CDA ACB
CANADIAN DAM ASSOCIATION
ASSOCIATION CANADIENNE DE BARRAGES

CDA 2015 Annual Conference
Congrès annuel 2015 de l'ACB
Mississauga, ON, Canada
2015 Oct 5-8

DEFORMATION ESTIMATION OF THE ROMAINE-2 DAM FROM MULTIBEAM ECHO SOUNDER SURVEY DATA

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ABSTRACT

This paper describes a deformation monitoring measurement method of the Romaine-2 dam, before and after loading. The joint use of a Terrestrial Laser Scanner (TLS) and a Multi-Beam Echo Sounder (MBES) system is described. Through a quality assurance process, the consistency of the different datasets has been analyzed. By using recent work on the identification of MBES systematic error on dumped rocks, we concluded that the Romaine-2 dam was not submitted to detectable global deformation after loading. However, some local deformations were observed on the up-stream side of the cofferdam.

RÉSUMÉ

Cet article décrit une méthodologie de mesure de déformations d'un barrage avant et après remplissage. L'emploi conjoint d'un LiDAR terrestre et d'un système de levé hydrographique de type multi-faisceau est décrit. L'analyse de la qualité des données est réalisée en vérifiant la cohérence des différents jeux de données. En s'appuyant sur des résultats récents concernant la détection d'erreurs systématiques des sondeurs multi-faisceau sur des enrochements, on a pu conclure à l'absence de déformation globale du barrage Romaine 2. Certaines déformations locales ont cependant été détectées en amont du batardeau.

1 INTRODUCTION

Since 2010, the CIDCO investigates the use of acoustic sensors (and in particular Multi-Beam Echo Sounders: MBES) for shallow water subsea structures inspection purposes. Following some works mainly done for ports quay wall inspections, the CIDCO proposed in 2012 the idea to use MBES systems to establish a complete diagnostic of dam structures (Rondeau et al., 2012). In spring 2013, the CIDCO set up a "Coastal Subsea Infrastructure Inspection Project", gathering infrastructure managers and owners, engineering consulting firms, equipment suppliers and software engineers. In the framework of this project and in support to a Hydro-Québec research project on the topic of dam measurement and modeling, the CIDCO was contracted to survey the Romaine-2 dam and to provide high-precision data of the submerged part of the dam.
Located at 100km North of Havre-St-Pierre (Québec), the Romaine-2 dam, has a height of 90m and is 500m wide. Its construction was completed in 2013. The objective of our study was to make an objective evaluation of the ability of a hydrographic survey vessel equipped with a MBES, an inertial navigation system and a GNSS receiver to provide data with sufficient accuracy and precision in order to measure structural deformations of a large dam.

The modeling of dams using hydrographic methods presents interesting challenges that differ from usual hydrographic applications. First, the required accuracy is fairly high with respect to the maximum depth, as deformations in structures such as the Romaine-2 dam are expected to be in the order of few decimeters, if any. Second, the inclined nature of the surface means that one must collect 3D points that are accurate in all dimensions, which raises the problem of optimal sensor orientation. Third, the presence of riprap in the upper part of embankment dams taints the MBES data with multipath errors that have to be accounted for. On the other hand, the resolution requirement is not very high, as the output that is looked for is more in terms of a general tendency in the surface than in the survey of specific small locations.

A Terrestrial Laser Scanner (TLS) survey, which was conducted by Hydro-Québec's geomatics department prior to impounding, was made available to be used as ground truth data. Two hydrographic surveys were then conducted, using a hydrographic vessel equipped with a MBES system: one when the reservoir was at mid-level and one when it was about to reach its operational level. The activity is not part of the dam construction quality control but is really a research experiment that benefits from the opportunity of collecting three datasets prior, during and following the impounding.

The three surveys were compared and analyzed using advanced data processing software and 3D modeling tools. The results of our study enable us to conclude that local deformations occurred on the dam, and that no global deformation was observed. In particular, the comparison between TLS and MBES datasets constitutes an interesting benchmark for the study of systematic errors from acoustic systems on complex structures and dumped rocks slopes.

The tools, methodologies and processing workflows that were used for surveys are presented in section 3 and 4. Section 5 will detail quality assurance methodology that was applied to the survey data and how this guarantees a high level of accuracy and precision. Section 6 describes the analysis of dataset that was conducted, in particular how the three 3D point clouds can be compared and analyzed in term of accuracy, precision and resolution and how the presence of local deformations can be identified. Finally, a methodology is proposed to identify and correct systematic errors of MBES systems on riprap slopes that constitute the upper part of the dam.

2 THE ROMAINE-2 DAM

The Romaine-2 dam and power plant are the largest of the four facilities that make up the Romaine river hydroelectric project and the first to be put into service. The dam is an asphaltic core rockfill dam (ACRD) of approximately 90 meters in height and 500 meters in length, which makes it the largest ACRD in North America. As mentioned in (Longtin et al., 2012), construction methods were specifically adapted to this type of work in order to minimize settlement and horizontal displacement following impounding. The upstream side of the dam has a slope of 1,6:1 in the bottom zone (elevations 165m – 222m) and a slope of 1,8:1 in the upper zone that is covered with riprap (elevations 222m – 248m). At bottom of the upstream side is the cofferdam that was built prior to construction. The Figure 1 presents a simplified view of the dam's cross-section.

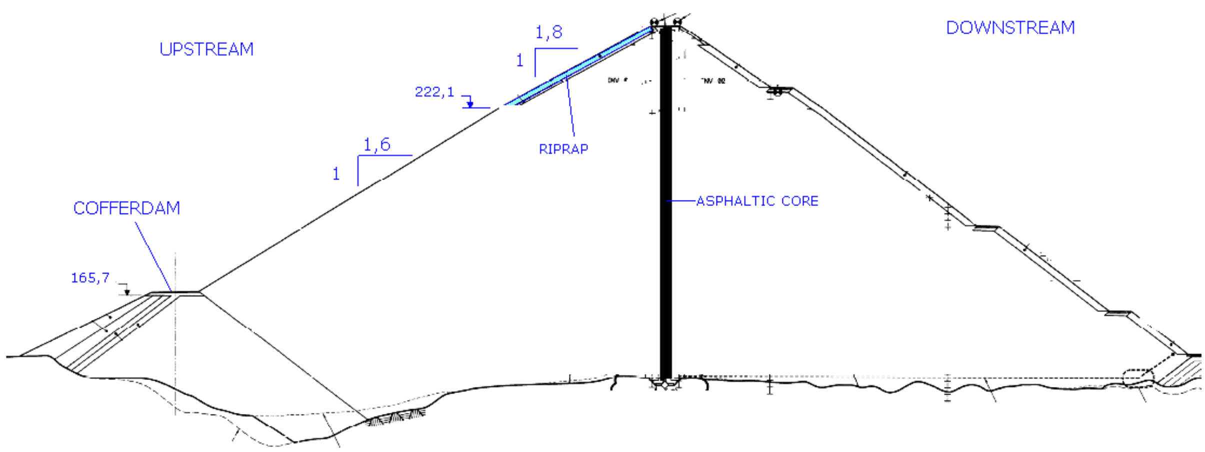

Figure 1: Sketch plan of the Romaine-2 dam

3 DESCRIPTION OF THE SURVEY SYSTEMS USED

3.1 Terrestrial Laser Scanner

After the construction of the Romaine-2 dam, and before its filling, it was surveyed using a TLS by the personnel of Hydro-Québec geomatics department in October 2013. Surveys were done by merging 27 datasets taken from static stations of a Leica ScanStation 2. 3D data were geo-referenced using a local geodetic network built for land surveys purposes.

Due to field constraints, the TLS datasets have various spatial resolutions, especially on the highest part of the dam, a slope built with large stones. In the framework of this study, the TLS dataset will be considered as the reference dataset for two reasons. First, the survey was done prior to the dam filling, therefore it does not incorporate terrain variations due to hydrodynamic and hydrostatic loading on the dam structure, that we want to monitor. Secondly, TLS measurements can be considered as less subject to uncertainty and with better resolution than MBES soundings. Indeed, MBES have a much larger footprint than TLS, and by essence, MBES survey fall into the category of mobile surveys which require mobile GNSS receivers, local level information from an IMU, and acoustic ranging data from the MBES itself.

Consequently, sounding uncertainty is the result of the propagation of uncertainty factors from the whole sensor suite, as explained in the next subsection.

3.2 Hydrographic survey vessel

A MBES system is generally composed by the MBES itself, a GNSS receiver and an IMU (see figure 2). The MBES delivers the range information between the MBES and the seafloor. The GNSS delivers positioning information as geodetic coordinates and ellipsoidal height of the vessel Positioning Reference Point (PRP), which can be transformed by appropriate transformations to Local Geodetic Frame (LGF) coordinates. The IMU delivers information to determine the local-level and heading information.

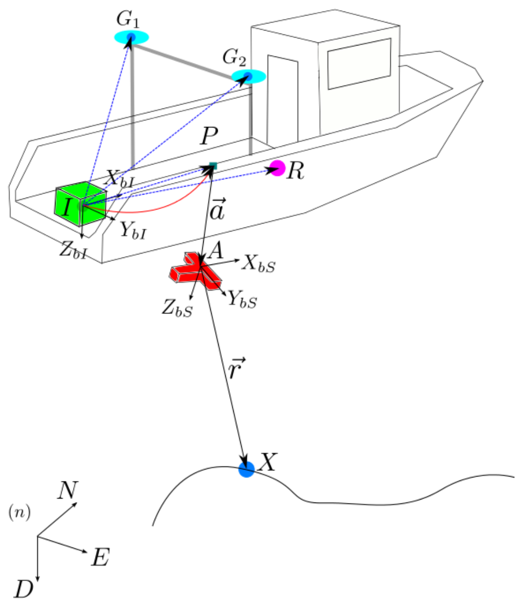

Figure 2: Geometry of the MBES system integration

Two surveys of the same areas were conducted in June 2014 (Phase 1) and October 2014 (Phase 2). The MBES system used included a Teledyne Reson SeaBat 7125 SV-2 MBES operating at 400kHz, an Applanix POS-MV 320 IMU, and Thalès Zmax GNSS base station.

It is to be mentioned that as the slopes of the Romaine-2 dam are relatively sharp (32 degrees), a mechanical tilt (thanks to a bracket which tilts the MBES) has been employed in order to direct the MBES central beam towards the expected normal to the dam surface. However, data quality analysis revealed that mechanically tilted MBES data have lower precision than non-tilted MBES data. The main problem came from the boresight angle calibration process, which is designed to estimate small angles between IMU and MBES frames. Tilting deliberately the MBES from about 40° increased the misalignment angle and the calibration results have not been conclusive. In the following, non-tilted, but electronically steered (in order to have a better coverage on the top of the dam) MBES data will be used.

4. DATA PROCESSING

4.1 Geo-referencing MBES data principle

The position of the sounding X can be geo-referenced in a LGF thanks to the knowledge of:

1) lever-arms measurements (3D distances between the survey vessel PRP (P), the MBES acoustic center (A), the IMU reference measurement center (I) and the vessel's center of rotation (R));
2) IMU measurements (heave, pitch, roll);
3) GNSS antennas positions measurements ($G1$) and ($G2$);
4) raw MBES returns measurements (r);
5) sound speed profiles measurements.

Thermoclines are common in dam lakes, and sounding processing have to be fed with proper and regular measurements of sound speed profiles (SSP) to guarantee the absence of systematic errors due to sound refraction in the water column. The two SSP that have been measured during phase 1 and phase 2 are given in Figure 3. One can see that the thermocline is completely different from phase 1 and 2, which can be explained by a warmer surface layer during phase 2 due to summer solar radiation.

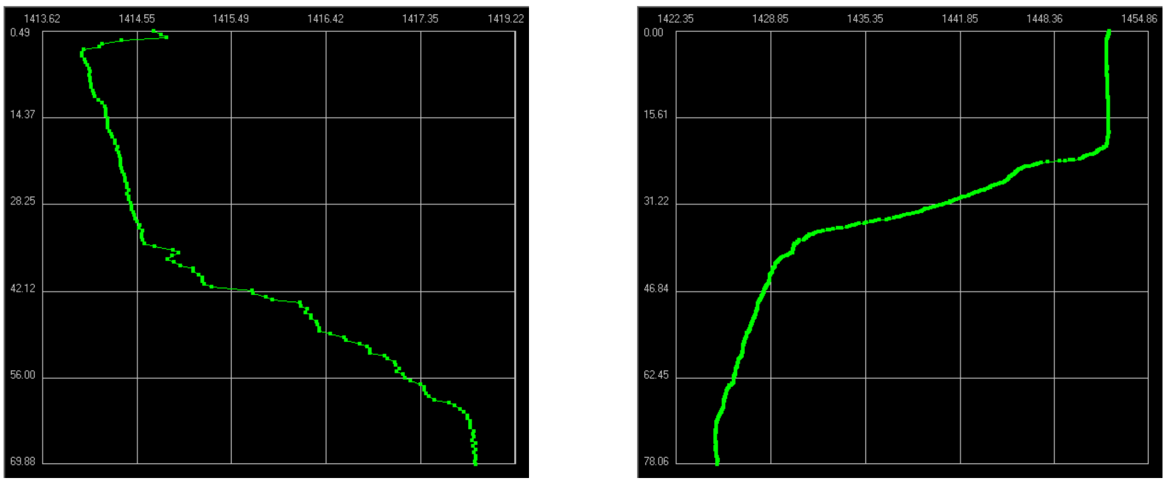

Figure 3: Two sound speed profiles (after and before loading of the dam)

The processed data can then be referenced in a Terrestrial Reference Frame (TRF), and transformed in planar coordinates thanks to geodetic coordinate transformations and appropriate map projections. In this particular survey, the geodetic system used for coordinate transformation was Nad83-SCRS following ITRF 1997 and the vertical reference used was CGVD-28 (HT2_0). The map projection used was MTM-5.

4.2 Positioning data processing

Both MBES surveys were referenced with respect to a geodetic point established and monumented by Hydro-Québec's geomatics department, which is shown along with a side view of the half-filled dam (Figure 4).

Figure 4: Side view of the Romaine-2 dam at half loading. The GNSS base station is located on the geodetic control point

In order to enhance the positioning data quality, GNSS data have been systematically post-processed in PPK mode, thanks to the POSPAC MMS software from Applanix. However, due to poor GNSS conditions in the area, it has been impossible to reduce the uncertainty of positioning data to a level compatible with survey requirements. Indeed, the following graphs (Figure 5) illustrate a clear drift of all position components (Nothing, Easting, Down) at the same time.

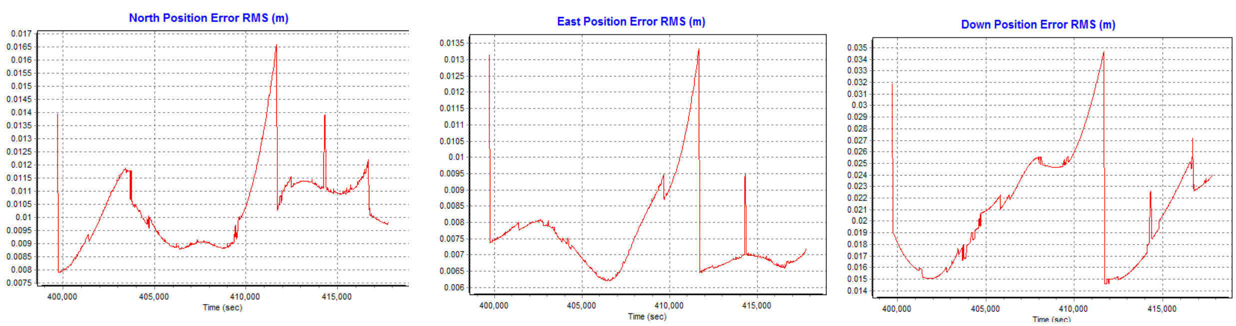

Figure 5: Positioning error after PPK processing of GNSS/INS data

Therefore, vertical referencing of sounding had to be achieved by using measurements of the water level, as given by a tide gauge, installed in the surrounding of the dam. However, due to the uncertainty of the tide gauge measurements, a water level curve has been synthesized. This synthesis has been done by using both height data from GNSS (which was accurate, but not precise) and water level as given by the tide gauge (which was precise, but not accurate). As shown on Figure 6, for the phase 1 survey period only, the blue line has been fitted on the tide gauge data, and vertically shifted to coincide with the GNSS data height. In summary, tide gauge information provided the water level variation, and GNSS height data provided the offset between tide gauge measurement and the GNSS height measurement.

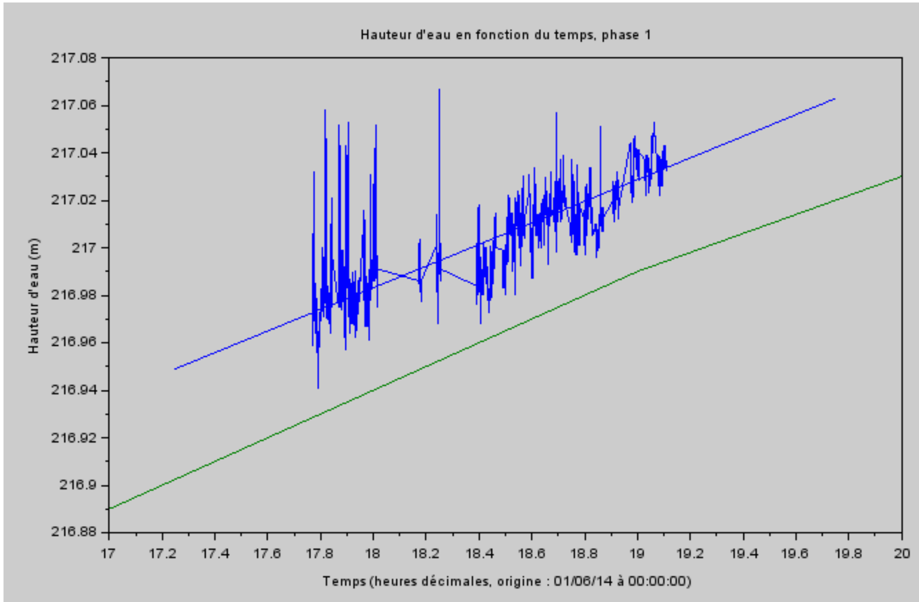

Figure 6: Tide gauge data (green), and GNSS data with its fitted line (blue), phase 1

4.3 Bathymetric data processing

As explained in part 4.1, bathymetric data processing consists in assimilating positioning, water level, attitude and MBES data thanks to a geo-referencing software. Sound speed profiles have been used for acoustic refraction correction of MBES data. Thanks to a prior MBES-IMU boresight calibration MBES data can be corrected from misalignment between the IMU-frame and the MBES-frame. This phase has been achieved using tools implemented in the CARIS HIPS/SIPS 7.1.2 software.

All data have been then projected (a MTM projection has been used) on a grid which resolution is 0.5m. The vertical datum chosen was CGVD-28.

As a result of the two survey campaigns, the following Digital Elevation Models (DEM) have been produced (Figure 7).

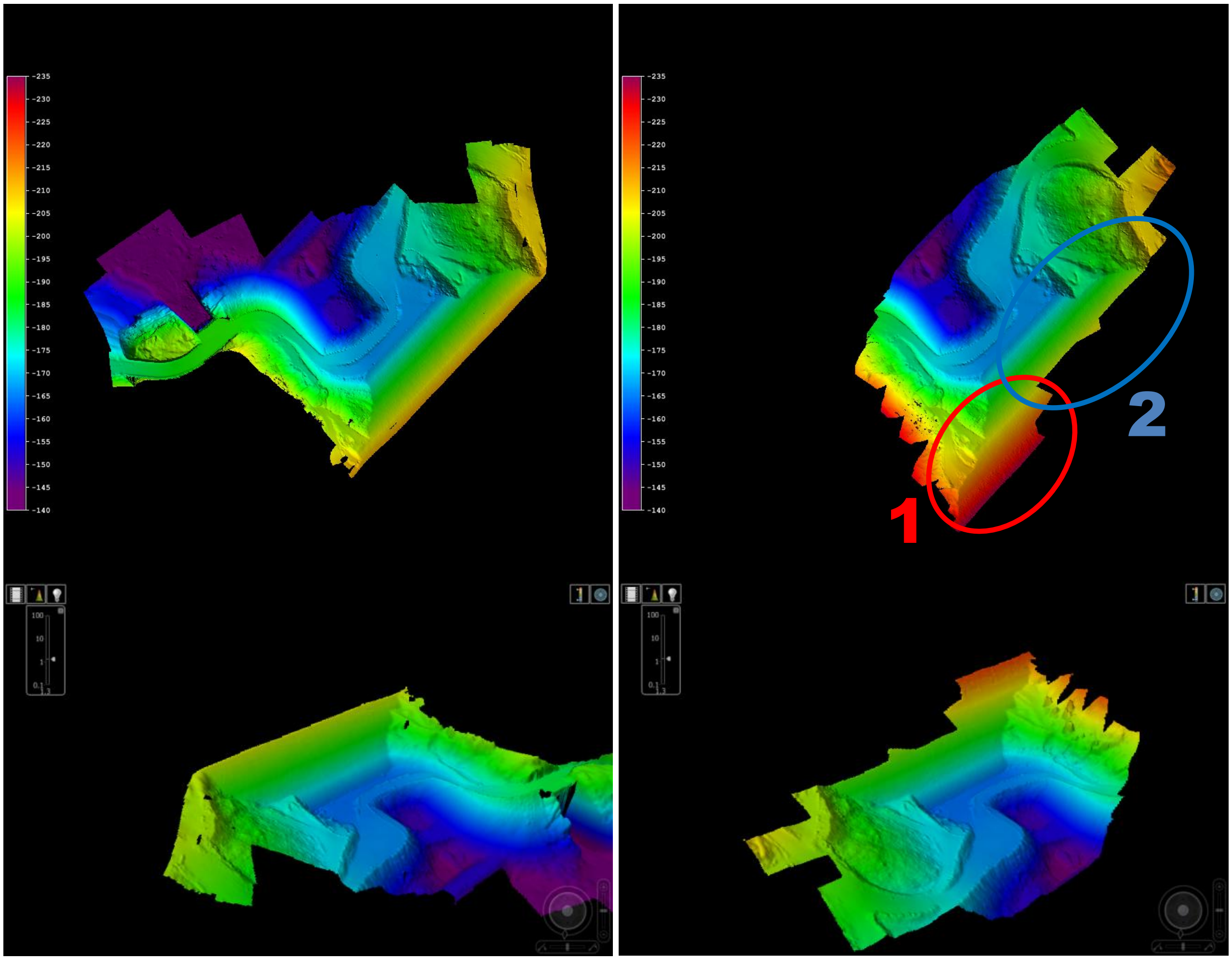

Figure 7 : Two elevation models from the two survey campaigns realized at mid-filling of the dam (left) and after filling of the dam (right). It can be seen in examining the southern part of the right figure (1), that surveys in the full reservoir enabled us to get data from the slope at higher levels. However, due to the presence of floating wood against the dam at the eastern part (2), this area of the slope has not been surveyed for phase 2.

From Figure 7 we can see that the MBES coverage overlaps most of the dam's slope, except its eastern part, which remains un-surveyed due to the presence of debris. The elevation models presented above require investigation at lower scale to enable us to validate the accuracy and precision of the data sets and to detect the presence of structural variations of the dam.

5 QUALITY ASSURANCE OF SURVEY DATA

The first task for validating the data is to perform a quality assurance analysis of the survey data. Quality assurance can be performed by two means: comparison of the two datasets with reference surface from 3D terrestrial laser scanner surveys, and comparison of overlapping areas between MBES strips.

5.1 Comparison with the 3D static LiDAR dataset

For the purpose of quality assurance, Hydro-Québec’s geomatics department performed a 3D laser scanner survey of the empty dam, just before starting the filling phase. LiDAR reference data needs to be located on areas that are not subject to deformation after dam impoundment. Three areas from natural rock slopes were selected as shown in the Figure 8 below. Figure 9 is a detail of one of the reference areas.

Figure 8: Reference LiDAR surfaces as defined by Hydro-Québec

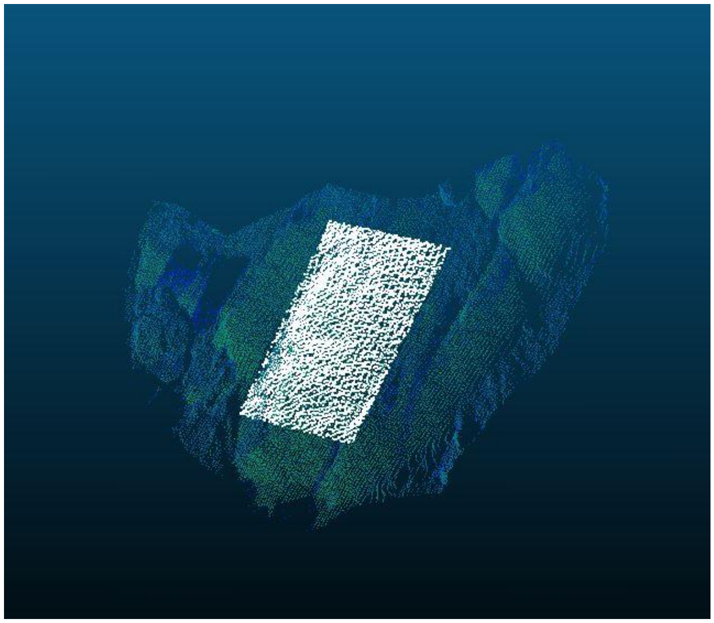

Figure 9: Zoom on the reference surface 2. In white, the selected area for MBES–LiDAR comparison.

MBES data from phase 1 and phase 2 have been compared with the LiDAR scan on the control surfaces 1 and 2. In that purpose, the software CloudCompare has been used to compare two point clouds to each other. The results obtained for the two MBES surveys are gathered in the following table.

Table 1: Average distance between point clouds of phase 1, phase 2 and reference LiDAR surface after data processing.

Reference surface	Average normal distance between phase1/LiDAR (cm)	Standard deviation (cm)
1	**0.5**	4.8
2	**3.0**	5.1
	Average normal distance between phase2/LiDAR (cm)	Standard deviation (cm)
1	**-0.6**	7.7
2	**1.2**	7.5

The above table reveals that in average the three datasets are consistent with the deformation monitoring requirement as the maximum of average distance is 3cm between the MBES survey and the LiDAR reference. The standard deviation between point cloud of phase 2 are a little bit greater than in phase 1, which can be explained by a larger average water depth and therefore larger water column uncertainty errors. One should notice that the reference surface being inclined with a relatively high angle, the MBES data are subject to footprint error. However, the precision and accuracy of the different point clouds are small enough to conduct the dam deformation analysis.

5.2 Overlap analysis and standard deviation errors

Beyond the reference surface analysis, the two MBES survey data sets were compared by a standard deviation analysis. Standard deviation analysis consists in comparing data from overlapping strips. Within each cell of the Digital Elevation Model (DEM), the average error and standard deviation between the two datasets is computed. Notice that this classical standard deviation analysis is only relevant over flat areas. Indeed, over slopes, the standard deviation is obviously biased as this analysis implicitly makes the assumption that the terrain is horizontal over each cell. Work to enable such an analysis on non-horizontal surfaces is underway (Leblanc et al., 2012 ; Rondeau et al., 2015). Figure 10 shows the standard deviation maps of the two survey data.

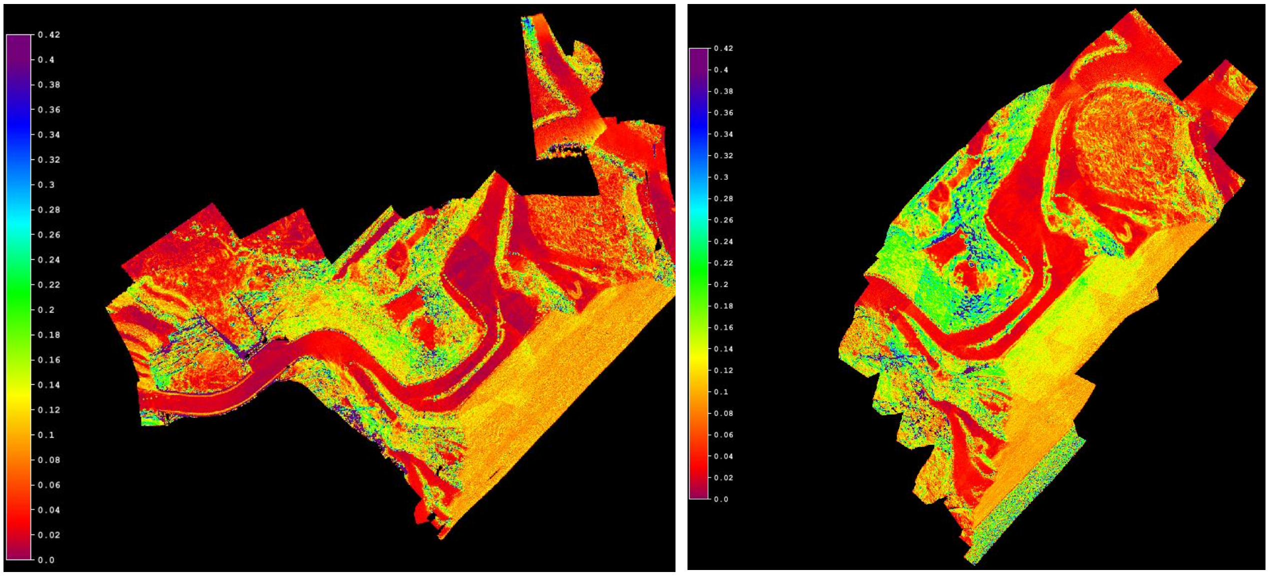

Figure 10: Standard deviation maps. Left: phase 1. Right: phase 2. Cell size: 0.5m x 0.5m. One can check that on flat areas (construction roads (in red) the standard deviation level is very low, which validates the quality of the surveys.

6 SURVEY DATA ANALYSIS

Survey data quality being assessed and validated, we can now study the dam deformation due to loading. As shown in Figure 11, two sets of surface patches have been selected in order to detect the presence of deformation of the dam:

- Nine surface patches located on the dam slope itself;
- Three patches located on the top of the cofferdam.

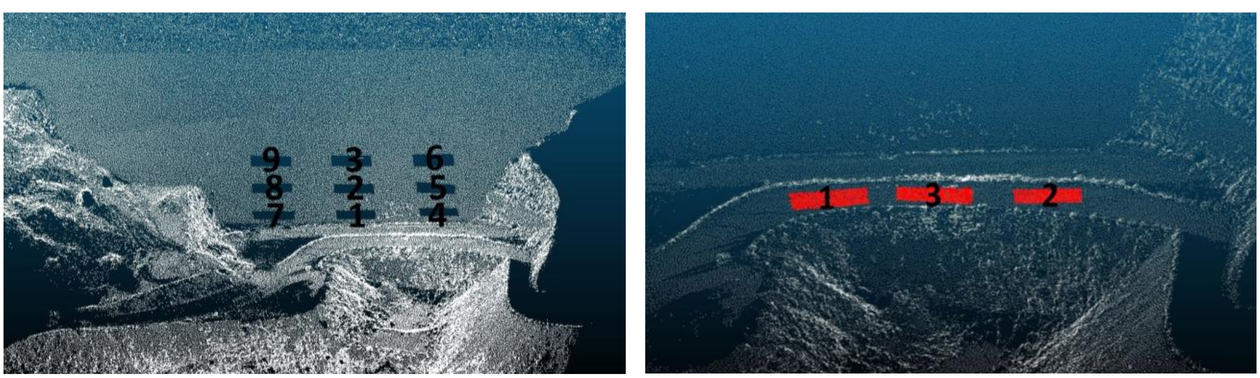

Figure 11: Surface patches locations for dam deformation analysis. Nine surface patches have been defined on the dam itself and three on the cofferdam.

The surface difference computation method (also used for the comparison on reference surfaces) is the following:

- The reference point cloud is chosen, and a plane is fitted on its data;
- All data from the reference point cloud are projected on this plane;
- A 2D Delaunay triangulation is constructed with those projected points;
- A 3D mesh is created with the reference points thanks to the links constructed during the 2D Delaunay triangulation;
- For all the points in the point cloud to be compared, the shortest distance between them and the 3D mesh is computed;
- Each point gets a value for its distance to the created mesh, and the whole patch mean distance is also computed.

The results obtained on the dam for the computations between phase 1 and LiDAR, and phase 2 and LiDAR can be seen on the following tables.

Table 2: Distance between phase 1 MBES survey and LiDAR reference, on the dam. The negative values indicate that the compared point cloud (MBES) is under the reference (LiDAR).

LiDAR – Phase 1 point cloud difference

Patch number			**Mean distance (cm)**			Standard deviation (cm)		
9	3	6	**-5.3**	**-3.3**	**-5.6**	3.7	5.4	4.1
8	2	5	**-2.5**	**-1.4**	**-1.3**	7.4	6.0	6.6
7	1	4	**-2.9**	**-2.6**	**2.6**	6.1	6.7	5.2

Table 3: Distance between phase 2 MBES survey and LiDAR reference, on the dam. The negative values indicate that the compared point cloud (MBES) is under the reference (LiDAR).

LiDAR – Phase 2 point cloud difference

Patch number			**Mean distance (cm)**			Standard deviation (cm)		
9	3	6	**-3.2**	**-3.0**	**-1.0**	7.5	8.1	6.6
8	2	5	**-5.0**	**-1.4**	**-2.0**	6.4	7.4	6.9
7	1	4	**-4.6**	**-3.4**	**-1.2**	10.9	9.2	7.8

According to the values (less than 6cm) and the standard deviation associated, we can conclude that no deformation has been detected on the dam between the LiDAR survey and both MBES surveys.

However, on the top of the cofferdam, the floor seems to have changed, as we can see in the following table.

Table 4: Distance between phase 1 MBES survey and LiDAR reference, and between phase 2 MBES survey and LiDAR reference, on the road. The positive values indicate that the reference (LiDAR) is under the compared point cloud (MBES).

	Mean distance (cm)			Standard deviation (cm)		
1 – 3 – 2 patches (LiDAR – Phase 1)	**0.9**	**1.6**	**8.9**	4.2	4.5	5.4
1 – 3 – 2 patches (LiDAR – Phase 2)	**0.3**	**1.2**	**8.9**	5.0	4.9	5.5

The positive values indicate a material intake between the LiDAR scan and the first MBES survey. A sediment transport has maybe occurred during the dam filling,

Moreover, when analyzing the two DEM from phase 1 and phase 2, a clear change of the cofferdam slope has been observed, as shown in Figure 12 and Figure 13. In analyzing the volume difference over the entire area of deformation, we concluded that:

- The volume of the difference between phase 1 DEM and phase 2 DEM is close to zero;
- The maximum amplitude of deformation is about 1,5m.

Thanks to these data, we concluded that the observed difference between phase 1 DEM and phase 2 DEM is due to a local landslide.

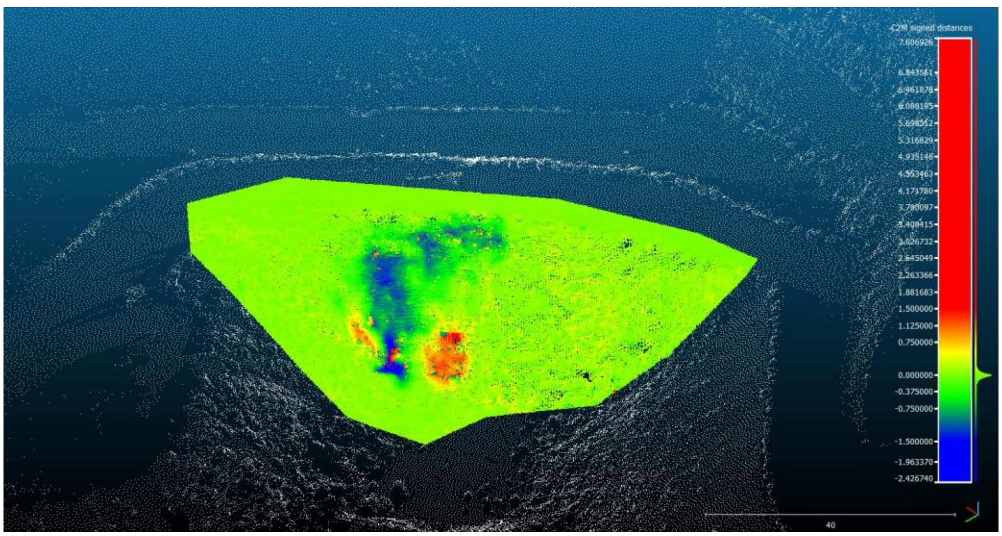

Figure 12: Difference between phase 1 DEM and phase 2 DEM. The difference DEM has a volume close to zero.

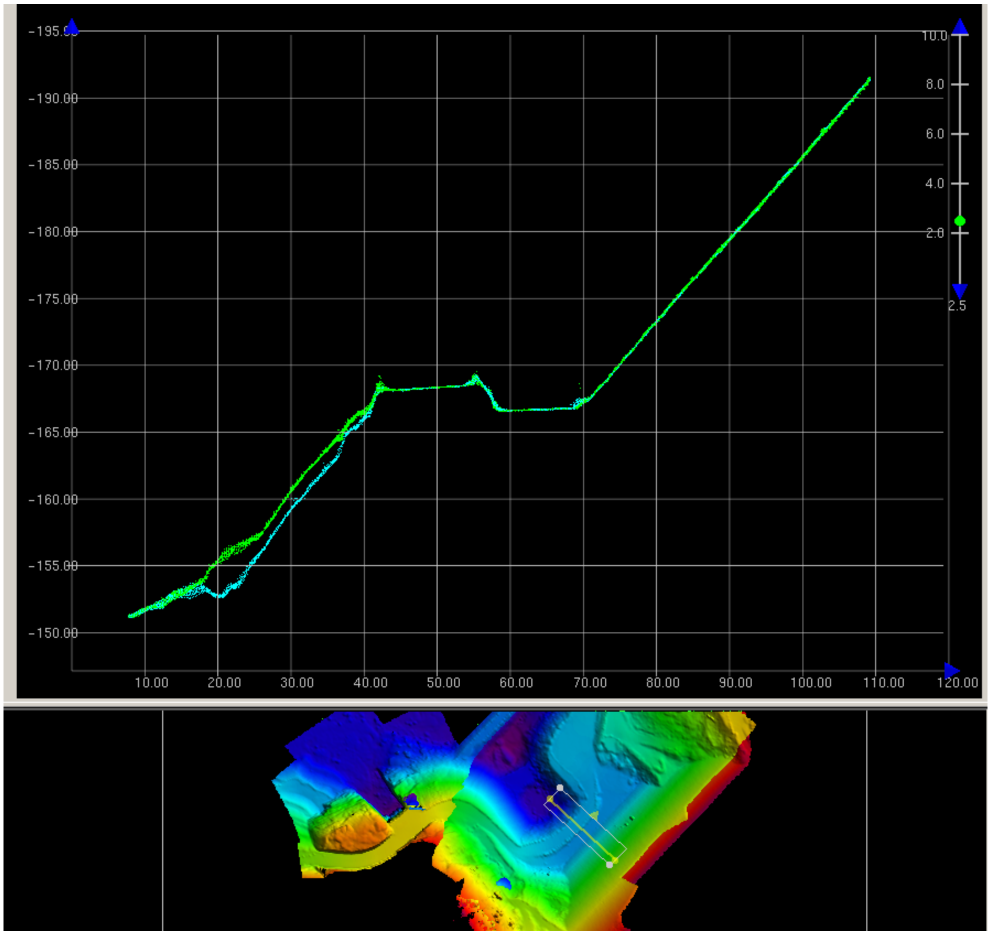

Figure 13: Vertical cut of the phase 1 DEM (in green) and phase 2 DEM (in blue) of the cofferdam. One can clearly see a variation of the cofferdam slope.

The upper part of the dam analysis was the most difficult to conduct, as a direct interpretation of the survey data could be misleading. We only performed a comparison between the phase 2 DEM and the LiDAR reference dataset, as during phase 1, the water level was not high enough to enable us to perform a MBES survey of this area.

The problem we encountered here is due to the fact that the highest part of the dam is covered with riprap, which are rocks with relatively large normalized diameter (about 1.2m). From a previous study (Debese et al., 2012), we know that MBES data from dumped rocks sea floor areas are submitted to systematic errors which depend on the normalized diameter of the rocks. Indeed, we observed on the highest part of the dam an error along the normal plan of the dam of 37cm between LiDAR and MBES data.

If no further analysis of this observation is done, one may conclude that a global deformation occurred on the top of the dam. In fact, most of this error can be explained by two facts:

- First, the presence of a systematic bias between MBES and LiDAR data on dumped rocks. From our prior experience and knowledge of this phenomena, MBES data should be about 24cm below LiDAR data on a 1,2m rock normalized diameter slope;

- Secondly, it appears that LiDAR data has been taken at low resolution on the highest part of the dam, due to the distance of the laser scanner station. This explains that most of cavities between rocks have not been scanned. As a result, the LiDAR DEM is seen above the actual rock slope, which should explain the residual error.

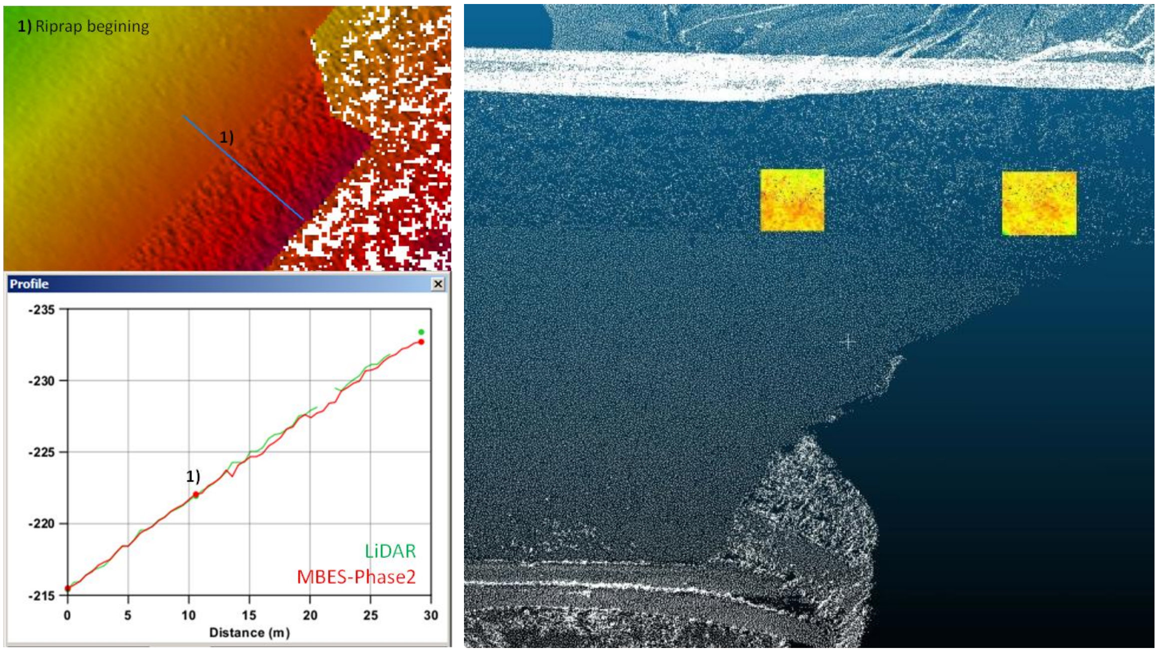

Figure 14: Profile view (left). Surface patch selected for the large rock diameter slope, composing the highest part of the dam slope (right). A systematic error of 38cm has been detected on this area which can be explained by acoustic systematic errors of MBES systems when surveying large diameter dumped rocks areas. This assumption is also confirmed by the fact that areas located just below which are composed of compacted rocks are not submitted to the same acoustic bias and were seen at the same level on LiDAR, MBES phase 1 and MBES phase 2 surveys.

In summary, the detailed bathymetric data analysis that was conducted enables us to highlight three main observations:

- No deformation of the Romaine-2 dam can be observed at a level greater than 6cm;
- Local deformations have been observed at the cofferdam level;
- Bathymetric survey data from dumped rocks must be corrected for systematic errors due to MBES.

7 ACKNOWLEDGEMENTS

The research project at Hydro-Québec was sponsored internally by the Hydro-Québec Production division. Éric Péloquin acted as the main contact person for HQP. The authors also wish to thank Stanimir Shahanski and Gilbert Dufresne from the geomatics department at Hydro-Québec Équipement for producing the LiDAR survey. The authors also benefited from diligent cooperation from the Engineering department personnel at the Romaine-2 construction site.

8 CONCLUSION

The Romaine-2 dam loading deformation has been monitored through three surveys. One reference land survey conducted with a TLS prior to impounding and two hydrographic surveys with a MBES: one at mid-level and one at about the operational level.

The two hydrographic surveys' datasets have been validated with success, in term of accuracy and precision on reference areas which were known to not be sensitive to the dam loading. The deformation analysis which is built on the comparison between surveys at different loading constraints shows that the dam wall did not move in a significant way (less than 6cm deformation observed). However a notable landslide has been monitored on the cofferdam's slope (about 1.5m in amplitude), and a potential material intake on its right part has been detected (almost 9cm).

A special attention has been paid to the upper part of the dam wall which is covered with riprap. Indeed previous works' results that shown that MBES are submitted to systematic errors on dumped rocks sea floor have been confirmed. A 37cm bias, which should not be interpreted as a deformation of the upper part of the dam, has been measured.

This study allowed us to confirm the ability of a hydrographic survey vessel, equipped with a MBES, an inertial navigation system and a GNSS receiver, to support the establishment of a reliable structural diagnosis on large dam. But one need to keep in mind that when conducted in complex subsea infrastructures, such hydrographic surveys required a specific knowledge and understanding of MBES in order to remove biases that could be misleading at the modeling interpretation level.

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