HIGH-RESOLUTION OFFSHORE 3D SEISMIC GEOPHYSICAL STUDIES OF INFRASTRUCTURE GEOHAZARDS

Daniel R. Ebuna MS, Fugro Pelagos, Ventura, CA
Todd J. Mitchell CMS, Fugro Pelagos, Ventura, CA
Phillip J. Hogan PhD, Fugro Consultants, Ventura, CA
Stuart Nishenko PhD, PG&E, San Francisco, CA
H. Gary Greene PhD, Moss Landing Marine Laboratories, Moss Landing, CA

Abstract

As global earthquake activity continues to impact communities, infrastructure, and lives, the necessity of better identification and characterization of seismic hazards becomes ever clearer. The tragic 2011 Tohoku, Japan earthquake and tsunami increased the attention on critical coastal infrastructure projects exposed to earthquake hazards. Offshore faults are more difficult to identify and characterize than onshore faults. While multibeam bathymetric surveys can reveal surface geomorphologic expression of faults, seismic source characterization studies also require investigations of fault geometry in the subsurface. High-resolution offshore geophysical surveys can be a highly valuable tool for these tasks. Specifically, the use of high-resolution three-dimensional seismic reflection investigations can provide some of the most precise information about fault location, activity, and geometry. This work will discuss how the latest generation of ultra-high-resolution/high-fidelity marine seismic systems can be used to investigate sub-sea faults, and how it applies to complex geologic hazards to coastal infrastructure.

Introduction

Nearly every year a large seismic event takes lives and causes significant damage to infrastructure. These can be particularly problematic when the fault lies below the ocean floor, especially in locations close to existing infrastructure and/or habitation. Events such as the devastating earthquakes in Tohoku, Japan (2011), Maule, Chile (2010), Chincha Alta, Peru (2008), and Sumatra (2004) are recent examples. The Tohoku earthquake was monitored globally as the impacts of the earthquake and tsunami devastated the Fukushima Dai-ichi nuclear power plant. The concern for our coastal infrastructure has likely never been greater.

New technologies and methods have improved our ability to detect and evaluate submarine fault hazards. Offshore geophysical investigations using seismic reflection exploration techniques have achieved a new level of quality and fidelity. In recent years, these methods have been refined and have demonstrated unparalleled ability to characterize information on the geometry of a fault. This paper discusses the P-Cable array, which was employed to acquire high-resolution 3-dimensional (3D) seismic reflection data coverage offshore Pacific Gas and Electric (PG&E) Company’s Diablo Canyon Power Plant (DCPP) in Central California (Figure 1).
Figure 1: Site location map showing PG&E low-energy 3D DCPP survey areas (Metzger and Campagnoli, 2001).
Surface versus Sub-surface Fault Expression

Seismically active faults are often visible on the Earth’s surface due to their geomorphic expression. These surface expressions can be viewed using aerial (or satellite) photography and/or Light Detection and Ranging (LiDAR) systems. On the seafloor, they are more often detected using sonar imaging and/or multibeam echo sounders. However, the nearshore seafloor environment is more dynamic than most terrestrial environments, and active erosion and sediment transport can rapidly remove or cover surficial geomorphic evidence. Geophysical techniques which allow imaging below the seafloor are generally a more reliable method for mapping offshore faults.

The P-Cable Seismic Reflection Data Acquisition System

The earliest design of the 3D seismic reflection array that would ultimately evolve into the P-Cable system was first patented in Europe in 2003 by Sverre Planke and Christian Berndt (Planke & Berndt, 2003). This technology was then developed from infancy by a collaboration of Volcanic Basin Petroleum Research (VBPR), the University of Tromsø, and the National Oceanography Centre, Southampton during a project known as HERMES (Hotspot Ecosystem Research on the Margins of European Seas). Following these efforts, the company P-Cable 3D Seismic AS was established in 2008 with the goal of continuing to develop and commercialize P-Cable technology (Planke et al., 2009). Today, the P-Cable Seismic Streamer System is an exclusive joint venture between P-Cable 3D Seismic AS of Oslo, Norway and Geometrics, Inc. of San Jose, California.

Manufactured in California and frequently tailored to meet specific project demands, the P-Cable system, utilizing an array of multi-channel GeoEel Solid digital hydrophone streamers, is among the highest-resolution and highest-fidelity offshore seismic reflection systems available. This is achieved through the use of closely-spaced hydrophone groups (down to 1.5625 meters apart) and short sampling intervals (as low as 0.125 milliseconds). The recent development of solid-core digital streamers also significantly reduces cable-borne noise and eliminates bulge waves. GeoEel Solid digital streamers are very compact with a diameter of only 4.45 centimeters, and can be deployed as a relatively short streamer system (often 25 or 50 meters long) allowing it to be used in more confined locations, such as in ports (Geometrics, 2012). This also vastly improves the efficiency of vessel mobilization, deployment and recovery of the sensor array, and maneuvering during data acquisition.

While GeoEel streamers in a 2-dimensional (2D) configuration are used often on projects for the detection of faults, the use of numerous streamers connected in a P-Cable array, providing 3D data coverage for complete fault characterization, has only been performed successfully on two occasions commercially. These two projects took place in 2011 and 2012 on behalf of PG&E through collaboration with Fugro Consultants, Inc., Subsea Systems, Inc., Geometrics, Inc., and NCS Subsea, Inc. Successful operation of the project-specific P-Cable array utilized for these nearshore geophysical surveys required detailed logistical planning well in advance of the field work, efficient placement and rigging of equipment, carefully-coordinated deployment and recovery procedures, and a state-of-the-art navigation and positioning system.

Technical Methodology

The P-Cable system was developed to concurrently acquire multiple, closely-spaced 2D seismic reflection profiles, which effectively provide a 3D dataset, without the tedious, time-consuming task of a vessel running a line for each individual profile. It allows for a large number of streamers, providing a wide data swath, to be deployed behind a relatively small vessel with a single cable relaying the data from all of the sensors to the acquisition computer. This is significantly more cost-effective and space-
efficient than towing multiple, widely-spaced streamers directly off of the stern of a large ship with acquisition systems required for each streamer. Furthermore, P-Cable arrays can be custom-tailored to a wide variety of geometries to fit the logistical and data resolution requirements of each individual project.

The desired resolution (bin size and fold) of the dataset dictates the hydrophone group spacing in the streamers themselves as well as the spacing between streamers. More widely-spaced hydrophone groups (both along streamer and streamer to streamer) will result in larger bin sizes. Closely-spaced hydrophone groups produce a denser gridding of data, and small bin sizes can be used to produce higher-resolution datasets. The drawback of closer spacing, however, is that the data acquisition swath width will be narrower, requiring more tracklines and therefore more line-kilometers traveled by the vessel to cover the same area. Typically, an array of 10-16 streamers is intended to be used with the P-Cable system, but streamer spacing, specific rigging, and the size of the vessel are generally the determining factors. The overall length of the streamers is also an important consideration when designing the array. When the capability to extract lithological acoustic velocity information from the seismic data is crucial to the project’s goals, a longer far-offset (greater distance to the farthest hydrophone group) is necessary. Longer offsets also provide increased resolution at greater sub-seafloor depths and sharpen the appearance of steeply dipping structures (Hawkins et al., 2001). However, longer streamers also bring about a number of logistical issues such as vessel drag, streamer towing depth, deployment and recovery time, and vessel deck space limitations.

The type of seismic source used is another component of the P-Cable seismic reflection system that can be modified to suit individual project requirements. Depending on the desired amount of seafloor penetration and frequency bandwidth of the data, various seismic source systems may be used, including low-energy CHIRP sub-bottom profilers, sparkers, Unibooms, or small air guns. Environmental permitting restrictions are often another critical factor controlling the type of seismic source utilized, as is the case offshore California. PG&E P-Cable surveys were done in full compliance with environmental restrictions and geophysical survey permits issued by the California State Lands Commission.

It is essential that the positioning of various components be tracked at all times so that the geometry can be accurately determined for data processing purposes. Several points on the P-Cable array are equipped with positioning sensors, including GPS units on the paravanes and buoys at each end of the cross-cable, and compasses attached at the heads and tails of the streamers. The seismic source is equipped with a GPS unit so that the source-to-receiver offsets can be calculated during processing. Figures 2a, 2b, and 2c show the 3D P-Cable system layout as deployed during recent surveys offshore California.

Figure 2a: Side-view layback diagram of the 3D P-Cable array used in the 2012 PG&E DCPP survey.
Figure 2b: Top-view layback diagram of the 3D P-Cable array used in the 2012 PG&E DCPP survey.

Figure 2c: Aerial photograph of the 3D P-Cable array during the 2011 PG&E DCPP survey.
(Photograph courtesy of Geometrics, Inc.)
2011 and 2012 PG&E DCPP Surveys Case Study

P-Cable technology is ideally suited to overcome the logistical challenges that PG&E’s DCPP nearshore geophysical survey faced, and provided the high-resolution data required to effectively characterize the offshore fault systems (Nishenko et al., 2012). California permitting restrictions requiring daylight operations only necessitated a seismic reflection data acquisition system that could be deployed and recovered on a daily basis and was capable of collecting enough data to be reasonably cost-effective. Additionally, the initial survey area of interest was relatively small, which meant short tracklines and an abundance of line turns, so a maneuverable vessel and towed array were necessary to minimize downtime lost switching survey lines.

In order to meet PG&E’s high-resolution requirement, 12 or 14 GeoEel Solid digital streamers were deployed from a single transverse cable (P-Cable) with streamer separations of 6.25 meters. Each streamer consisted of 8 channels with hydrophone group spacing of 6.25 meters. Combined with a distance-based shot interval of 3.125 meters, the system was capable of producing eight-fold data with a bin size of 3.125 meters by 3.125 meters. The data were acquired at a sampling rate of 0.25 milliseconds and a record length of 750 milliseconds. This sampling interval provided a Nyquist frequency of 2 kHz, which is appropriate for the frequency bandwidth associated with the type of seismic source (Uniboom) used. A record length of 750 milliseconds was more than sufficient for capturing all subsurface reflectors of interest since the project’s focus was on imaging shallow paleochannels that may have been offset by faults. Furthermore, the low-energy boomer seismic source (operated at less than 2000 Joules in accordance with California State Land Commission’s permitting requirements), combined with the near-surface heterogeneous bedrock present at the site, prevented the return of any coherent reflectors deeper than 750 milliseconds two-way travel time.

Navigational services provided by NCS Subsea, Inc. gave these surveys the advantage of pre-processed positioning data that could be monitored in real-time to ensure data quality (Figure 3a), and real-time binning (Figure 3b). The NCS system obtained positions of common depth points (CDP) as they were acquired and plotted them on the survey bin grid as fold (data density). Color-coded values were assigned to each grid cell to identify the amount of coverage obtained for that location. This allowed the surveyor steering the vessel to see which areas still needed additional coverage and to adjust accordingly. The 3D swath width of the 14-streamer spread was 43.75 meters, so the 3D binned survey areas were designed with a line spacing of 37.5 meters to allow some overlap in order to minimize data gaps and the number of infill lines.
Figure 3a: Real-time monitoring of the P-Cable array to ensure quality of hydrophone positioning data.

Figure 3b: Real-time binning display used by a surveyor to steer the ship for maximum data coverage.
At the end of each day of data collection, the navigational data were post-processed onboard to confirm the completeness and accuracy of the array positioning. The resulting data files were then passed on to an onboard seismic data processor to carry out quality control processing of the 3D data volume. Seismic processing was performed using Fugro’s proprietary UNISEIS software. The processing flow utilized for onboard quality control consisted of the following: conversion from SEG-D to UNISEIS format, offset (geometry) determination, trace editing, navigation merge, low-cut filter,statics correction, gain recovery, CDP sorting, normal-moveout (NMO) correction, muting, and a brute stack. A complete, shore-based processing routine for the 3D data volume was performed by Fugro Seismic Imaging, Inc. in Houston, Texas, also using UNISEIS software. During final processing, more sophisticated and complex techniques were employed, including multiple velocity analyses, swell noise attenuation, surface-related multiple elimination, signature deconvolution, and a 3D pre-stack Kirchoff time migration.

While the dataset from the survey that took place in 2012 is currently being processed and thus not yet available, two images generated from the 2011 data acquisition and processing effort are shown in Figures 4a and 4b. A merged 3D volume that includes both 2011 and 2012 data is currently being generated. The final product to be presented to PG&E for geologic interpretation will consist of a complete 3D data volume that can be spatially manipulated to provide a range of visualizations using seismic viewing software such as IHS Kingdom VuPak. The most commonly produced and useful images tend to be 2D vertical profiles, horizontal (map view) coherency or amplitude time slices (Figure 4a), and 3D data cubes (volumes or bricks) (Figure 4b).

Figure 4a: An example horizontal amplitude time slice from the 2011 PG&E dataset.
Figure 4b: An example 3D data cube from the 2011 PG&E dataset.

Conclusions

Improvements in offshore seismic geophysics have resulted in higher resolution systems, which are now being used successfully to identify and study offshore faulting and other geologic hazards. Comprehensive assessment of these hazards, especially those that may affect essential infrastructure, is vital for the implementation of appropriate safeguards that can minimize the societal impact of geological events. While 2D seismic reflection profiles have been invaluable for subsurface investigations for many decades, the advent of truly three-dimensional seismic reflection data acquisition and processing now allows geoscientists to evaluate geologic structures in a much more intuitive manner. The vivid 3D data examples shown above clearly demonstrate the significant stride forward that modern high-resolution, three-dimensional seismic reflection technology provides.

Acknowledgements

The authors would like to thank PG&E DCPP plant personnel, in particular Richard Van der Linden and Geoscience QA manager Marcia McLaren. Also, thanks go to the offshore crews of the M/V Bluefin, the M/V Pacific Star and the M/V Michael Uhl.
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