

Deformation monitoring of earth dams using laser scanners and digital imagery

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Introduction

Monitoring earth dams plays an essential role in evaluating the structural safety condition of this type of dams. Monitoring activities are related mainly with safety but also with the collection of valuable data to enhance the understanding of the behaviour of these structures. These purposes are not mutually independent but rather complementary (ICOLD, 1982). Monitoring a dam involves several activities, namely: design of the monitoring plan, installation of monitoring devices, reading those devices at some pre-established frequencies, conversion of measurements to meaningful engineering quantities, interpretation of these quantities, comparison with models, dam (visual) inspection and issuing a safety report. A monitoring plan should define which observable quantities are needed and which devices should be installed to measure those quantities. Furthermore, the plan should establish the location of the devices, their measuring procedures and monitoring frequencies depending on the age of the dam, extreme events, height, external actions, conservation conditions, available know-how and technology, human and economic losses in the case of failure, etc.. The quantities involved in dam monitoring are those related both with the actions in the dam and with the dam response. Surface displacements are important quantities to be determined, especially in what concerns safety and long term behaviour (Tedd et. al, 1997). Surface displacement can be related to internal deterioration processes, such as internal erosion or slope failure or to less important phenomena as secondary consolidation or creep. In order to evaluate these displacements, surface marks should be located at regular space intervals, usually in the dam crest, at the upstream and downstream sides, in the berm or berms, and less commonly in other places in the downstream slope. Several combined terrestrial imaging systems (CTIS) have been made commercially available during the last decade and are now a reliable and proven technology. The laser component of these CTIS provide a dense set of instrumental spherical polar coordinates of any unknown point that reflects the laser radiation; the CCD photo sensors component provide the RGB intensities for those points. The polar coordinates can be easily transformed into a meaningful object Cartesian reference system. Given their high sampling frequency CTIS offer an unprecedented density of spatial information concerning an object under study. This technology has been widely used by the architectural and archaeological communities but there is enormous potential in monitoring applications where such dense data sets could provide great insight into the nature of structural deformations (Lichti et al, 2000). This paper tries to evaluate this new technology and points to a methodology for measuring surface deformations on earth dams.

1 Available technologies for surface deformation measurement

Geodetic monitoring is widely used to measure the components of displacement vectors of materialized representative points in a dam face. Unlike some instruments that measure relative values, geodetic methods measure absolute displacements in a monitoring network which is referenced to stable points outside the influence zone of the dam and reservoir. A specific observation plan for geodetic monitoring should define the reference system, network configuration and its reliability, functional models relating observables and unknowns, blunder detection techniques, equipment and accessories, operational methodologies, expected quality for measurements and results, database organization, data presentation, metadata, etc.. The observables are slope, horizontal and vertical distances as well as vertical angles and horizontal directions. If the network is redundant the most likely

values for the components of displacement vectors are estimated, together with other statistical parameters to assess the quality of data and results as well as pertinent calibration parameters. The solution is usually found with the unified approach to the least squares criteria. Mainly when robotized total stations are used, it is advisable to use blunder detection techniques (Berberan, 2007). Usually the variation of coordinates method (Cooper, 1987) is used to relate the observables to displacement vector components. Total stations are used to measure the observable quantities defined in the plan and spirit levels might be used for more precise determination of the vertical components of the displacements. Motorization of total stations together with automatic pointing and reading capabilities have provided a fast and reliable monitoring tool, often permanent, at reasonable costs. As far as accuracy is concerned the millimeter range is achievable with total stations, for horizontal components of the displacement, and the sub-millimeter range is achievable using geometric levelling at a time cost.

Recent technological developments, especially miniaturization in image sensor and laser technologies, made available a new combined data acquisition type of systems which are capable of obtaining an accurate 3D representation of objects, including pictorial information. Terrestrial Laser Scanners (TLS) equipped with CCD digital cameras merge the advantages of tacheometry with photogrammetry thus giving rise to a myriad of applications whose limits remain to be foreseen.

1.1 Laser scanning and referencing

Terrestrial laser scanners (TLS) became available during the last decade and operate on one of three principles: triangulation, time-of-flight or phase comparison. Scanners using time-of-flight principle are more suitable for engineering scales. They can measure upwards of 10,000 points per second with accuracy better than 6 mm depending on distance, reflecting surface and equipment (Mills, 2004). By measuring the time between the emission of pulse of laser energy and the detection of the reflected signal, the distance between the equipment and the point that reflected its emission can be calculated. The laser beam is incrementally deflected in two planes which are perpendicular. Both angles of deflection and corresponding distance will provide a set of spherical polar coordinates which can be transformed into an instrumental set (xyz) of Cartesian coordinates. Each scan position will provide a dense cloud of points referenced to their respective instrumental independent system of coordinates. Obstructions usually require scanning from different positions and, in order to get a complete model of the object under study, it is necessary to concatenate several clouds into a single one. As each cloud is referenced in an independent instrumental system it is necessary to find the three-dimensional transformation parameters relating each independent reference system with a common one, preferably the XYZ Cartesian system related to the object.

It is possible, using shape matching techniques (Pulli 1999, Pottmann 2002), to find the transformation parameters among multiple clouds as long as they have enough overlapping coverage of the scenario. However in order to transform the data to a known reference system the identification of control points and an estimation of the transformation parameters (Mills 2004) is needed. At this point a unique cloud composed of a very dense set of points attached to a meaningful reference system of coordinates and covering the object under study has been acquired. This numerical XYZ representation of the object surface, although discrete in nature, might be considered continuous for almost every practical application, provided the spatial resolution is high enough.

Because laser scanners have been developed outside the geodetic community, only recently some TLS have their own referencing capabilities. On the other hand some studies are being carried out in order to reduce their instrumental errors (Rietdorf et al, 2004).

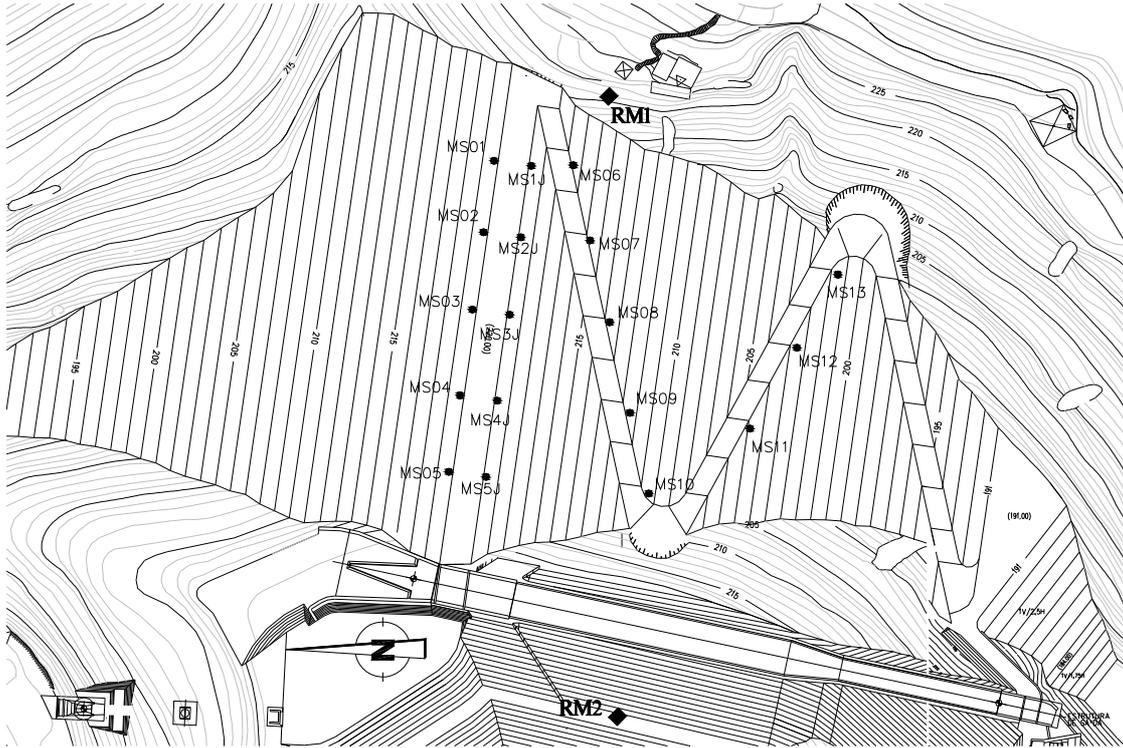


Fig 1. General layout of Lapão dam and the location of surface marks (MS) and reference stations (RM)

1.2 Photo imagery and data fusion

It is possible to attach a digital camera to a TLS. Provided the inner calibration of the camera has been carried out (and the camera is dimensionally stable in what concerns the image formation) and the exterior orientation parameters have been determined for every picture taken, the XYZ points collected by the laser scanner can be associated with their RGB values via the fundamental formulation of photogrammetry. The fusion of these two types of data leads to a rather dense set of points whose XYZRGB values are known and one gets a texturized geometric model, a 3D photograph. In practical terms a continuous model with metric quality and pictoric information can be collected in a question of minutes. Only CCD image sensor technology should be used on the camera despite the similar qualities of CMOS image sensor technology which is available in some cameras.

2 Lapão dam

Lapão dam (Marcelino, 2004) is a 39.5 m high earth dam and has a crest with just 96 m length. It is located in the centre of Portugal near a small town called Mortágua and was in an emergency situation during the 2002/2003 winter. 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 behavior was detected. The monitoring surveying network has 18 surface marks located on the crest and the downstream slope grouped in 5 transversal profiles (Figure 1).

During the first filling of the reservoir (2001/2002 winter) the dam showed a deficient performance, exhibiting 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

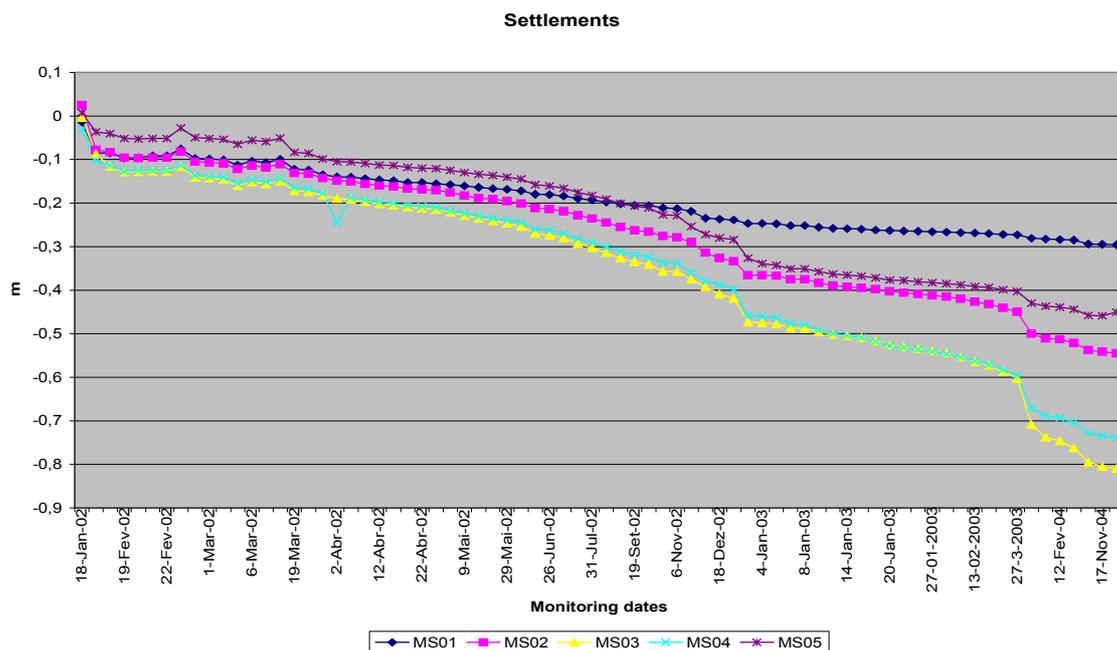


Fig. 2 Traditional presentation of surface marks settlements, MS01 to MS05

monitoring campaigns were performed, including one (March 2003) with a 3D laser scanner. In February 2005, prior to the rehabilitation design a new 3D laser scanner campaign was made.

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 1 shows the location of reference and object points. There has been 74 observation epochs with a variable frequency ranging from two a day (on 4th January 2003) to one every 3 or 4 month. Figure 2 shows a traditional graphical presentation of the settlements of some surface marks. On 18th July 2007 the surface marks were observed from the reference stations with a total station Pentax ATS-101 (linear accuracy: $\pm(2\text{mm}+2\text{ ppm})$; angular accuracy: $\pm 1''$) 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.

2.2 Combined terrestrial imaging system monitoring

On March 2003, February 2005 and July 2007 a combined laser scanning and photogrammetric survey has been carried out. Riegl Z360 laser scanner and a 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.

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.



Fig. 3 Retro reflector targets on forced centering materializing an object point.

The data acquired by the scanner depending on sensor attitude and position, is referenced on several arbitrary instrumental systems of coordinates and must be transformed into a common and meaningful reference system, related to the object. This particular CTIS uses the indirect referencing approach meaning that it relies on a set of well distributed control points, materialized by retro-reflectors and with their coordinates determined by tacheometric methods. Tie points, only measured by the scanning system, are used to strengthen the geometry of the concatenation of the point clouds. Usually a preprocessing of the data is done in order to guarantee its quality, before leaving the site. 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 made using 15 retro-reflectors, 7 control points and 8 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 4 shows the configuration of the network including scan positions, targets and the connections between scanning positions and targets.

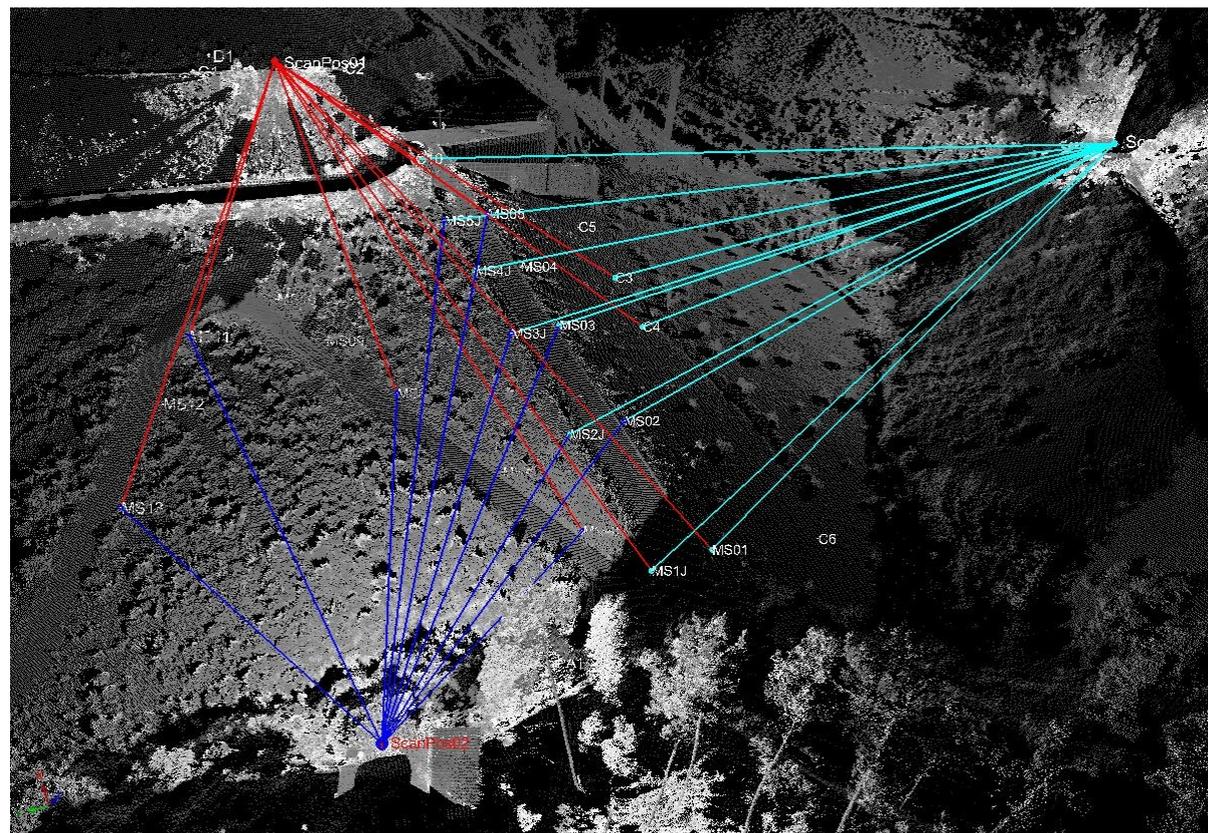


Fig. 4 Laser intensity 3D point cloud of the Lapão Dam (2007) showing the 3 scan positions, retro-reflector targets and vectors between scan positions and surface marks.

Images were taken in each scanning station with the digital camera to get RGB information and texturize the point clouds acquired with the laser. 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 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 is 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 which produces cubes of a predefined dimension with just one point in the center of gravity of a larger number of averaged points. For the mesh creation and production of contours, cross sections and profiles, a dimension of 30 cm for the cube was selected. 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 an horizontal reference plane. For the example cited above (2005) the resulting mesh had 0.945 million triangles. It is now possible to process these surfaces, in various computer applications and according to the aim of the work, so it can have a more useful and concise presentation.

Direct use of point clouds in CAD, CAE or DTM software packages (Microtation XM was used) is possible in order to extract conventional cross-sections, profiles, contours, lay-outs, vectorized 3D models and other engineering documents.. This can be done by using specific plugged-in software that allows normal CAD software to manage point clouds.

For instance, photogrametric monoploting applications running on CAD software allows the vectorization of objects by using simultaneously point data and oriented images. After the vectorized model is built, it is possible to map rectified images on the surfaces creating realistic 3D objects and environments.

3.1 Conventional formats

After pre-processing, the volume of information gathered by combined laser scanning and photo sensors consists of a (sometimes) huge file of points with a (ID,X,Y,Z,R,G,B) structure. This file is of little direct interest and one needs to post process the data. With CAE software, conventional engineering documents like contours, longitudinal and transversal cross sections have been produced (Figures 5, 6, 7 and 8) in order to systematise the information and to get an engineering document which will be easily analysed by the engineer.

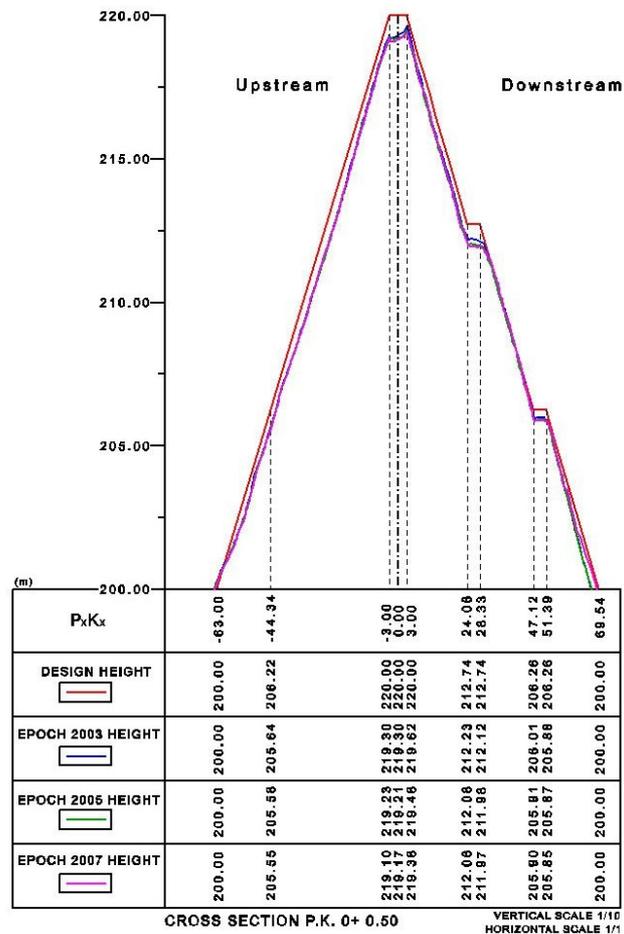


Fig. 5 Transversal cross section

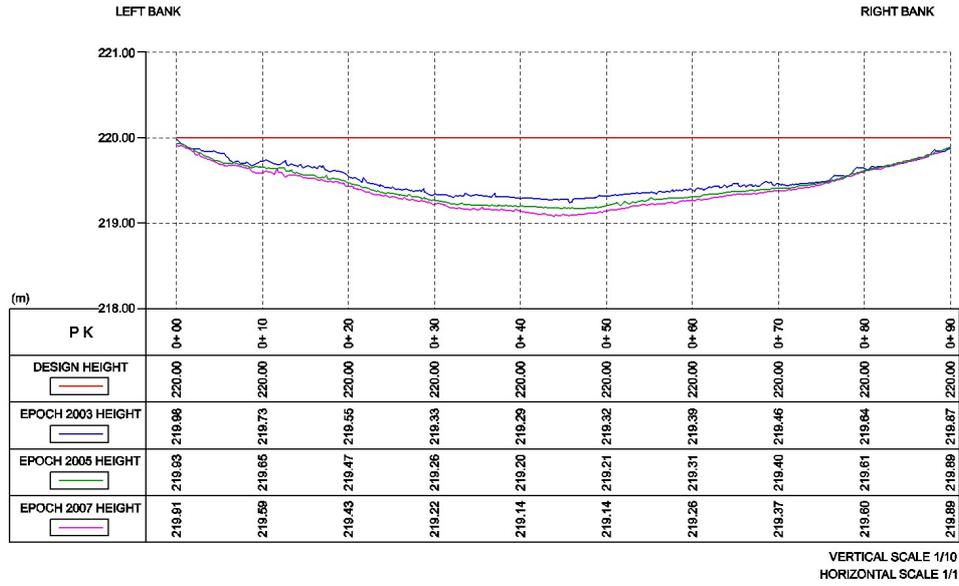


Fig 6 Logitudinal cross section

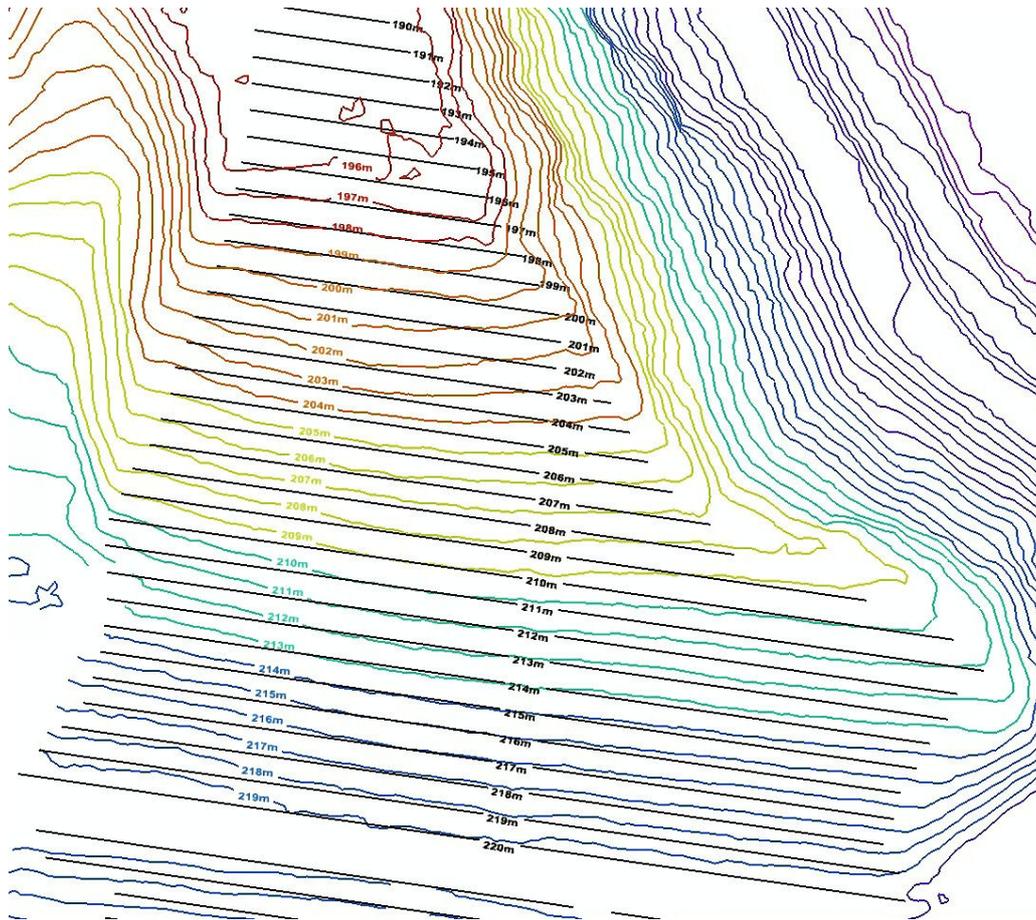


Fig 7 Contour lines for design (straight lines) and for the 2005 epoch.

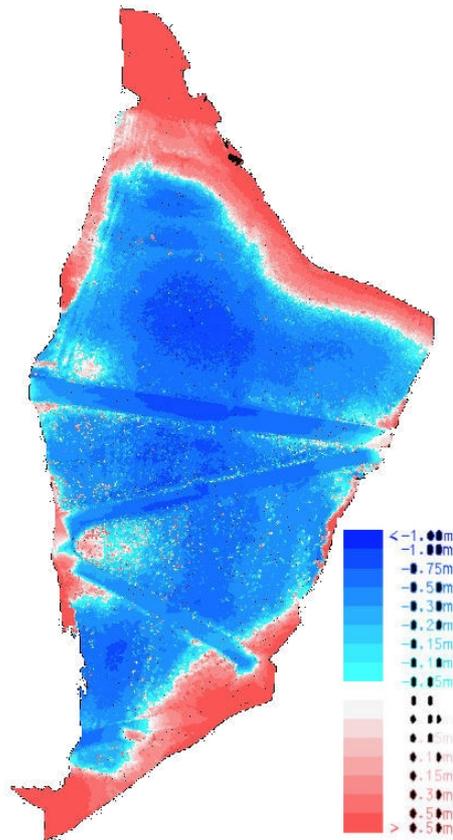


Fig. 8 Settlements: 2005 epoch as compared to the design

like flooding.

The colored point clouds can be a useful document immediately available in site as it can be visualized in free and user friendly viewers just after the scanning and some pre-processing. This particular document can be available for the engineer at the end of the field work day to measure directly over the point clouds without any modeling.

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.

However, a new type of software is emerging to deal with this wealth of information and generate unconventional engineering documents, in electronic supports. These documents, mostly, can only be viewed in computer monitors.

3.2 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.

The 3D texturized models can be visualized in Virtual Reality environments where 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,

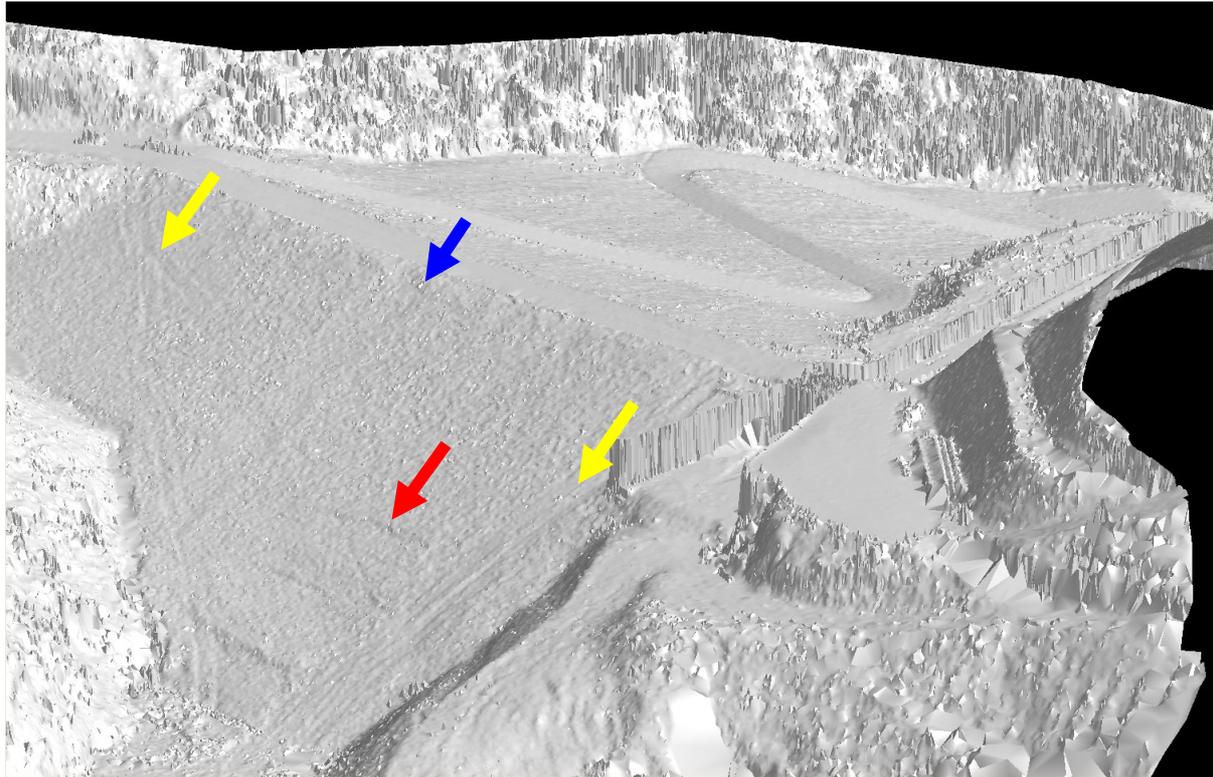


Fig. 9 Mesh of the cloud of points showing the sliding waves on the bottom of the upstream face (red arrow), one strip where rocks have been removed (and replaced) to inspect the face of the dam below the rockfill (blue arrow) and two paths left by rolling machinery (yellow arrows).

4 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.

4.1 Positional quality comparison for materialised points

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). 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).

| | LS-GEO | | | SP1-GEO | | | SP2-GEO | | | SP3-GEO | | | SP2- SP1 | | | SP3- SP1 | | | | |
|--------------------|--------|--------|--------|---------|--------|--------|---------|--------|--------|---------|--------|--------|----------|--------|--------|----------|--------|--------|---|---|
| | D x | D y | D z | D x | D y | D z | D x | D y | D z | D x | D y | D z | D x | D y | D z | D x | D y | D z | | |
| Avg. abs. values | 5 | 2 | 3 | 4 | 4 | 4 | 6 | 3 | 3 | 1 | 0 | 5 | 6 | 7 | 3 | 3 | 1 | 0 | 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 | 1 | 7 | 7 | 1 | 1 |
| n | 18 | | | 17 | | | 15 | | | 9 | | | 14 | | | 10 | | | | |

From Table I it is possible to detect an 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 as computed according to the formulas:

$$RMSE_X = \sqrt{\frac{\sum_{i=1}^n (X_{iL} - X_{iG})^2}{n}} \quad \therefore \quad RMSE_Y = \sqrt{\frac{\sum_{i=1}^n (Y_{iL} - Y_{iG})^2}{n}} \quad RMSE_Z = \sqrt{\frac{\sum_{i=1}^n (Z_{iL} - Z_{iG})^2}{n}}$$

$$RMSE_{XYZ} = \sqrt{\frac{\sum_{i=1}^n [(X_{iL} - X_{iG})^2 + (Y_{iL} - Y_{iG})^2 + (Z_{iL} - Z_{iG})^2]}{n}}$$

where coordinates labelled G refer to the Geodetic method and are assumed to be exact and coordinates labelled L were observed and computed with the laser scanner.

| | 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 | | |

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 centimeter.

4.2 Operational comparison

A comparison should be done also in terms of operational costs. The laser scanner provided in 6 hours the coordinates for some millions of points on the surface of the dam and the coordinates for the artificial points materialized with retro reflector targets. The total station provided in the same period the coordinates for the artificial points. As for the non materialised dense grid of points it is unrealistic to collect such grid using total stations. The cost of the CTIS equipment (including software, hardware and training) is roughly three times larger than that for the total station.

5 Conclusions

On a previous paper (Berberan, 2007a) CTIS have been shown to be able to enhance visual inspections of concrete dams. In the application to a concrete dam the resolution of the images is the challenge in order to get useful semantic information concerning the structure under study.

The laser scanning approach to earth or embankment dam monitoring, in terms of materialized points, can get a sub-centimeter positional accuracy at this early stage of the application. This accuracy will improve with the advance of laser technology, which is occurring. Progress on the mechanical design of the scanner and development of calibration models will reduce instrumental errors. Thus, applied research on methodologies including the design of specific accessories and on the development of mathematical models which are specific to this application are advisable to occur. It is expectable that this approach will achieve in the near future the positional accuracy of the so called geodetic method. Whether the actual laser scanning accuracy is enough to analyze the behavior of the dam is a decision for the engineer responsible for the analysis.

Besides 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.

The use of combined (laser scanner and digital imagery) approach to monitoring, allows the texturization of the above referred model of the dam surface and the fusion of both types of data is a valuable asset in terms of semantic interpretation of several meaningful phenomena to dam safety assessment.

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