New methodologies to support structural monitoring of a very large dam

H. Silva, E. Carvalho
henrique.silva.sng@hcb.co.mz
ezequiel.carvalho.sng@hcb.co.mz

HCB – Hidroeléctrica de Cahora Bassa, SARL

Cp 263 – Songo – TETE
MOÇAMBIQUE

J. Boavida
jboavida@artescan.net

Artescan Digitalização Tridimensional

IPN Incubadora
Rua Pedro Nunes
3030-199 COIMBRA
PORTUGAL

A. Berberan
berberan@lnec.pt

Laboratório Nacional de Engenharia Civil

Av. do Brasil 101
1700-066 LISBOA
PORTUGAL

Introduction

Cahora Bassa dam is a very large dam built on the Zambezi River in Tete Province, Mozambique. A comprehensive and redundant structural monitoring system has been established both on the dam and on its quasi vertical abutments regarding the serviceability of the dam and its safety control assessment.

Besides direct measurements taken more frequently on pendulums, extensometers, deformeters, drains and piezometers, a geodetic monitoring system has been redesigned and put into operation in 1999. Since the same year, a systematic and referenced photographic coverage of the dam and abutments has been taking place on a regular basis. In 2007, a 3D texturized model of the visible part of the faces of the dam and the neighbouring banks, including the abutments, was acquired. In order to obtain this model, a multi sensor platform - based on a passive Charge Couple Device (CCD) type of photo-sensors and on an active sensor Time Of Flight (TOF) type of laser scanner - was used. These activities have been designed, implemented and explored on a "building on capacity" approach regarding *Hidroeléctrica de Cahora Bassa* (HCB) staff.

Fig. 1 – Panoramic photograph of Cahora Bassa dam

The purpose of the laser scanning and photographic coverage of the dam is manifold. Firstly we must obtain a sufficiently accurate 3D geometric model, of the dam and surroundings, from where measurements can be taken, for instance for the planning of repair works. Secondly we must obtain a record of the dam and surroundings on a given date including both its visual aspect and geometry up to a 2 to 3 cm uncertainty. Finally, this type of record, if performed with sufficient image resolution, can be used to help the supervisor of the dam structural security to prepare his assessment regarding that safety.

On the other hand, the vast amount of data recorded directly on an electronic support can be further processed on-line, in order to generate both classical synthesized information, like contour lines and cross-sections, and new era engineering documents. For instance, from a 3D texturized model, it is possible to obtain an easily accessible 3D PDF file or to record a digital video with a virtual inspection, through a pre-defined path, along the dam or abutments, by emphasizing some meaningful views of representative anomalies or their absence.

Clearly, both the image resolution and the electronic processing of huge amounts of data are a tangible challenge that needs to be properly addressed.

1. Assessing the Structural Behaviour of the Dam

Cahora Bassa dam was built on the Zambezi River, 150 Km North of Tete city in Mozambique. It is a double curvature arch dam with a 170 m height, a 303 m crest length, a 23 m thickness at the base, a 4 m thickness at the top, 8 spillway radial gates and 1 surface gate. The total discharge capacity is 14,000 m^3/s. The reservoir created by Cahora Bassa dam has a maximum volume of 65×10^9 m^3, a useful capacity of 52×10^9 m^3, a 270 km length, a 30 km maximum width and the maximum flooded area is 2900 km^3 [Silva & Carvalho, 2005]. On the right bank, an underground power house was built, with a 216.7 m length, a 28.9 m width and a 57 m height, one transformer hall and two chambers (downstream). It has 2075 MW installed power. A total of about 2,534 m of tunnels, galleries and caverns was excavated with an estimated 1,545,599 m^3 removed volume of rock and an approximately volume of 500,000 m^3 of placed concrete. The entire complex is founded on a granite-gneiss rock mass of good quality, sparsely jointed and with a young modulus higher than 50 GPa and a very low permeability. The layout of the Cahora Bassa hydroelectric scheme is presented elsewhere [Silva & Carvalho, 2005; Carvalho *et al*, 2007].

The assessment of the structural behaviour and of the safety of Cahora Bassa dam is achieved, step by step, in 3 levels of actions and cognitive procedures (Fig. 2):

1. *The 1st level* includes local raw data acquisition, validation by admissible ranges and storage in a pocket computer. A couple of hours later, the data is transferred to the main office computer in which the raw observations are converted into structural engineering quantities.
2. *In the 2nd level*, those engineering quantities are validated comparatively with expected results obtained from statistical models.
3. *In the 3rd level*, the assessment of the structural behaviour and of the safety control is done using evolution graphs, statistical models, mathematical models, etc..

The maintenance fits in the preventive type of program supported by an overall annual plan. As part of a strategy recently implemented to achieve a compromise between better performances – aiming at reducing abnormalities and occurrences – and the operating costs, a check list is assigned to each monitoring device, as well as to the specific components of the dam and appurtenant works. Nonetheless, the maintenance includes also every kind of safety assessments, either structural, environmental, hydraulic or operational, all of them contributing to the management performance and compliance. The maintenance plan and programme is managed by SAP/R3 software.

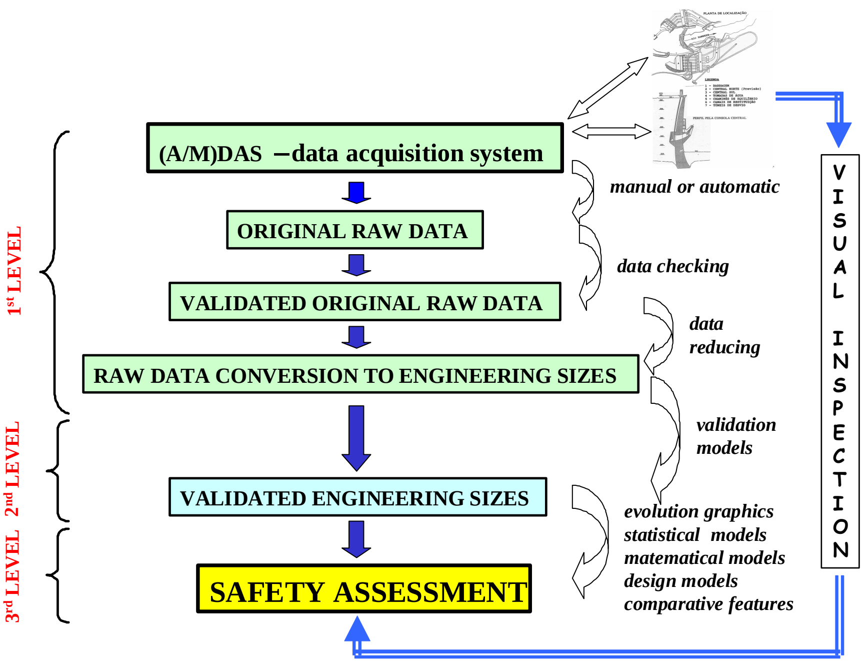

Fig. 2 – Flowchart for dam behaviour and safety control assessment

Visual inspection is a very useful and consensual tool to complement this assessment by numerical means. However, the personal influence on this type of inspection should be minimized. Therefore, a referenced visual inspection has been developed and implemented, in 1999, by HCB. The methodology consists of obtaining digital photographs using a camera on a tripod at predefined “stations” from where it is possible to cover the downstream abutments, the galleries in the dam and the banks. Magnetic azimuth, inclination, focal distance, orientation referenced to control points, station identification, date and hour are registered for every taken photograph.

2. Main criteria used in visual inspections

As stated before, visual inspections are carried out as a complement to the instrumental monitoring system. During the reading operations of the monitoring instruments, the operators carry out systematically a first and simplified visual inspection. In addition to this daily monitoring, several routine visual inspections are planned and carried out monthly to get an insight into the following aspects:

1. On the dam, the operability and maintenance of the monitoring devices, the cracks on the exposed surfaces and the chemical deposits. Also the beams and other reinforced structures of the gates are subject to inspection.
2. On the banks, the operability and maintenance of the monitoring system and accesses, the stability of the rock boulders and slopes, the resurgence of seeping water and the efficiency of the drain trenches.
3. On the underground, the operability and maintenance of the monitoring system, the stability of the rock walls and the resurgence of seeping water.

Some of the features to be considered during crack surveying, in the visual inspection are described in Table I.

Table I – Example of a file for cracking visual inspection

VISUAL INSPECTION: Routine - Speciality - Exceptional			DAM: Cahora Bassa		INTERVENIENTS
PARAMETER	PLACE	QUALIFIER	QUANTIFIER	REMARKS	FILE-RECORD
CRACKING		Cause/Origin	Construction	Retracting or other	Photographs
			Thermal	Sun radiation, gradient	Videos
			Chemical	Reactivity, dissolution	Paper
			Structural	General, local, foundation	Other means
		Openning	Capillary		
			<0.2 mm		
			0.2-0.5 mm		
	Block		0.5-1.0 mm		
	Downstream face		1.0-2.0 mm		
	Upstream face		>2 mm		
	Gallery	Development	<2 m		
	Ceiling		2-5 m		
	Wall		5-10 m		
	Floor		>10 m	In all the block, interblocks	
	Walls	Dynamic	Stable		
	Buttress		Progressive	Rate, Former record	
	Face	Orientation	Nearly horizontal		
	Etc.		Nearly vertical		
			Upright Foundation		
			Parallel Foundation		
		Geometry	Linear		
			Sinuous		
			Branched off		
			Random-MapCrack	Narrow or Large Strip	
		Hidrochemistry	Active Percolation	Intensive, humidity	
			Inactive Percolation		
			Carbonate deposition	Recent, old, reactivated	
			Ferrous deposition	Idem	
			Efflorescence	Idem	

On a yearly basis or whenever judged advisable, specialized visual inspections are carried out by the head of the safety department. If requested, independent experts, for instance, from the design office, from LNEC (Laboratório Nacional de Engenharia Civil, the Portuguese laboratory for civil engineering) and recently from USACE, the Nippon Koey/Manitoba Hydro and ATKINS also take place during the inspections.

During the last 9 years, after starting the referenced visual inspections, a database has been populated, containing now 500 photographs, which are duly catalogued and that can be used to study the evolution of deteriorations. Two sequences of photographs, respectively for the downstream right bank and for a sector of the downstream face of the dam, are shown in Figures 3 and 4. Although the scale of the images in this paper is not suitable to make any statements, at full scale, it is possible to conclude that the banks present no evidence of modifications. The same conclusion can be drawn from the sequential analysis of the dam face: with a more appropriate scale it is possible to see that no modification occurred concerning major cracking, water soaking through the concrete or chemical depositions.

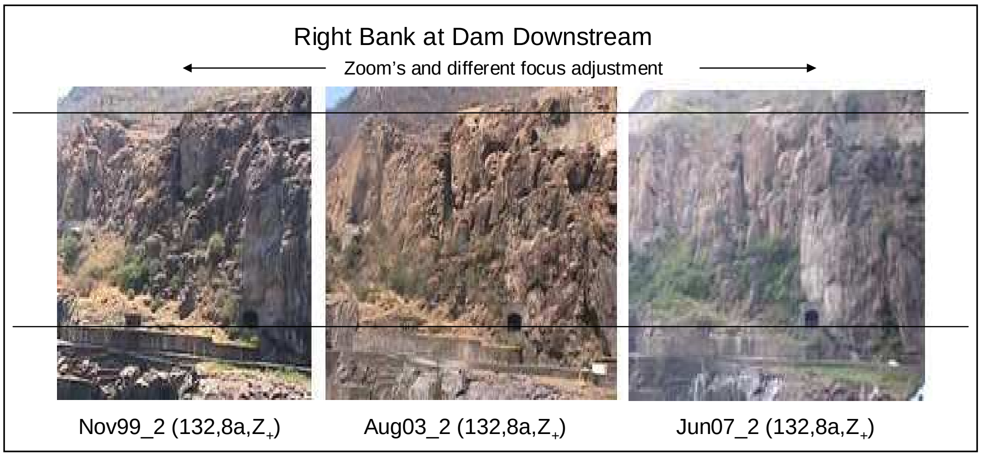

Fig. 3 – Historical sequence of photographs from the downstream right bank

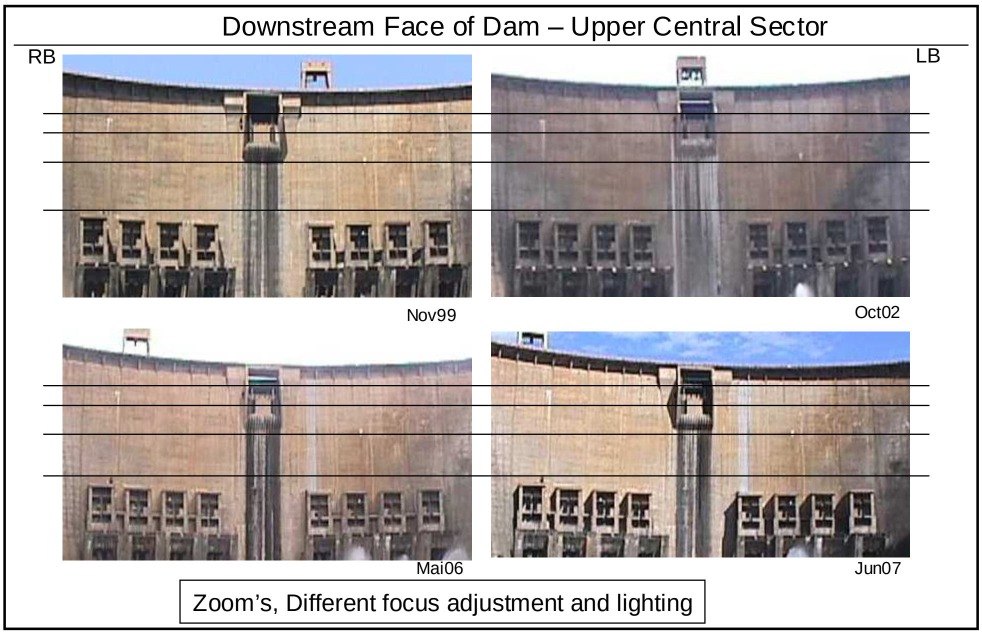

Fig. 4 – Historical sequence of photographs from the downstream face of the dam

3. Assisted visual inspection using laser scanning technology

As already stated, in 2007, a decision was made to carry out a first survey of the downstream face, abutments and nearby downstream and upstream banks using laser scanning and digital imagery. The next few paragraphs present first the technology adopted and, then, its application to the dam.

3.1 The technology

The equipment (RIEGL LMS Z360I) has two main sensors: an active one (laser scanner) and a passive one (a CCD – Charge Coupled Device – type of photoelectric light sensor). The 3D laser scanner belongs to the so-called type of "time delay" sensors and among these it belongs to a "time of flight" subtype. It consists of a laser emitter, a detector of the returned signal and an orientation mechanism system for the laser beam. The typical uncertainty for this type of sensor is in a range below one centimetre and decreases with the distance between emitter and the reflecting surface [Gordon, 2001]. Acquisition frequency goes up to 12 000 points per second. The laser beam is deflected according to parameterized angular increments (α, β) by a rotating or oscillating mirror contained in a rotating head. Distance (D) is computed from the time the impulse takes to return to the detector. These three observables (α, β, D) are spherical polar coordinates of the reflecting points. Intensity (I) of the returned signal is also associated with the reflecting point giving rise to the so-called intensity map, a kind of 3D photograph that can be taken during the night. The spherical coordinates are transformed into the instrument Cartesian coordinates (x,y,z) which is an arbitrary system related to the geometry and position of the instrument. To cover the whole object several stations (locations) of the instrument are necessary, each having different positions (attitudes) which gives rise to many clouds of points with equal number of different arbitrary reference systems. These clouds need to be concatenated into a single cloud of points in a meaningful reference system (X,Y,Z) most likely being the one meaningful to the object under study.

As regards digital imagery a digital photographic reflex camera (NIKON D200) with a 23,7mmx15,6mm photo sensor array and 10.2 million photo sensor elements has been used. After a calibration process, which takes place prior to the photographic coverage, the computed inner parameters accurately model the geometry of the image formation. The offset parameters of the camera, in relation to the previously mentioned instrument Cartesian coordinate system are also calibrated. With these parameters and according to the fundamental formulae of photogrammetry, it is possible to fuse the data coming from both sensors. With this fusion it is possible to obtain a discretized yet very dense virtual model of the real object under study. This virtual model has metric quality and radiometric properties (in the RGB bands of the visible part of the electromagnetic spectrum) and can be further processed in order to synthesize the collected set of wealth of information.

3.2 The application

After field reconnaissance 29 retro-reflector targets were scattered on the dam and surrounding areas including targets on the geodetic monitoring network pillars of the dam. A surveying team from HCB, using electronic tacheometry, has measured both the geodetic monitoring network and the retro-reflector targets and, using EpochSuite (www.epoch-suite.com) adjustment programs has computed the coordinates of all the targets, in the reference system used on the dam. During 3 full days 14 scanning stations were set up to achieve the complete laser and photographic coverage of the downstream face of the dam, abutments and banks as well as the visible part of the upstream face of the dam and the left bank of the reservoir. In a scanning station the scanner head can have several positions, if requested by the coverage angle of the lens focal distance of the camera, and in total there were 41 positions of the scanner. In some stations, up to 8 scanning tilted positions were used. The banks have been surveyed up to 500 m far from the dam. Figure 5 illustrates the surveyed area and scanning stations.

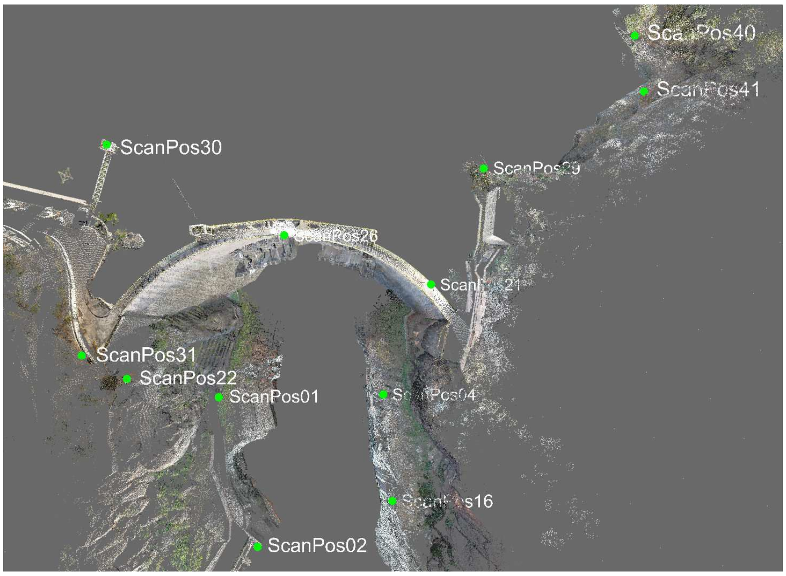

Fig. 5 – General view of the stations using the filtered cloud of points as background

Data was processed in real time on site allowing the team to evaluate locally its radiometric and geometric quality and to repeat the operations whenever deemed necessary. The referencing of the acquired information is achieved also in this processing phase, identifying, on the cloud of points, the targets of which the coordinates are known. The achieved average uncertainty of this referencing operation was around +/- 3 cm, in terms of standard deviation for the position of the points on the model of the dam and envelope area.

In the post-processing phase in office, the several referenced clouds of points were concatenated into a single cloud which, on its turn, was filtered into a new one with a single point in every cube of $1dm^3$. A triangulation was carried out (plane triangulation) generating a continuous model (triangular irregular network - TIN) of the reflecting surface or surfaces. A Laplacian smoothing is than applied to the TIN model to generate a mesh where high frequency information was reduced. This smoothing filters erase points reflected by the vegetation on the river banks. From this model contour lines were extracted every 50 cm and cross-sections could also be derived.

The fusion of raw tridimensional information and duly referenced original photographs made it possible to create, using PHIDIAS software on a Microsation platform, a CAD model of the dam and of other constructions (Figure 6). From the original images a 2D seamless high resolution orthoimage was created. Because this orthoimage has metric quality it was possible to generate a CAD file incorporating the previously mentioned geometric and radiometric processed data: contour lines, construction edges and construction surfaces (3D CAD vectors and surfaces) on top of which the orthoimage was overlapped, creating a texturized model of the dam. This model was exported to a 3D PDF file and can be easily and interactively accessed using the widespread Adobe Reader software. Finally, an application was developed also in PDF, in which several types of synthesized information (video including comments, contours, cross-sections, layouts, images) supported by different types of electronic formats (wmv, dwg, jpeg, pdf) can be seen and analyzed interactively. This vast amount of information can be easily acceded from a single file in the fairly ordinary Adobe Reader software (Figure 6).

This virtual reality type of document represents a new era engineering document. With the texturized model displayed in his monitor, the structural safety expert can carry out, interactively, a virtual inspection of the dam. Finally, using a predefined inspection path, stopping at meaningful deteriorations he will be able to record his spoken comments in a video format type of report.

Fig. 6 – A 3D PDF file in which the main window has an interactive 3D model of the dam and envelope area and the hyperlinks to different files containing synthesized information on several electronic formats

In brief the information that can be obtained from this type of multi-sensor platforms is varied:

1. a geometric and radiometric ASCII discrete model of the dam and its surroundings (*X*, *Y*, *Z*, *I*, *R*, *G*, *B*);
2. a continuous model (TIN) of the dam and the envelope area;
3. automatically generated contour lines and cross-sections;

4. automatic computation of volumes (from deformations, excavations, debris, etc.);
5. a CAD tridimensional model of the dam with graphic primitives;
6. orthoimages, either segmented or seamless;
7. virtual animations of visual inspections including the expert comments;
8. an interactive 3D PDF or VRML file with the texturized 3D model of the dam and surroundings.

4. Conclusion

The high potential and the usefulness of laser scanning and photogrammetry to assist visual inspections was demonstrated. The advantage of this approach is manifold: i) the result is a register of the object, rather than a symbolic and subjective, usually incomplete, interpretation of the dam condition; ii) the retrieval of the information is easy and might be subject to a renovated interpretation of the visible anomalies; iii) comparison with subsequent records is easy and more conclusive.

Further improvements are possible and expected within the short term both as regards laser scanning and image technologies. As far as image is concerned a larger format of the CCD array will diminish the number of photographs taken, leading to an easier processing phase and consequently lowering the costs and making assisted visual inspections more attractive and more frequent.

Image quality, which is dependent on a variety of factors, is the challenge in this particular application of combined laser scanning and photogrammetry. Among those several factors, and due to the use of a 180 mm lens, the stability of the camera showed up as the image quality limiting factor. The upward movement of the mirror, which deviates the incoming light from the sensor array to the eyepiece, shakes the camera in such a way that, given the large focal distance of the lens, it is registered by the sensor when the shutter is released in order to capture the image, immediately after the mentioned movement. This problem can be solved by creating a delay between the release of the mirror and the one of the shutter, improving even further the image quality.

Virtual reality needs to be exploited in order to create new era engineering documents that can synthesize the vast amount of data collected by very fast multi-sensor platforms. The wealth, accessibility, interactivity, completeness and compactness of this type of documents have been, so far, not fully used to the engineers advantage.

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The authors:

Henrique Silva is an Geologist engineer, PhD (in civil engineering), Head of the Civil Engineering Structures and Environment Division at HCB (Cahora Bassa Hydroelectricity Company) between March 1995 and December 2006 and Consultant onwards, former Senior Research Officer and Dam Expert at LNEC, Associate Prof. of Civil Engineering Faculty of Lusofona University of Lisbon, former Secretary General of the Portuguese Geotechnical Society, Consultant on Dam Safety Control and Management, author and co-author of 158 technical reports and 70 technical and scientific papers and articles on structures and geotechnics, land use management, hydrology and environment.

Ezequiel Carvalho is the Civil Engineering Structures and Environment Engineering Division Manager at the Cahora Bassa Hydroelectricity Company in Mozambique. He got a Civil Engineering degree in 1999 at the Eduardo Mondlane University and a post-graduation in Business Administration in 2005 at Porto University School of Economy; he attended a specialisation course on dam safety engineering in Mozambique, Zambia, Portugal and Spain. Ezequiel Carvalho was a former research assistant at Laboratory for Civil Engineering of Mozambique. He is co-author of 8 technical reports and papers on dam behaviour and management.

João Francisco Boavida graduated in Geographic Engineering. He worked in GPS double frequency observables and their computations, at the Geodesy group of the *Technische Universität Berlin*. At the *Geoforschung Zentrum Potsdam* (Germany), he processed gravitational data in the AGMASCO EU project. He worked for the *Potsdamer Platz* and *Reichtag* renovation, as well as for the cadastre of the renewed underwater system in eastern Berlin. From 1999 to 2003, J. Boavida was the technical director of UNAVE, a Geoinformation and Remote Sensing laboratory at Aveiro University, Portugal. In 2003, he founded *Artescan*, which uses Combined Terrestrial Imaging Systems and produces detailed "*as built*" 3D models in the engineering and heritage domains.

Antonio Berberan is a research engineer at LNEC, Dams Department, Applied Geodesy Unit. He graduated in Geographic Engineering, post-graduated in photogrammetry, presented a thesis in automatic outlier detectionn and elimination in heterogeneous models and proposed the Hybrid Method for this purpose. Antonio Berberan has been involved in the design of several geodetic monitoring systems for large dams including Cahora Bassa and in the design of specifications for the use of Combined Terrestrial Imaging Systems for assisted visual inspections and spatially continuous observation of concrete dams.