Deformation analysis of harbour and dam infrastructure using marine GIS

ABSTRACT

The standard methodologies for infrastructure monitoring in a port environment rely on visual inspection by divers, and are necessarily ad hoc, infrequent, and dependent on favourable conditions. While systems have been deployed to take advantage of laser scanning and multibeam data collection capabilities, it has been a challenge to present the results in a way that facilitates deformation analysis and decision making.

Many analysis tools operate on sampled representations, such as raster surfaces. It is known that standard raster surfaces become increasingly poor representations of the seafloor as the slope increases, and become unusable as the slope approaches vertical. However, the problem is not with the raster surfaces themselves, but their orientation. If the coordinate reference system of raster surfaces could be aligned to a vertical quay wall, for example, these raster surfaces could be used to create a more representative model of the current state.

This article covers the needs of data acquisition for infrastructure monitoring, and discusses how GIS tools working on raster surfaces allow a wide breadth of analysis operations. That includes the visualization of the current state of the infrastructure, the detection of changes, and the calculation of the volume of deformations.

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PRESENTER BIOGRAPHY

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INTRODUCTION

In recent years, the use of acoustic technologies for infrastructure inspections has emerged naturally in response to the poor visibility and conditions encountered by divers and Remotely Operated Vehicles (ROVs). From 2010 to 2012, the CIDCO proposed and evaluated a new survey method based on a hybridised multibeam echosounder (MBES) and Light Detection and Ranging (LiDAR) capture solution to quickly obtain a complete and accurate 3D model of an infrastructure at a decimetre resolution (Rondeau and Pelletier, 2012; Rondeau et al., 2012). However, beyond the classical 3D point cloud representation of the scanned infrastructure, managers and engineers need to be provided with a range of 2D products suitable for informed decision making.

Traditionally, GIS tools used to model 3D sonar and LiDAR data in the subsea environment have focused on gridding the seafloor, which is a nearly horizontal plane. These tools have limitations when creating raster surfaces to represent vertical and near vertical structures encountered during infrastructure inspection surveys as referenced above.

In late 2013, a project was initiated by the Montreal Port Authority with CARIS[1] to further address these challenges through the use of commercial software tools. A goal of the project is to provide engineers and decision makers with a GIS product to enhance infrastructure analysis. This resulted in CARIS making improvements to the Engineering Analysis Module^{TM}, part of the Bathy DataBASE^{TM} suite, to support the modeling of vertical features commonly found in the port environment. It also included a series of enhancements to support the visualization, deformation analysis, and database storage of raster surfaces for vertical structures.

The capabilities to accurately model and analyze vertical features in a GIS environment have applications in the port and waterway environment, but also apply to the monitoring of dams and surveying of other subsea structures using sonar and laser scanning technology. Survey methods and earlier approaches developed by the CIDCO to facilitate infrastructure inspection, as well as the current vertical feature modeling capabilities of the Engineering Analysis Module are further detailed below. The application of the technology is also explored through initiatives undertaken by the CIDCO in recent years. This includes the establishment of a test bench at Port of Rimouski to support research and training, as well as the inspection of the Hydro-Quebec Romaine 2 dam.

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[1] This term is a trademark of CARIS (Universal Systems Ltd.), Reg. USPTO & CIPO.

TECHNOLOGY SUMMARY

Conventionally, MBES are used to acquire bathymetry and backscatter imagery of the seafloor. Water column data is also collected to aid in activities such as least depth detection. Processing solutions, such as HIPS[2] and SIPS[3], have been used to efficiently process these sonar data types, which include the creation of a raster surface to model the seabed. Although HIPS and SIPS processes the sonar data types effectively, the gridding algorithms used by it and other processing solutions are best designed for the standard use case of nearly horizontal surfaces.

More recently, sonar systems have been installed in innovative ways to collect information about other submerged structures, including vertical quay walls. The assumptions embedded in the software made it difficult to create an effective digital terrain model for these surfaces. To work around this limitation, the CIDCO prototyped 3 solutions based on HIPS and SIPS and Matlab software packages (Leblanc et al., 2012) in order to produce a vertical digital terrain model (VDTM) of a quay wall.

CIDCO Prototypes

The first prototype is based on HIPS and SIPS only. It involved introducing a 90° rotation for the MBES in the HIPS and SIPS vessel file to manipulate the software into believing that the quay wall is the seabed, and vice versa (Figure 1 – top). The second prototype is based on HIPS and SIPS and Matlab. First, the dataset was processed with HIPS and SIPS and then Matlab was used to filter and grid the dataset using an inverse-distance Weight Moving Average (WMA) algorithm (Figure 1 – middle). The third prototype is based on Matlab and HIPS and SIPS. The 90° rotation was performed directly in the raw data files (*.XTF) with Matlab and then the dataset was processed and gridded with HIPS and SIPS (Figure 1 – bottom).

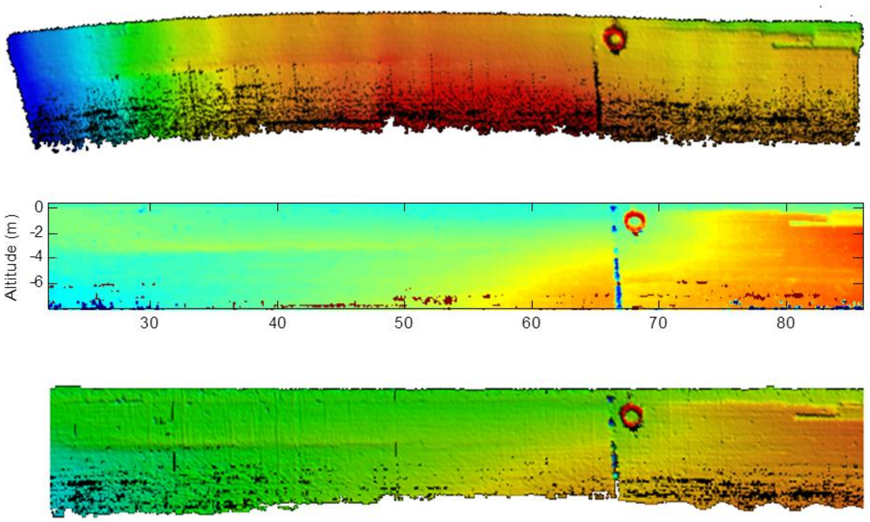

Figure 1 : VDTM of a quay wall section at the Port of Montreal. Top: vessel file 90° rotation HIPS and SIPS). Middle: Inverse distance WMA filter (HIPS and SIPS-Matlab). Bottom: XTF file rotation (Matlab-HIPS and SIPS).

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[2] This term is a trademark of CARIS (Universal Systems Ltd.), Reg. USPTO.

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The third prototype allowed the CIDCO to produce, for various clients, VDTMs of quay wall infrastructures that can be used to derive: 1) deformation maps (Figure 2), 2) acoustic backscatter maps and 3) series of longitudinal and transverse profiles.

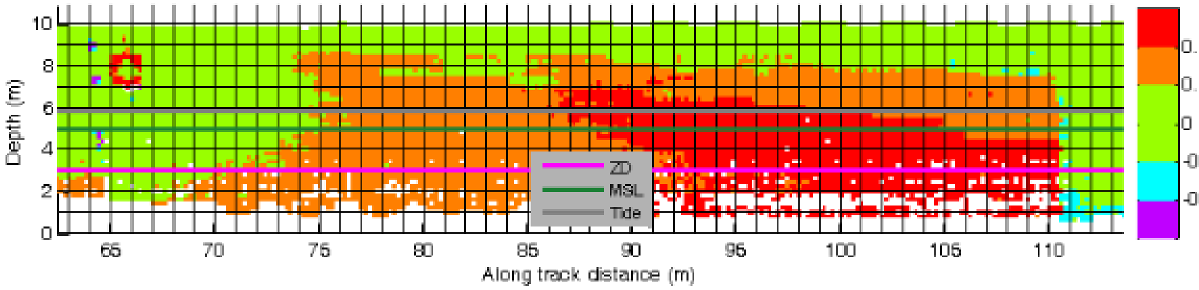

Figure 2 : Five colour deformation map. The colour scale goes from green (no deformation compared to the structure's theoretical position) to purple (more than 60cm of gouging) and to red (more than 60cm protruding).

CARIS followed up on the CIDCO's findings and developed a plan to model vertical surfaces as another coordinate reference system. The plans were presented at the CIDCO's Symposium on Underwater Inspection Challenges (Leblanc and Brodie, 2013).

Engineering Analysis Module

Through a project with the Montreal Port Authority, CARIS determined how best to integrate the vertical surface modeling functionality in the Engineering Analysis Module. This module already supported the modeling of infrastructure, such as waterway channels and port berths, as a collection of three dimensional planes – inclined and/or horizontal at specified depths. It also offered a variety of functions to easily compare data collected to the theoretical reference model, to visualize how the current state conforms to the model in 3D, in top-down 2D views and cross-section profile views. Several algorithms suitable for high density data were available to calculate the volume of material above the model, and create features where the data does not conform to the model. While reference models had supported vertical steps between areas maintained at different depths, the vertical plane of the step itself had not previously been considered of interest. Now, it had become apparent it needed to become an integral of the model, in order to define a basis for a wide breadth of analysis operations on vertical structures. That includes the visualization of the current state of the infrastructure, the detection of changes, and the calculation of the volume of deformations.

While a collection of 3D points produced from the processing of a sonar and/or laser scan dataset is difficult to analyze, a raster surface representation of the processed data is well suited to a wide variety of analysis tools. However, the existing gridding algorithms were dependent on coordinate reference systems that are aligned with a projection representing a flattened, horizontal geodetic datum that is a valid approximation of a certain area. A new way to reference the coordinates was required that could support vertical and inclined areas. It was decided that the spatially limited planes that form the reference model would be an ideal referencing system, where each plane could be used as the coordinate referencing system for a raster surface.

In addition to simply defining the spatial location and extent of the vertical planes of interest, it is also necessary to define the direction the plane is facing. This controls whether data is considered to be above or below the plane, and accordingly whether the values are positive or negative.

With standard planes representing the seabed or channels, it is generally safe to assume that values vertically above the plane are positive and below are negative. That convention could not be applied to vertical planes. It was decided that if there were pre-existing parts of the model above and/or below the plane, the most intuitive way to define a positive direction for the plane was for it to be facing out over the lower part of the model. If the model is not already defined in that area, the software would propose a direction for the plane, but the user would have the option to override the direction.

Another consideration is to limit the points contributing to any given raster surface. This is needed because the default gridding strategies consider all points infinitely far from the plane. This does not work when two quay walls meet at an acute angle, or when there is a bridge pier or other infrastructure that is surveyed close to the quay wall. As a result, a tolerance distance above and below each plane can be defined, relative to the planar normal (Figure 3).

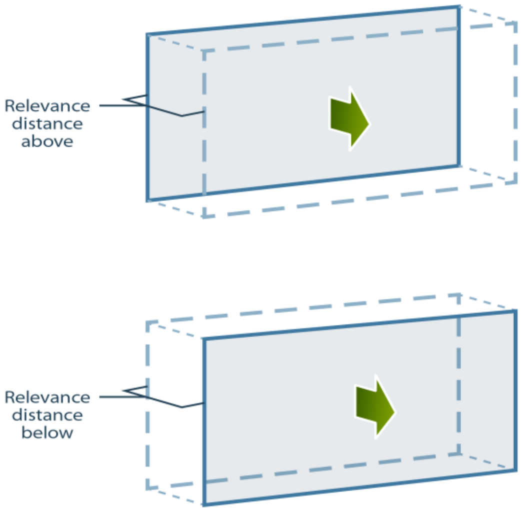

Figure 3 : Relevance distance above and below a vertical reference plane

For completeness, a relevance distance around each plane can also be defined to enlarge the area considered for the raster surface (Figure 4). This can be used to ensure the raster surface covers the entire area of interest. The same type of relevance distances can also be defined for horizontal or inclined planes.

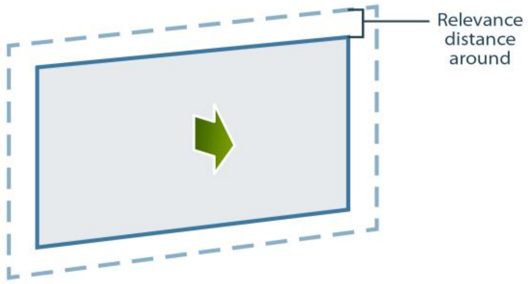

Figure 4 : Relevance distance around a vertical reference plane

With the planes defined with a given location, extent and direction, there is sufficient information to define an unambiguous coordinate reference system for new raster surfaces. Also by setting appropriate distances, the standard gridding algorithms, such as an inverse distance weighting methodology or a bias to preserve the points that are the farthest from the plane, can be used to create raster surfaces based on the surveyed data. By creating the raster surface relative to the plane, the values for the nodes already represent the variation from the theoretical model, and can be used to find areas of deformation or where tidal forces are causing the structure to wear down.

The raster surfaces can also be displayed meaningfully in a top-down 2D view and 3D view, and the data can be queried to find the 3D location and the distance from the plane at each point. Distances and angles can also be measured to locate points of interest, and interpolation can be used to fill holes in the surface. Perhaps most importantly, differences between two raster surfaces defined with respect to the same plane can be computed. This allows analysis to be performed on the deformation that occurs between surveys and detect any changes.

USE CASES AND RESULTS

Port Infrastructure Inspection (CIDCO Test Bench)

In the spring of 2013, the CIDCO and its many partners, including infrastructure managers and owners, engineering consulting firms, equipment suppliers and software engineers, launched an infrastructure inspection expertise centre in Rimouski (Quebec). The objectives of the centre are:

- to intensify research and development (R&D) efforts already in progress and allow Canadian companies to remain well positioned on the international market,
- to establish a training centre to assist companies interested in taking control of newly available inspection equipment, and
- to develop a certification centre to assess the performance of new equipment and support the legitimacy of their use with clients.

The installation of a test bench at the Port of Rimouski serves each of these three objectives.

The test bench detailed specifications were defined by the CIDCO. It is composed of 6 concrete panels, each one including different shapes of different sizes protruding or gouging (Figure 5 – left). Before the installation, the 6 panels were scanned at a millimetre resolution with a HandyScan 3D by Creaform (Figure 5 - right). Once in place on a quay wall at the Port of Rimouski, the test bench was surveyed so that each feature is properly georeferenced. In that way, by using an acquisition system to scan the test bench, one can evaluate how it performs to detect shapes and how well it can size and position them. Because the performance of an acquisition system depends on many parameters, the added value of such an artificial but very well controlled infrastructure is to allow the evaluation of each parameter separately.

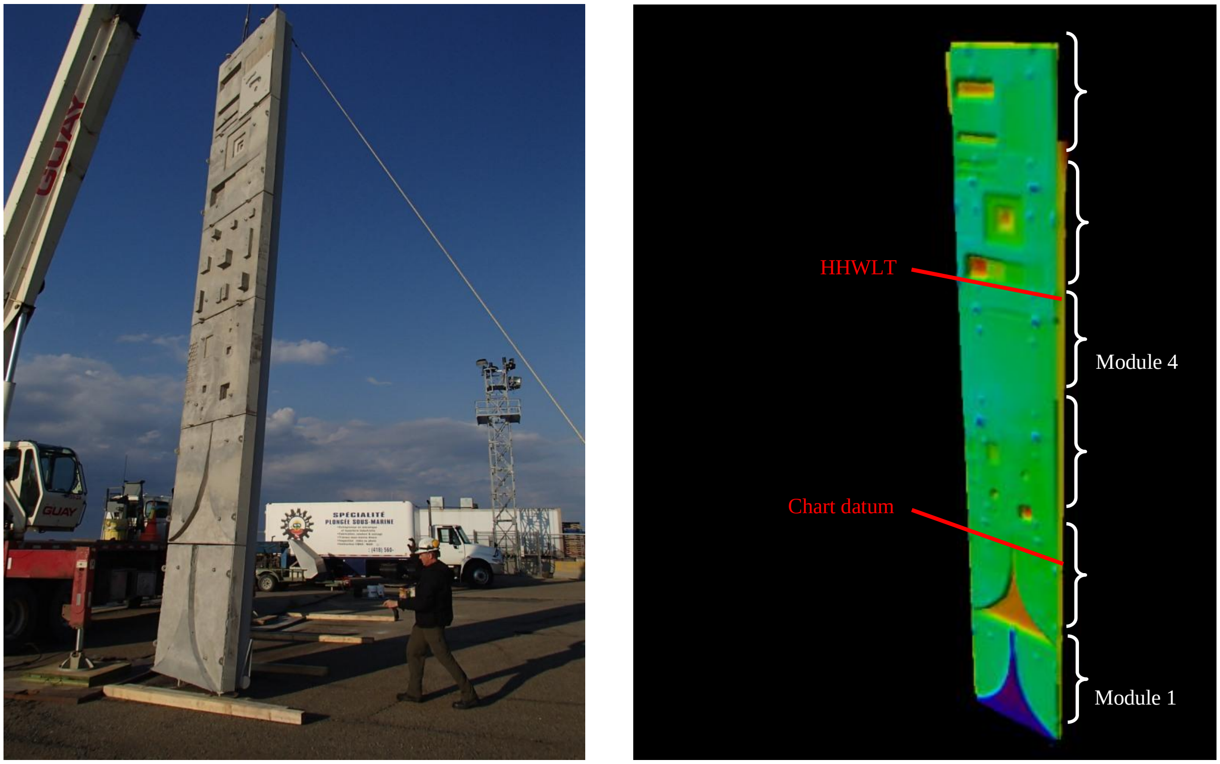

Figure 5 : Test bench just before deployment (left). VDTM of the test bench built from the HandyScan 3D reference dataset gridded at 2cm resolution.

The Engineering Analysis Module appears to be very useful to support the evaluation of acquisition systems, such as MBES, 3D scanning sonar and Underwater Laser Scanner (ULS), in terms of accuracy, precision and resolution. The capabilities of this module to model vertical features and to calculate differences between VDTMs make it particularly efficient in the framework of such a study where several acquisition scenarios are to be analyzed. The CIDCO's survey launch "F.-J. Saucier," equipped with a Reson Seabat 7125SV2 MBES mounted on a Hydropod and an Applanix PosMV320 position and orientation unit, was the first acquisition system evaluated.

Accuracy evaluation is performed by doing the difference between the reference VDTM and the VDTM of the equipment to be evaluated. In this case, the reference VDTM (VDTM1) was built from the HandyScan 3D reference dataset gridded at 5cm resolution and the VDTM to be evaluated (VDTM2) was built from one MBES survey line dataset gridded at 5cm resolution. The acquisition parameters are given in the table below.

Survey line speed	1 knot
Distance from test bench	2m
Swath angle	90°
Steering angle	40°

The figure below (Figure 6) does not show any significant georeferencing issues.

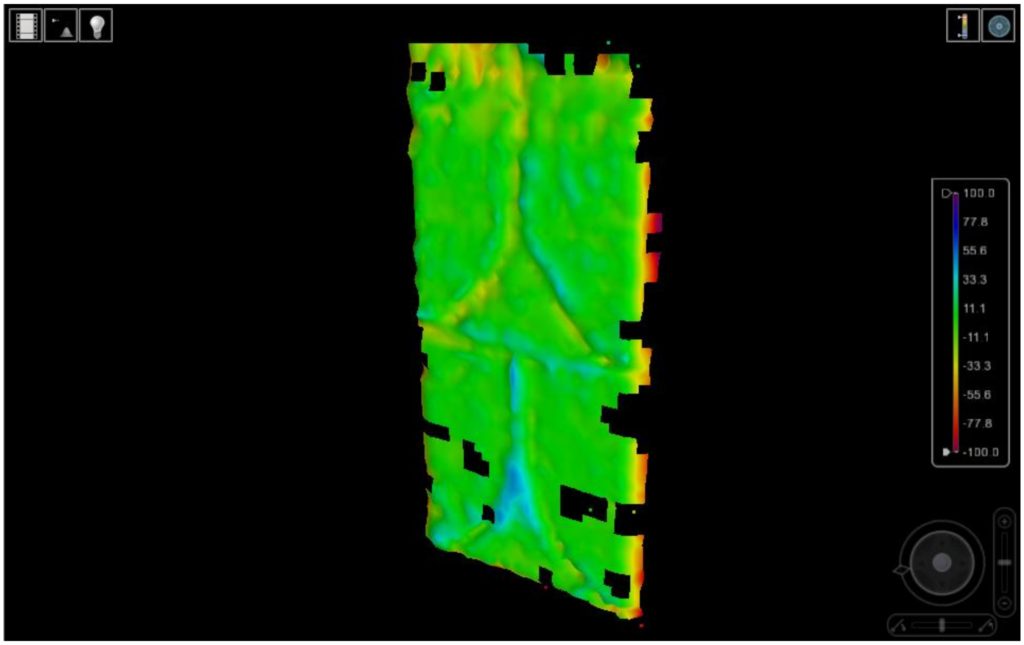

Figure 6 : Difference surface between VDTM1 and VDTM2. No georeferencing issue detected. The colour bar on the right shows distances in mm above (blue) and below (red) of the VDTM1 with reference to VDTM2.

The MBES dataset was then deliberately modified (translated along the Z axis) to show how a georeferencing issue can be illustrated. The figure below (Figure 7) shows a vertical shift of about 5cm. No bias is observed along other axes.

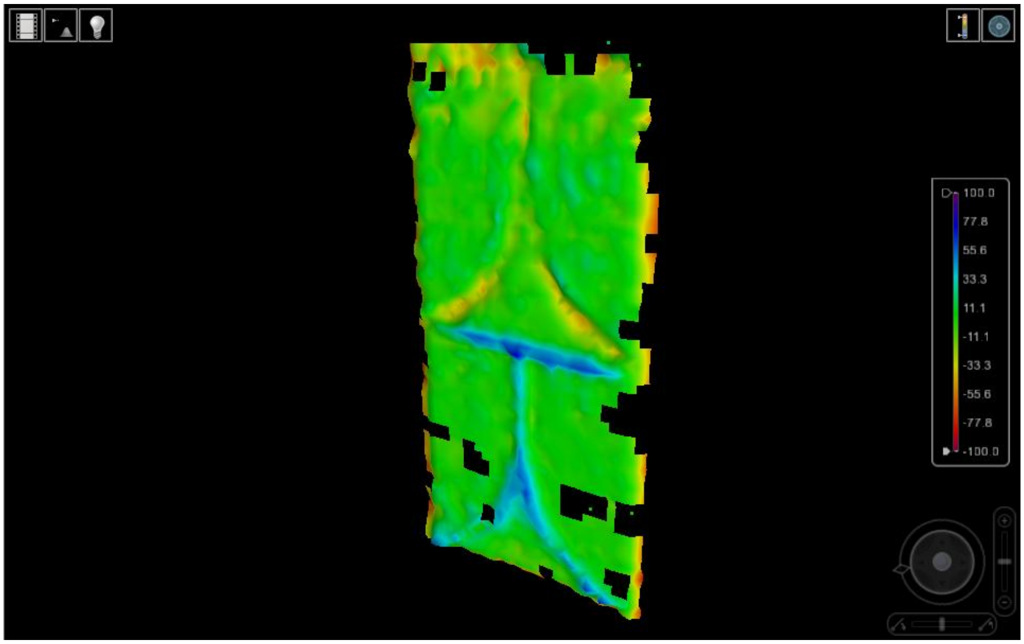

Figure 7 : Difference surface between VDTM1 and VDTM2. A georeferencing issue along the Z axis is detected. The colour bar on the right shows distances in mm above (blue) and below (red) of the VDTM1 with reference to VDTM2.

Precision evaluation is performed by doing the difference between VDTMs of the equipment to be evaluated. In this case, the two VDTMs (VDTM1 and VDTM2) were built from two different

MBES survey lines datasets gridded at 10cm resolution. The acquisition parameters are given in the table below.

	Survey line 1	Survey line 2
Survey line speed	1 knot	1 knot
Distance from test bench	2m	2m
Swath angle	90°	140°
Steering angle	40°	0°

The figure below (Figure 8) does not show any significant precision issues.

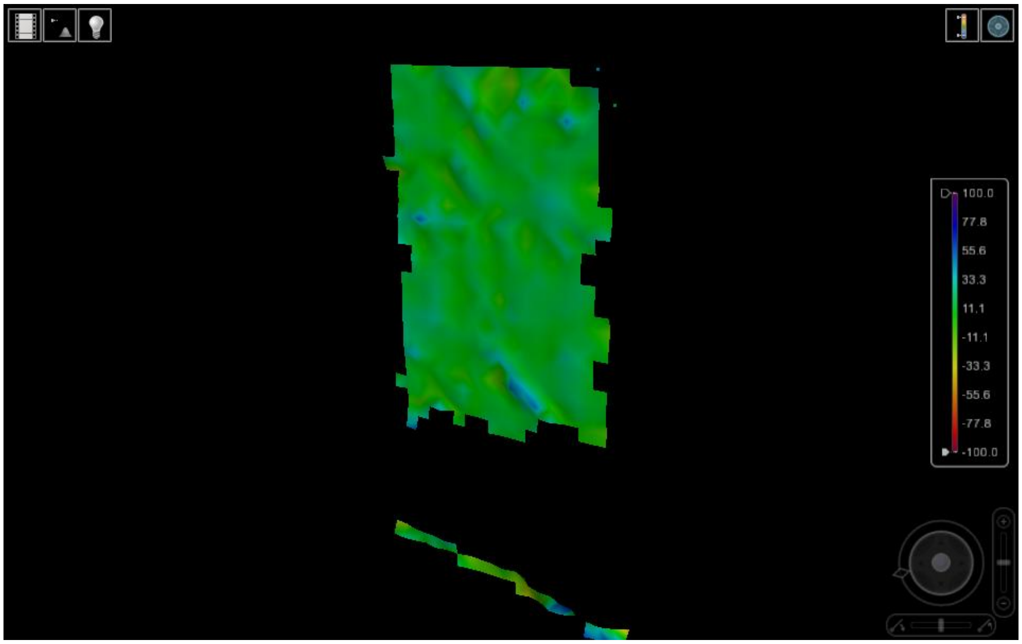

Figure 8 : Difference surface between VDTM1 and VDTM2. No precision issue detected. The colour bar on the right shows distances in mm above (blue) and below (red) of the VDTM1 with reference to VDTM2.

Resolution evaluation is performed by doing an analysis of the VDTMs of the equipment to be evaluated. In this case, the two VDTMs (VDTM1 and VDTM2) evaluated were built from two different MBES survey lines datasets gridded at 5cm resolution. The acquisition parameters are given in the table below.

	Survey line 1	Survey line 2
Survey line speed	1 knot	1 knot
Distance from test bench	**2m**	**5m**
Swath angle	90°	90°
Steering angle	40°	40°

The figure below (Figure 9) shows the influence of the distance of the MBES from the quay wall on the capacity to resolve features.

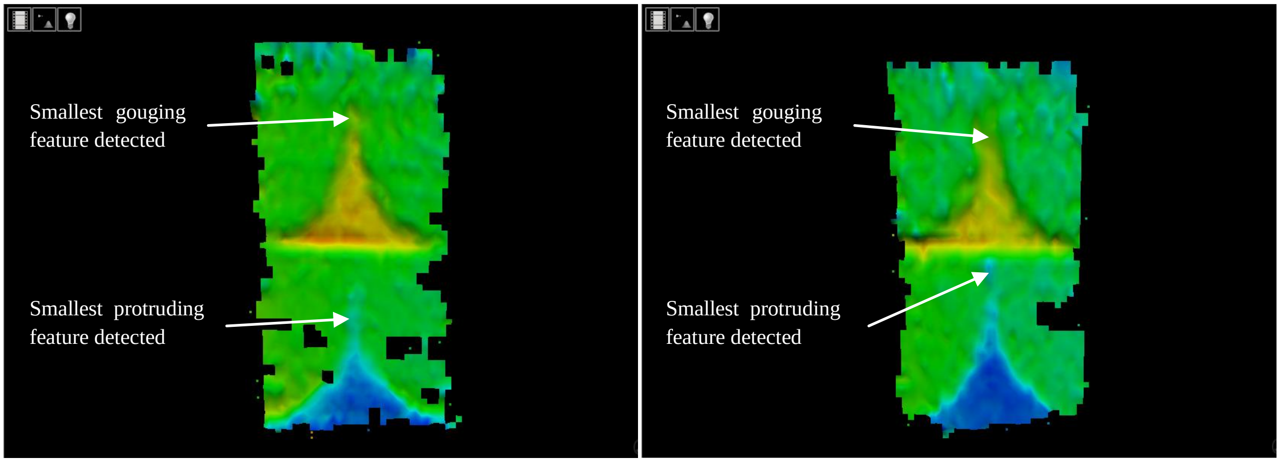

Figure 9 : Impact of distance from quay wall on resolution capacity. On the left the MBES is about 2m away from the test bench. On the right the MBES is about 5m away from the test bench.

A sizing diagram was developed to help to evaluate the resolution capacity of a VDTM. On VDTM1, one can identify a gouging feature (crack) that is about 3cm large and a protruding feature that is about 3cm large. On VDTM2, one can identify a gouging feature (crack) that is about 8cm large and a protruding feature that is about 2cm large.

As expected, the resolution capacity to detect cracks is better the closer the acquisition system is to the structure. More surprisingly, a protruding feature is better detected at a greater distance. This needs to be investigated in more detail.

Dam Infrastructure Inspection (Hydro-Quebec Romaine 2 Dam)

In support of a physical modeling project of the Romaine 2 dam conducted by the IREQ and the Hydro-Quebec geomatics group, the CIDCO was contracted to survey and to provide high-precision data of the submerged part of the dam.

Located at 100km north of Havre-St-Pierre (Quebec), the Romaine 2 dam is 90m high and 500m wide. Three surveys were conducted between October 2013 and October 2014 (Figure 10). They were done 1) when the reservoir was still empty using a 3D scanner laser, 2) when the reservoir was at mid-level, using the CIDCO’s survey launch “F.-J. Saucier,” and 3) when the reservoir was at its maximum level, using the same survey launch.

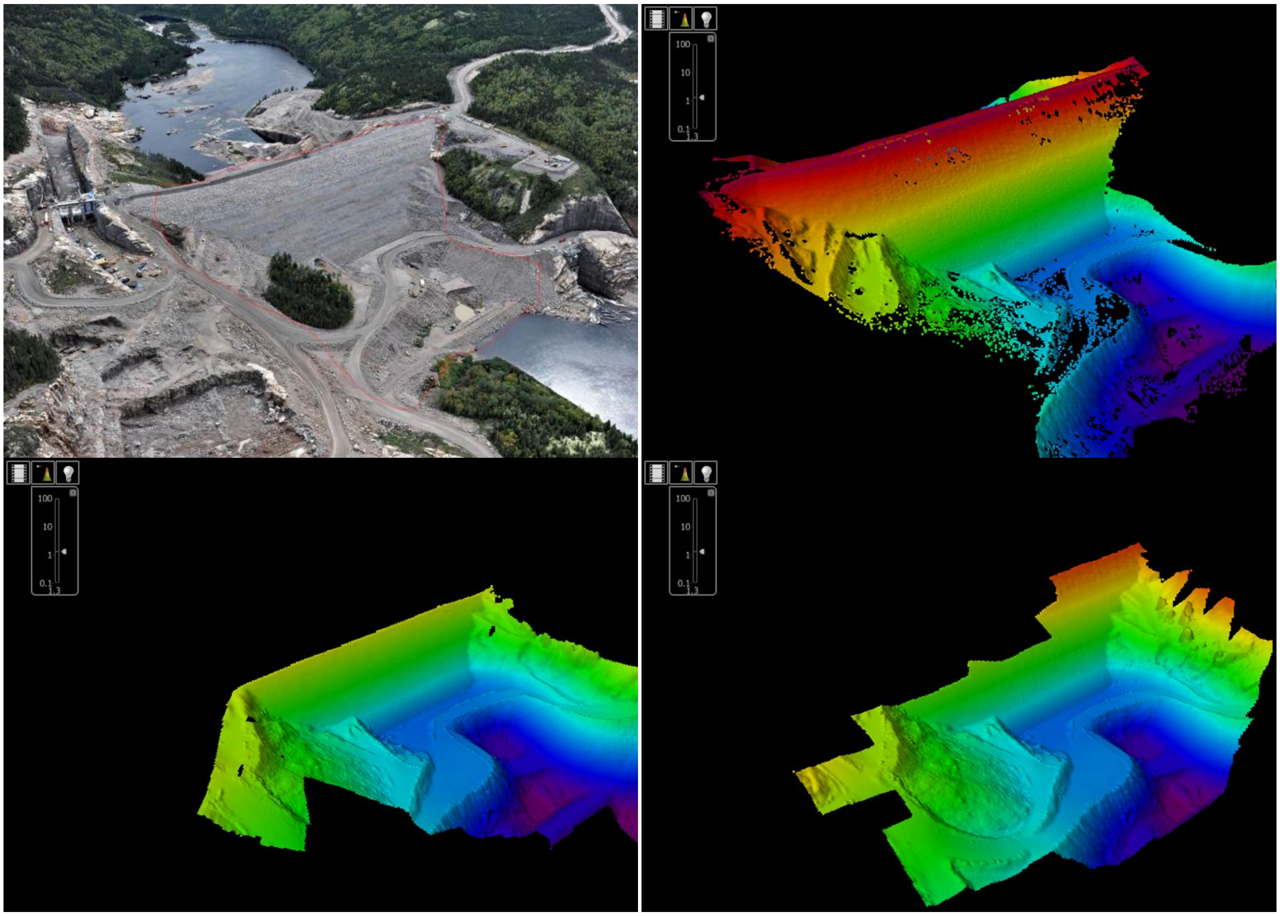

Figure 10: Aerial photo of Romaine 2 dam before reservoir filling was started (top-left). LiDAR 3D model (top-right). MBES1 3D model (bottom-left). MBES2 3D model (bottom-right).

The Engineering Analysis Module appears to be very useful to support the detection of changes between different surveys of the same infrastructure. The three surveys have been compared and analyzed using this module, specifically on the upstream incline plane of the dam (Figure 11).

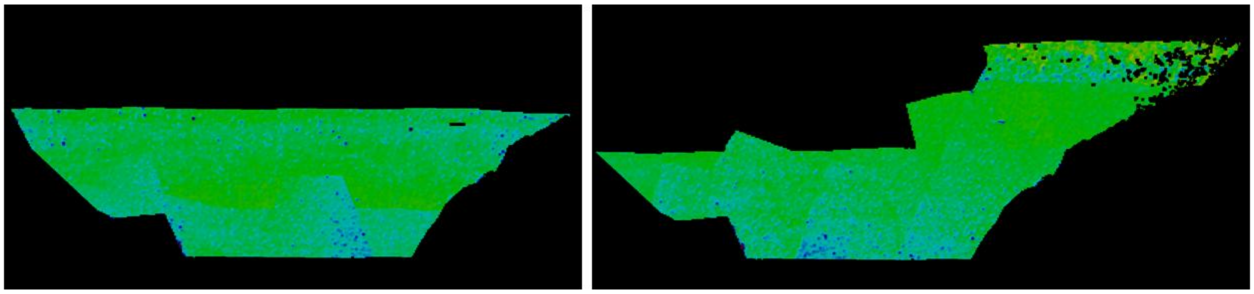

Figure 11: Difference surface between LiDAR and MBES1 datasets (left). Difference surface between LiDAR and MBES2 datasets (right).

In this case, the CIDCO's study enables to conclude that local deformations occurred on the dam, and that no global deformation (less than 5cm) was observed. The most substantial differences were along one side of the dam, where some of the material shifted slightly when the reservoir was filled (Figure 12).

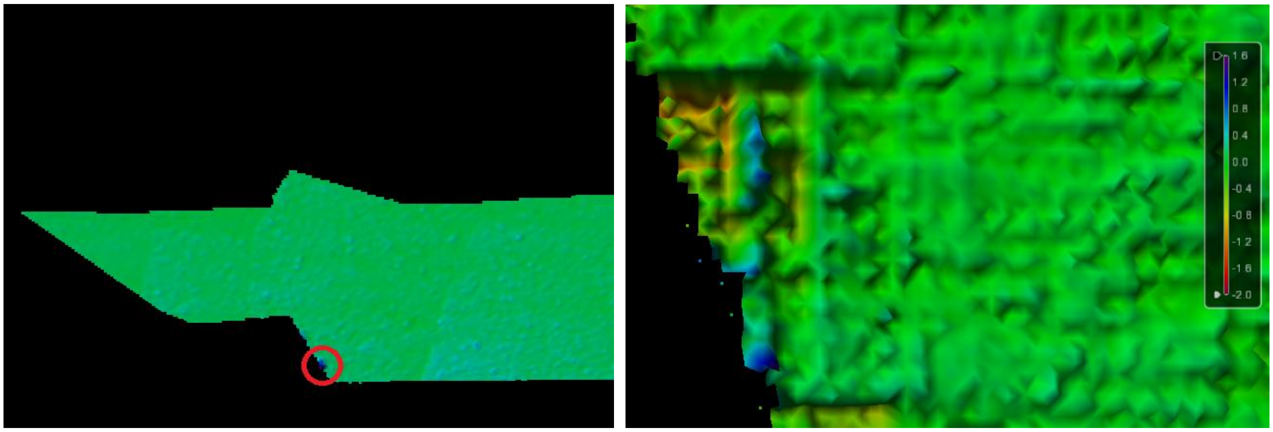

Figure 12: The most substantial difference in the area where a model was created, in the difference surface between LiDAR and MBES2 datasets. The area marked (left) is seen close up (right).

ADDITIONAL REQUIREMENTS

Additional analysis functionality has also been identified to further support decision making for port infrastructure maintenance. Through an ongoing project with the Montreal Port Authority, CARIS is enhancing analysis tools for volumes and profiles, as well as contour creation. This will allow for the calculations of the amount of material that is above or below the theoretical planes, as well as the amount of material that has shifted between surveys of an area. Standard profile lines will be able to be created at regular intervals, showing both gouging and protrusions along the vertical wall, with exact georeferenced positioning. Three dimensional contour lines will be able to be created to highlight areas of the structure that deviate significantly from the model.

In addition, there is also interest in adopting uncertainty models as an optional gridding strategy. As more organizations begin to try out the raster surface representations of vertical and near vertical infrastructure, it is expected that more use cases and ideas will be developed into additional requirements to be pursued.

CONCLUSIONS

The CIDCO, together with numerous partners, have run a number of pilot projects related to maintaining underwater infrastructure such as quay walls and dams. The ability to create a raster surface representation of vertical structures, with the coordinates referenced to the theoretical model, facilitates this analysis. Even by simply visualizing the resulting surface in 3D, it is immediately obvious where the greatest differences are, when the colouring is based on the distances from the model. Comparing raster surfaces of successive surveys of the same area allows for the detection of changes, which are most important to organizations responsible for maintaining infrastructure. This produces precise georeferenced information, and can be done without sending divers down to perform manual inspections, so is much more efficient and exact than existing methodologies. Of course, this does not preclude sending divers to confirm the nature of specific anomalies, but this can now be done based on accurate detailed surveys, and the accuracy of the systems can be verified using a test bench such as the one developed by the CIDCO.

The functionality already available in commercial software is powerful. As additional functionality is adapted to this context, there promises to be increasing technological support to simplify decision making for the maintenance of harbour and dam infrastructure.

ACKNOWLEDGEMENTS

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2) Hydro-Quebec, Montreal, Canada to give permission to use Romaine2 dam data.

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