Mapping displacements of a dam crest based on the synergy of high-precision remote sensing

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Keywords: Dam safety; Geomatics; GIS; Mapping displacements

Abstract

The synergy of GNSS and high-leveling techniques allows the possibility to measure displacements, while the use of Geographical Information System (GIS) and geomatic techniques allows a better visualization through 2D and 3D maps validated using traditional topographical methods. In this research four 3D surveys were conducted on a dam crest in northeast Mexico. During a period of 5 years GNSS observation were used to assist in understanding the actual dam kinematics and the possible correlation with the reservoir level. The mapping and assessment used high-precision leveling and close-range remote sensing data of 84 established permanent control points (of approximately ± 0.003m errors). The mapping of displacements shows off positive and negative translations (maximum uplifts 11 mm and maximum subsidences - 5 mm) in different positions of the dam crest and across the riverbank. A Ground Laser Scanner (GLS) produced 3D digital models, detecting displacements among the dam crest elements. Please refer to Yépez Rincón et al. (2024) https://doi.org/10.1155/2024/6220245 for more detailed information.

1. Introduction

Reservoirs are highly relevant infrastructure assets; and they play an essential role in society's welfare and national security. Their importance is related to their capacity to store water for different uses, such as human consumption, agricultural irrigation, flood control, and hydroelectric energy production, among other important services that allow regional socio-economic development.

Worldwide however, many reservoirs are reaching the end of their period of life, and others are showing undesired displacements and cracking. A possible failure in the dam system represents risks in the form of material losses to the environment, especially if they are close to urban communities. Examples of this cathastrophes are reported in during a dam failure in China during Typhoon Nina (Yang et al., 2017), or the Banqiao dam failure (Yang et al., 2019).

Regular inspections could, in many cases, prevent failures. All possible causes of dam failures are considered during their design. Furthermore, the values or assumptions consider the theoretical stresses and deformations, which have to comply with fields such as balance, compatibility, boundary conditions, and material (Scaioni et al. 2018).

Even though there are some studies, such as the two-dimensional (2D) mapping using an interpolation method to simulate an uneven deformation rate. The interpolation method has been used in many fields of knowledge. Wang et al. (2014) used a method based on the radial basis function for land cover mapping at the sub-pixel scale by hardening the soft class values.

Poreh and Pirasteh (2020) reported vertical deformations and analysed several CosmoSkyMed images utilizing the interferometric synthetic aperture radar (InSAR) technique to improve the understanding of 3D surface displacements. Three-dimensional (3D) models using ground laser scanners (GLS) have been applied to monitor dam deformation. Authors such as González-Aguilera et al. (2008) concluded that the GLS alone is not sufficient to monitor dam displacements, and used GLS for earthen dams, and Li et al. (2021) for arch dams.

The contribution of this research is as follows:

- A consistent, decisive, and stricter displacement monitoring method, that enhances millimetric accuracy for longitudinal and transverse displacements was attained based on 2D and 3D models.
- The data collected can be used to validate theoretical and numerical models of structural behavior, improving understanding of the actual conditions of the dam and the accuracy of predictions.
- Studies employing these techniques offer essential information for the management, maintenance, and security of critical infrastructures such as dams, contributing to informed decision-making and the prevention of potential risks.
- The ability to identify dam displacements even before they reach critical levels can be crucial for making preventive decisions and early warning.

1.1 Background

The water supply for the population in Monterrey Metropolitan Area (5.9 million) is carried out through three dams: Rodrigo Gómez "La Boca", José López Portillo "Cerro Prieto" and Solidaridad "El Cuchillo". "El Cuchillo" dam site is located at 25°42' N and 99°17' W in China City, Nuevo León in the Northeast of México and it started operations in 1994 with a 1,123 Mm3 of storage capacity.

El Cuchillo is operated by Water and Sewer Services of Monterrey (Guerra Cobián et al., 2020), supplies approximately 5,000 L/s to the Metropolitan Area of Monterrey. The reservoir captures has seven radial gates control the surplus spillway, which is 13 m wide by 16 m high, with a maximum discharge capacity of 10,477 m3/s. The lowest point of the foundation is 134.00 m above sea level, and the upper elevation is 151.75 m.a.s.l. There are seven spillways, each one delimited by two piers.

Cracks were detected in the dam crest since 1995 (one year after its construction was finished). In 2016, the National Water Commission (CONAGUA) started a surveying project. Topographic monuments were built for survey control data, as well as other 84 permanent control points (PCP) were established in the spillways area. The surveying team used these marks to monitor the displacements of this dam.

Fig. 1. El Cuchillo dam.

2. Methodology

2.1 Monitoring of displacements

Data acquisition, specifications, and preparation was achieved with geodetic and topographic high-leveling surveys that can assess the longitudinal and transversal displacements of the crest and the correlation to the levels of the official reservoir records. A master polygon was established by using the five superficial control points (SCP) on the dam crest, a master polygon was calculated as a reference plane.

Table 1. Coordinates used to build the master polygon.

SCP	COORDINATES	
Vertices, LB and PCP	**X**	**Y**
V1 (LB-B)	472,211.948	2,843,702.639
V2 (PCP-84)	472,219.635	2,843,747.305
V3 (PCP-7)	472,176.891	**2,843,853.632***
V4 (LB-A)	472,139.686	2,843,883.873
V5 (PCP-29)	**472,168.162***	**2,843,798.630***

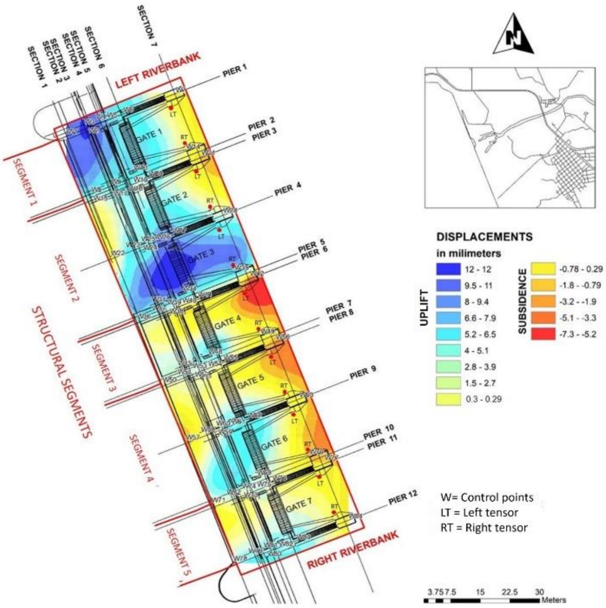
Note: *these measurements presented 1mm difference for the second survey.

2D mapping displacements by an interpolation method. The objective of any 2D mapping is to estimate the value of the unmeasured locations based on a finite set of measurements. Inverse Distance Weighted (IDW) interpolation determines cell values using a linearly weighted combination of a set of sample points (Childs, 2004). The weight is a function of the inverse distance.

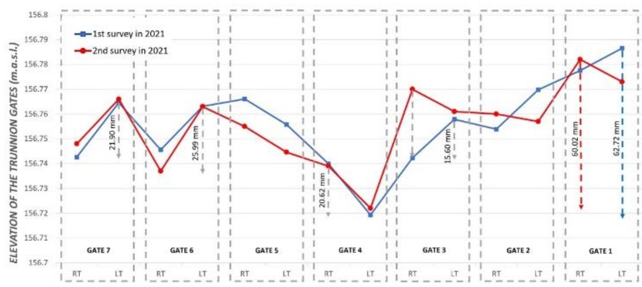
3D mapping displacements by a cloud-to-cloud comparison method. Was achieved with a very-high density point cloud, a detailed scanning was required to cover the entire structure using stepwise horizontal and vertical GLS. Every scan was set on the highest possible angular resolution, resulting in point clouds of 70,000 to 170,000 points on the farthest section.The two surveys made in 2021 were processed using the CC software. The set of scans obtained in each surveying campaign was merged to have a complete, detailed 3D survey.

3. Results

The altimetry differences in the structure revealed a deformation pattern over the crown of the dam, consisting of both uplift and subsidence areas. The total measured differences in the field go up to 11 mm (uplift) at the left riverbank to -5 mm (subsidence) from the middle part to the right riverbank, specifically in the longitudinal section 7, where the Trunnions are located. Piers 5 to 9 present the most consistent subsidence in the order of -7.3 mm in piers 5 and 6. Conversely, in both the LB-A and above gate 3, there are uplifts up to 12 mm (Fig.2A). The digital 3D model, aligned and validated, allows an understanding of the kinematic behavior of the central axis of the Trunnion gates. The change of position was used to monitor the longitudinal and transversal displacements. The results indicate that the displacements can rise to 6.272 cm among the Trunnion central bolts of gate 1 and gate 4 (156.72m to 156.78m) (Fig. 2B) along the monitored period.



A)



B)

Fig. 2. Displacements A) in Z-direction of the crown, based on the IDW method between 2016 and 2021, and B) in Z-direction using 3D scans.

4. Conclusions

Reservoirs as the “El Cuchillo” dam are essential infrastructure assets, and they require both a more decisive and stricter displacement monitoring program. The use of remote sensing technologies as high-precision levelling and laser scanning, together with more traditional sensing technologies, can provide much more reliable information about dam kinematics; This type of study, however, could have some limitations in a field, such as the time-consuming, heavy equipment or computational challenges. This way, the decision-makers can make better judgements. Three conclusions emerge from this study:

1. First, “El Cuchillo” dam displaced 1.16 mm annually since 1994.
2. Both the 2D and 3D models revealed similar altitudinal displacements in the upper part, as in the case of piers 5 to 9, present the most consistent subsidence in the order of -7.3 mm in piers 5 and 6.
3. Further research of “El Cuchillo” dam requires a stricter experiment design, mainly under different filling dam scenarios and thermal fluctuations due to seasonal differences, and to explore InSAR analysis, as well as integrate geological and geotechnical information under the dam.

Acknowledgements (optional)

The authors sincerely thank the CONAGUA, Civil Engineer Institute of the UANL and Technoproject SA de CV.

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