Assessment of cracks on concrete dams by image processing. The Case-study of Itaipu dam, at the Brazil-Paraguay border

Jónatas VALENÇA, Eduardo S. JÚLIO

CERIS, Instituto Superior Técnico, Universidade de Lisboa
Lisboa, Portugal
E-mails: jonatas.valenca@tecnico.ulisboa.pt, eduardo.julio@tecnico.ulisboa.pt

Abstract

Maintenance strategies for large infrastructures rely on the accurate surveillance of their state of conservation. Therefore, monitoring key-parameters related to structural behaviour is always a major concern. In the case of concrete structures, the identification and characterization of crack patterns, and the evaluation of crack widths, plays a critical role. More specifically, stable values indicate an adequate structural performance, whereas unstable values alert for possible structural faults. In the particular case of concrete dams, to monitoring cracks is essential to ensure the integrity of the structure or to detect and correct on time possible problems, avoiding accidents that otherwise could lead to major disasters with huge human losses.

In spite of the importance of crack monitoring in dams, this is usually simply based on visual inspections, resulting in drawings and/or photographic records. This traditional approach also includes hand-held measuring, using crack width rulers, performed by technical staff. To access cracks at high locations, it is necessary to install provisional scaffolding, or to use the rappel technique, also with very significant constraints and costs. Thus, it can be stated that, contrary to other significant key parameters, crack monitoring in dams is currently performed adopting a low-tech, high-cost, and time-consuming methods.

In this paper, an innovative method, named MCrack-Dam, based on image processing and designed to automatically monitoring cracks in dams, is presented. The method was first tested in controlled laboratorial conditions, and later validated on site. Finally, it was applied to a predefined region of the Itaipu Dam. Results demonstrate the ability of the MCrack-Dam method for performing a comprehensive characterization of cracks in dams, not comparable to the traditional method currently used. Most relevant conclusions drawn are herein presented, as well as the improvements needed to allow its use to perform an exhaustive survey of the whole surface of the dam.

Key words: crack; dams; concrete; monitoring; computer-vision; image-processing.

1 INTRODUCTION

The suitable maintenance of large infrastructures has always been committed to the correct understanding of the evolution of its state of conservation. In this sense, monitoring of key indicators of structural problems is a permanent concern. In the case of concrete structures, the evaluation of the crack patterns evolution plays an important role in the maintenance

strategies. In fact, crack patterns can provide information about possible structural faults, being able to be connected to different types of internal forces and stresses.
The assessment of cracking on concrete structures is usually addressed by direct sketches based on visual observations, and the cracks width measure by hand-held instrumentation, namely crack width rulers and measuring magnifiers. These manual approaches exhibit disadvantages related to the need of physical and close contact with the crack. This frequently required the use of expensive means of access to reach all key-sections of the structures, ensuring not only suitable inspection conditions but also the safety of the maintenance crew, in order to have efficient crack detection. On other hand, the inspection quality will depend on the type of access provided and cracks' location.
In this paper, a method named MCrack-Dam, based on image processing and previously validated during experimental testes, is applied to characterize cracks on Itaipu Dam, at the Brazil-Paraguay border. The method was applied in a predefined region for calibration and to define possible adjustment to be scale-up for a generalized application in real structures. The method presented shows the ability for comprehensive characterization of cracks on concrete surfaces. Furthermore, an incomparable amount of information, in all cracks profile, can be achieved from the data acquired, comparing with the traditional instrumentation applied.

2 ITAIPU DAM, BRAZIL-PARAGUAY BORDER

The Itaipu Dam (Figure 1) is an infrastructure located in the Paraná River, at the border between Brazil and Paraguay. Its reservoir goes from Foz do Iguaçu in Brazil and Ciudad del Este in Paraguay, to Guaíra and Salto del Guaira, respectively, about 150 km north. The 20 turbines of Itaipu Dam has an installed power generation of 14,000 MWh, just recently exceeded by the Three Gorges Dam in China (Caetano de Souza 2008). In 2008 it generated a record amount of 94.7 TWh, and provided 87% of Paraguay's energy and 19% of Brazil's energy (Rivarolo *et al.* 2012; Itaipu-Binacional 2015). Since the beginning of its construction, the Itaipu Dam has been concerned to monitor the behaviour of the structure (concrete, rock-fill and earth-fill), and of several mechanical and electrical components. In addition to uses the most modern technology, the Itaipu Dam has invested in-house technological developments, and created the Itaipu Technological Park (PTI) and the Center for Advanced Studies on Dam Safety (Ceasb) for that purpose (PTI-Ceasb 2015).
In this paper, only the issue of detection and monitoring of cracks in the concrete dam will be addressed. These results mainly from the construction phase and do not represent any alarm signal. Its regular assessment has been carried out by a specialized inspection team, using traditional methods, including visual observation and width measurement through graduated magnifiers. However, given the huge size of the infrastructure, this survey is labor intensive and time-consuming, highly dependent on the technicians, and practically impossible to be carried out systematically, especially at high levels. The Itaipu Dam includes a set of structures: earth-fill dam, rock-fill dam and concrete dam, including the spillway. To validate the applicability of the method presented to the concrete dam, an area-of-study was defined by the inspection team. This consists of a region with about 4.5 m height and 40 m length, in the base block D54 (Figure 2a). The selected region presents biological colonization and a wind-area rain, and has been previously cleaned with water jet, having removed all the material deposited on the surface (Figure 2b).

Figure 1. General downstream view of Itaipu dam.

(a) (b)

Figure 2. Itaipu dam, block D54: (a) location; (b) surface to assess.

3 METHOD MCRACK-DAM

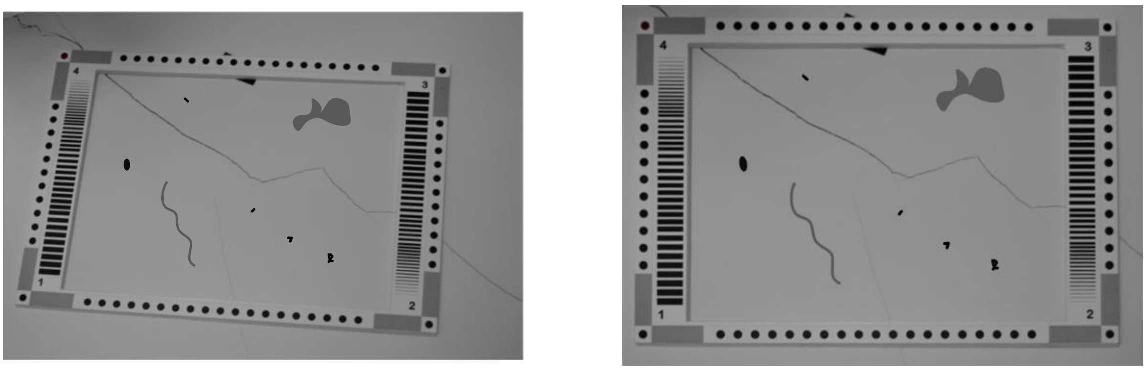
3.1 BACKGROUND

The application of image analysis and processing in Structural Engineering is a research topic that has been developed in the last decade by the authors. The most relevant modulus of the methods were validate in laboratorial environment (Valença *et al.* 2012a; Valença *et al.* 2013a; Valença *et al.* 2013b; Valença *et al.* 2014; Dias-da-Costa *et al.* 2016; Valença *et al.* 2017a; Valença *et al.* 2017b). The first approaches were the application of photogrammetry to the geometric survey of existing constructions and the evaluation of displacements in structures subjected to load tests. In the latter case, the methods developed were initially validated in experimental tests and then applied to bridge monitoring (Valença *et al.* 2012c). Following these studies, a method was developed to calculate displacement and strains fields on test specimen surfaces (Dias-da-Costa *et al.* 2011). Simultaneously, computer vision techniques were applied in the development of a method for characterization and monitoring of cracking on concrete surfaces (Valença *et al.* 2012a). Later, the two tools were combined, and the strains field was used to define the critical regions, where crack characterization is detailed performed (Valença *et al.* 2013a; Valença *et al.* 2017b). The combination of the several methods referred to, operating as modules, allowed to design a robust method for evaluating concrete structures (Valença *et al.* 2014).

3.2 PROCEDURE

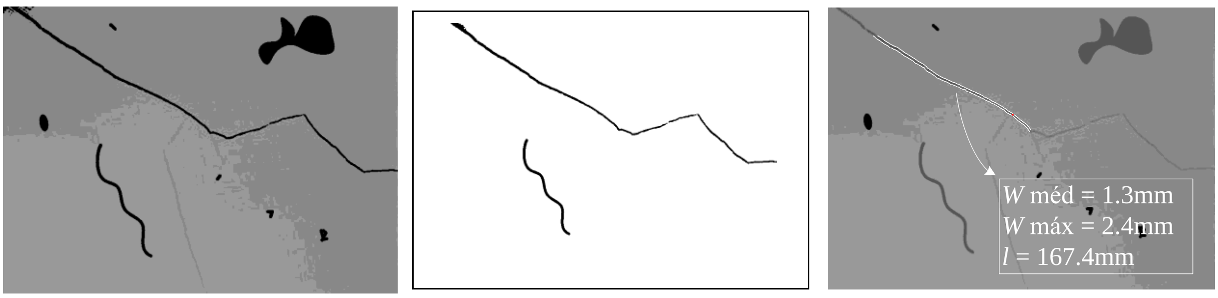
Image processing algorithms, used an implemented in-house code (Valença *et al.* 2012a; Valença *et al.* 2013a), was applied to identify and characterize cracks on concrete surfaces. The MCrack-Dam comprises the following main steps:

1. Acquisition of a set of images of concrete surfaces for mosaic built;
2. Stitching of a high resolution image from the mosaic of images;
3. Establishment of a homography matrix for produce ortho-rectified images (Figure 3);
4. Computation of the ortho-images based on homography matrix and spatial resolution;
5. Definition of Regions Of Interest (ROI);
6. Application of a specialised algorithm to detect linear discontinuities in images;
    a. Detection of discontinuities (Figure 4a);
    b. Link and clean operation to remove non-crack discontinuities (Figure 4b);
7. Application of a specialized algorithm to characterize cracks – MCrack method (Figure 4c);
    a. Detection of cracks boundaries;
    b. Measurement cracks width, length and area;
8. Assembling of the final cracks pattern map.



(a) (b)

Figure 3. Pre-processing for remove distortion, alignment and orientation of images: (a) original image original; (b) ortho-rectified image.



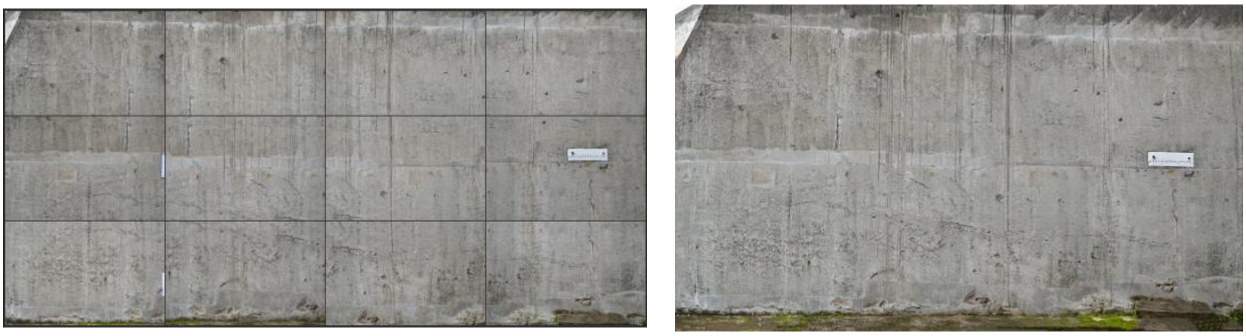
(a) (b) (c)

Figure 4. Processing procedures: (a) detection of discontinuities; (b) definition of regions of interest; (c) characterization of cracks in the regions of interest.

4 RESULTS

4.1 IMAGE ACQUISITION

Images were acquired with a resolution of 4608×3072 pixels and a focal length of 55 mm, with the camera stations placed at a distance of 5 m from the surface. Images focusing details were acquired from a distance of 1 m from the surface, in areas previously identified with cracks by the inspection team of Itaipu Dam. An example of a set of images acquired to compute the mosaic and the final mosaic are provided bellow (Figures 5).



(a) (b)

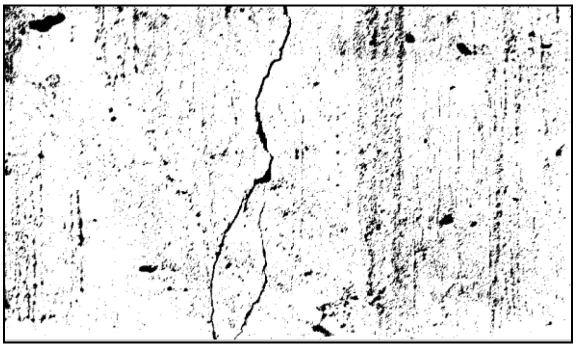
Figure 5. Section of the area-of-study: (a) set of images used; (b) final mosaic.

4.2 PRE-PROCESSING

In this step, the images captured in the dam surface are ortho-rectified. Note that image acquisition should be performed with an accurate positioning of the camera station and the support of a predefined pattern, in order to perform the pre-processing operations. The procedure consisted of acquiring two sequential images from each photographic station, the first with and the second without the pattern. Since the images were captured exactly in the same conditions, the first one was used to calculate the Homography matrix, which was later used to compute the ortho-rectified image used for crack characterization, from the image acquired without pattern. This results in high precision estimation of the spatial resolution. An orthomosaic was also computed only aiming to mapping the crack pattern, since the image processing procedure adopted to measure the cracks was performed in isolated images.

4.3 GLOBAL ANALYSIS – IDENTIFY CRACKING AREAS

The global analysis reveals all main discontinuities on the concrete surfaces analysed. To illustrate this, Figure 6 presents a global analysis of the ortho-rectified image and the result of applying this step of MCrack-Dam. From the identified discontinuities, only those having crack characteristics are selected, in particular, those which are linear and continuous objects, being set as ‘Region Of Interest’ (ROI) in the map of discontinuities. The ROI is extracted from the ortho-rectified image, for later local analysis. In Figure 7 the results from applying this step of the method in the previously example is presented.

(a) (b)

Figure 6. Identification of main discontinuities: (a) ortho-images; (b) discontinuities detected.

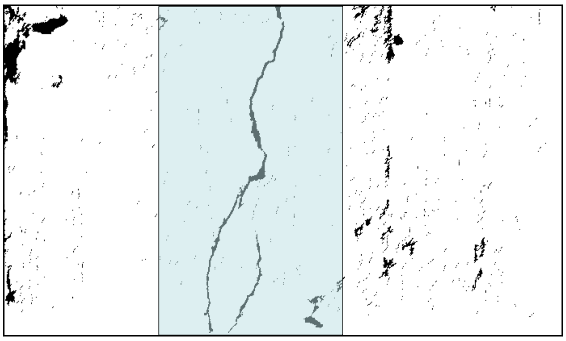
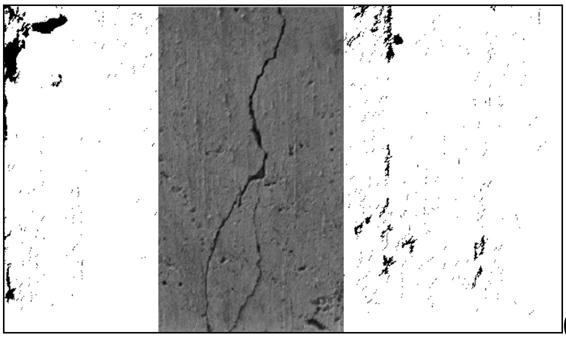


(b)

Figure 7. Definition of the Region Of Interest (ROI): (a) on the map of discontinuities; (b) on the ortho-image.

4.4 LOCAL ANALYSIS – CHARACTERIZATION OF CRACKING AREAS

The local analysis consists in processing the ROI of the ortho-rectified images. It can be applied in several areas of a given crack, allowing to reach sub-millimetre accuracies. Figure 8 shows the result of this step, once again for the first selected example, for an image acquired from one of the stations closer to the surface. In the local analysis, it is possible to characterize and, subsequently, consult all relevant parameters of the cracks in user-defined critical regions. Figure 9 illustrates the application of the step in a critical region manually selected (blue shading in Figure 9), with a spatial resolution of 0.07 mm. Studies on the precision and accuracy of measured values can be found in (Valença *et al.* 2013a; Valença 2014).

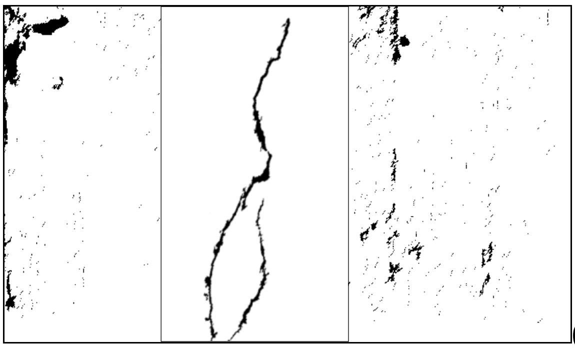
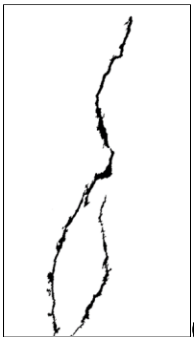
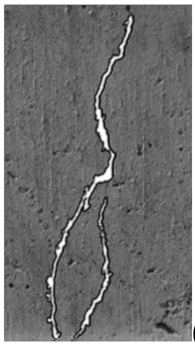
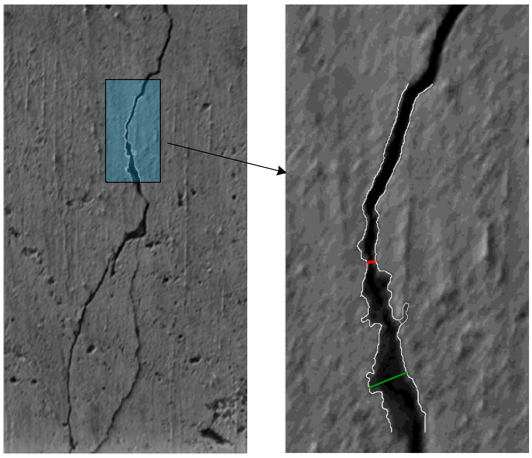

(a)

(b)

(c)

Figure 8. Processing of the Region Of Interest: (a) definition; (b) extraction: (c) mapping on original image.



Crack characteristics		
Whidt	average	1.39 mm
	maximum	2.86 mm
	minimum	0.57 mm
Length		54.16 mm
Area		2275 mm^2
Precision		0.075 mm

Figure 9. Consultation of the crack characteristics through a local analysis.

4.5 FINAL CRACKING MAPS

In the final map (Figure 10a), the cracks are identified with less resolution, in order to allow easy and fast navigation and visualization. However, detailed analysis of critical regions can subsequently be performed throughout the crack. The user will be able to access any region of a given crack and to select and detail analyze the sections of interest (Figure 10b).

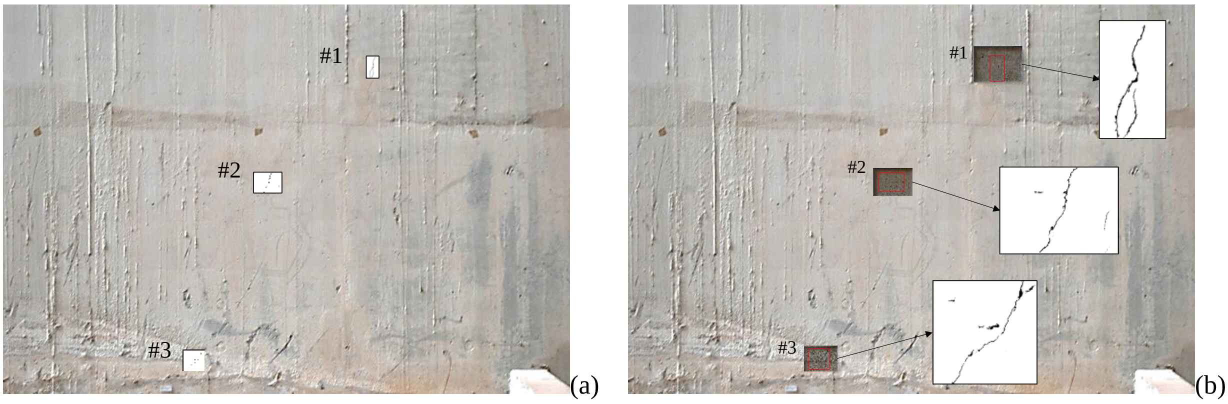


Figure 10. Map of critical cracking areas analysed: (a) location of the areas analysed; (b) zoom of the local areas.

5 CONCLUSIONS

In this paper, a method previously developed and validated in laboratorial environment, named MCrack (Valença *et al.* 2012b), was customized and applied to a large structure, the Itaipu Dam, at the Brazil-Paraguay border. The application of the novel method, 'MCrack-Dam', allowed demonstrating its viability for identification and characterization of cracks on concrete surfaces of the Itaipu Dam. A precision of 0.075 mm was reached in pre-selected critical region of the cracks analysed.

Due to the huge dimensions (length and height) of the dam, the systematic collection of images using autonomous vehicles is mandatory. This is expected to significantly reduce execution time. In addition, the precision required for the survey to be carried out should be pre-defined, to reach an effective implementation of the system for monitoring cracks.

Cracks in the concrete surface, hidden due to the presence of biological colonization, dirty stains, and efflorescence, is a real problem that requires to be adequately addressed, regardless of the method for crack characterization. Note that cleaning the surface with water jet satisfactorily resolved this issue in the present case-study.

ACKNOWLEDGMENTS

Authors would like to acknowledge the Portuguese Foundation for Science and Technology (FCT) by funding the project PTDC/ECM-EST/6830/2014, entitled `Crack Monitoring in concrete bridges through multi-spectral image processing acquired by unmanned aerial vehicles'. Jónatas Valença also acknowledges the support of FCT through the post-doctoral grant SFRH/BPD/102790/2014.

REFERENCES

Caetano de Souza, A. C. (2008). Assessment and statistics of Brazilian hydroelectric power plants: Dam areas versus installed and firm power. *Renewable and Sustainable Energy Reviews* 12(7): 1843-1863.

Dias-da-Costa, D., et al. (2011). Laboratorial test monitoring applying photogrammetric post-processing procedures to surface displacements. *Measurement* 44(3): 527-538.

Dias-da-Costa, D., et al. (2016). Crack propagation monitoring using an image deformation approach. *Structural Control and Health Monitoring*: n/a-n/a.

Itaipu-Binacional. (2015). site of Itaipu Binacional http://www.itaipu.gov.br. retrieved 23 October, 2015.

PTI-Ceasb. (2015). site of Parque Tecnológico de Itaipu (PTI), http://www.pti.org.br/. retrieved 13 October, 2015.

Rivarolo, M., et al. (2012). Time-dependent optimization of a large size hydrogen generation plant using "spilled" water at Itaipu 14 GW hydraulic plant. *International Journal of Hydrogen Energy* 37(6): 5434-5443.

Valença, J. (2014). Systems based on photogrammetry to evaluation of built heritage: Tentative guidelines and control parameters. M. F. Remondino F., International Society for Photogrammetry and Remote Sensing. **5:** 607-607.

Valença, J. and R. N. F. Carmo (2017a). Method for assessing beam column joints in RC structures using photogrammetric computer vision. *Structural Control and Health Monitoring*: e2013-n/a (in press).

Valença, J., et al. (2014). Automatic concrete health monitoring: assessment and monitoring of concrete surfaces. *Structure and Infrastructure Engineering* 10(12): 1547-1554.

Valença, J., et al. (2012a). Characterisation of concrete cracking during laboratorial tests using image processing. *Construction and Building Materials* 28(1): 607-615.

Valença, J., et al. (2013a). Automatic crack monitoring using photogrammetry and image processing. *Measurement* 46(1): 433-441.

Valença, J., et al. (2012b). Characterisation of concrete cracking during laboratorial tests using image processing. *Construction and Building Materials* 28(1): 607-615.

Valença, J., et al. (2013b). Damage assessment on concrete surfaces using multi-spectral image analysis. *Construction and Building Materials* 40(0): 971-981.

Valença, J., et al. (2012c). Application of photogrammetry to structural assessment. *Experimental Techniques* 36(5): 71–81.

Valença, J., et al. (2017b). Assessment of cracks on concrete bridges using image processing supported by laser scanning survey. *Construction and Building Materials* 146: 668-678.