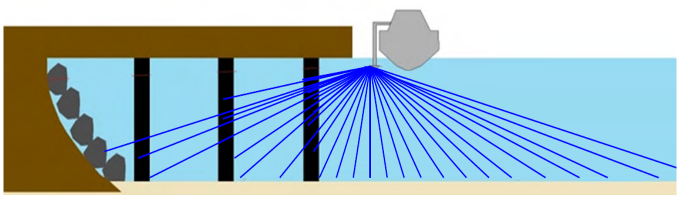

Fig. 2. Schematic of multibeam sensor operation.

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 sea-going vessel and sensor to operate. A multibeam sensor is typically pointed downward (or at a 30 degree angle from nadir) and collects a swath 4 times to 8 times the water depth below the sensor. Wider data is less reliable and requires more data cleaning/editing but is more efficient for field work.

When surveying nearshore infrastructure, such as piers, docks, harbours and other facilities, MBES has the advantage of being able to survey the vertical sides of submerged structures or underneath submerged structures with an overhang, like a dock.

B. 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 sensor to create monochromatic imagery of the seafloor. The sensor can be a dedicated imaging device or can be a captured attribute 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. Fig. 3 is an example of side-scan imagery of a shipwrecked vessel. The level of detail (resolution) required dictates the appropriate approach since a dedicated SSS sensor will provide superior imagery data at the expense of the MBES data quality and vice versa.

Fig. 3. Side-scan sonar imaging of a shipwreck on the seafloor [2].

III. 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 which allow imaging below the seafloor can be essential for mapping these hidden faults. Geotechnical drilling and core sampling is typically integrated with the geophysical data for calibration and verification, especially when supporting any sort of marine construction project, such as a bridge or offshore terminal.

A. 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. These issues may demand operating only during daylight hours and thus necessitate nimble deployment/recovery and operations. In addition, infrastructure engineering projects typically require high-fidelity investigations of the shallow subsurface, rather than the deep-penetration systems that are typical of most seismic exploration programs.

The digital multi-channel GeoEel (2-D) and P-Cable (3-D) systems built by Geometrics (San Jose, CA) are among the highest-resolution and highest-fidelity offshore seismic reflection data acquisition systems available. This is partly achieved through the use of tightly spaced hydrophone groups (which have allowed 3-D data binning as fine as 3.125 meters square) and a short sampling interval (down to 0.125 milliseconds). The recent development of a solid-core streamer also significantly reduces data noise caused by bulge waves, with levels under 5 microbars **Error! Reference source not found.**.

1) 2-D Marine Seismic Reflection System (GeoEel)

Digital GeoEel streamers are very compact with diameters of only 4.1 cm for the liquid-filled and 4.45 cm for the solid-core streamers. The GeoEel can also be deployed as a relatively short streamer system (down to 12.5 meters, although up to 1200 meter streamers is also possible) allowing it to be used in more confined locations, such as in ports or near bridges [3]. This also vastly improves the efficiency of vessel mobilization (including shipping the system, where required), deploying/recovering the sensor array, and maneuvering (turns).

The two-dimensional GeoEel systems have been used on a number of projects related to fault characterization across the globe, including the San Francisco Bay Bridge replacement, the Bay Area Rapid Transit (BART) seismic retrofit (both in California), and the İzmit Bay Bridge, in Turkey. The use of a 2-D sensor array is most applicable to surveys of larger areas, including the initial detection and location of faults.

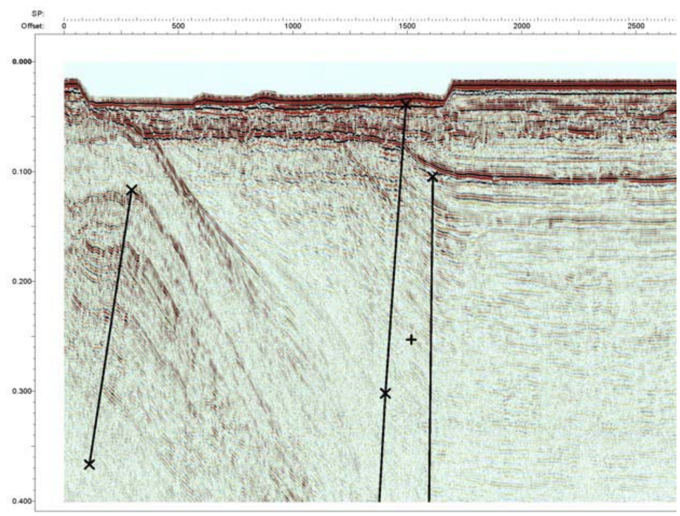

Fig. 4. 2-D Geophysical data collected with GeoEel in Port of Los Angles. Note sub-surface faulting and folding as well as dredging at seafloor.

2) 3-D Marine Seismic Reflection System (P-Cable)

The P-Cable system is well-suited to addressing a wide range of logistical requirements. It is comprised of an array of digital multichannel GeoEel streamers to be deployed in combination with any marine seismic energy source for conducting three-dimensional seismic reflection surveys. With the aforementioned benefits of the GeoEel streamers and the ability to reliably migrate out-of-plane reflections, the P-Cable system is capable of acquiring some of the most accurate, high-resolution seismic reflection data yet observed. In recent surveys, P-Cable arrays have been designed to utilize 12 to 24 streamers connected in parallel, with lengths of 25 or 50 meters [4]. The size of the array is generally dictated by the size of the vessel, and as nimble operations are a key ad-vantage, keeping the vessel size (and thus cost) low is generally highly desirable. Deployment using as few as 4 winches on deck and a crane for paravanes makes it extremely compact compared to typical 3-D seismic arrays. This drastically increases the number of local vessels of opportunity that are capable of performing such 3-D seismic reflection surveys, and reduces the amount of time required for mobilization/demobilization of vessels. Figure 5 presents an example P-Cable layback schematic.

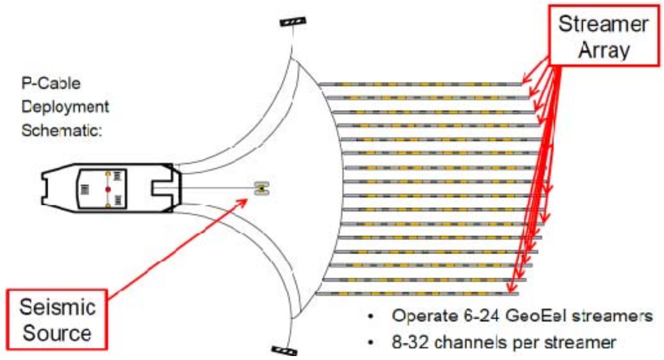

Fig. 5. Layback diagram of Geometrics P-Cable 3-D seismic system [2]

B. 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 used in age dating for quantifying the hazard level. Geotechnical investigations are typically conducted from floating barges, jack-ups, lift boats, or drilling ships.

Floating barges typically only operate in sheltered water bodies (e.g. harbors, embayments, or lakes) and shallow water (less than 20 meters). Floating barge suppliers are found in most large ports and harbor areas which often make them a cheaper plant option due to low mobilization costs. However, geotechnical data quality is often lower than when collected from fixed platforms since they are collected from a floating platform which moves during sampling and testing.

Jack-ups and lift boats provide stable platforms that can work in water depths typically up to about 20 to 25 meters and can work in unprotected water bodies since they can elevate above the wave zone (Figure 6). Jack-ups and lift boats suppliers are typically limited to areas with abundant nearshore construction work (e.g. oil and gas regions along the Gulf of Mexico coastline) and thus, mobilization costs typically increase relative to mobilization distance. Modular jack-up rigs break down into 20-foot long containers that can be shipped, trailered by truck, and assembled at most ports in a few days (see Figure 6). Recently, a jack-up was developed that can "walk" into intertidal zones or areas with adverse sea states. Jack-ups offer many advantages since they can be transported to remote areas, can work in intertidal zones, and provide stable work platforms. However, their operations are one with the highest risk in the coastal investigation scheme since they work in dynamic environments where scour around the legs can lead to punch-through and tip over.

Fig. 6. Geotechnical drilling from offshore jack-up rig.

Drilling ships are used for water depths that exceed jack-up and lift boat operational water depths. There are few dedicated geotechnical drilling ships in the world and due to long mobilization distances, typically have the highest mobilization and operating costs.

Exploration typically involves drilling or in situ testing (e.g. cone penetration testing [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. Fig. 7 shows a seabed CPT being deployed.

Fig. 7. Deploying a seabed CPT system from a barge in Norfolk, Virginia.

CPT data provide continuous vertical profiles and engineering data faster than drilling. The continuous vertical profiling provides detailed information that can be used for mapping turbidite deposits, slide masses, or used to interpret strata that have been offset by faulting when transects of CPT's across fault traces are performed. Moreover, CPT data provide valuable soil strength data used in evaluating slope instability. CPT data are the preferred data type for constraining seismic data interpretation. CPT tip resistance (which is influenced by soil density) correlates very well to seismic impedance and the detailed vertical profiling augments the seismic interpretation very well.

Recent developments in wheel- and block-drive, seabed CPT equipment has led to improved penetration in sandy environments commonly encountered in coastal areas. These new systems can now penetrate significantly deeper and into denser materials than their predecessors.

Drilling provides physical soil and rock samples for testing (e.g. strength and age dating) and visual observations which are important for analyzing detailed sediment structure. Continuous coring can be performed in rock and certain soil conditions and be used to identify fault and slide planes.

Shallow (up to 5 meters) sampling and testing in coastal environments is typically performed using vibracore and seabed CPT's. If the shallow sediments are comprised of fine-grained deposits, then box cores, gravity cores, or piston cores may be used.

IV. NEARSHORE TOPOGRAPHY

As with the seafloor, marine geohazards may have surface expressions that extend onto land also. Evidence of these hazards are often best preserved and thus detected in the nearshore topography, thus topographic mapping is often a key supplement to studying marine geohazards.

A. Satellite and Airborne Photogrammetric Imagery

Among the most readily available and most simple to interpret is conventional photogrammetric imagery. Satellite imagery is available globally in high resolution. For more detailed and accurate imagery, aircraft can be tasked to collect photogrammetric imagery as well. Due to the availability of archived data, it is frequently possible to identify topographic changes, such as erosion and landslides. Where geohazard expression is visible on the earth's surface, this technique can be extremely valuable. However, a key limitation is that many surface expressions can be masked by the presence of vegetation. Fig. 8 is an example of airborne photogrammetry.

Fig. 8. Airborne phototrammetric mosaic of a marina in Alicante, Spain.

B. Airborne Topographic LiDAR and LiDAR Bathymetry

Airborne LiDAR sensors uses laser pulses to observe the range between the scanner and the topographic features to map above the water surface. Most sensors are not designed to work below water as the commonly used infrared frequencies cannot penetrate water. However, there are some sensors that operate in the blue-green (532 *nm*) wavelength that are able to capture both topographic data as well as bathymetric data to a depth limited by environmental conditions (principally water clarity and water aeration) [5]. Fig. 9 is an example of a coastal area surveyed using a bathymetric/topographic LiDAR system, which demonstrates the ability to capture a seamless land-sea interface.

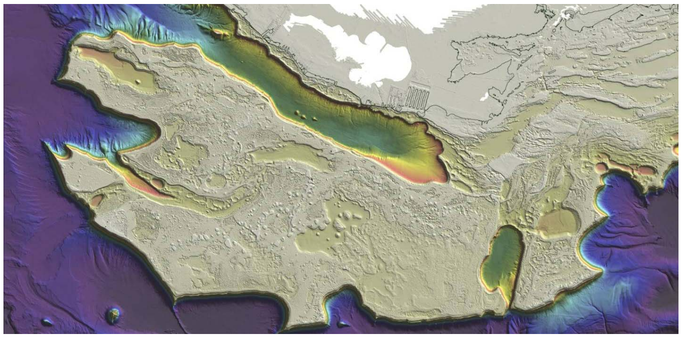

Fig. 9. Coastal LiDAR survey using airborne bathymetric LiDAR system from Jeddah, Saudi Arabia [5]

Airborne LiDAR sensors are particularly efficient for investigation of large sites and/or sites that are difficult or unsafe to access from the ground. Data resolution is generally a function of both the sensor and the aircraft operating parameters, but detection of many geohazards – even within heavily vegetated areas – is often possible. However, capturing data on vertical objects (vertical cliffs, sea caves) or beneath facilities (such as a wharf) are not possible with the technology, as the sensor requires a direct line-of-site to the target.

C. Mobile Laser Scanning

Mobile Laser Scanning operates with the same principles as a topographic LiDAR sensor – the difference being the vehicle platform being used. In the case of mobile laser scanning, the vehicle will typically be either a land based vehicle (such as a truck or ATV) or a waterborne vessel. Fig. 10 shows the schematic of mobile laser scanning of the coast from a vessel.

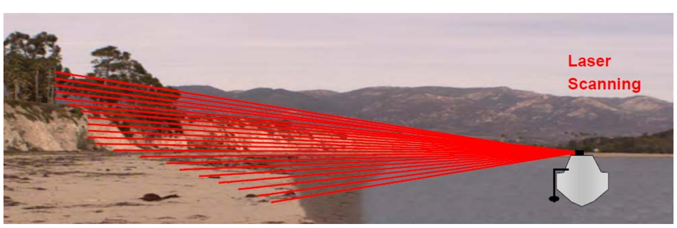

Fig. 10. Schematic of mobile laser scanning from a vessel.

Mobile laser scanning is capable of collecting extremely detailed data sets and has the distinct advantage of being able to survey vertical objects very well – especially features like building fascia, port/harbor infrastructure, and the sides of bridges to name a few. Thus, this technique can be very effectively applied to coastal surveys [7]. Another advantage is the ability to map underneath some structures, such as piles under a pier when deployed from a boat.

However, laser scanning is a line-of-sight technology and therefore one object in the foreground will completely obscure any object behind it. For example, it is only possible to map the side of a building facing the sensor – the backside of the building is hidden and therefore requires driving/sailing behind the building to get the missing side(s). Some aspects, such as the roof, typically cannot be captured at all from the ground based platform unless the scanner is brought onto the roof.

Mobile Laser Scanning can be cost effective for smaller projects because operating costs for a small boat are significantly lower than those for operating an aircraft. Fig. 11 shows a project where mobile laser scanning was used to calculate cliff retreat compared to an older aerial LiDAR survey.

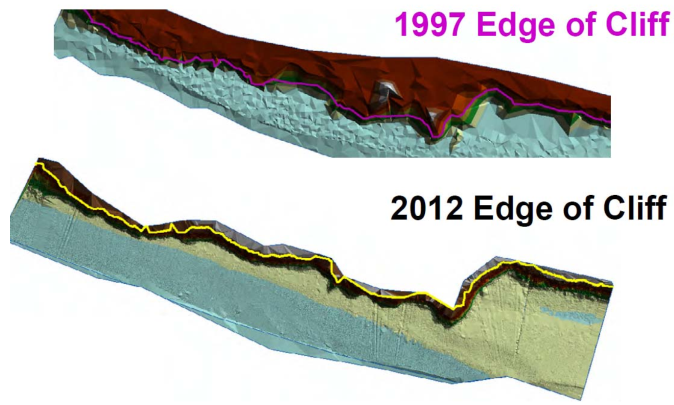

Fig. 11. Coastal cliff retreat monitored using LiDAR (1997) and mobile laser scanning (2012) together [8].

V. Assessment in GIS

Marine geohazards may have a variety of expressions and GIS is an exceptional tool for integrating the disparate datasets discussed previously and for identification and investigation of geohazards.

For surface data, bathymetric and topographic terrain data may be fused to produce the topmost layer in a 3-dimensional model. The imagery data (sonar backscatter/reflectance or aerial imagery onshore and/or in shallow water) can then be draped onto this top layer.

Geophysical data is too vast to import and manipulate in GIS. Instead, it is generally interpreted in specialized software packages (such as Kingdom Suite). However, after layer strata 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.

Seismic reflection data is not a direct representation of the physical subsurface, but rather a measurement of the two-way travel time of seismic energy to distinct acoustic impedance interfaces. Interpretation software is used to map out these horizons of significantly different acoustic properties (which correspond to different material types) to create XYZ surfaces that represent the bounds of different soil layers. These layers are imported into ArcGIS as gridded surfaces. However, once again the source data do not provide a true spatial representation. In order to calculate the actual vertical positions (depths) of stratigraphic changes, the acoustic properties of each layer of material must be known. Such values are typically obtained through downhole geophysical surveying in geotechnical borings, velocity analyses of multichannel seismic data, or using empirical relationships based on soil or rock physical properties. ArcGIS can be used to import borehole log data which is 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.

In addition, the geophysical data can be sliced across a plane at a specific travel time of the seismic record. This data can be captured as raster imagery and can often be valuable for the geologist in identifying features such as fault lines or paleochannels.

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. In doing so, the datasets can be integrated and allows the development of a 3D ground surface and sub-surface model. This 3D model can be used to conduct comprehensive hazard and risk assessments for areas. Various interpretations of faults, slope instability features, sediment transport features (e.g. sand wave fields), gas escape, environmentally sensitive areas, are cataloged and are also 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 [9].

These 3D ground models are principally used by engineers in order to support design engineering. The models are also used to depict site stratigraphy and geologic features via a variety of renderings and perspectives. Fig. 12 demonstrates the presentation of some of this data using ArcScene in conjunction with topographic and bathymetric survey data and geotechnical borings.

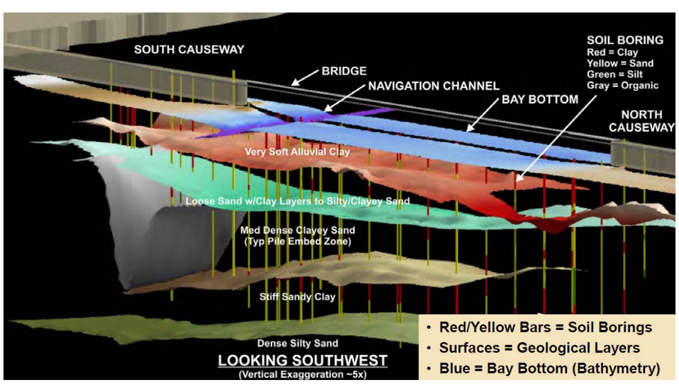

Fig. 12. Integrated bathymetry, topography, geophysical, and geotechnical data from Choctowhatchee Bay Bridge, Florida presented in ArcScene [9].

Such renderings of integrated information make it effective to communicate complex conditions and associated hazard to an audience with varying technical backgrounds. Thus, perhaps the most valuable role GIS can play is in the dissemination of all collected information among all stakeholders. Although data interpretation is the role of the geophysicist and geologist, many other disciplines require use of the data. Disseminating the data results among geotechnical and civil engineers, construction contractors, government agencies, and infrastructure owners is critical. The flexibility of GIS to present the data in a variety of formats – from paper plans to 3-D renderings – is frequently the key to a successful project.

VI. 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 risk – such as nuclear power generation stations, immense bridges, liquefied natural gas 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 sub-surface datasets enables investigation of specific aspects of these hazards to improve understanding their potential impacts on our coastal infrastructure.

VII. References

[1] International Centre for Geohazards, "Offshore Geohazards", http://www.ngi.no/en/Geohazards/Content/Shortcuts/Research-and-development/to-be-filled-1/ Accessed July 23, 2013.

[2] D. R. Ebuna, Client Report, EdgeTech 4125 Side-Scan Sonar System, Bahia Las Minas, Panama, June 2013, unpublished

[3] Geometrics, 2012, GeoEel Solid Streamer, Geometrics, Inc., retrieved January 15, 2013, <http://www.geometrics.com/files/geoeelsolid.pdf>.

[4] D. R. Ebuna, T. J. Mitchell, P. J. Hogan, S. Nishenko, H. G. Greene, "High-Resolution Offshore 3D Seismic Geophysical Studies of Infrastructure Geohazards", SAGEEP 2013 Conference Proceedings, Denver, Colorado, USA, 2013.

[5] Jerlov, N.G., Marine Optics, Elsevier Scientific Pub. Co., Amsterdam, 1976, 231 pp.

[6] C. Spencer, D. Ventura, M. H. Al Harbi, E. M. Al Motairi, "Successful Integration of Vessel-mounted Multibeam Echo Sounding (MBES) Swath and Airborne Light Detection and Ranging (LiDAR or ABL) bathymetric measurement for ENC-Charting Surveys: A Survey of Complex Coastal and Deep Water Tropical Bathymetry for Navigational Charting and Port Engineering, Red Sea, Kingdom of Saudi Arabia", Hydro 2010 Conference Proceedings, Rostock-Warneumuende, Germany, 2010.

[7] T. J. Mitchell and S. Varnell, "Evaluation of Coastal Slopes Using Mobile Laser Scanning and Bathymetric Surveying Techniques", Coastal Zone 11 Conference Proceedings, Chicago, Illiniois, USA, 2011.

[8] E. Von Thury, "Using Laser Scanning Technology to Monitor Coastal Erosion and Sea-Cliff Retreat in Southern Santa Barbara County,

California", Masters Degree Thesis, University of California, Santa Barbara, California, USA, 2013.

[9] K. Smith, K. Morris, and Mekkawy, M. "Response to Request for Additional Compensation for Underwater Obstructions and Change of Conditions, Stage 1 Construction, Marine Terminal", Client Report, Virginia Port Authority, Norfolk, Virginia, USA, July 2012, unpublished.

[10] K. Smith and K. Morris, Client Report, Choctowhatchee Bay, Florida, USA, October 2012, unpublished.