BASICS OF HYDROGRAPHY & INSPECTION OF SUBSEA INFRASTRUCTURES

Principles and Practice

1st Edition
The Manual of Surveyor

Geraud NAANKEU WATI

Positioning & Geomatic Specialist

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"*This book reflects my desire to share my knowledge and experience of the field with you*"
Geraud NAANKEU WATI

PREFACE

My name is Geraud NAANKEU WATI, positioning and geomatic specialist. In 2015, I obtained a Master's degree in Hydrography and Oceanography at ENSTA Bretagne, with knowledge in management, mathematics, computer science and robotics. For the past five years, I have worked on several survey campaigns and research and development projects in hydrography and subsea infrastructure inspection such as:

- Error budget analysis of underwater and surface survey systems,
- Trajectory computation of an autonomous underwater vehicle (AUV) from an inertial navigation system (INS) coupled with a Doppler velocity log (DVL) and an Ultra Short BaseLine (USBL) positioning system,
- Positioning of a subsea vehicle in opened and confined underwater environments (tunnels, galleries, etc…),
- Tide prediction from tidal observations,
- Implementation of an altimetry reference network along a river, etc. (see **Figure 1**)
- Acquisition and processing of data provided by 3D laser scanner (see **Figure 2**), multibeam echosounder, sub-bottom profiler, video camera, etc…
- Design of a Pulse Per Second (PPS) Box for distributing GPS timing signals in a survey system,
- Software development for analysis and visualization of seismic data (see **Figure 3**),
- Software development for simulating NMEA (National Marine Electronics Association) sentences output by a GNSS positioning system,
- Software development for data acquisition of singlebeam echosounder survey system,
- Monitoring of maritime works from an 2D acoustic camera /multibeam echosounder,
- Control of maritime works from multibeam echosounder,
- Inspection of subsea infrastructures from subsea vehicles and vessels,
- Bathymetry estimation of a lake from aerial images acquired by drone,
- Optimization of the acquisition chain of hydrographic surveys and inspection operations,
- Data acquisition protocols in serial and Ethernet (UDP/TCP).

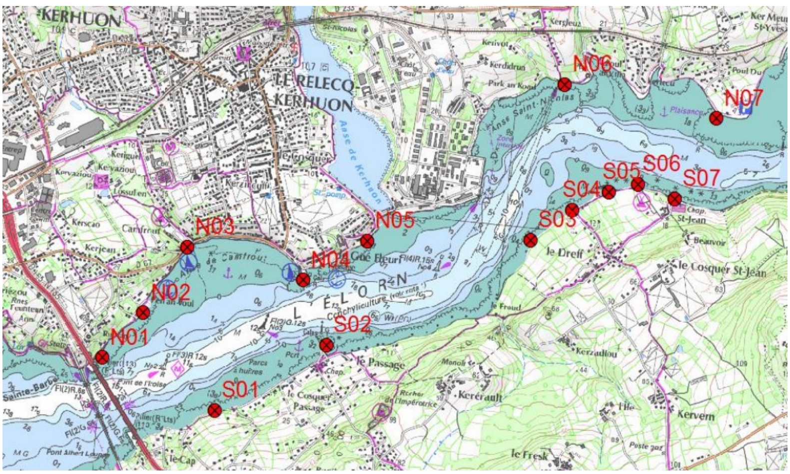

Figure 1: Implementation of an altimetry reference network along river Elorn, Brest

During these different projects, I learned a lot of new things and encountered several issues such as:

- Properly implement a software of coordinate transformation,
- Properly implement a multibeam echosounder acquisition system,
- Understand and correct various time errors in a data acquisition system,
- Manage a survey project (survey constraints will vary depending on whether the project is performed on smaller water bodies (rivers, lakes, channels) or on larger ones such as oceans and seas.
- Properly calibrate a multibeam echosounder and 3D laser scanner acquisition systems,
- Implement an inertial navigation system on a remotely operated vehicle (ROV),
- Choosing the right surveying software solutions,
- Managing large volumes of data in various formats (LAS, LAZ, MP4, etc.), etc.

I started out as Junior Surveyor. Due to the lack of field experience and solid basics in hydrography and subsea infrastructure inspection, I usually spent so much time these above mentioned issues. For instance:

- My first field experience was to work as data processor offshore on a vessel where all equipments were already installed and calibrated.
- Moreover, I really didn't understand the working principles of some sensors (USBL, DVL, CVL, etc.), protocols of data transfer, time stamping, time servers, etc.
- Neither, did I understand the general field constraints just like most young surveyors,
- I had however a good generalist training in management, mathematics, computer science and robotics, which allowed me to quickly adapt to new situations.

In addition, I usually spent several hours to perform repetitive operations in the office. As I don't like losing time, I often developed small software to automate long processes and to optimize the processing time of data (navigation, multibeam, videos, etc.).

From time to time, I attended conferences to have an exchange with other professionals of the hydrographic community on themes and issues affecting several areas of our activity. During my exchanges, I noticed that some hydrographic surveyors were not aware of some aspects such as: the non-necessity to use a heave sensor for hydrographic sounding reduction using a separation model between the chart datum and the ellipsoid reference (Sanders, RTK Tides without a heave sensor, 2015). They carried out multibeam surveys without understanding the theory of sounding geo-referencing. I also noticed that some hydrographic surveyors as I was spent several hours to process and merge multibeam data; while it was often enough to reverse one attitude measurement or to do a good calibration process in order to properly merge data and save time.

After spending much time to resolve several issues in hydrography and inspection of subsea infrastructures, I understood that it is important for professionals and also stakeholders to have a good knowledge of these fields for ensuring the success of projects linked to those ones. Then, I decided to write this book for four main reasons:

1. To share my knowledge and experience of the field in positioning, hydrography and inspection of subsea infrastructures with stakeholders, and the members of hydrographic and topographic communities (teachers, students, surveyors, survey engineers, managers, institutes, etc.)

2. To contribute to the training of surveyors, and to help them to overcome numerous issues and to meet the needs in hydrography and inspection of subsea infrastructures in the world,
3. To help the stakeholders to specify their internal standards and to evaluate the technical aspects of contractor proposals, in order to get high accurate data,
4. To initiate people without theoretical and practical knowledge in hydrography and inspection of subsea infrastructures and to promote these fields.

This book has several purposes:

- It provides an introduction to hydrography and inspection of subsea infrastructures,
- It describes the various sensors used in survey projects (role, applications, working principle, technical specifications, output, etc.),
- It describes various communication connectors and protocols used in a survey system,
- It presents some basic notions in management, mathematics, electronics, oceanography and geodesy necessary in hydrography and inspection of subsea infrastructures,
- It provides an introduction to tide prediction and to determination of a chart datum,
- It provides algorithms for geo-referencing in data (multibeam, 3D scanner laser, etc.),
- It describes the principles of operation of GNSS satellites, inertial systems, and many other navigation technologies, both qualitatively and mathematically,
- It provides an introduction to underwater acoustics, and timing in survey systems,
- It provides an introduction to error budget analysis of survey systems, etc…

According to Frédéric GUILLOT, CEO at SUBCMARINE: The new book: **"Basics of Hydrographic and Inspection of Subsea Infrastructures – Principles and Practice"** is very useful for students and professionals in topography, hydrography and inspection of subsea infrastructures (surveyors, survey engineers, scientists, etc.). They will learn many theoretical and practical basics about GNSS, acoustic and inertial positioning systems, 3D laser scanner systems, sub-bottom profilers, multibeam echosounders, 2D acoustic cameras and methods for geo-referencing, calibrating system and data analysis. Experts or specialists in hydrography and inspection of subsea infrastructures could learn something new such as concrete/practical solutions to better manage a survey project, to efficiently install survey system, and to optimize survey operations in terms of time and quality. Stakeholders, chief surveyors, experts and CEOs could find some good solutions such as: how to build a successful survey team? How to choose (acquisition, processing, visualization, etc.)? How to estimate the error budget of acquisition system? This book is also useful for hydrographic professionals involved with emerging national hydrographic offices wishing to comply with the International Hydrographic Organization (IHO) standards. This book can then be considered to be a manual for surveyors.

The layout of this book is divided into 12 chapters:

- **Chapter 1:** This book begins with brief definition of hydrography and inspection of subsea infrastructures in presenting surveys various applications of hydrography and inspection of subsea infrastructures (nautical charting, port and coastal management, offshore engineering). It also presents types of hydrographic and inspection surveys and some constraints commonly encountered in these applications.
- **Chapter 2** presents the various types of survey systems commonly used for hydrographic and inspection operations namely: surface survey systems (traditional survey vessels, Diving support vessels, unmanned surface vehicles, buoys, etc.) and

underwater survey systems (Submersibles, Remotely Operated Vehicles (ROV), Autonomous Underwater Vehicle (USV)).

- **Chapter 3** refers to basic general knowledge in hydrography and inspection of subsea infrastructures. Topics covered include an introduction to management of survey projects, some mathematical recalls (least squares method, statically recalls vectors, law of uncertainty propagation, etc.), coordinate systems and projections, tides, software solutions for surveying, programming etc.
- **Chapter 4** refers to computers and input/output interfaces. It describes various computers (standard computers and industrial computers) and communication ports or interfaces (RS 232, USB, UART, RS 485, Ethernet, BNC, HDMI, DVI, VGA, etc.) commonly used in an acquisition system during operations of hydrographic surveys and inspection of subsea infrastructures. This chapter will help them to better understand the data transmission principle in an acquisition system, and to properly install, and maintain a system and to resolve any IT issues during the operations of hydrographic surveys and inspection of subsea infrastructures.
- **Chapter 5** is focused on Global Navigation Satellites Systems (GNSSs). It describes the architecture of some global navigation satellites systems such as: Global Positioning System (GPS), Global Navigation Satellite System (GLONASS), Galileo and Beidou. It contains several fundamentals of the GNSS positioning, explanation of code and phase observations, including error sources, and various positioning techniques. It also describes the GNSS positioning systems by presenting their basic working principle, hardware architecture, technical specifications, and output messages (NMEA, RTCM and binary sentences) in order to better enlighten readers in their choices during the implementation or the acquisition of GNSS positioning system for a specific application. This chapter also focuses on the installation and the configuration of a GNSS positioning systems. It provides some guidelines installation and configuration of a GNSS positioning system in order to help readers to get an optimum GNSS signal reception and a good accuracy during a survey.

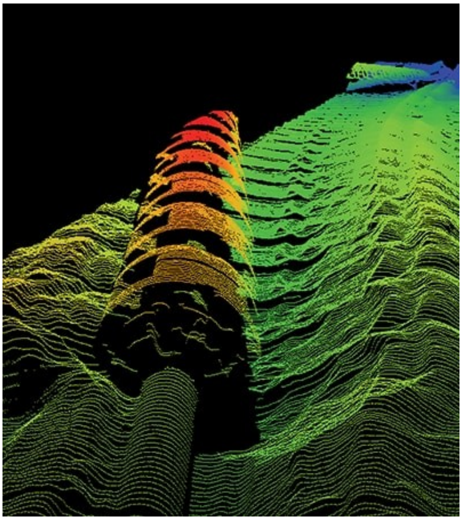

Figure 2: Example of subsea 3D laser scanner data (2GRobotics, 2018)

- **Chapter 6** introduces to underwater acoustics. It presents the basic knowledge of underwater acoustics in order to help readers to understand the properties of acoustic wave, the specificities of subsea environment, the working principle of the acoustic sensors and the main parameters which affect the propagation of acoustic waves in the water.
- **Chapter 7** is focused on the subsea acoustic positioning systems. It describes subsea acoustic positioning systems commonly used for subsea operations: Ultra Short BaseLine (USBL), Long BaseLine (LBL) and Short BaseLine (SBL) positioning systems, Doppler Velocity Log (DVL) and Correlation Velocity Log (CVL). A particular attention is focused on their working principles, accuracies, applications and implementations on survey platforms in order to help readers to better manage operations of hydrographic surveys and inspection of subsea infrastructures.
- **Chapter 8** refers to inertial navigation system. It provides an introduction to inertial navigation to help readers to better understand the working principle of the inertial navigation systems, to know the various errors which characterize the inertial navigation systems, and to properly choose, deploy and use an inertial navigation system during survey operations.
- **Chapter 9** is focused on swath bathymetry survey systems. The aim of this chapter is to describe in depth the swath-mapping systems (multibeam echosounder and side scan sonar), the most used for mapping of subsea environment in order to help readers to better manage mapping projects. It presents the architecture, implementation, technical specifications of swath mapping systems and also the survey methodology for swath-mapping systems (mobilization, quality control, calibration, acquisition and processing of data, deliverables, etc.).
- **Chapter 10** is focused on systems suitable for operations of subsea infrastructures inspection (docks, channels, bridges, dams, subsea infrastructures, etc.). The purpose of this chapter is to describe in depth the systems commonly used for investigating the emerged and immersed parts of coastal and subsea infrastructures in order to help readers to better manage operations of subsea infrastructures inspection and ensure the monitoring and the durability of infrastructures.
- **Chapter 11** is devoted to sub-bottom profilers. It is to present various sub-bottom profilers which are commonly used for geophysical surveys such as chirp, pinger, parametric, boomer and sparker sub-bottom profilers. It describes briefly their characteristics, applications, working principles, and also their survey methodologies (installation, acquisition, processing and interpretation of seismic data).

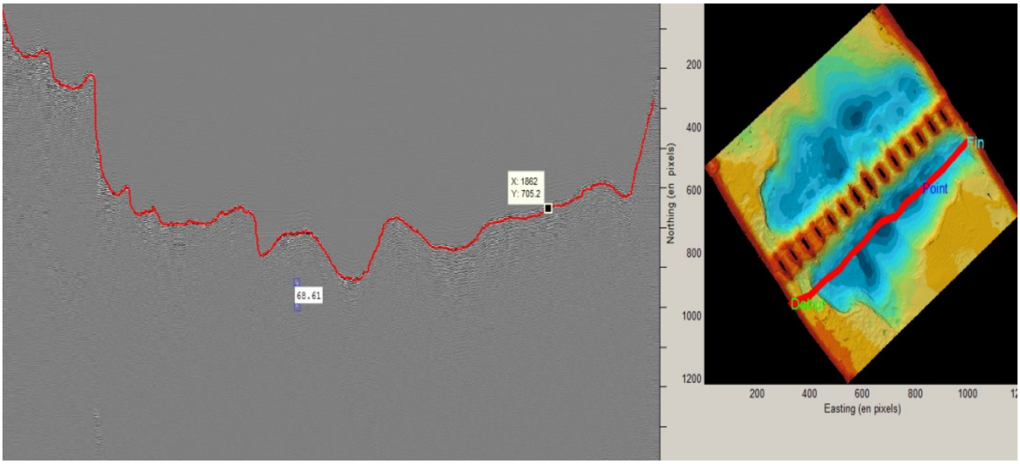

Figure 3: Analysis and visualization software of 2D seismic data (SEGY) (SUBCMARINE, 2017)

- **Chapter 12** refers to error budget analysis for multibeam echosounder (MBES) survey systems (see **Figure 4**). The purpose of this study is to estimate the measurement uncertainty on the sounding position acquired by MBES underwater and surface survey systems in order to enable readers to control quality of data acquired by MBES survey system. This chapter presents firstly the various errors which affect the quality of MBES, and the equations for geo-referencing MBES data to finally propose algorithms to estimate the error budget of MBES underwater and surface survey systems.

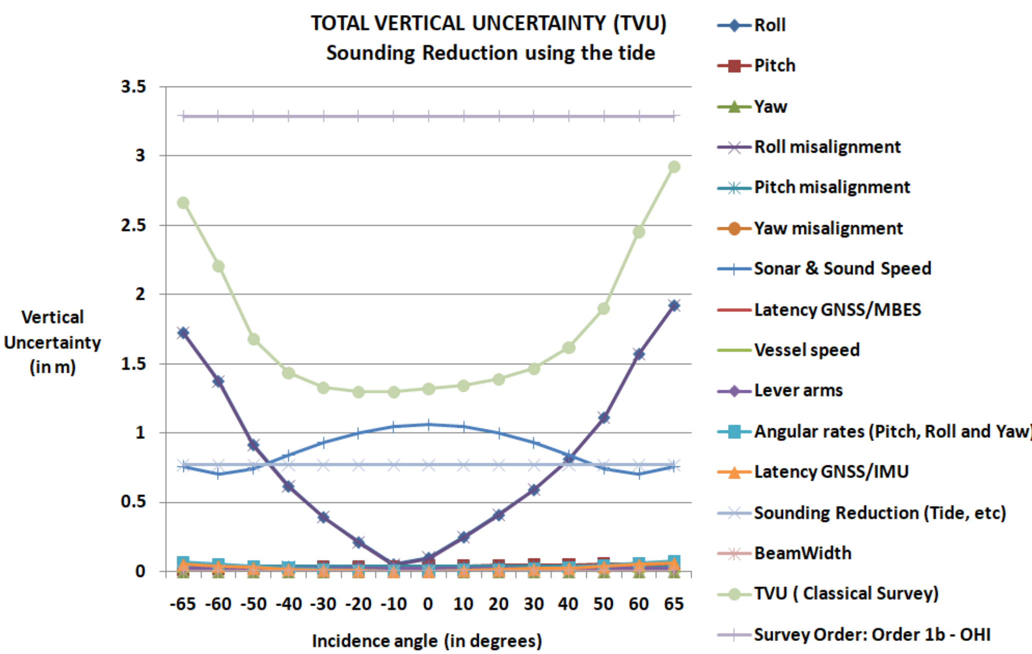

Figure 4: Total vertical uncertainty for classsical survey. For a depth=250 m, roll=6°, roll uncertainty=0.1°, roll misalignment=0.5°, Latency GNSS/MBES=0.1s, latency GNSS/IMU=0.01, angular rates uncertainties roll, pitch and yaw =0.1°, 0.1° and 0.2 °, etc.

According to Rabine KEYETIEU, Senior Geomatics Scientist at Geown Data Solutions, the new book: **“Basics of Hydrographic and Inspection of Subsea Infrastructures – Principles and Practice”** can be considered as a good tool for teachers and students involved in hydrographic surveying courses or program, because it covers many subjects of the standards of competence for hydrographic surveyors (S-5A and S-5B) defined by the International Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers such as: B1 (mathematics, statistics, theory of observations and errors), B2 (Information and Communication Technology), F1 (Earth models), F2 (Oceanography), H1 (Positioning), H2 (Underwater Sensors and Data Processing), H3 (LiDAR and remote Sensing), H4 (Survey Operations and Applications), H5 (Water Levels and Flow) and H6 (Hydrographic Data Acquisition and Processing) and other subjects related to inspection of subsea infrastructures. It presents many mathematical basics in positioning and also explains the theory behind the mathematical models in positioning with really good illustrations.

The new book: **“Basics of Hydrographic and Inspection of Subsea Infrastructures – Principles and Practice”** contains more than **250 detailed illustrations** and **100 recommendations** to enable readers to easily learn and perform operations of hydrographic surveys and inspection of subsea infrastructures and further. This book also contains references which are denoted by square brackets and listed at the end of book. These references contain additional information. Further information can also be found on my blog:

https://www.geraudnaankeuwati.com

Apart from my efforts, the success of my book largely depends on encouragements, advice and guidelines of many. I would like to thank especially Daris NEMBOT, Doriane TEGOUNDIO, Cynthia KAMTO and Dominic NDEH for carefully proofreading this book. I would like to also thank a few friends and members of hydrographic and topographic communities for their support, advice, encouragements, and helpful comments: Cees Van DIJK, Christophe PAGES, Dapo Owotuyi, Flora MELONG, Frédéric GUILLOT, Guy NANKAM, Harvey STOELINGA, Helen ATKINSON, Irène MOPIN, Helen AUKEN, Jean-Baptiste GELDOF, Jules GUILLOT, Michel HABERKORN, Nancy ONGOLO, Olivier SAMAT, Ouahib OUESLATI, Rabine KEYETIEU, Valter Ngako, Wilfride KAMTA and William KIAGE. I would like to thank also my parents Thérèse KANOUO and Maurice WATI, for values that they instilled in me and for fighting to finance my studies. I would like to thank particularly my darling Sandra TAGNE for her advices and for fighting to take care of me throughout writing this book. I would like to thank infinitely my teachers of ENSTA Bretagne: Amandine NICOLLE, Michel LEGRIS, Nathalie DEBESE, Nicolas SEUBE, Pierre BOSSER, Pierre SIMON, Roderic MOITIE and Thomas TOUZE from ENSTA Bretagne for their support and for initiating me in geodesy, hydrographic data processing, underwater acoustics, inertial navigation, oceanography, programming and Geographic Information System. Finally, I would like to thank my family, friends and colleagues for their encouragements and support.

"*Practice without theory is blind, Theory without practice is sterile"*

Emmanuel KANT

CHAPTER 1.

GENERAL INTRODUCTION

As part of subsea site investigation projects, the operations of hydrographic surveys and inspection of subsea infrastructures are more and more conducted simultaneously; because they enable to provide complementary information. The hydrographic surveys mainly enable, on the one hand, to provide hydrographic information (information of position, depth, tide, current and wave), the seabed nature and the first layers under the seabed, on the other hand the inspection operations enable to provide detailed images in order to better detect and follow the evolution of anomalies on subsea infrastructures, to do a state-of-the-art of the marine environment, etc… (see **Figure 5**).

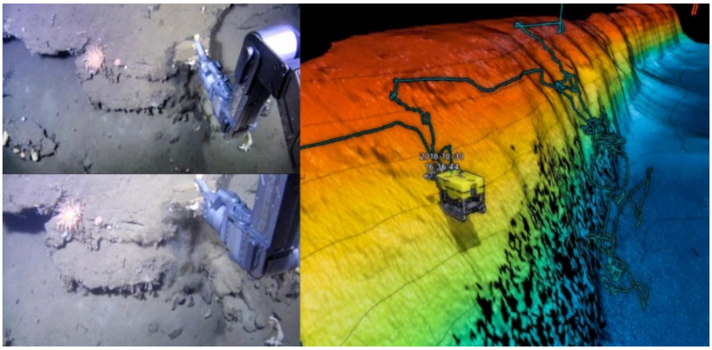

Figure 5: Subsea inspection and hydrographic surveys (Center For Artic Gas Hydrate, Environment and Climate, 2018)

These two operations are very useful for the effective management of subsea projects. In fact, they should be managed or conducted by professionals having solid basic knowledge of hydrography and inspection of subsea infrastructures in order to overcome numerous needs in the World such as:

- The safety of navigation,
- The knowledge more accurate maps and marine habitat,
- The monitoring and the durability of subsea infrastructures,,

Therefore, I decided to write this book to share my knowledge and field experience with stakeholders and the members of hydrographic and topographic communities in order to initiate them to some basic concepts that can help them to better manage or perform operations of hydrographic surveys and subsea infrastructure inspection from the bid response process to data analysis. From this of book, the readers should be able to do the following things:

- To present the importance of operations of hydrographic surveys and of subsea infrastructure inspection for the economic development of a country,
- To describe some applications of hydrography and inspection of subsea infrastructures (nautical charting, port, offshore engineering, hydroelectricity dam, etc…),
- To enumerate the international standards applicable to hydrographic surveys,

- To manage and perform the hydrographic surveys and inspection inspections,
- To create a successful survey department,
- To choose right software solutions for a survey company or a survey project,
- To setup and use subsea acoustic and GNSS positioning systems,
- To setup and use a tide gauge and explain the tide theory,
- To describe the concepts behind hydrographic survey systems and ancillary sensors,
- To control and assess the quality of survey data,
- To state the concepts and methods of survey data processing and acquisition,
- To install, configure, and calibrate an acquisition system for operations of hydrographic surveys and inspection of subsea infrastructures,
- To analyze hydrographic data, point cloud, acoustic and optical images,
- To promote hydrography and inspection of subsea infrastructures in the world, etc.

I will introduce the first chapter of the book by presenting briefly the fields of hydrography and subsea infrastructure inspection. This first chapter is divided into 3 sections. In the Section 1.1, I will define the notion of hydrography and present some techniques of hydrographic surveys. In the Section 1.2, I will define the notion of subsea infrastructure inspection and, I will present the importance of inspection for the monitoring and the durability of subsea infrastructures, and also some sensors commonly used for investigating subsea infrastructures. In the Section 1.3, I will describe some applications of hydrography and subsea infrastructure inspection such as: hydroelectricity dam, oil and gas, civil and dredging works, coastal infrastructures, confined spaces, etc…

1.1 WHAT IS HYDROGRAPHY?

The International Hydrographic Organization (IHO) defined Hydrography as a branch of applied sciences which deals with the measurement and description of the physical features of oceans, seas, coastal areas, lakes and rivers, as well as with the prediction of their change over time, for the primary purpose of safety of navigation. In addition to supporting safe and efficient navigation, hydrography serves as support in most of inlands, coastal and offshore activities, including: maritime transport and navigation, hydroelectricity power, defense and security, offshore oil and gas, subsea renewable energy, infrastructures and works of art, archeology, aquaculture, environmental works, civil works and dredging and galleries.

1.1.1 Hydrographic survey techniques

As part of inlands, coastal and offshore projects, the hydrographic companies or hydrographic offices are commonly solicited to produce marine information such as: bathymetry, geophysical, tidal and seismic information. This information is very important to ensure the safety of operations and navigation, to plan future repair works, etc... They are obtained through the following survey techniques, namely:

- Hydrographic surveys by echosounder,
- Geophysical surveys,
- Positioning,
- Tide prediction and support operations.

1.1.1.1 Hydrographic surveys by echosounder

A Hydrographic survey by echosounder is a survey technique which consists of describing physical features of seabed for primarily the safety of navigation of vessels and military submersibles (see **Figure 6**) based on determining the travel time of acoustic signal emits from an echosounder. When the purpose of the survey by echosounder is not to guarantee the security of navigation, it is usually called bathymetry survey. A bathymetric survey is however performed to determine the depth, know the morphology of the seabed, verify the position of existing subsea installations, detect anomalies and scouring areas on the civil engineering of subsea infrastructures, etc…

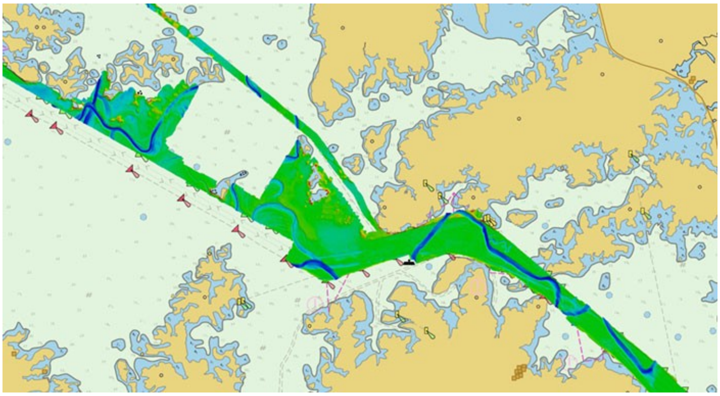

Figure 6: Hydrographic surveys performed to ensure the safety of navigation in Panama canal (Panama Canal Authority)

1.1.1.1.1 Classification of hydrographic surveys

To accommodate in a systematic manner different accuracy requirements for areas to be surveyed, four orders of survey have been defined by the IHO S44. These are described at **Table 1** below which summarizes the overall requirements that are in fact the essence of the complete standard.

1.1.1.1.2 Special order

Special order hydrographic surveys are intended to be restricted to specific critical areas with minimum under-keel clearance and where bottom characteristics are potentially hazardous to vessels. These areas have to be explicitly designated by the agency responsible for survey quality (harbors, berthing areas, and associated critical channels. All error sources which affected the accuracy of sounding measurement should be minimized or cancelled.

The use of side scan sonar, or multi transducer arrays, or high-resolution multibeam echo sounders is required to detect the feature size to be detected. In required areas, appropriate sounding equipment and methodologies must be employed in order to ensure that all features greater than 1m cubed are detected. The use of side scan sonar in conjunction with multibeam or multi-transducer echo sounders may be necessary in areas where pinnacles and dangerous obstacles may be encountered.

1.1.1.1.3 Order 1a

Order 1a hydrographic surveys are intended for harbors, harbor approach channels, recommended tracks, inland navigation channels, and coastal areas of high commercial traffic density where under-keel clearance is less critical and the geophysical properties of the seafloor are less hazardous to vessels (e.g. soft silt or sand bottom). Order 1a surveys should be limited to areas with less than 100 m water depth. Although the requirement for seafloor search is less stringent than for Special order, full bottom search is required in selected areas where the bottom characteristics and the risk of obstructions are potentially hazardous to vessels. For these areas searched, it must be ensured that cubic features greater than 2 m up to 40 m water depth or greater than 10% of the depth in areas deeper than 40 m can be discerned by the sounding equipment.

1.1.1.1.4 Order 1b

Order 1b hydrographic surveys are intended for areas with depths less than 200 m not covered by Special Order and Order 1a and where a general description of the bathymetry is sufficient to ensure there are no obstructions on the seafloor that will endanger the type of vessel expected to transit or work the area. It is the criteria for a variety of maritime uses for which higher order hydrographic surveys cannot be justified. Full bottom search is required in selected areas where the bottom characteristics and the risk of obstructions may be potentially hazardous to vessels.

1.1.1.1.5 Order 2

Order 2 hydrographic surveys are intended for all areas not covered by Special Order, and Orders 1a and 1b in water depths in excess of 100 m.

It is important to note that for Special Order and Order 1a surveys, the agency responsible for the survey quality may define a depth limit beyond which a detailed investigation of the seabed is not required for safety of navigation purposes. Side scan sonars should not be used for depth determination but to define areas requiring more detailed and accurate investigation.

Table 1: Summary of Minimum Standards for Hydrographic Surveys

Order	Special	1a	1b	2
Examples of typical areas	Harbors, berthing areas, and associated critical channels with minimum under keel clearances	Areas shallower than 100 m where under-keel clearance is less critical but features of concern to surface Shipping may exist.	Areas shallower than 100 m where under-keel clearance is not considered to be an issue for the type of surface shipping expected to transit the area	Areas generally deeper than 100 m where a general description of the sea floor is considered adequate.
Horizontal accuracy (95%	2 m	5 m +5 % of depth	5 m +5% of depth	20 m +5% of depth

confidence level)				
Depth accuracy for reduced depth (95% confidence level)	a= 0.25 m b=0.0075	a= 0.5 m b=0.013	a= 0.5 m b=0.013	a= 1 m b=0.013
100% bottom search	Required	Required	Not required	Not required
System detection Capability	Cubic features >1 m	Cubic features > 2 m in depths up to 40 m; 10% of depth beyond 40 m	Not applicable	Not applicable
Recommended maximum line spacing	Not defined as full sea floor search is required	Not defined as full sea floor search is required	3 x average depth or 25 m, whichever is greater. For bathymetric LiDAR a spot spacing of 5 x 5 meters	4 x average depth
Positioning of fixed aids to navigation and topography significant to navigation (95% confidence level)	2 m	2 m	2 m	5 m
Positioning of fixed aids to navigation and topography significant to navigation (95% confidence level)	10 m	20 m	20 m	20 m
Mean position of floating aids to navigation	10 m	10 m	10 m	20 m

(95% confidence level)				

The limits for total vertical uncertainty (TVU) or (depth accuracy of sounding) at 95% is function of parameters ‘a’ and ‘b’ listed in table above with the depth ‘d’ have to be introduced into the formula as below:

$$TVU = \pm\sqrt{a^2 + (b * d)^2}$$

Where:

- a represents that portion of the uncertainty which doesn’t vary with the depth
- b is a coefficient which represents that uncertainty portion that varies with the depth,
- d is the depth.
- b*d corresponds to the portion of the uncertainty that varies with the depth.

1.1.1.2 Geophysical site survey

The geophysical site survey is a survey technique which allows investigating subsurface structure (see **Figure 7**), particularly as related to exploration for petroleum, natural gas, and mineral deposits. This technique is based on determining the time interval that elapses between the initiation of a seismic wave at a selected shot point (the location where an explosion generates seismic waves) and the arrival of reflected or refracted impulses at one or more seismic detectors.

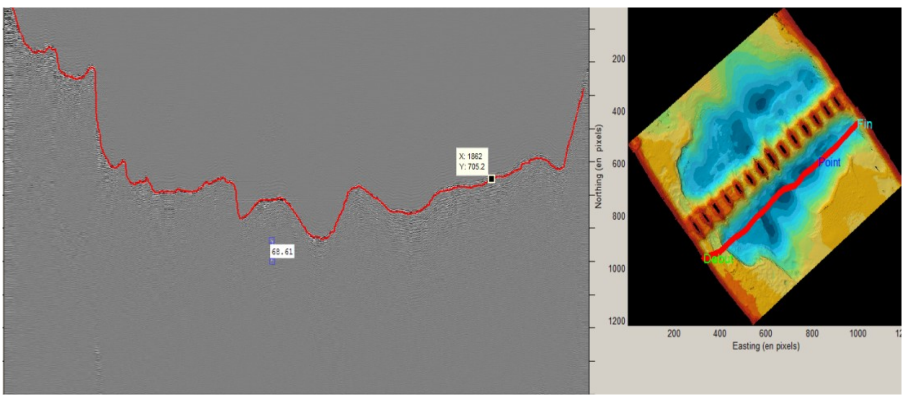

Figure 7: Analysis of subsurface of an area (SEGY) (SUBCMARINE, 2017)

1.1.1.3 Positioning

The positioning is a technique which enables to determine the position of survey platforms, hydrographic data, subsea infrastructures (pipelines, wrecks, etc.) and anomalies (cracks, free span, etc.) in local or global frame during site investigation operations. There are several methods of positioning, namely: subsea acoustic (Doppler Velocity Log, LBL (Long BaseLine), USBL (Ultra Short BaseLine), etc.), inertial and GNSS positioning. The positioning method used depends on several parameters such as the survey site (water or, air), the desired accuracy, etc...

It is important to note that the acoustic and inertial positioning systems are commonly used for positioning subsea vehicles and infrastructures in deep waters (see **Figure 8**).

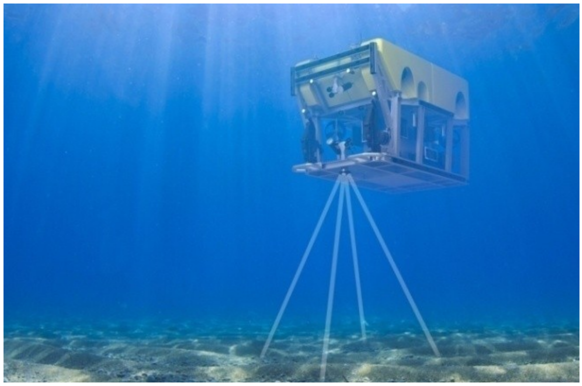

Figure 8: ROV positioning using Doppler Velocity Log and inertial navigation system (Nortek, 2018)

1.1.1.4 Tide prediction

The Tides are the variations of water level due to the gravitational attraction of the moon and sun on the liquid particles of the Earth. The knowledge of the tide prediction model in a survey site is very important; it enables to:

- Know in advance the schedules and water heights in order to plan the operations of mapping and subsea infrastructures inspection in inlands coastal and offshore areas.
- Determine the altimetry reference levels (for instance: the chart datum),
- Correct the depth measurements and attach them relative to the chart datum during survey operations,
- Plan boat entrances and exists in a harbor,
- Develop numerical models to predict the impact of evolution of the water level on coastal infrastructures, etc…

In a survey site, tide is predicted or calculated well in advance from algorithms of tide prediction because it depends only on constant parameters such as:

- The respective trajectories of the Earth, the Moon and the Sun,
- The configuration of the sea and coasts.

These algorithms of tide prediction are particularly developed by and national hydrographic offices and the METEOCEAN departments of private companies of survey.

1.1.1.5 Support operations

Support operations are survey operations which consist to monitor in real time engineering operations (research, oil & gas installations, subsea wind energy field, hydroelectric subsea turbine, pipes, cables installation, etc) using acoustic sensors such: 2D acoustic camera, multibeam echosounder, video camera, etc (see **Figure 9**).

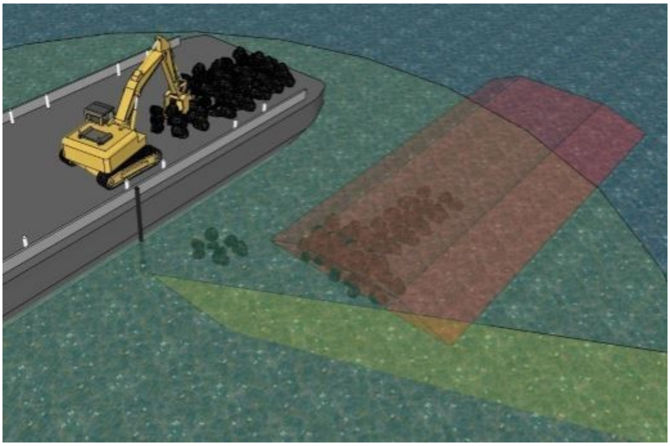

Figure 9: Support and monitoring in real time of the installation of objects on the seabed from 2D acoustic camera (Longchamp, 2018)

1.2 WHAT IS INSPECTION OF SUBSEA INFRASTRUCTURES?

The subsea infrastructures (dams, pipelines, bridges, offshore platforms, quays, dikes, channels, etc.) generally suffer from several types of deterioration (erosion, scaling, spalling, cracking, chemical attack, etc.), which are generally accelerate by the presence of oxygen, moisture, and chemicals in the water. These infrastructures present important security challenges, as their breaks would have catastrophic devastating environmental and human consequences, but also in economic terms, because of the high cost of rehabilitation works. In fact, inspection campaigns of these infrastructures are generally performed by hydrographic companies in order to ensure the safety and the durability of these infrastructures, the security of people, to reduce long-term costs as part of an asset management plan, etc…

1.2.1 Inspection techniques

In function support used, the inspection techniques can be divided into three categories:

- Inspection by divers: These inspections operations are performed by scuba divers using visual and conventional direct methods (see **Figure 10**).
- Inspection by tripod: The inspection by support is performed from sensors (camera video, GNSS receiver, etc.) installed on a tripod,
- Inspection by survey platforms (ROVs/AUVs/vessels): This type of inspection is performed in shallow and deep waters sensors (video camera, subsea LiDAR, acoustic camera, etc.) installed on survey platforms (ROVs/AUVs/vessels).

The choice of support to use mainly depends on several parameters such as the depth, the weather and environmental conditions, the desired accuracy, access and operational constraints, etc.

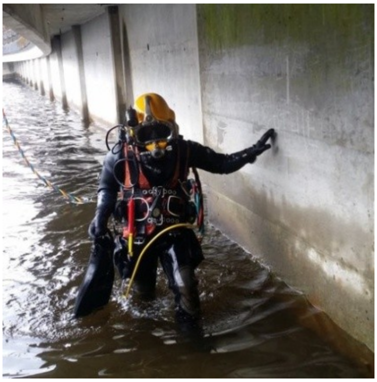

Figure 10: Visual inspection by divers (UK Diving Services, 2018)

1.2.2 Sensors for investigating subsea infrastructures

The sensors commonly used to investigate subsea infrastructures (dams, pipelines, bridges, cables, galleries, penstocks, quays of harbor, etc.) are the followings:

- **Video Camera**: it is particularly used to detect and follow anomalies of subsea infrastructures in less turbid waters. Because, it enables to provide high resolution images because in these conditions.
- **2D acoustic camera or imaging sonar**: it enables to obtain in real time high resolution images both in clear and turbid waters. The resolution of acoustic systems mainly depends on its distance relative to the seabed or target and the beam width. The sonar 2D is ideal to detect in real time cracks of minimum 2 cm.
- **3D acoustic camera**: it is particularly used to inspect in real time and in 3D images the subsea infrastructures.
- **Multibeam echosounders**: it classically used to know the morphology of subsea infrastructures with a resolution about centimeter (depending of depth and system performance) (see **Figure 11**).
- **3D subsea laser scanner:** it is commonly used to investigate the subsea infrastructures or map the seabed with a resolution and accuracy better than 1 cm.
- **Side scan sonar**: it is particularly used to inspect areas requiring more detailed and accurate investigation.

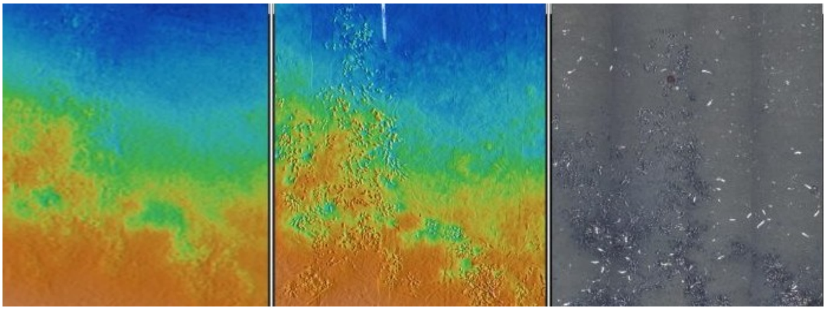

Figure 11 : Results from multibeam (5 cm resolution), 3D subsea scanner laser (1 cm) and color video camera(2 mm resolution) (3D at Depth)

1.3 APPLICATIONS OF HYDROGRAPHY AND INSPECTION OF SUBSEA INFRASTRUCTURES

The operations of hydrographic surveys and inspection of subsea infrastructures are commonly performed for many purposes such as:

- The safety of navigation,
- The monitoring and the durability of subsea infrastructures,
- The safety of people
- The positioning of survey platforms and subsea installations,
- The development of oil field, coastal infrastructures, offshore wind turbines, etc...
- The transportation of goods and property,
- The coastal zone management,
- The national defense and security at coasts,
- The preservation of marine habitation,
- The search of subsea infrastructures (for instance: wrecks),
- The detection of seabed features (like pockmarks, boulders, coral reefs, etc...).

In fact, the purpose of this section is to present some applications of hydrography and inspection of subsea infrastructures: hydroelectricity dam, lake, rivers, channels, offshore oil and gas, civil and dredging works, confined spaces, national defense and security and marine renewable energy.

1.3.1 Hydroelectric dam

1.3.1.1 Description of a hydroelectric dam

A dam is an engineering structure built across a watercourse and intended to regulate its flow and / or to store water, particularly for flood control, irrigation, the production of electricity, fish farming and a supply of drinking water. A dam which enables the production of electricity is usually called hydroelectric dams. The hydroelectricity dams are commonly investigated by the hydrographic companies in order to ensure their durability and the security of downstream people. Their frequency of inspection varies from one country to another and depends on legal requirements of country and the fall height of dam. In Brazil and France, there is a legal requirement to inspect all hydroelectric dams and power plants, every five to ten years. In function of the height of the fall and the flow of the water, these dams can be regrouped in 3 types: dams of high fall, medium fall and to water wire.

1.3.1.2 Types of hydroelectric dams

In function of their shape, the hydroelectric dams can be classified into three categories, namely: gravity dam, arch dam and buttress dam.

- **Gravity dam**

In concrete or stone, the gravity dam is the simplest and heaviest. It is vertical with respect to the reservoir and inclined with respect to the valley. It relies solely on the ground (see **Figure 12**). Thus, it opposes all its mass to the pressure of the water.

Figure 12: (A) Gravity dam, (B) Arch dam, and (C) Buttress dam

- **Arch dam**

The arch dam relies in part on rock walls (see **Figure 12**). Thanks to its curved shape, it postpones the pressure of the water on the banks. It can also be supported by buttresses. It inclines relative to the reservoir and vertical to the valley. It is commonly built in narrow valleys.

- **Buttress dam**

The buttress dam has a triangular buttress which allows it to postpone the pressure of the water towards the ground (see **Figure 12**). It is very light because its weight is reduced only to the foothills.

1.3.1.3 Working principle of a typical hydroelectric dam

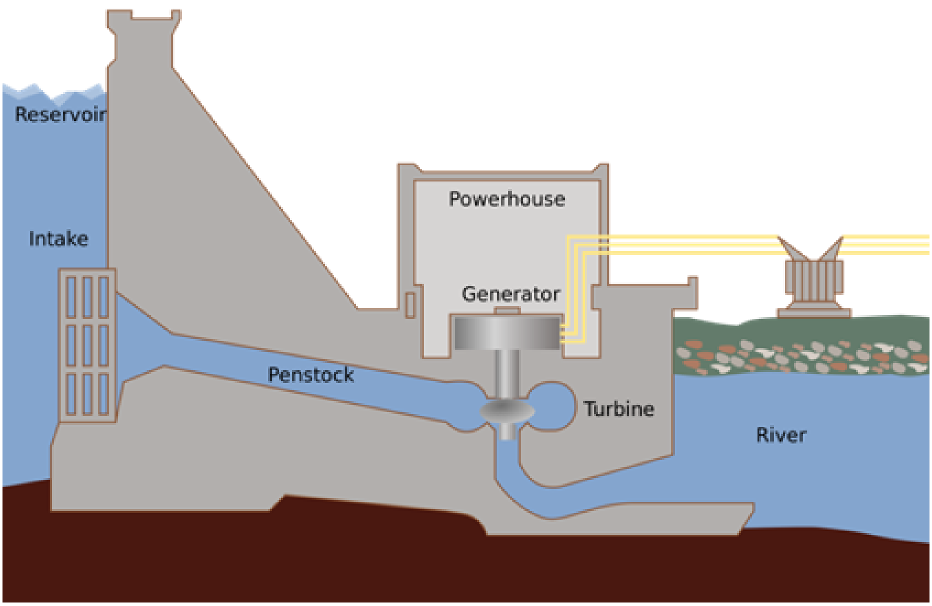

Figure 13: Elements of typical hydroelectricity dam (TVA, 2005)

A hydroelectric dam is basically composed of following elements (see **Figure 13**) to produce the electricity:

- **Water retention**

  Firstly, the dam retains the natural flow of water. Large amounts of water accumulate and form a reservoir[1].

- **Penstocks**

  Once the water is stored, valves of intakes are opened so that the water rushes into long metal pipes called penstocks. These pipes lead the water to the hydraulic power station, located below. Most hydraulic power plants are automated. Each plant starts according to a pre-defined program according to the electricity needs.

- **Electricity generation**

  At the exit of the pipe, in the power station, the force of the water rotates a turbine which in turn operates an alternator. Thanks to the energy provided by the turbine, the alternator produces an alternating electric current. The power of the plant depends on the height of the waterfall and the flow of the water. The more important they are, the higher this power will be.

- **Adaptation of the tension**

  A transformer raises the voltage of the electric current produced by the alternator so that it can be more easily transported in very high and high voltage lines. The turbined water that has lost its power joins the river by a special channel called tailrace.

Inspection operations are commonly performed for investigating various compartments of hydroelectricity dams (raft, penstocks, dams, intakes, etc.). These operations enable to provide valuable data to:

- Follow the evolution of anomalies (degradations and defaults) observed on the civil engineering of the various compartments (factories, intakes, penstocks, dams, riffles, weirs, etc…),
- Inspect the state of air power grids,
- Control the state of valves
- Detect leaks on the civil engineering,
- Check the condition of a road after frost, road accidents, etc.

The bathymetric surveys are also regularly performed in upstream and downstream of dams to:

- Check the state of seabed in the reservoir,
- Detect some seabed features: scour areas, boulders, etc…
- Know the fill rate and characteristics of accumulated sediments in the reservoir and bottom drain and forecast dredging operations (see **Figure 14**).

[1] A dam lake or reservoir is a body of water fed by runoff and or directly by one or more streams and formed upstream of a dam built for that purpose.

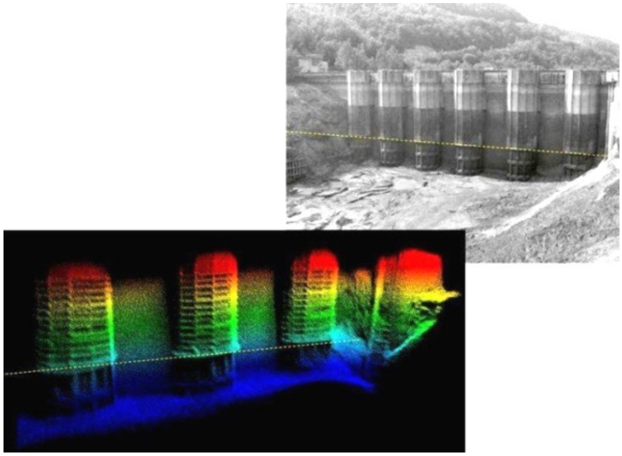

Figure 14 : Submergence study of dam at 50 m of water depth (Guillot, 2015)

1.3.2 Lake

A lake can be defined as a large expanse of water surrounded by water. It is fed by surface and / or underground water, more or less dependent on geological, meteorological and climatic conditions. The lakes are generally very calm environments, without agitation. The investigation operations (seabed mapping, oceanographic surveys, etc.) are generally performed in the lakes for many purposes such as:

1. **Seabed mapping**
   - To measure the depth variations in order to monitor the evolution of seabed and to ensure the security of navigation (see **Figure 15**),
   - To provide a precise knowledge of the area, volume, average and maximum depths,
   - To monitor erosion of banks of the lake, which is a major environmental issue,
   - To search wrecks, etc…
2. **Oceanographic surveys**
   - To analyze the water quality,
   - To measure the turbidity of the water, the flow rate of water, etc…

Figure 15 : Bathymetric survey of lake (ENSTA Bretagne, 2018)

1.3.3 Rivers and channels

The rivers and channels are navigational ways used daily by the vessels to transport goods and people to docks of port (or a mooring area, shelter, etc.) or to perform survey operations. To safely navigate, the vessels access to shelter (port, etc.) via a channel which has the greatest depth of water under the keel. The channel is usually delineated by regularly spaced beacons and a line of landmarks in order to confirm their correct positions in the event that beacons are degraded. In a channel, the buoyage conventions are peculiar: the shape and the color of the beacons are codified under the name of lateral marking system. Signs of important channels are lit by fires at night. The rivers and channels have significant economic importance for countries with a well-equipped waterway network such as the France, the England, etc. Thus, hydrographic surveys and inspection campaigns are regularly performed in these areas to:

1. **Bathymetric surveys of control**
   - Verify the presence and positions of beacons or markers,
   - Measure the depth variations in order to monitor the evolution of seabed and to ensure the security of navigation, etc.
   - Check the quantity of dredged material volume during dredging operations,
2. **Bathymetric surveys of reconnaissance**
   - Determine the waterways,
3. **Inspection campaigns**
   - Search wrecks,
   - Assess the state of the submerged (docks, banks, etc.) (see **Figure 16**) and emerged parts.

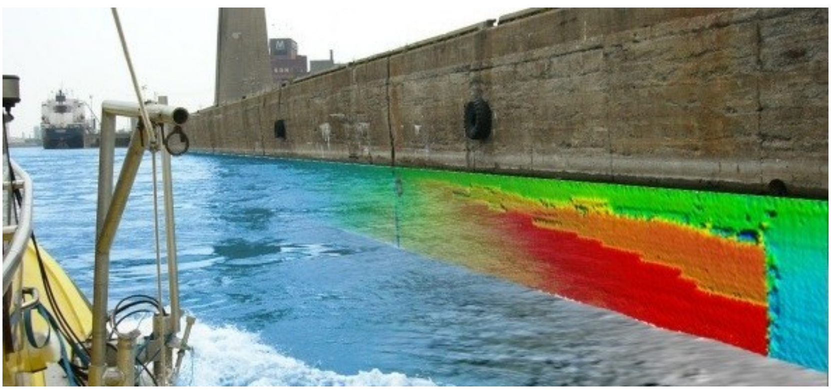

Figure 16: Inspection of port's docks (CIDCO)

It is important to note that the rivers are sometimes very particular environments. They are generally influenced by the particular hydrodynamic and hydrologic phenomenon (strong turbidity, strong current, high tidal range, strong debit etc.) which affect the time of operations, the data quality, the water quality, the transport and the deposition of fine sediments and siltation of the channels. It is the case of Garonne's river at Bordeaux in France (see **Figure 17**) where the survey operations can only be performed during periods the high and low tide slack due to strong current and turbidity during flow and ebb. It is very important to take into account these operational constraints during the planning of operations in this kind of environment.

Figure 17 : Garonne's river estuary in Bordeaux-France. It is characterizes by strong turbidity and currents

1.3.4 Coastal infrastructures and works of art

The coastal infrastructures and works of art (dykes, banks, bridges, etc.) are generally monitored and investigated by the companies specialized in inspection of subsea infrastructures to ensure their safety and durability. The inspection operations on these infrastructures are generally related to:

- A general aspect control of civil engineering (see **Figure 18** and **Figure 19)**,
- A check of the good functioning of various compartments: opening / closing of the valves, descent / rise of the hammers, maneuver of the removable parts,
- The knowledge of the distribution of materials,
- The calculation of volumes,
- An audit of the state of maintenance of infrastructures, etc...

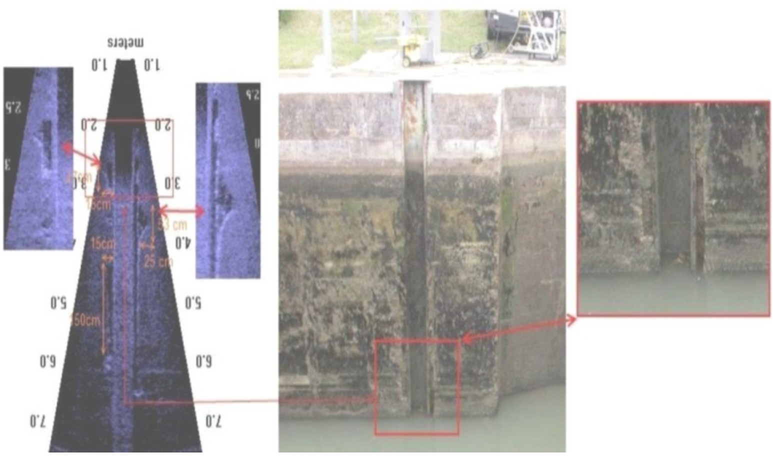

Figure 18: Inspection of lock (Guillot, 2015)

Depending on inspection area, the inspection methods can be classified into two types, namely:

- **Visual and acoustic inspection of the civil engineering**, using hydrographic and inspection techniques (GNSS receivers, the optic and acoustics cameras, the multibeam echosounders installed on a tripod, survey platforms or divers).
- **Internal inspection of the civil engineering**, using destructive methods (geophysical techniques) and non-destructive methods electromagnetic methods).

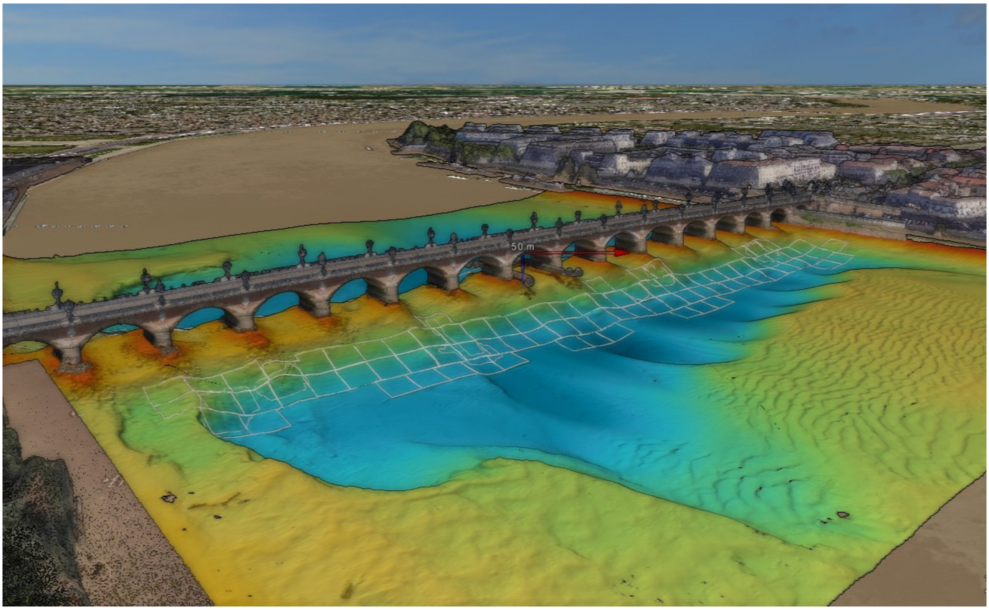

Figure 19: Bathymetric and topographic surveys of Pont de Pierre via a surface vessel (SUBCMARINE, 2018)

1.3.5 Offshore oil and gas

As part of projects (installation of subsea infrastructures (pipelines, subsea wells, manifolds, risers, drill centers (see **Figure 20**), etc.), asset integrity management program of oil fields, etc.), necessary for development of hydrocarbon resources, while ensuring the safety of operations and human life. Oil and gas companies regularly contract hydrographic and subsea inspection companies to conduct survey operations such as: seabed mapping, offshore geophysical soil investigations, subsea installation baseline survey. These companies mainly use two types of survey systems: surface survey systems (generally used in near shore and in shallow water (0-100 m)) and underwater survey systems (generally used in offshore and in deep offshore (100-3000 m)). These systems are generally equipped with several sensors to perform at the same time operations of hydrographic surveys and inspection of subsea infrastructures.

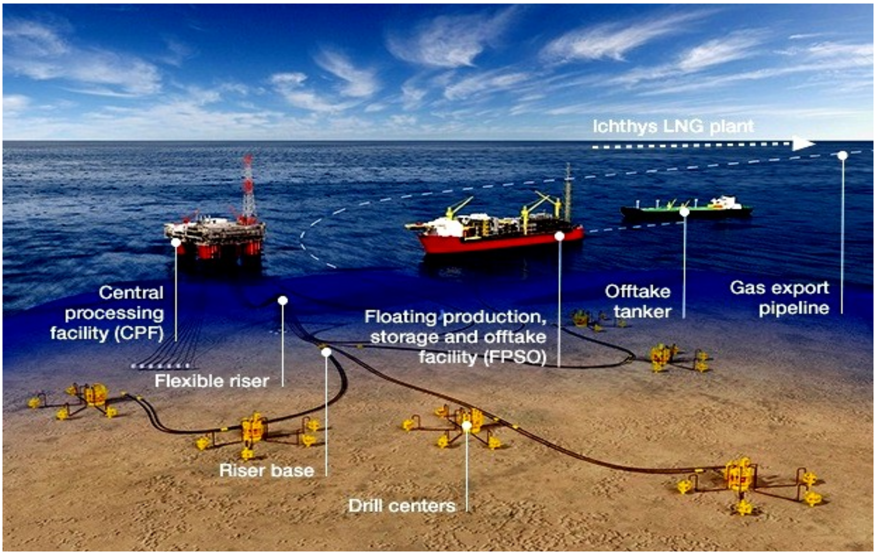

Figure 20: Major systems in subsea oil field development (Mant, 2016)

The survey operations are commonly performed to:

1. **High resolution reconnaissance or control surveys**
   - Verify the positions of existing subsea infrastructures (manifolds, risers, pipelines, jumpers, etc.) and seabed obstructions (wrecks, debris, boulders, etc.).
2. **Inspection operations**
   - Measure the water depth variations and slope changes,
   - Detect the magnetic metals buried in the seabed (pipelines, flexible risers, etc.).
   - Create photo mosaics of subsea infrastructures (pipelines, manifolds, etc.)
   - Create an accurate 3D modeling of pipelines and adjacent seabed (see **Figure 21**),
   - Investigate the subsea infrastructures (pipelines, risers, drill centers, etc.) in order to assess pipeline displacement (free span, lateral buckling, etc.),
   - Identify the areas of interest for further detailed inspections.

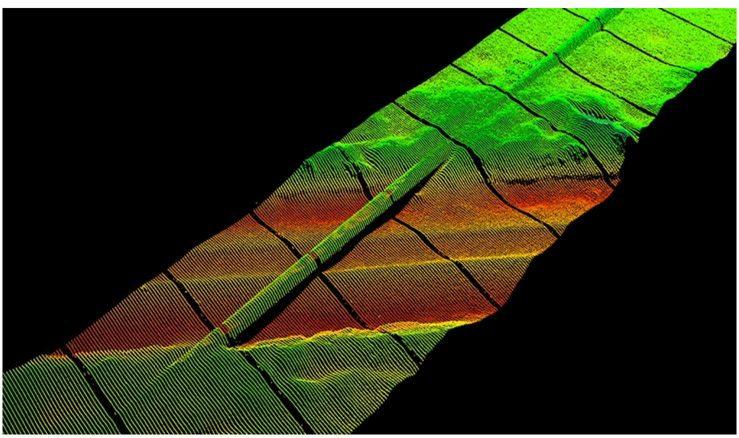

Figure 21: Pipelines inspection by AUV in Angola in 2014 (Cauquil, Geldolf, & Latron, 2017). On this image, you can observe a free span.

3. **High resolution 3D investigation surveys**
   - Investigate sub-seabed conditions,
   - Evaluate any shallow geohazards (slope stability, probability of shallow gas, etc.) in the first 100 meters under the seabed,
   - Investigate anchoring conditions,
4. **Support and monitoring in real time of installation operations in sea**
   - Guide machines,
   - Install or investigate subsea structures on the seabed (see **Figure 22**),
   - Remove some jams or objects on the seabed,
5. **Subsidence monitoring along predefined routes**
   - Establish the water depth variations and slope changes,
   - Investigate the local seabed/sub-seabed conditions.
6. **Search**
   - Search wrecks, shallow gas or leaks,

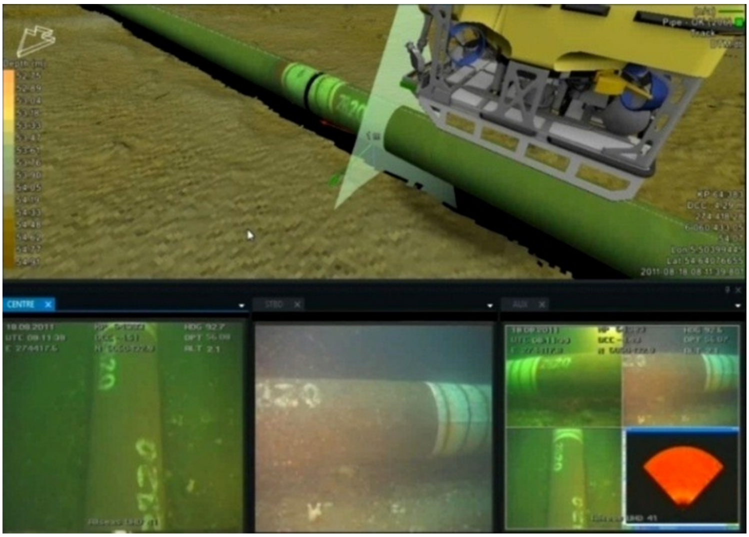

Figure 22: Pipelines inspection by ROV providing multiple data: video, bathymetry and sonar imaging (EIVA, 2015)

The dataset acquired (bathymetric, 3D laser scanner, GNSS, video and seismic data, sonar imaging, etc.) during these various operations are generally federate on single geospatial platform in order to help various stakeholders of project (Specialists and Experts in hydrography, geotechnique, geophysics, geomatics, oceanography, etc.) to make some analyses such as (see **Figure 23**):

- Stress and displacement analysis of pipelines (free span, lateral buckling, etc.),
- Analysis the state of subsea structures in order to detect any corrosion problems, etc…

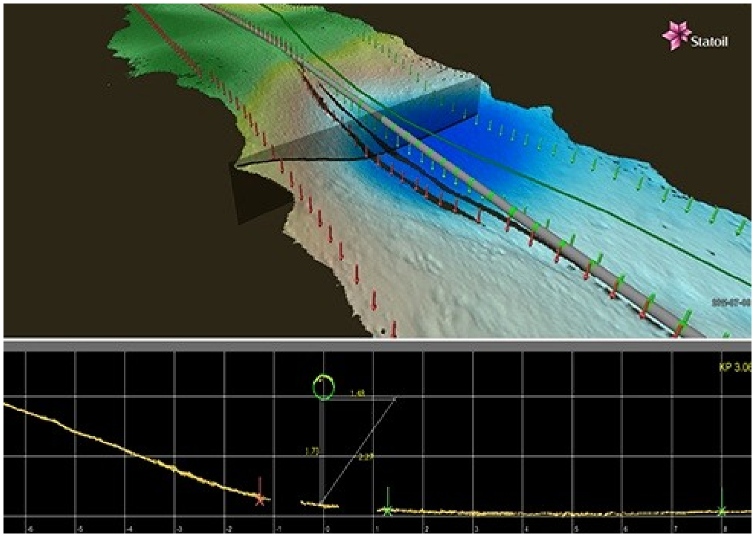

Figure 23: 3D and 2D free span analysis of pipeline (EIVA, 2018)

And to take further decisions for various purposes:

- Achieve the objectives of the project while ensuring the safety of all operations throughout the oil field's life and limiting all major hazards in the oil field (pipelines corrosion, collapse of the oil platform, natural hazards, leaks, etc.) (see **Figure 24** below),
- Define an optimal solution for future development projects.

Figure 24: Potential hazards in the oil field if the survey operations are not regularly performed (Fulop, 2015)

1.3.6 Civil and dredging works

As part of from civil and dredging works such as comfort works of bridge's stakes, port's dredging, stakes inspection, the hydrographic companies are generally solicited to perform operations of hydrographic surveys and inspection of subsea infrastructures in order to ensure the durability of works, the safety of navigation, etc…

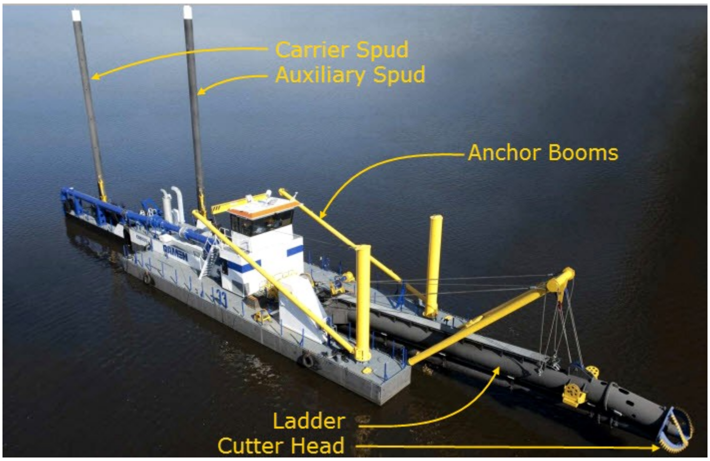

Figure 25 : A dredger (QPS, 2018)

The investigation operations (seabed mapping, support operations, etc.) are commonly performed from multiple platforms such as: dredger (see **Figure 25** above), pontoon and vessels for multiple purposes such as:

1. **Seabed mapping**
 - To measure the depth variations in order to monitor the evolution of seabed and to ensure the security of navigation of various platforms (vessels and pontoons),
 - To provide a precise knowledge of the area, volume, average and maximum depths,
 - To identify the areas of interest of filling,
 - To determine the volume to fill and dredge.
2. **Support and monitoring in real time of civil operations**
 - To guide machines,
 - To install objects on the seabed with a centimetric accuracy,
 - To remove some jams or objects identified on the high resolution bathymetric maps,
3. **Bathymetric surveys of control**
 - To verify the position of objects (rock fillets, gabions, etc.) installed during civil operations,
 - To validate the filling of various pits,
 - To verify the positions of subsea installations (beacons, markers, etc.),
 - To verify the volume of dredged material volume during dredging operations (dredging surveys),

1.3.7 Confined spaces

The operations of hydrographic survey and inspection are generally performed in the confined spaces (galleries, tunnels and pipelines) using video cameras, multibeam, 3D laser scanner (see **Figure 26**) in order to:

- Do a state of the art of work and examine the configurations (geological, hydro-geological, geometrical, environmental, etc.) in order to better understand the instability phenomena and their initiating mechanisms (INERIS, 2018),
- Detect some anomalies,
- Model in 3D the confined subsea spaces to make the flow simulation of fluids
- Accurately calculate the volumes of cavities,
- Detect some obstructions or seabed features,
- Digitize and to follow the evolution of the most critical sectors, etc…

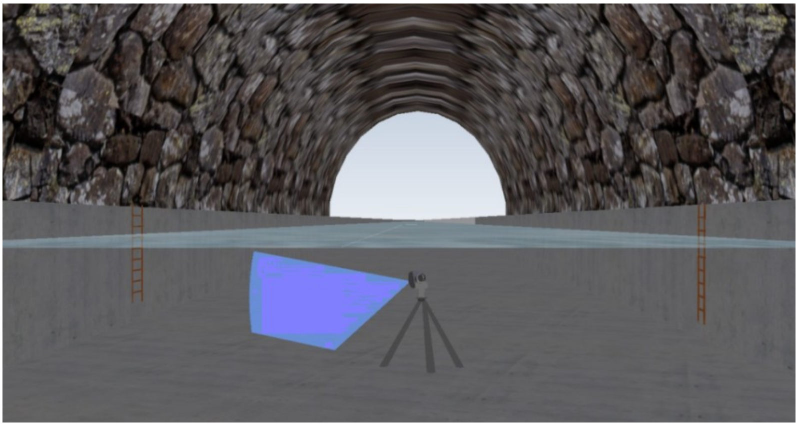

Figure 26: Inspection of a gallery from on 3D scanner laser mounted on a tripod

1.3.8 National defense and security

For national defense and security, the national navy of each coastal state needs marine information (such as point coordinates and bathymetric charts of subsea zones) to support their operations in sea and to ensure safety of their surface or sub-surface navigation. This information also aids in naval operations against terrorism, privacy, smuggling and other illegal and anti-safety activities (detection of mines, obstacles, etc.) as well as in decision making that ensure national and international security. It is mainly obtained from hydrographic surveys and inspection operations performed by themselves, the national hydrographic offices or private companies.

1.3.9 Marine renewable energy

For marine renewable energy projects necessary to produce clean source of energy (see its working principle on **Figure 27**), the hydrographic and geophysical surveys (multibeam, side-scan sonar, sub-bottom profiler, magnetometer, etc,) are generally performed jointly with inspection operations to support and facilitate the engineering operations at every stage of project. The objectives of these survey campaigns are multiples, such as:

1. **Reconnaissance surveys**
   - To measure the depth variations in order to monitor the evolution of seabed and to ensure the security of the navigation of various platforms (vessels and pontoons),
   - To provide a precise knowledge of the area, volume, average and maximum depths,
   - To map the sub-bottom geology or improve the understanding of geology of the survey area,
   - To identify and study cable routing, etc…
2. **Geophysical site investigation**
   - To measure the thickness of layers under the seabed,
   - To highlight and assess any potential geohazards,
   - To detect archaeological-related anomalies at a sensitive site of high archaeological significance.
   - To map buried objects, etc..
3. **Inspection of subsea infrastructures**
   - To perform a diagnostic of the state of various subsea infrastructures (wind turbine, subsea cable, tethers or mooring lines, sea anchoring system, etc.)
4. **Route surveys**
   - To investigate cable routing and installation site options for the infrastructure,
   - To assess electrical cable route corridor selection,
5. **Control surveys**
   - To verify the positions of subsea infrastructures (tide gauge, anchor, electrical cable, mooring lines, turbines, etc...) of a wind farm.

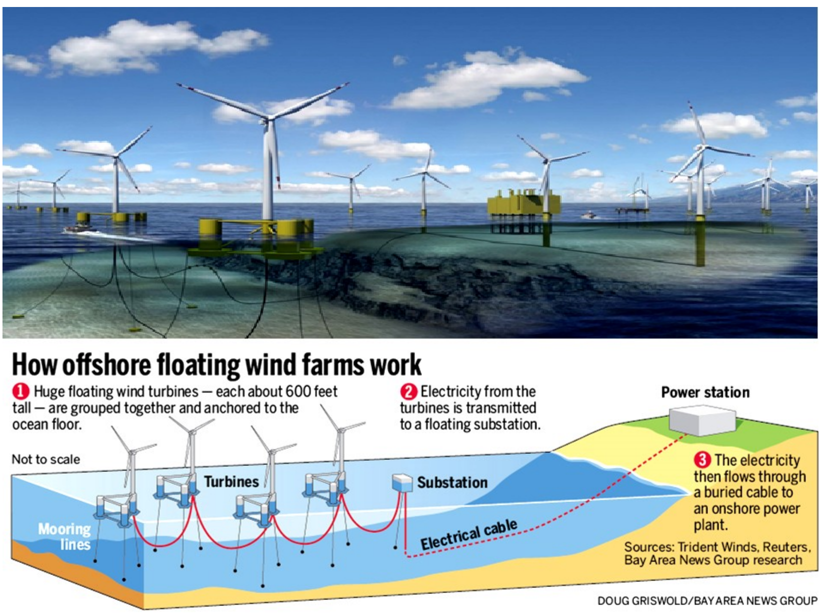

Figure 27: Marine renewable energy – Working principle (PRINCIPIA, 2018)