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DAM MONITORING USING COMBINED TERRESTRIAL IMAGING SYSTEMS

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Abstract: Thousands of registered large concrete and embankment dams have now more than five decades of operation and age related problems. Structural safety condition assessment is the main aim of dam monitoring activities and a concern for authorities. Laser scanners combined with digital calibrated reflex cameras provide accurate and very dense 3D numerical models as well as spatially continuous high-resolution RGB information of the objects under study. These combined terrestrial imaging systems (CTIS) provide a huge amount of geometric and radiometric well structured data in a short period of time. A 3D scanning company, Artescan, and a research organization (LNEC, Laboratório Nacional de Engenharia Civil, in Portugal) have been, since 2003, developing positional monitoring methodologies for embankment dams and assisted visual inspection methodologies for concrete dams. Interesting results have been achieved in what concerns positional accuracy, system reliability and cost-effectiveness of this approach to enhance dam monitoring capabilities. This paper presents different examples of the developed methodologies as applied to dam monitoring.

1. INTRODUCTION

Thousands of registered large concrete and embankment dams have now more than five decades of operation and age related problems. Monitoring plays an essential role in evaluating the structural safety condition of dams. On the other hand monitoring activities are useful for the collection of valuable data to enhance the understanding of the behaviour of these structures.

In what concerns embankment dams, surface displacements related to internal deterioration processes, such as internal erosion or slope failure, can occur. Surface displacements are important quantities to be determined, especially in what concerns safety and long term behaviour [Tedd et. al, 1997]. The determination of these values are made by measuring surface marks located at regular space intervals, usually in the dam crest and downstream face. However this methodology is based on a discrete sample instead of the surface itself.

Up to now and in what concerns concrete dam visual inspections, they have been carried out by expert personnel, without the assistance of any dedicated device or system. Due to operational difficulties, the collected information is often inaccurate, from a positional point of view, rather subjective and costly, yet very important. Laser scanners combined with calibrated reflex digital cameras provide accurate and very dense 3D numerical models as well as spatially continuous high-resolution RGB information of the objects under study. These combined terrestrial imaging systems (CTIS) provide a huge amount of geometric and radiometric well structured data in a short period of time. A 3D scanning company, Artescan, and a research organization (LNEC, Laboratório Nacional de Engenharia Civil, in Portugal) have been, since 2003, developing positional monitoring methodologies for embankment dams and assisted visual inspection methodologies for concrete dams. Interesting results have been achieved in what concerns positional accuracy, system reliability and cost-effectiveness of this approach to enhance dam monitoring activities. This paper presents three case studies (2 concrete and 1 embankment dam) of the developed methodologies as applied to dam monitoring.

2. OVERVIEW OF THE TECHNOLOGY

The equipment used in the projects has two main sensors: a passive photo sensor (digital photographic camera) and an active laser emitter/sensor (terrestrial laser scanner). For both sensors a short description of the respective principles as well as the specifications will be given.

2.1 Laser scanning

The laser scanner used for this research (RIEGL LMS Z360I) belongs to the so-called “time delay systems” group of sensors and is a “Time-Of-Flight with pulsed lasers” type of long-range sensors. It is an active sensor that basically consists of a laser source, a return signal detector and a beam deflection mechanism. The laser source is a Class I laser product, it works on the near infrared wavelength and has a range of up to 300 m. The beam divergence is 0.25 mrad. Computed distance accuracy decreases slightly with range [Gordon, 2001]. The measurement rate goes up to 12000 points per second. A typical accuracy value for average conditions is better than one centimetre for the measured distance.

The pulsed beam is deflected according to parameterised angular quantities by a rotating or oscillating mirror located on a rotating head. The mentioned rotations (α, β) occur according to two axes which are supposed to be perpendicular. Distance (D) is computed as a function of the measured Time Of Flight (TOF) that the impulse of light takes to make a round trip from the source and back to the sensor after reflecting on a surface. The strength (I) of the returned signal is recorded as an intensity attribute value for each point. Thus, sets of (x, y, z, I) are determined by the TLS for every reflecting point of the object under study. From a single position it is not usually possible to cover the whole object and therefore one needs to scan from different positions in order to get the whole object surveyed. For every position there is an independent reference system related to the instrument and one concatenates every point cloud into one single point cloud covering the whole object in a unique and meaningful Cartesian reference system.

2.2. Digital photo imagery

A SLR Nikon D100 reflex digital camera with 6.31 million Red Green and Blue (RGB) Charged Coupled Device (CCD) photosensitive elements organised in a 23.7mmx15.6mm array was used along with the RIEGL LMS Z360I terrestrial laser scanner. The precise inner geometry of image creation by the camera lenses modelled by focal distance, eccentricity of principal point, radial and tangential distortion parameters was determined during calibration procedures that took place before the photographic coverage. The offset of the photographic principal point, in relation to the origin of the co-ordinates of the laser scanner, is known.

According to the fundamental formulation of photogrammetry it is possible to get the RGB values for every particular point where the co-ordinates have been determined by the TLS. It is then possible to merge the data of both sensors to become (*x*, *y*, *z*, *I*, *R*, *G*, *B*).

3. CASE STUDIES

This paper focuses on three dams, two concrete arch dams and one embankment dam.

Alto Ceira is a concrete arch dam with 37 m maximum height above the foundation, 120 m crest length and a thickness of 1.20 m at the crest and 4.5 m at the base.

Cahora Bassa arch dam in Mozambique, with 170 m maximum height above foundation, 360 m crest length.

Lapão dam [Marcelino, 2004] is an embankment dam 39.5 m high, has a crest with 96 m length. It is located near the town of Mortágua and was in an emergency situation during the 2002/2003 winter.

3.1. The experiment at Alto Ceira dam (visual inspection)

The Alto Ceira project, Fig. 1 and 2, is a concrete arch dam located in the region of Coimbra, Portugal, which was completed in 1949. It is a thin arch dam defined by circular arches with constant thickness. Alto Ceira dam has shown an anomalous behaviour that has been closely monitored by dam experts who developed many studies aiming at identifying the main causes of deterioration and the effects on the serviceability and safety of the dam. Numerous visual inspections conducted by trained personnel, have been of utmost importance to support the studies carried out during the dam lifetime.

Among the most important deterioration signals detected exclusively by visual inspections, the cracking state plays a vital role when assessing the structure serviceability and safety requirements. Crack surveying and mapping, have been major problems for dam experts.

Cracks wider than 2 or 3 mm are supposed to be surveyed and this means that the spatial resolution of the images has to be better than 6 mm. The main challenge is focused on the resolution of the image rather than on its metric quality [Berberan et al, 2007b].

As a full coverage of the dam downstream face was required, three stations have been setup for the laser scanner. Every position produced a cloud of points referenced on an arbitrary instrumental system. In order to get the point clouds referenced in a unique and meaningful reference system a set of 21 retro-reflector targets were positioned in the dam vicinity, Fig. 1.

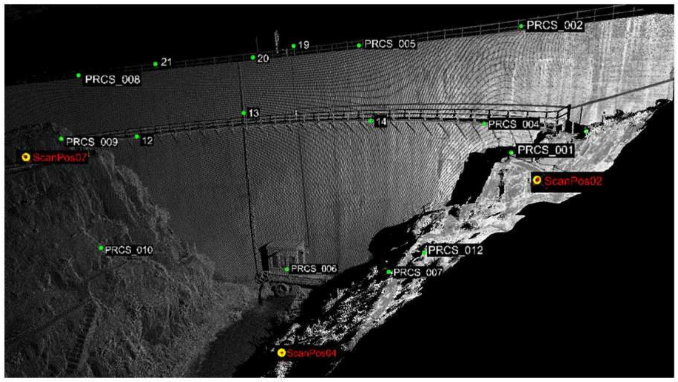

Figure 1 - A perspective of the laser intensity 3D model of Alto Ceira dam downstream face, layout of stations (with red labels) and retro-reflector targets (with white labels).

Eight of these reflectors had their co-ordinates determined by tacheometric methods. The remaining reflectors were measured only by the scanning system and were used as tie points to strengthen the geometry of the concatenation of the different clouds. For each scanning position a number of targets is finely scanned and used to compute the 3D transformation parameters relating every different independent instrumental reference system (x, y, z)i (i=1,..,9) associated with each of the 9 scanning positions to a unique and meaningful reference system (X, Y, Z).

The TLS was parameterised to get the co-ordinates of one point every tenth of arc degree on both rotational axes. The camera body was equipped with an 85 mm focal distance. The total number of photographs is 99. In total, the co-ordinates of about 13.504 million points were collected both of the dam and its surroundings during 6 hours.

3.1.1. Processing and vectorization

The data collected in the dam in one single day occupied one skilled person for 5 days in office. The workflow in terms of data fusion and processing is as follows.

Firstly the pre-processing phase allows the referencing of every point cloud, concatenation and cubic filtering of all the point clouds into a single one. Cubic filtering is intended to specify the size of the cube where no more than one point will be filtered into, generating an octree structure. The total number of points after filtering was 1.191.563 for a 3 cm parameterised cube. A second phase deals with mesh generation (triangulation) of the filtered point cloud, image undistortioning and, lastly, the fusion of the undistorted images with the mesh (texturing).

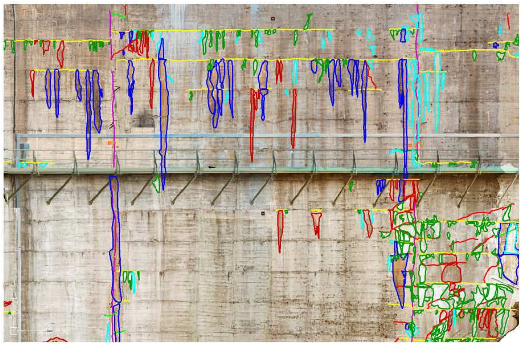

Figure 2 - Ortoimages as a base map for heads up vectorisation of anomalies classified and symbolised according to a catalogue.

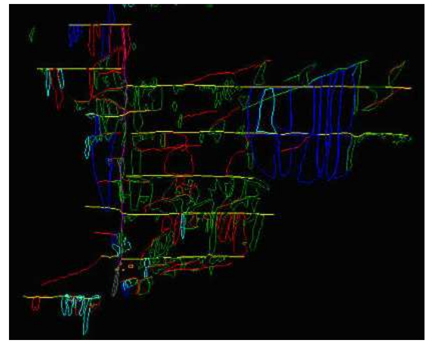

Figure 3 - Vectorisation of cracks, spalling, leaching, leakage, indicators of chemical reactions, erosion or cavitation according to a predefined legend.

A third phase is the processing of images in order to transform their originals, which are the result of a central projection, into images artificially generated as a product of a normal projection. These are the so-called ortoimages and they were concatenated in a single mosaic that looks like a normal photograph but with a known scale all over its extension.

The final step was the vectorization heads up and on top of the orthomosaic of the anomalies in a conventional CAD software, namely Microstation V8 (Bentley) or AutoCad 2004 (AutoDesk), Fig. 2. The vectorization of the anomalies was done according to layers and, graphic characterization specified in the inspection data catalogue. The final result of the vectorization, for a particularly damaged area of the dam, can be seen in Fig. 2 and 3.

3.1.2. Study results

Visual inspection techniques are the primary methods used to evaluate the condition of many concrete structures, such as bridges, dams, tunnels. Despite the fact that for the last few years concrete dams have been equipped with monitoring systems to support safety requirements, visual inspection is still an activity of paramount importance, as many deterioration signs are detectable only through an accurate visual inspection.

Along with the laser scanning and the digital image registration used, a visual inspection support system was developed to facilitate data acquisition and manipulation. Effective implementation of such systems requires a previous identification of the main symptoms to be associated to any possible deterioration process [Portela, E. 2000]. The assisted visual inspection framework requires a process of data standardisation. For all deteriorations a damage symptom catalogue must be created. To each damage symptom a comprehensive set of descriptors must be assigned. For cracks, descriptors may include geometrical parameters, such as length, continuity, orientation, opening and type (craquelet, linear, etc.), or any associated symptom such as leakage or deposits.

The scanning was conducted by a team of 2 specialised surveying engineers and field operations took 6 hours. The generation of the ortoimage, the vectorisation and codification of the anomalies took 40 hours. Fig. 4 illustrates the final result of the codification by association of CAD points, vectors and polygons with their attributes in a data base management system (DBMS) environment. Once the anomaly is registered in the assisted visual inspection support system, it is possible to follow up the evolution between two visual inspections epochs through a process of imaging and descriptors comparisons, which will be very convenient to identify any new degradation or the evolution of an old one.

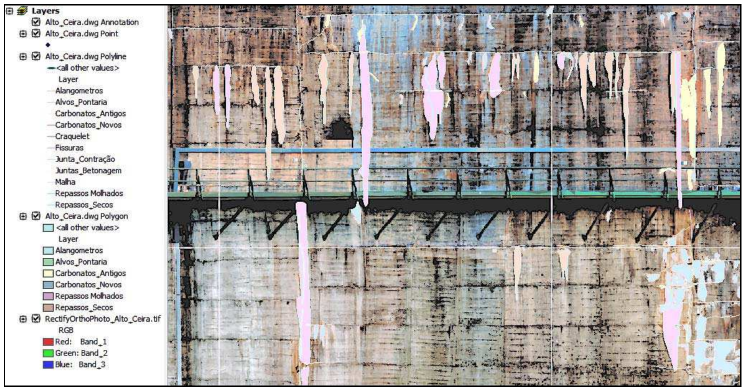

Figure 4 - Association of CAD and DBMS technologies in order to get points, vectors and polygons associated with alphanumeric classifications according to an inspection data catalogue.

3.2. Surface deformation measurement on Lapão embankment dam.

During the first filling of the reservoir (2001/2002 winter) the Lapão dam showed a deficient performance, exhibiting unusually large displacements. Despite the drawdown of the reservoir, a hard rainfall during December 2002 raised the water level up to its maximum and large displacements occurred. Settlement rates reached 15 mm/day during 2002/2003 winter (Marcelino, 2004). After a new complete drawdown of the reservoir in February 2003, several monitoring campaigns were performed, including one (March 2003) with a 3D laser scanner. In February 2005, prior to the rehabilitation design for the dam a new 3D laser scanner campaign was made.

3.2.1 Geodetic Monitoring

The geodetic monitoring network configuration of Lapão dam is composed by 2 reference stations and 18 object points with forced centring. Figure 5 shows the location of reference and object points.

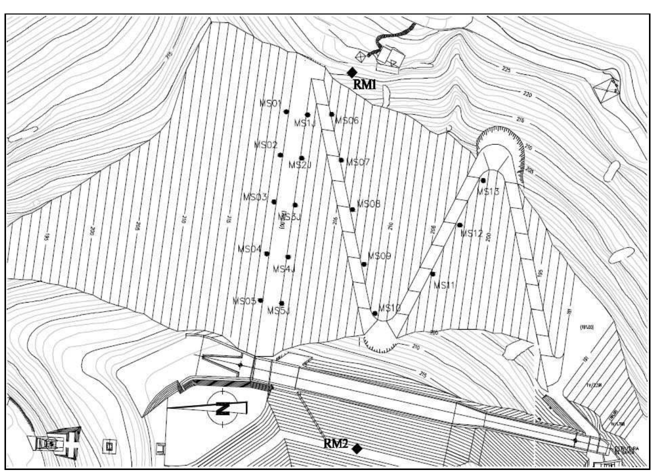

Figure 5 - Lapão dam location of reference and object points

On 18th July 2007 the surface marks were observed from the reference stations with a total station Pentax ATS-101 (linear accuracy: ±(2mm+2 ppm); angular accuracy: ±1”) and an adjustment was carried out using the program EpochSuite (www.epoch-suite.com). Object points were signalized with retro-reflector targets which were used for both laser scanning and geodetic measurements. One survey team (2 people) took 6 hours to set up equipment, observe (position I and II) and compute the network.

This case is a paradigm of the importance of surface displacements monitoring to access the dam security because it was due to this type of monitoring, during the first filling of the reservoir, that abnormal behaviour was detected.

3.2.2 Combined terrestrial imaging system monitoring

On March 2003, February 2005 and July 2007 the same combined laser scanning and Nikon D100 digital camera with 20 mm lens were used together with RiscanPro software to operate the combined system and pre-process the data on site.

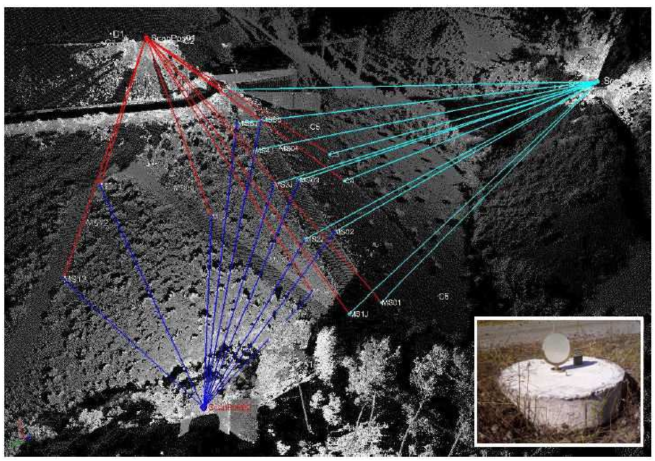

Figure 6 – Laser intensity 3D point cloud of the Lapão Dam (2007) showing the 3 scan positions, retro-reflector targets and vectors between scan positions and surface marks. The smaller image is a retro reflector target on forced centering materializing an object point

The general workflow in a CTIS campaign consists in acquiring data, both point clouds and images, from different stations and attitudes, to obtain a whole coverage of the object under study. In 2003, 4 scan positions were required and 21 reflectors were used, 9 of them as control points and 12 as tiepoints. In 2005 a larger area was surveyed, with 7 scan positions and using 15 retro-reflectors, 7 as control points and 8 as tiepoints. During the July 2007 epoch, 3 scan positions targeted a total of 27 retro-reflectors, including the 18 surface marks. Five of these surface marks (MS05, MS06, MS08, MS11 and MS13) were used as control points and the other 13 were used as tie points for the concatenation of the clouds. The remaining points were used also as tie points to strengthen the geometry of the concatenation. Figure 6 shows the configuration of the network including scan positions, targets and the connections between scanning positions and targets.

For both 2003 and 2007 epochs the field work, including target positioning, 3D scanning and image acquisition, took 6 hours. In the 2005 epoch the field work took 7 hours due to the larger area covered and the higher number of scanning stations.

3.2.3 Processing

In what concerns the acquired model, TLS technology gets the so called DSM (Digital Surface Model) meaning that every laser reflecting point in the scenario will be present in the model (people, bushes, etc..). In earth dams, vegetation might be an obstruction as far as the object under study is concerned. Using Riscan Pro software the point clouds were manually edited in order to get rid of the vegetation. The resulting clouds were then filtered on an octree structure of 30 cm. These cleaning and filtering operations on the clouds allowed a significant and crucial reduction of the amount of data in a supervised way. After reduction procedures the final cloud of the dam had 0.5 million points, from an original 10 million on the 2005 campaign. Mesh surfaces were created from point data using a 2D-Delaunay triangulation algorithm, computed from the 2D coordinates of the vertices mapped onto a horizontal reference plane. Direct use of point clouds in CAD, CAE or DTM software packages (Microstation XM was used) is possible in order to extract conventional cross-sections, profiles, contours, lay-outs, vectorized 3D models and other engineering documents.

3.2.4 Conventional formats

With CAE software, conventional engineering documents like contours, longitudinal and transversal cross sections have been produced in order to systematize the information and to get an engineering document which will be easily analyzed by the engineer. However, a new type of software is emerging to deal with this wealth of information and generate unconventional engineering documents, in electronic supports. These new generation engineering documents, mostly, can only be viewed in computer monitors.

3.2.5 Non conventional engineering documents

Collected three-dimensional data is traditionally transformed into 2D data in order to represent it in paper, screens, etc. and synthesized in order to make it legible. These transformations imply a subjective loss of information so, the ideal situation would be to keep the 3D model untouched and as close as possible to reality.

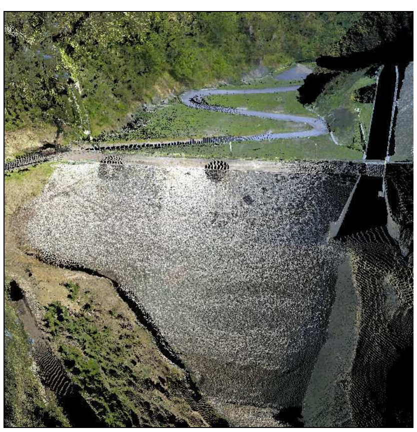

Figure 7 - True color point cloud.

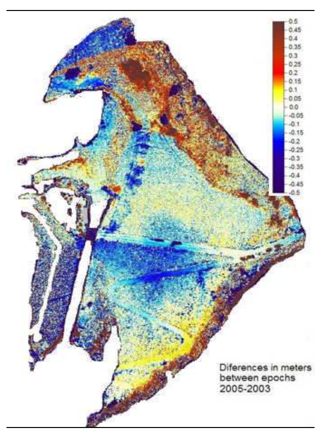

Figure 8 - Settlements - 2005 epoch as compared to 2003.

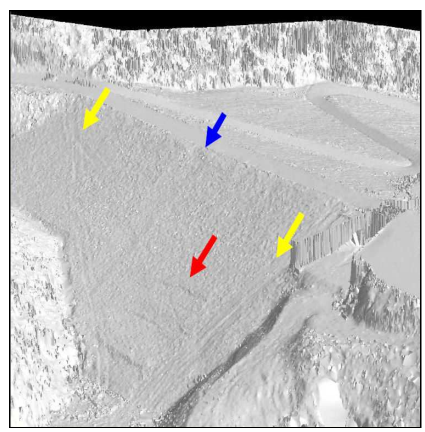

Figure 9: Mesh showing the sliding *waves.*

The 3D texturized models can be visualized in Virtual Reality environments were analysis and decision can be made sparing additional field work. VRML and 3dPDF formats are both capable of representing such models and displaying them in free and easy-to-use viewers where the engineer can navigate through or around the object under study, measure and examine details.

An imaginary camera can move in a predefined path through 3D models evidencing some detail. Dynamic scenarios can simulate the visualization of an event, like flooding. The true color point clouds (fig.7) can be a useful document immediately available in site as it can be visualized in free and user friendly viewers just after the scanning. Figure 9 illustrates the importance and advent of new type of engineering documents, in this case a mesh, besides profiles, contours and the like. None of the phenomena shown on the mesh, whether they are important or not in this particular case, can be easily recognized in conventional engineering documents, and some of them not even on site. At the bottom of the upstream face (red arrow), one strip where rocks have been removed (and replaced) to inspect the face of the dam bellow the rock fill (blue arrow) and two paths left by rolling machinery (yellow arrows).

3.2.6 Comparison of laser scanning method versus geodetic method

Laser scanning can automatically provide coordinates for two types of discrete points: artificial (materialized) points and natural points. The first type can be checked against the results provided by the geodetic method during the same epoch of observation. In order to evaluate the positional quality of laser scanning the coordinates computed via the CTIS and those provided by the geodetic method were compared.

3.2.6.1 Positional quality comparison for materialized point

Table I shows estimated values for the average of absolute discrepancies, average of discrepancies and standard deviations concerning the individual discrepancies between the average of the coordinates from the three laser scanner positions (SP1, SP2, SP3) and the total station (columns LS-GEO).

TABLE I
Global statistical values concerning the individual discrepancies (in mm)
between coordinates provided by the laser scanner positions (SP1, SP2, SP3) and the total station.

	LS-GEO			SP1-GEO			SP2-GEO			SP3-GEO			SP2-SP1			SP3-SP1		
	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz
Avg. abs. values	5	2	3	4	4	4	6	3	3	10	5	6	7	3	3	10	7	5
Avg. discrepancies	3	0	2	1	-1	2	4	0	3	9	4	1	3	1	0	6	5	-3
Stand. deviation	5	3	4	5	4	4	7	4	3	8	5	9	8	4	4	11	7	7
n	18			17			15			9			14			10		

In addition it shows the estimations for the same statistical concepts but concerning the individual discrepancies between every independent Scanner Position and GEO (columns SP1-GEO, SP2-GEO, SP3-GEO) as well as between scanner positions (columns SP2-SP1 and SP3-SP1).From Table I it is possible to detect homogeneity on the quality of the components, X, Y and Z. Table II shows the root mean square error (RMSE) both for every component X, Y, Z and for the triplet XYZ. It is defensible to assert that the uncertainty of laser scanning, as a positioning system and under the same operational and computational environment, is below one centimetre [Berberan et al, 2007a].

Table II
Root mean square error (mm) of whole set of points, check points and control points as computed from Table I

	LS-GEO			SP1-GEO			SP2-GEO			SP3-GEO			SP2-SP1			SP3-SP1		
	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz	Dx	Dy	Dz
RMSE total	5.9	2.7	4.2	5.1	4.3	4.7	7.7	3.8	3.6	11.7	5.7	8.4	8.3	4.4	3.5	12.0	8.3	7.2
RMSExyz		7.8			8.2			9..3			15.5			10.0			16.3	
RMSE check	6.8	2.1	5.0	5.6	4.2	5.5	8.8	4.0	4.2	12.3	5.4	9.0	8.4	4.4	3.5	10.3	7.0	6.3
RMSExyz		8.7			8.9			10.5			16.1			10.1			14.0	
RMSE control	2.7	3.8	0.9	3.6	4.5	1.2	2.6	2.7	1.1	5.0	8.0	1.0	2.9	2.1	1.5	3.6	3.1	0.4
RMSExyz		4.7			5.8			3.9			9.5			3.9			4.8	

3.3. The Cahora Bassa campaign

Cahora Bassa is a very large arch dam in Songo, Mozambique. In late June 2007 a four day campaign was carried out with two main proposes: the processing of a one centimeter per pixel resolution ortoimage of the concrete wall and the near slopes high resolution survey.

As the dam concrete wall dimensions are very large, the distances from the adequate equipment stationing and the wall laid between 100 and 250 meters, 180mm lenses were used to accomplish he demanded image resolution. More than 200 photos were taken for the full dam wall coverage. The campaign had 40 scanpositions. In order to access, visualize and analyze the different data produced an application based on PDF was developed (fig.10). The main window of this application is a 3D window with an embedded 3D PDF CAD model from the Cahora Bassa dam and the level contour lines of the near slopes.

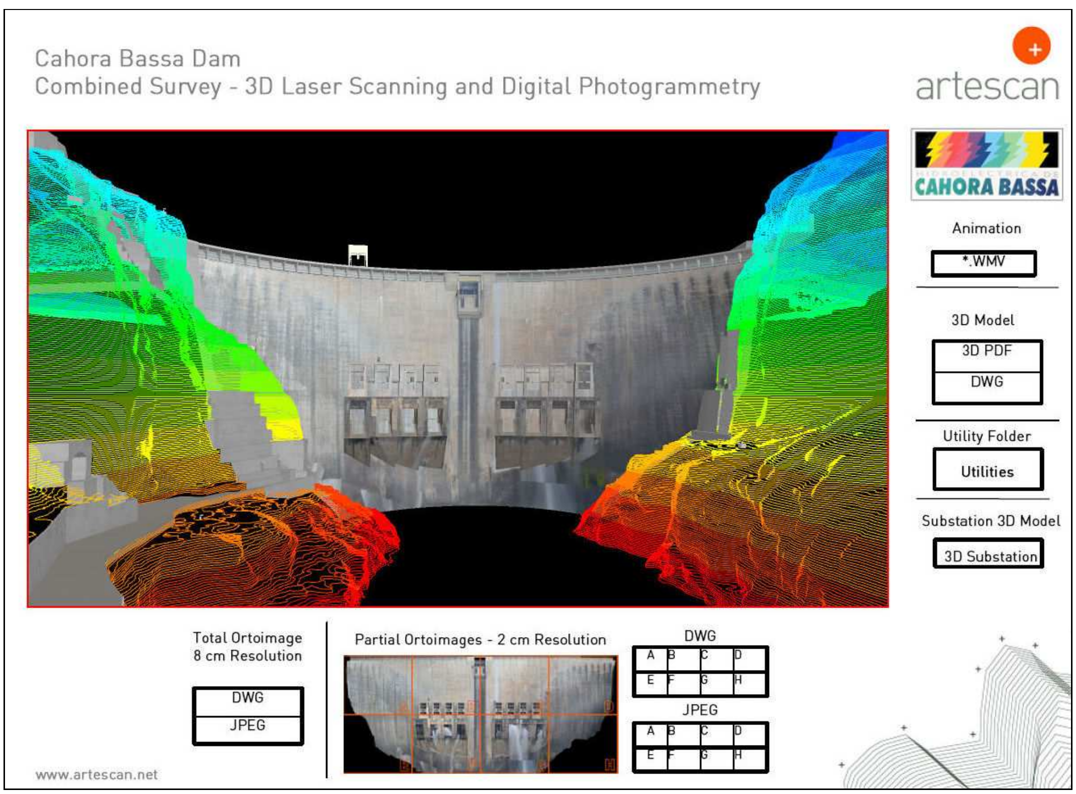

Fig. 10 – PDF Application with embedded 3D CAD model of Cahora Bassa dam and its near slopes.

4. CONCLUSION

Maximizing the benefits of existing dams is a wise approach to a correct management of economic resources. In this paper we have discussed laser scanning technology as applied to dam monitoring. We have presented developed methodologies for 3 different real case studies of embankment, concrete and very large dams.

The laser scanning approach to earth or embankment dam monitoring, in terms of materialized points, can get a sub-centimeter positional accuracy. This accuracy will improve with the advance of laser technology, which is occurring. Whether the actual laser scanning accuracy is enough to analyze the behaviour of the dam is a decision for the engineer responsible for the analysis. However one have to emphasize that beside materialized points, the spatially continuous numerical model of the dam surface is acquired in a very dense grid, at one centimeter accuracy, at a reasonable extra cost. Also for this type of points the positional accuracy will improve soon for the same reasons as referred above. With this type of model the production of new era engineering documents will enhance the capability to evaluate in less time and more correctly the history or status of a dam, namely in case of eminent failure.

In what concerns concrete arch dams, visual inspections play a major role during its life span and particularly during its ageing process. On the other hand, visual inspections provide a huge amount of diversified types of data which needs to be systematised and codified into an electronic environment. When compared to the conventional approach the present methodology provided an economic and reliable way of acquiring very quickly some of the data typically gathered during traditional visual inspections of dams. Through the methodology presented in this paper, the data was directly collected with conventional Computer Assisted Drawing (CAD) software and classified into a Data Base Management System (DBMS) environment. The gathered information is more accurate from a positional point of view and less subjective from a semantic point of view [Berberan et al, 2007b].

In the case of very large dams, and considering the large distances involved, the use of the adopted methodology reveals itself to be particularly adequate, as it allows a complete coverage of the structure, as well as of the near slopes, in a fast, accurate and economical way.

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