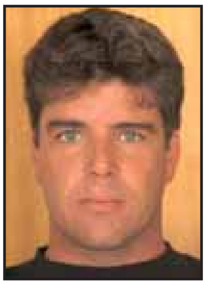

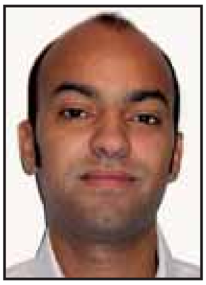

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Dam monitoring using combined terrestrial imaging systems

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

Embankment dams can suffer from surface displacements related to internal deterioration, such as internal erosion or slope failure. Surface displacements are important quantities to be determined, especially in relation to safety and long term behaviour. The determination of these values is 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 until now, concrete dam visual inspections 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 dense 3D numerical models as well as spatially continuous high-resolution colour (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, the Laboratório Nacional de Engenharia Civil, in Portugal (LNEC) have been developing positional monitoring methodologies for embankment dams and assisted visual inspection methodologies for concrete dams since 2003. This paper presents three case studies (two concrete and one embankment dam) of the developed methodologies as applied to dam monitoring.

Alto Ceira is a concrete arch dam with 37m maximum height above the foundation, 120m crest length and a thickness of 1.20m at the crest and 4.5m at the base. The Cahora Bassa arch dam in Mozambique has a 170m maximum height above foundation and 360m crest length. The Lapão dam is an embankment dam 39.5m high with a crest of 96m length. It is located near the town of Mortágua and was in an emergency situation during the 2002/2003 winter.

An 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).

The laser scanner

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 laser-type of long-range sensor.

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 300m. The beam divergence is 0.25mrad. Computed distance accuracy decreases slightly with range. The measurement rate goes up to 12,000 points per second. A typical accuracy value for average conditions is better than 1cm 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 terrestrial laser scanner 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 you need 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 you can join every point cloud into one single point cloud covering the whole object in a unique and meaningful Cartesian reference system.

Digital photo imagery

An SLR Nikon D100 reflex digital camera with 6.31 million 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 coordinates 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 coordinates have been determined by the laser scanner. It is then possible to merge the data of both sensors to become (x, y, z, I, R, G, B).

Alto Ceira

The Alto Ceira project 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 has shown an anomalous behaviour that has been closely monitored by dam experts who developed many studies aimed 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's lifetime.

Among the most important deterioration signals detected exclusively by visual inspections is cracking.

Figure 2: Orthoimages used as a base map for vectorisation of the anomalies classified according to a catalogue.

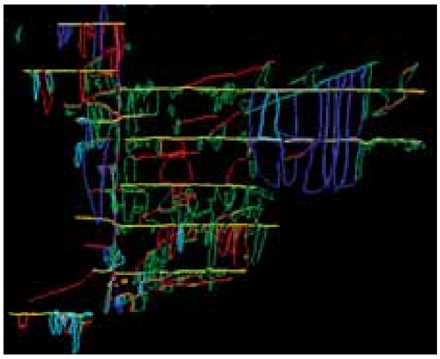

Figure 3: Vectorisation of cracks, spalling, leaching, leakage, indicators of chemical reactions, erosion or cavitation according to a predefined legend.

Crack surveying and mapping have been major problems for dam experts. Cracks wider than 2 or 3mm are supposed to be surveyed and this means that the spatial resolution of the images has to be better than 6mm. The main challenge is focused on the resolution of the image rather than on its metric quality.

As full coverage of the dam's downstream face was required, three stations were set up 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 meaningful reference system, a set of 21 retro-reflector targets were positioned in the dam vicinity (Figure 1).

Eight of these reflectors had coordinates 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 were finely scanned and used to compute the 3D transformation parameters relating every different independent instrumental reference system (x, y, z)i where i=1-9 associated with each of the 9 scanning positions to a unique and meaningful reference system (x, y, z). The laser scanner was parameterised to get the coordinates of one point every tenth of arc degree on both rotational axes. The camera body was equipped with an 85mm focal distance. The total number of photographs was 99. In total, the coordinates of about 13,504 million points were collected, both of the dam and its surroundings, during six hours.

Processing and vectorisation

The data collected in the dam in one single day occupied one skilled person for five days in the office.

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 3cm 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).

A third phase is the processing of images in order to transform the originals, which are the result of a central projection, into images artificially generated as a product of a normal projection. These are the orthoimages joined in a single mosaic that looks like a normal photograph but with a known scale.

The final step was the vectorisation on top of the orthomosaic of the anomalies in a conventional CAD software (Microstation V8 or AutoCad 2004, see Figure 2). The vectorisation of the anomalies was done according to layers and the graphic characterisation specified in the inspection data catalogue. The final result of the vectorisation, for a particularly damaged area of the dam, can be seen in Figures 2 and 3.

Study results

Visual inspection techniques are the primary methods used to evaluate the condition of many concrete structures, such as bridges, dams and 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. 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 two specialised surveying engineers and field operations took six hours. The generation of the orthoimage, the vectorisation and codification of the anomalies took 40 hours. Figure 4 illustrates the final result of the codification by association of CAD points, vectors and polygons with their attributes in a database management system environment. Once the anomaly is registered in the assisted visual

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

Figure 4: CAD and DBMS technologies were used to get points, vectors and polygons associated with alphanumeric classifications according to an inspection data catalogue.

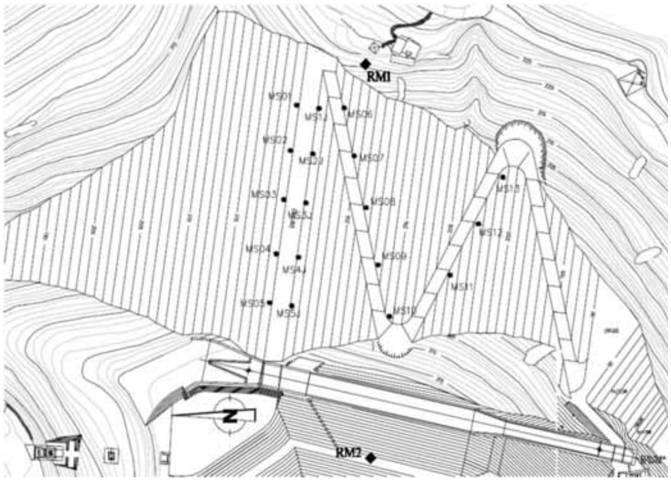

Figure 5. Lapão dam location of reference and object points.

inspection support system, it is possible to follow up the evolution between two visual inspections epochs through a process of imaging and descriptor comparisons.

Lapão

During the first filling of the reservoir (in the 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 15mm/day during the 2002/2003 winter.

After a further complete drawdown of the reservoir in February 2003, several monitoring studies were performed, including one in March 2003 with a 3D laser scanner. In February 2005, prior to the rehabilitation design for the dam, a new 3D laser scanning survey was conducted.

Geodetic monitoring

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

On 18 July 2007, the surface marks were observed from the reference stations with a total station (the Pentax ATS-101 with a linear accuracy of ±2mm+2 ppm and angular accuracy of ±1") and an adjustment was carried out using the program EpochSuite. Object points were signaled with retro-reflector targets, which were used for both laser scanning and geodetic measurements. One survey team (two people) took six hours to set up equipment, observe and compute the network.

This case demonstrates the importance of surface displacement monitoring, because it was due to this type of monitoring, during the first filling of the reservoir, that abnormal behaviour was detected.

Combined terrestrial imaging system monitoring

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

The general workflow in a combined system consists of acquiring data, both point clouds and images, from different stations and attitudes, to obtain a whole coverage of the object under study. In 2003, four scan positions were required and 21 reflectors were used; 9 as control points and 12 as tiepoints. In 2005, a larger area was surveyed, with seven scan positions using 15 retro-reflectors; 7 as control points and 8 as tiepoints. During the July 2007 epoch, three 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 joining 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 the 2003 and 2007 epochs, the field work, including target positioning, 3D scanning and image acquisition, took six hours. In the 2005 epoch, the field work took seven hours due to the larger area covered and the higher number of scanning stations.

Processing

Terrestrial laser scanning technology acquires a digital surface model (DSM); meaning that every laser reflecting point in the scene 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 30cm.

These cleaning and filtering operations of 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, vectorised 3D models and other engineering documents.

Conventional and non conventional formats

With CAE software, conventional engineering figures, like contours, longitudinal and transversal cross sections, can be produced in order to systemise the information in a format that can be easily analysed by the engineer. However, a new type of software is emerging to deal with this wealth of information and generate unconventional engineering documents. These new generation engineering documents, mostly, can only be viewed on computer monitors.

Collected 3D data is traditionally transformed into 2D data in order to represent it on paper, screens etc and synthesised 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.

The 3D texturized models can be visualised in virtual reality environments where analysis and decisions can be made, sparing additional field work. VRML and 3D pdf 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.

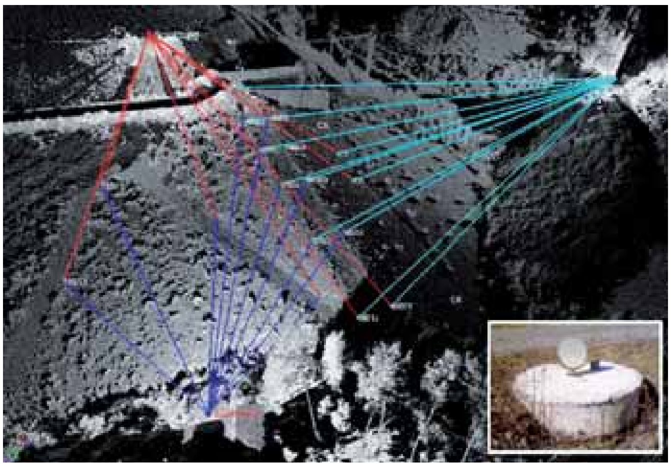

Figure 6: The laser intensity 3D point cloud of the Lapão Dam (2007) showing the three scan positions, retro-reflector targets and vectors between scan positions and surface marks. The smaller image is a retro reflector target.

Figure 7: A True colour point cloud.

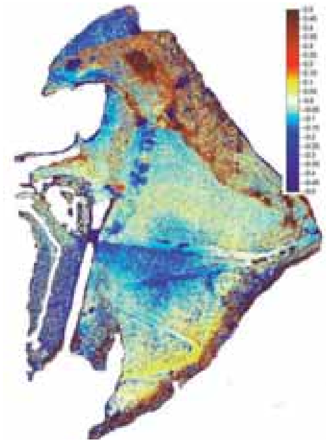

Figure 8: Settlements - 2005 epoch as compared to 2003.

Figure 9: Mesh showing the sliding waves.

An imaginary camera can move in a predefined path through 3D models. Dynamic scenarios can simulate the visualisation of an event, like flooding. The true color point clouds (Figure 7) can be a useful document immediately available on site, as it can be visualised in free and user friendly viewers just after the scanning. Figure 9 illustrates the importance and advent of this new type of engineering documents, in this case a mesh, besides profiles and contours.

None of the phenomena shown on the mesh, whether they are important or not in this particular case, can be easily recognised in conventional engineering documents, and some of them not even on site. At the bottom of the upstream face (red arrow), one strip shows where rocks have been removed (and replaced) to inspect the face of the dam below the rock fill (blue arrow) and two paths left by rolling machinery (yellow arrows).

Laser scanning versus geodetic method

Laser scanning can automatically provide coordinates for two types of discrete points; artificial (materialised) 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 combined system and those provided by the geodetic method were compared.

Positional quality

Table 1 shows estimated values for the average of absolute discrepancies, discrepancies and standard deviations from the three laser scanner positions (SP1, SP2, SP3) and the total station (columns LS-GEO). From Table 1 it is possible to detect homogeneity on the quality of the components, x, y and z. Table 2 shows the root mean square error (RMSE) both for every component x, y, z and for the triplet xyz. It can be said that the uncertainty of laser scanning, as a positioning system and under the same operational and computational environment, is below 1cm.

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		

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		

Cahora Bassa

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 purposes; the processing of a 1cm per pixel resolution orthoimage of the concrete wall and a high resolution survey of the near slopes.

As the dam concrete wall dimensions are very large, the distances from the equipment and the wall were 100-250m. 180mm lenses were used to accomplish the demanded image resolution. More than 200 photos were taken for the full dam wall coverage. The campaign had 40 scanpositions. In order to access, visualise and analyse the different data, an application based on pdf was developed (Figure 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.

Conclusion

Maximizing the benefits of existing dams is a wise approach to the management of economic resources. The laser scanning approach to earth or embankment dam monitoring, in terms of materialised points, can get a sub-centimetre positional accuracy. This accuracy will improve with the advance of laser technology. Whether the actual laser scanning accuracy is enough to analyse the behaviour of the dam is a decision for the engineer responsible for the analysis. However we have to emphasise that besides materialised points, a spatially continuous numerical model of the dam surface can be acquired in a very dense grid, at 1cm accuracy, at a reasonable extra cost. Also for these type of points, the positional accuracy will improve in line with technological advances. 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 state of a dam.

Visual inspections play a major role during the life span of concrete arch dams; particularly during the ageing process. They

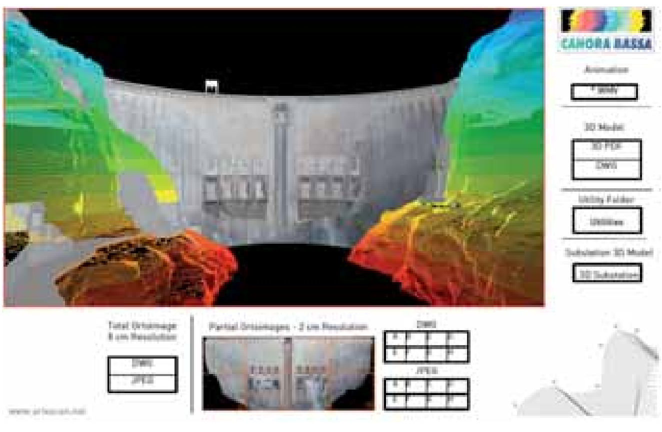

Figure 10: PDF application with embedded 3D CAD model of the Cahora Bassa dam and its near slopes.

The 3D texturized models can be visualised in virtual reality environments, where analysis and decisions can be made, sparing additional field work.

provide a huge amount of diversified types of data which need to be systematised and codified into an electronic environment. When compared to the conventional approach, the present methodology provides 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 CAD software and classified into a database management system. The gathered information is more accurate from a positional point of view and less subjective from a semantic point of view.

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

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