Monitoring the structural integrity of large concrete dams: the case of Cabril dam, Portugal

S.Oliveira
soliveira@lnec.pt
Research Officer
LNEC
Av. do Brasil, 101
Lisbon, Portugal

I.Ferreira
ilidio.ferreira@edp.t
Hyd. Power Gen. Div EDP
Lg. Dr. Tito Fontes, 15
Oporto, Portugal

A.Berberan
berberan@lnec.pt
Research Officer
LNEC
Av. do Brasil, 101
Lisbon, Portugal

P.Mendes
pmendes@dec.isel.ipl.pt
Assist. Prof.
ISEL
R.C.Emídio Navarro
Lisbon, Portugal

J.Boavida
jboavida@artescan.net
ARTESCAN
Campus Uni. Santiago, Pav. 1, 3810-193
Aveiro, Portugal

B.Baptista
bbaptista@lnec.pt
MSc.Student
LNEC
Av. do Brasil, 101
Lisbon, Portugal

Introduction

The safety control of large dams under static and dynamic loads, involving observation data and numerical modeling, is now one of the challenges of structural engineering. The complexity of the dam-reservoir-foundation geometry, the presence of different types of discontinuities, the water-structure interaction, the influence of thermal and water level variations, the development of deterioration processes over time and the occurrence of exceptional events such as major floods or earthquakes, makes the structural safety control of large dams an activity that requires a continuous updating, both in terms of the equipment for measuring, transmission, and storage of the observation data, and in terms of computer applications to support the automation process of collecting, processing, analysis and management of all information required to the safety control. The recent LNEC and EDP experience on the revision of the monitoring system of Cabril dam, the highest portuguese arch dam, is presented as a case study in this paper. After a brief presentation of the main dam characteristics – a 57 year old dam with some cracking problems since the first filling and a swelling process that has been recently detected - it is described: i) a new system that was recently installed for the continuous measurement of dam vibrations; and ii) an experience on the use of laser scan technology and digital imagery for measuring dam displacements and to support assisted visual inspections on Cabril dam.

1. Recent trends in the development of dam monitoring systems

In countries where water resources are still underused, as is the case of Portugal, are currently being launched programs for the construction of new large dams for power strengthening in some of the major actual dams and for revision of the safety conditions of most existing dams. Under these programs it is promoted the development / improvement of monitoring systems regarding automation which requires the development of methodologies to monitor and analyze "real time" evolution of dam structural behavior over time.

Employing the latest technologies that enable automation of the process of collection, transmission and storage of data, new monitoring systems must rely on computational modules which allow automatic comparison of observation data and numerical model results. These numerical models should be developed in order to take into account the dynamic water-structure interaction, the effects of deterioration processes, and the effects associated with exceptional events such as major floods and earthquakes of high intensity.

In this paper, the most recent developments on the Cabril dam monitoring system (Cabril is the highest portuguese arch dam - 132 m high; was built in 1953 and presents some horizontal cracks in the central upper zone) are presented, namely in what concerns the use of a continuous vibration monitoring system [1,2] for controlling the damage evolution over time and the use of laser-scanning technologies and digital imagery for assisted visual inspections and deformation monitoring.

1.1 Dynamic measurements and damage control

The development of systems for monitoring the dynamic behavior of large dams in order to obtain information on the evolution of its structural integrity over time (Fig.1) and in order to obtain experimental data on its seismic behavior [3,4] is nowadays a subject of great topicality. In fact, with recent technological advances are already commercially available equipments that allow the continuous measurement of dam vibrations (acceleration sensors and signal digitalization and acquisition systems), under ambient excitation and under seismic loads. The presented Cabril dam vibration results shows that the installation of dynamic monitoring systems in large dams allows: i) the identification of the main modal parameters that characterize the dynamic behavior of concrete dams, ii) gather information to study the correlation between changes in the modal parameters and structural changes due to deterioration processes, especially between the development of cracking and changes in modal shapes, iii) the use of existing modal identification models (in frequency or time domain) [5] to implement computational modules for performing efficient automatic modal identification, iv) to measure the dynamic dam response under ambient excitation and under seismic actions, v) to study the long-term variation of the main natural frequencies of the dam-foundation-reservoir system using simple statistical models based on the principle of effects separation (effect of water level in the reservoir, effect of annual thermal waves and time effects), vi) to study the influence of the reservoir on the structural dynamic behavior of the dam-foundation-reservoir system, namely the hypothesis of added water masses for simulate the hydrodynamic pressure and the reservoir influence on the damping of the system, examining the assumptions of proportional and non proportional damping based on experimental identification of real or complex modes for different water levels [6,2].

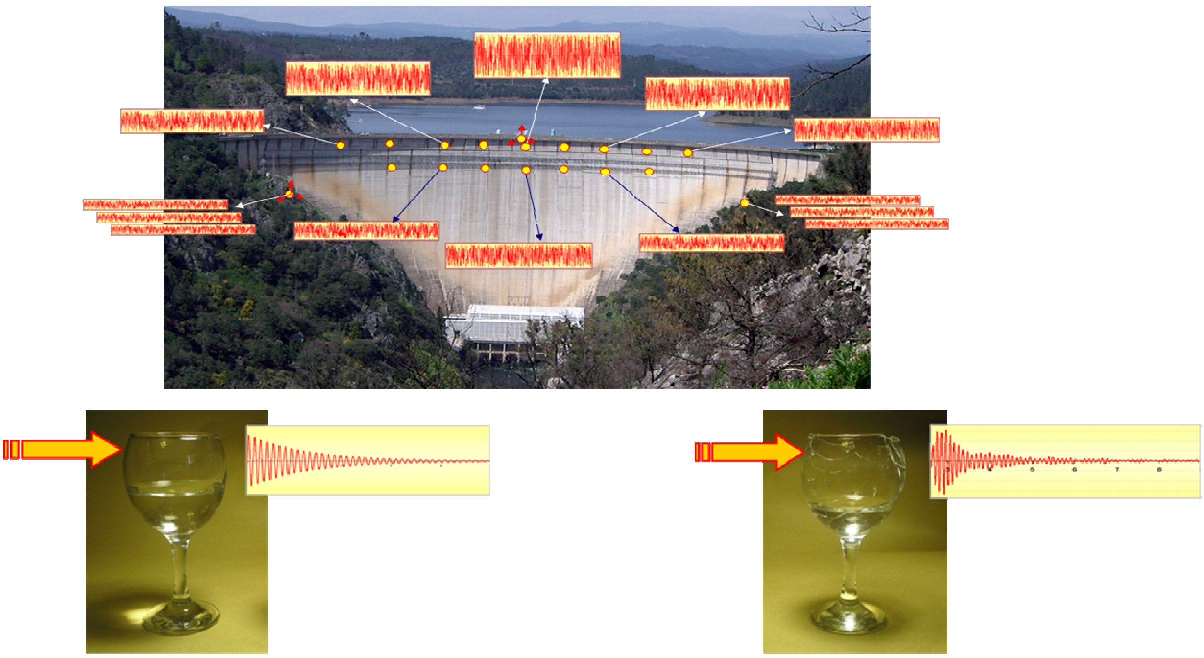


Fig. 1. Cabril dam. The measured dam dynamic response (under ambient excitation or under vibration induced by the power groups or even earthquakes) can reveal the structural integrity conditions: As a damaged glass can be identified from the different sound (vibration) it produces, also the dam deterioration can be identified from the analysis of its vibration data.

1.2 Laser scanning technologies and digital imagery for assisted visual inspections and deformation control

Cabril dam was surveyed using a Combined Terrestrial Imaging System (CTIS) in March 2010, nearly at the maximum capacity of the reservoir (294 m). The laser component of the CTIS provided a geometric representation (over 19 million points with known X,Y,Z) of the downstream wall of the dam. The photo sensor array of the same system provided a referenced photographic coverage of the scenario (over 750 R,G,B digital photographs). A second survey, only with laser scanner, will be carried out when the reservoir is at its lower level during the 2010 summer. The deliveries of these two surveys will be, concerning the downstream wall: a 3D geometric model (X,Y,Z), a 3D photo model (X,Y,Z,R,G,B), a 2D orthoimage, a 2D development of the projection of the referred 3D photo model onto a cylinder and a deformation model of the dam wall between the wet and dry season. This last model will be generated after the last survey, expected early September 2010 [7,8].

The use of these electronic engineering documents is manifold as it will 1) provide the owner with a representation of the dam wall which can be shared in the intranet as well as among consultants, designers, contractors and authorities, 2) be used to map visible deteriorations and 3) monitor spatially continuous deformations with an uncertainty quantified with an expected standard deviation around 1 cm [8]. Finally, and not in the scope of this paper, the metric quality of these documents will be evaluated later comparing the 3D coordinates measured on the deliveries with the coordinates obtained by the geodetic method [9].

Regarding visual inspections, this approach, when compared to the traditional one has shown that the collected information has better quality in terms of accuracy, resolution, completeness and consistency [10]. Also, the information can be quickly gathered at a reasonable cost.The main technical specifications of the CTIS used are listed below:

Table 1 [11]	Specifications
Laser scanner Riegl VZ-400	Range up to 600 m @ Laser Class 1; Repeatability 3 mm; Rate up to 122000 measurements/sec; Field of View up to 100º x 360º
Photographic cameras Nikon D300 and D50	12.3 Million (Effective pixels); 23.6 x 15.8 mm CMOS sensor; 4288 x 2848 Pixels; 5.5 µm (Pixel size)
Lenses	20mm; 180mm; 300mm

Fig.2 illustrates the network configuration, namely the scanning stations and the points used to 1) materialize an Cartesian reference system, 2) to tie the several scanning and 3) to check the positional accuracy after processing the data.

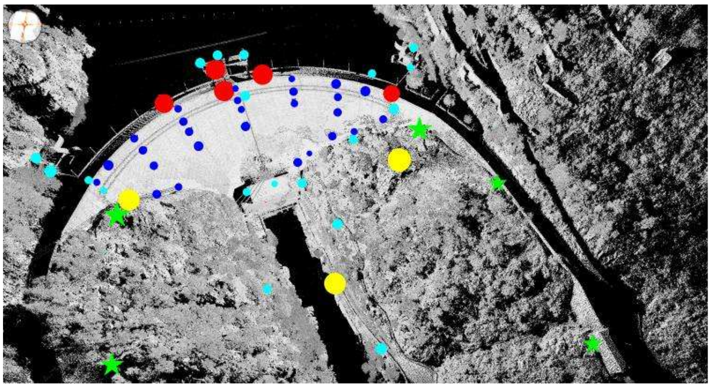
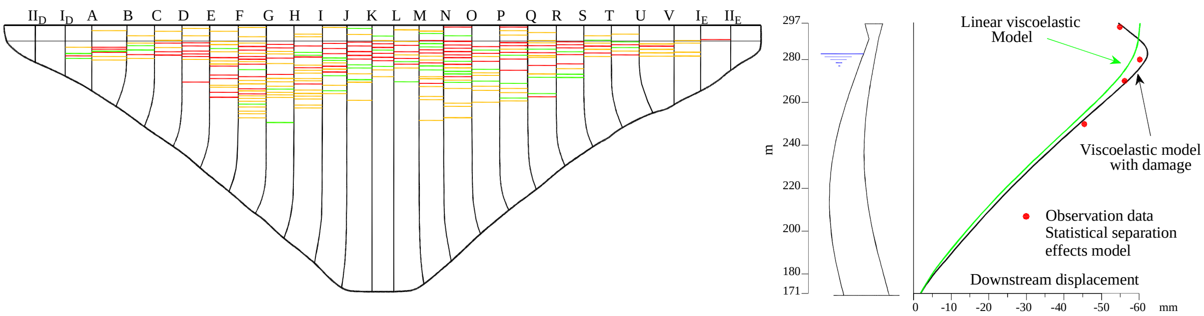


Fig.2 Point cloud of Cabril dam and surroundings with the scanning stations (yellow and red circles), reference points (green stars), tie points (light blue circles) and check points (dark blue circles)

2. Cabril dam

The Cabril dam (Fig 1) was built on the river Zêzere, in 1953. It is an arch dam approximately symmetrical, with a maximum height of 132 m. At the crest there is a non usual greater thickness (Fig. 3).



a) b)

Fig.3 Cabril dam. a) Cracking at downstream dam face in 1996 [12,13]; b) Displacements at central cantilever [12].

Early in the first filling of the reservoir it was detected a significant horizontal cracking in downstream face, located in a range between 10 m and 20 m below the crest. In 1981, after analyzing the structural behavior it was decided to carry out repairs [14] concerning the treatment of the cracks with injections of resin after the characterization of their openings and depths. With the refilling of the reservoir was found that cracks occur again in the same area. Figure 3 presents the cracking in 1996, and the deformation of the central cantilever (full reservoir) - observation data and numerical results- showing the cracking influence on the structural dam behavior (which can be simulated using a viscoelastic model with damage [12, 13]). A swelling process has been recently detected.

3. Continuous vibration monitoring system in Cabril dam

The installed system consists of 16 uniaxial accelerometers, calibrated to measure dam vibrations of low intensity, and three triaxial accelerometers calibrated to measure the vibrations in the foundation and dam during earthquakes of medium and high intensity (Fig.1).

The accelerometers (Fig. 5) are connected to a modular system composed of several digitization units (next to each accelerometer), which are controlled by four acquisition units that receive and forward the collected data by a local network (optical fiber) to a local computer, where all information is continuously processed and stored (using software for the automatic identification of natural frequencies, modal damping and settings). The system can be controlled remotely from a computer center located at LNEC.

a) 

b) 

Fig.4 Accelerometers installed at the dam: a) center of the crest gallery b) left abutment.

3.1 Acquisition, processing and continuous data storage

The values of the measured accelerations are recorded continuously with a sampling frequency of 1000 Hz and are assembled in four acquisition units and sent to a local computer where they are stored in binary files (1 hour long). This data is automatically analyzed (each hour) using the aforementioned software for automatic modal identification. After the identification of the main natural vibration modes – natural frequencies, damping and mode shapes –the identified results should be compared with numerical results from finite element models (Fig. 5). The analysis of the maximum acceleration values recorded allows the detection of exceptional events such as earthquakes (Fig.5b).

3.2 Dynamic monitoring along the service dam-life

This section presents the first dynamic monitoring results of Cabril dam obtained for a period of about one year (Nov2008 to Oct2009) in which there is a reservoir level variation of about 13 m (see Figure 6b). The variations of the main natural frequencies identified (Figure 6a) show a strong correlation with the water level.

Figure 6a) shows the results of a statistical separation effects model in the analysis of the main natural frequencies identified (1st to 4th; the shape of the 4th mode is related with the referred horizontal cracks near the crest [15]). The adjustment of the model to experimental data allows us to evaluate separately the effects of water level variations, annual temperature and elapsed time on the values of the main frequencies identified. Given the short period under analysis (less than 1 year) the obtained results can only be used to study the correlation with the water level. However it is expected that the analysis of longer periods will give us useful information on the influence of time effects on the dynamic dam response that can be used in the characterization of evolutionary deterioration processes.

a) b)

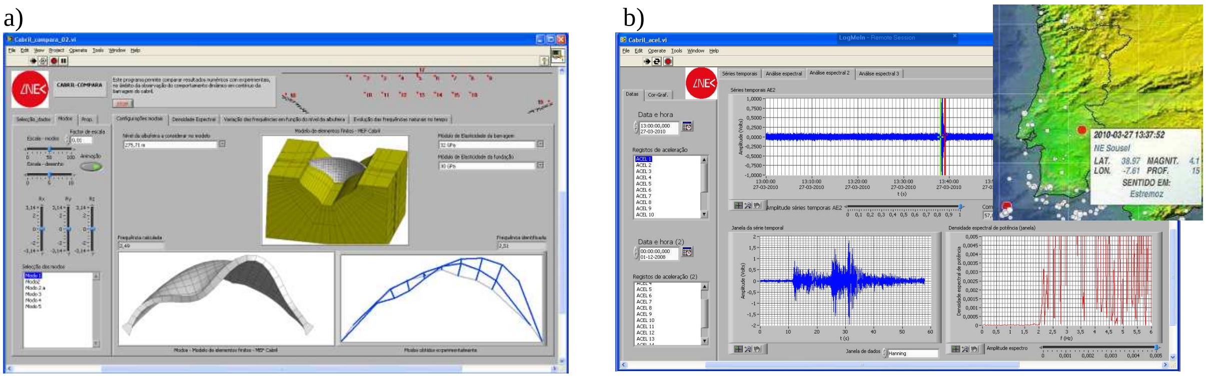


Fig.5 a) Computational module for automatic modal identification and comparison with results of numerical FE models; b) Identification of special events - Sousel earthquake(March 2010): accelerations register in Cabril dam (top of central cantilever)

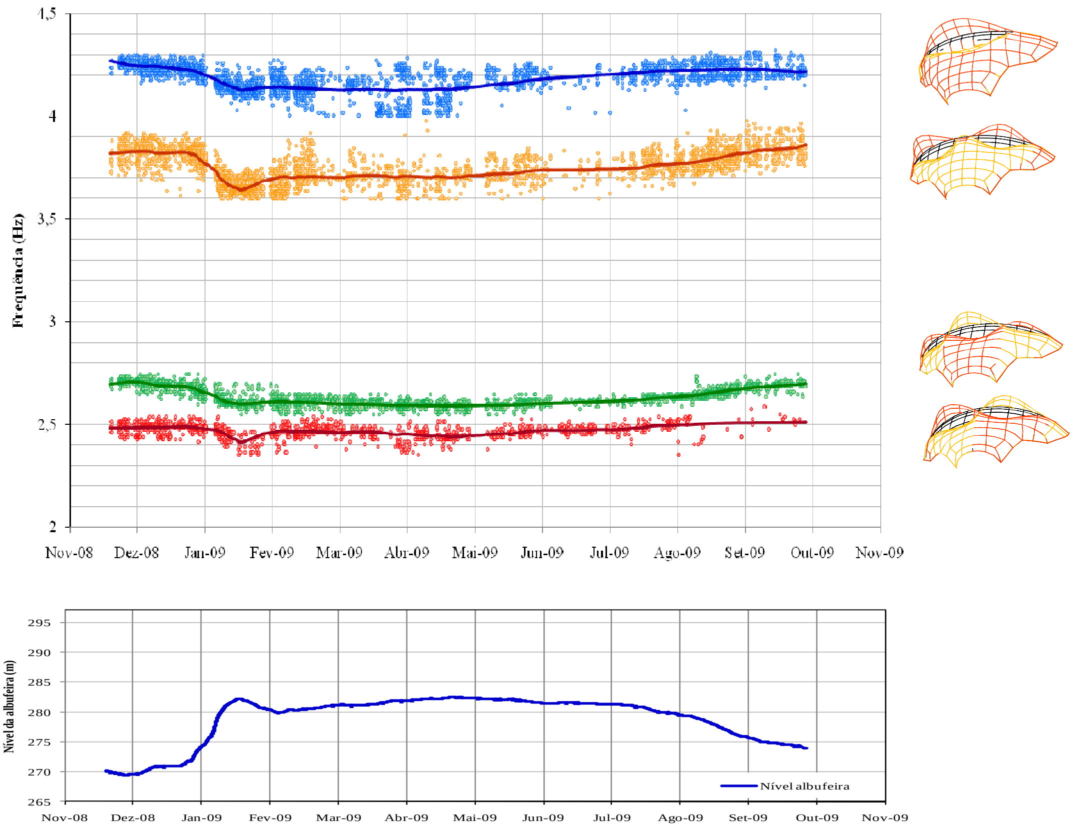


Fig.6 Analysis of the evolution of the main natural frequencies (1st to 4th) of Cabril dam, from Nov2008 to Oct2009. Study of the water level influence using a statistical separation effects model [2].

4. Laser scanning and digital imagery tests in Cabril dam

4.1 Network configuration

In March 2010, 8 laser scanning stations were set up to cover the downstream wall and the surroundings of Cabril dam. In 3 stations (yellow circles on Figure 2), and due to the long focal distance (180mm) of the attached photographic camera lens, the scanner head was set up with different tilts, totalizing 17 positions to fully cover photographically the scenario. A 20mm lens was used both in the remaining 5 stations (red circles on Figure 2), with a single position of the laser scanning head, and in the previously referred 3 stations. An additional photographic coverage, with a 300 mm lens, was carried out independently of the laser scanner operation. To reference the images and the laser scanner positions 6 reference points of the geodetic monitoring network and 30 tie points were used.

The position of 30 check points materialized on the wall were determined using tacheometric methods and will be used to check the accuracy of both the deformations surveyed with the laser scanner and the metric quality of the remaining representations of the dam (3D photo model, 2D orthoimage and 2D cylinder development) [16,17]. Before the photographic coverage a calibration procedure was carried out in order to achieve two goals. First, to determine the inner parameters ruling the formation of the image inside the lens/camera system. Once the parameters are known, the raw image is artificially undistorted. Second, to determine both the angular attitude of the optical axis of the lens and the positional offset of the pixel coordinates system of the photo sensor array in relation to the instrumental Cartesian system in which the laser scanner operates [18]. Next table summarizes some figures concerning the set up and the gathered data.

Table 2		
Stations - 8	Positions - 24	Number of 20mm photographs - 72
Number of 180mm photographs - 295	Number of 300mm photographs - 465	Number of XYZ points - 19,004,632
Groundel - 3, 3mm	Photographic (180mm) - 1,94 Gb (JPG)	Groundel (pixel on the object) - 5.5mm
Photographic coverage (300 mm) - 7,19 Gb (JPG and NEF)	Spatial resolution of the point cloud - 10 points/decimeter^2	Memory space (point clouds and images) - 11.8 Gb
Total number of tie points - 30	Total number of reference points - 6	Total number of check points - 30

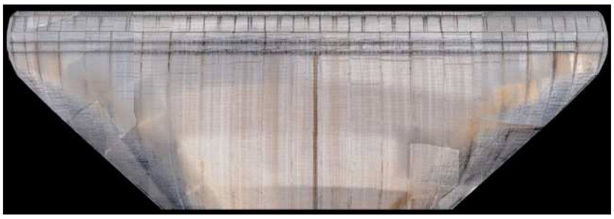
4.2 Data processing and deliveries

During three working days in the field the raw data was collected and pre-processed. Pre-processing consists mainly on validation and referencing of the raw data. Referencing was achieved by indirect methods and individually for every specific cloud of points. Processing in the office takes considerably longer. The actual duration of the processing phase depends on the type and diversity of final deliveries as well as their specifications. It is estimated that, to fulfil the aims of this project, one month will be needed to get the final deliveries, using a work force of two persons.

The processing phase is still time consuming and mainly a manual procedure albeit being electronic and on-line from the beginning to the end of the workflow. The workflow of this phase consists of the following main steps: noise filtering, resampling, meshing, hole filling, mesh decimation, texturizing of the mesh and quality control.

In this particular case additional steps have to be carried out. Firstly the 300 mm pictures have to be referenced as the scanner doesn't allow the physical attachment of such a lens. Secondly the two meshes of the two different epochs need to be compared in order to map the deformations.

The detailed workflow varies from software to software and usually there is several ways to achieve the same results in the same software. Also the huge amount of data suggests the sectioning of the point cloud representing the object under study in order to be able to process the data. For every particular dam section the respective set of points was triangulated. On the resulting triangulated mesh a set of chosen photographs was mapped in order to generate a virtual 3D representation of the dam wall [19]. As a by product of this step an orthoimage with a resolution of 1cm was produced (Fig. 11a.). The 3D representation of the dam is then mapped in a cylinder whose 2D development is illustrated in Fig.11b.


a.

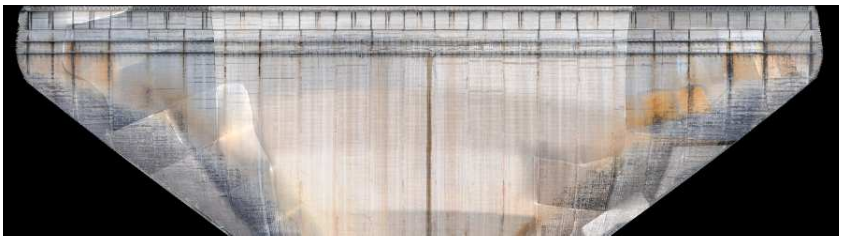

b.

Fig. 7 – a) Mosaic of orthoimages with metric quality and scale to assist on the manual or semi-automatic mapping of deteriorations; b) Development of the cylindrical projection of the texturized 3D model of the dam

The 3D representations of the dam can only be fully and interactively explored in a computer. Figure 12 shows three perspective views of a 3D PDF file that can be accessed using Adobe Reader.
The remaining phases are the comparison between the 3D models of the as-is surface in March 2010 and the as-is surface in August 2010 and the quality control of the processed data. These phases are dependent on the water level in the reservoir and are due to be complete before Hydro2010.

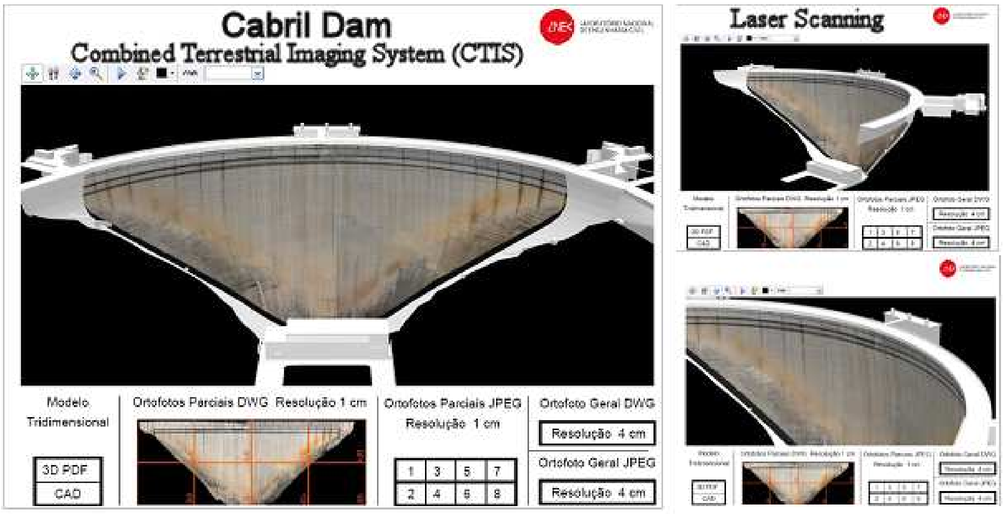


Fig. 8- Several displays of a 3D PDF file with the 3D model of the dam, central image, and links to 1 cm resolution 2D orthoimages [20].

5. Conclusions

The use of modal identification methodologies in the analysis of acceleration records obtained from the dynamic monitoring system installed in Cabril dam since late 2008 showed that it is possible to identify continuously (every hour) the main modal parameters of the dam - natural frequencies, modal damping and mode shapes - with a precision that allows the detection of small water level variations by the detection of small changes on the modal parameters identified. It was shown that the variation over time of the main natural frequencies can be studied by statistical models for effects separation. Using this type of statistical models in the analysis of several years dynamic monitoring periods, results can be achieved that will contribute to a better characterization of evolutionary deterioration processes as is the case of the horizontal cracking in the upper part of Cabril dam. The cracking progression may affect the dynamic response of the dam: in this case the 4th vibration mode has a shape that is fully determined by the referred cracking. On the other hand it was shown that this continuous dynamic monitoring system also allows the detection of special events such as was the case of the Sousel earthquake (low intensity).
In what concerns the use of laser scanner technology and digital imagery the experience obtained in Cabril dam showed that to set up a unit to acquire and process 3D image models needs large initial investments in laser scanner, camera and lenses, high processing speed computers with large data storage capacities and good graphic cards, software copies and maintenance licenses, as well as training, which is significant.
The data quality is expected to improve as laser scanner technologies, which were not developed in a geodetic environment, are now incorporating know how that is common among manufacturers of total stations. The positional uncertainty and range of laser scanners is now sufficient for most engineering tasks that need an high frequency positioning system including deformation monitoring provided the magnitude of the displacement vectors is larger than half centimetre, that is almost the case of Cabril dam.

Acknowledgments

By funding the project “Study of evolutionary deterioration processes in concrete dams. Safety control over time”- (REEQ/815/ECM/2005) thanks to FCT. For their support during the installation of the equipment at the Cabril dam thanks to the EDP. For the design and development of the dynamic monitoring system thanks to Centro de Instrumentação Científica (CIC-LNEC), namely, thanks to Eng Almeida Garrett, Eng. Oliveira Costa and Eng. João Reis.

References

1. **Oliveira, S.** (2002) "Continuous monitoring system for the dynamic performance assessment of arch dams. Sub-programme D", in Candidacy program "Study of evolutionary deterioration processes in concrete dams. Safety control over time.". Project (LNEC-FEUP) funded by FCT (REEQ/815/ECM/2005).
2. **Mendes, P.** (2010) "Monitoring and analysis of the dynamic behavior of concrete dams (in portuguese)". PhD Thesis ,Oporto Univ, Portugal.
3. **Chen, H.** (2009) "Lessons learned from Wenchuan earthquake for seismic safety of large dams". Earthquake Engineering and Engineering Vibration, Vol. 8, Nº 2, pp 241-249.
4. **Wieland, M.** (2003) "Seismic aspects of dams". 21st Congress on Large Dams, ICOLD. General Report of the question 83, vol. 3. Montréal, Canada.
5. **Peeters, B.** (2000) "System identification and damage detection in civil engineering". Ph.D. Thesis, Department of Civil Engineering, K. U. Leuven, Belgium.
6. **Oliveira,S.; Mendes,P.; Espada,M.** (2010) "Dynamic Analysis of Structures by the Finite Element Method. Application to concrete dams and appurtenant structures"(in Portuguese) ICT, LNEC (nearing completion).
7. **Beraldin, J.** (2004) "Integration of laser scanning and close range photogrammetry the last decade and beyond" XXth Congress International Society for Photogrammetry and Remote Sensing. Istanbul.
8. **ICOLD**, (1998) "World register of dams", ICOLD, Paris.
9. **Tucker, C.,** (2002) "Testing and verification of the accuracy of 3D laser scanning data", Symposium on geospatial theory, Processing and Applications, Ottawa.
10. **Portela, E.,** (2000) "Visual inspections in concrete structures. A methodological approach", 42º Brazilian Concrete Congress, Fortaleza, Brazil.
11. **Riegle** (2010), www.riegl.com
12. **Oliveira, S**. (2000) "Models for the analysis of concrete dam's behavior considering cracking and time effects. Damage formulations (in portuguese)" FEUP Oporto Univ., Oporto, Portugal.
13. **Florentino, C.; Oliveira, S.; Silva, H.** (2003) "Cabril dam observation (Exploitation period of 1982 to 2001) 3rd Report. Behavior analysis and safety evaluation (in Portuguese)". Report 397/2003 – NMMF, LNEC, Lisbon, Portugal.
14. **WGPCOLD** (1985) "Cracking and repair works in Cabril dam". Work group of the Portuguese National Comission on Large Dams. 15th International Congress of Arch Dams, Lausane. Memória LNEC nº 659, Lisboa, Portugal.
15. **Oliveira,S.; Rodrigues,J.;Mendes,P.;Costa,C.** (2003) "Dynamic behavior monitoring of concrete dams (in portuguese)" VII Congresso Mecânica Computacional ,pp687-698, Évora, Portugal.
16. **Gordon, S. et al,** (2001) "Metric performance of a high-resolution laser scanner", Proceedings of SPIE Electronic Imaging Conference, San Jose, California.
17. **Schulz, T. et al,** (2004) "Terrestrial laser scanning – investigations and applications for high precision scanning", FIG Working Week, Athens.
18. **Lichti, D. et al,** (2000) "Calibration and testing of a terrestrial laser scanner", International archives of Photogrammetry and Remote sensing, Vol. XXXIII, part B5, Amsterdam.
19. **Ramos, J. et al,** (1996) "Reliability of arch dams subject to concrete swelling. Three case histories", Memory nº 808, LNEC, Lisbon.
20. **Berberan,A.;Portela,E;Boavida,J** (2007) "Enhancing on-site dams visual inspections2 Proc. 5th Int. Conf. on Dam Engineering, pp55-62, Lisboa, Portugal.

The Authors

Sérgio Oliveira Ph.D (University of Oporto) on Civl Eng. Research officer at the National Laboratory for Civil Engineering, Concrete Dams Department, Group of Mathematical and Physical Models.

Ilídio Ferreira graduated in structures of civil engineering at Porto University. He works at the EDP Group (Electricity of Portugal), Hydro Generation Division, Safety of Dams Department and has been involved in civil maintenance works and safety control of dams. He is a member of Portuguese Dam Safety Commission and Portuguese Commission on Large Dams.

Antonio Berberan is a research engineer at the National Laboratory for Civil Engineering, Department of Dams, Applied Geodesy Group. He graduated in surveying engineering and post-graduated in photogrammetry. He has presented a thesis in automatic outlier detection and elimination in heterogeneous models and proposed the Hybrid Method for this purpose.

Paulo Mendes is an assistant at the ISEL (High Institute of Engineering of Lisbon), Civil Engineering Department. He graduated in Civil Engineering, post-graduated in Structural Engineering and he is finishing his Ph.D., which thesis involves the development and implementation of an on-line continuous dynamic monitoring system for Cabril dam.

João Francisco Boavida, graduated in Survey Engineering at Coimbra University. He worked in GPS double frequency observables and its computations, in the Geodesy group at the *Technische Universität Berlin*. At the *Geoforschung Zentrum Potsdam* (Germany). He was the technical director of UNAVE, a Geoinformation and Remote Sensing laboratory at the Aveiro Univ.. Since 2003, he founded *Artescan*, which uses Terrestrial Laser Scanners and produces detailed "as built" 3D models on the engineering and heritage domains.

Bruno Baptista MSc.student in Survey Engineering at Coimbra University, currently doing the final dissertation at National Laboratory for Civil Engineering, Department of Dams, Applied Geodesy Group.