ENHANCING ON-SITE DAMS VISUAL INSPECTIONS

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Abstract

Dams represent one of the most important achievements of the engineering activity throughout the centuries. Its impact in human society is enormous. The safety of such structures is a major concern for inhabitants and authorities. Safety control of existing structures requires the definition of appropriate monitoring and surveillance programs, including instrumentation and visual inspections.

The main purpose of a visual inspection is to identify deficiencies that potentially affect the dam safety and serviceability. Up to now visual inspections rely heavily on the inspection team skills. Very often, due to operational difficulties, the collected information is positionnally inaccurate, subjective, costly, time-consuming, human-dependent and, yet very important.

In recent years the availability of combined terrestrial imaging systems, has encouraged the development of new methodologies which will change drastically the procedures and outcome of visual inspections. Terrestrial laser scanners (TLS), which can get the co-ordinates of millions of points in reflecting surfaces, provide new means for rapid and precise electronic geometric representation of objects. Moreover, it is possible to integrate laser scanner measurements with digital photo-imagery in a combined terrestrial imaging system (CTIS). The dense geometric and radiometric data collected by a combined terrestrial imaging system constitute a wealth of data that can be used for a myriad of applications of which the diversity remains to be limited. The use of such methodology requires a previous classification of deterioration evidences identifiable through a visual inspection.

This paper reports a case study in which the methodology was applied to a concrete arch dam.

Keywords: Dams, Visual Inspections, Safety Control, Laser Scanning, Terrestrial Imaging Systems.

1. Introduction

Dam safety relies on the proper design, construction, operation and the monitoring of the dam behaviour. Thousands of large concrete dams all over the world are now facing problems related to ageing scenarios. Specific monitoring and surveillance schemes are assigned for each dam and include the acquisition, management and analysis of diversified information, such as information collected from monitoring instruments and visual inspections, among others. This information will support safety control experts in evaluating the safety condition of the dam.

Up to now visual inspections have been performed in a rather conventional way and without the support of sophisticated technology. Combined laser scanning and digital image technologies are recent fields of research and the use of such technologies will certainly enable the automation of visual inspection data collection. Moreover, this calls for an effective implementation of a visual inspection support system which will enable the identification of deterioration processes in a rather accurate, complete and faster way.

During the last decade Combined Terrestrial Imaging Systems (CTIS) have been matured and marketed. This multi-sensor solution integrates laser scanning and digital photo-imagery technologies. On the one hand, Terrestrial Laser Scanners (TLS) can get the co-ordinates of millions of points in reflecting surfaces thus providing new means for rapid and precise geometric, discrete but very dense, electronic representation of objects. On the other hand, digital photo-imagery acquired by calibrated photographic cameras can obtain the spatially continuous radiometric record of the same objects. The corresponding data fusion has encouraged the development of a new methodology to register and to codify into an electronic environment the main deficiencies typically surveyed during visual inspections.

The codification process can be separated into four levels. Level one is just a digital geometric and pictorial recording of the scanned parts of dam. Level two includes the vectorisation of the deficiencies that are classified with a legend. In level three a link is established between the graphic representation of the deficiencies and their alphanumeric attributes on a database. The last level leads to the creation in office of a visualisation environment that includes a 3D model of the dam, on which the engineer can interactively carry out an inspection as complete as allowed by the resolution of the images. Using available network data server technology the 3D model can be visualised by owner, authorities, consultants and other experts related to the safety of the dam.

This paper reports a case study in which the methodology was applied to a concrete arch dam. Firstly, an overview on the technology is presented, followed by the presentation of the case study where level three of codification has been attained. Finally, conclusions are drawn.

2. Proposed Strategies

The equipment used in the project 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 Digital photo imagery

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

According to the fundamental formulation of photogrammetry - namely the colinearity equations and the error model used for the calibration of the digital camera, as well as the above mentioned offset of both reference systems (associated to the TLS and photographic camera) - 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).

2.2 Digital photo imagery

According to different characteristics and authors, a number of taxonomies for active sensors are available. We refer to Beraldin (2004) for a concise explanation of the operating measurement principles of the so-called “time delay systems” group of sensors. The laser scanner used for this research (RIEGL LMS Z360I.) belongs to the previous group and is a “Time-Of-Flight with pulsed lasers” type of long-range sensors. It 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 (for natural targets with a reflectance higher than 80%, flat targets with size in excess of the laser beam diameter and close to normal incidence of the laser beam). 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. In bright sunlight, the operational range is considerably shorter than under an overcast sky. There are many types of laser scanners and, unlike surveying instruments and cameras, terrestrial laser scanners have no standard geometry even if they operate on the same technology.

The pulsed beam is deflected from an angular quantity according to parameterised quantities by a rotating or oscillating mirror located on a rotating head. The mentioned rotations (□□) 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. As the increments of the rotating head are also parameterised a set of 3D polar co-ordinates (D, □, □) is known for every reflecting point and the (x, y, z) Cartesian co-ordinates may be computed in a system of co-ordinates related to the instrument. The strength (I) of the returned signal is recorded as an intensity attribute value for each point. The final result of a scanning is a cloud of points of which the instrumental Cartesian co-ordinates were registered together with the intensity of the reflected laser pulse. Thus, sets of (x, y, z, I) are determined by the TLS for every reflecting point of the object under study.

The uncertainty in the determination of the co-ordinates for this particular instrument, operating at a few hundred meters distance, is empirically assumed to be between 1 and 2 centimetres. This uncertainty is affected by the mechanical setup that locates the angular attitude of the beam and by the accuracy of the measured distance which is dependent on the optical characteristics of the reflecting object area. On the other hand, this type of instrument is only one decade old and has been designed so far by disregarding how to minimise instrumental errors. This means that there is no established error model for terrestrial laser scanners data or an established calibration procedure for the scanners. However, a considerable number of papers and articles have already contributed to assess the accuracy of TLS systems and data [Tucker, 2002], [Lichti, 2000], [Schulz, 2004].

From a single position it is not usually possible to cover the whole object and there is the 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.

3. Case Study

The Alto Ceira project, Fig. 1, 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. The dam has 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. The foundation rock mass consists of schist and greywacke. The dam is supported at the higher levels by concrete abutments, the right bank abutment being continued by a masonry spillway. Its main purpose is to generate hydroelectric power

Alto Ceira dam has shown an anomalous behaviour ever since the first filling of the reservoir [Mora et al. 1996]. This anomalous behaviour 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.

The visual inspections conducted by trained personnel (Fig. 2) played an important role when the experts performed the structure safety assessments. Numerous crack surveying and mapping, both on downstream and upstream faces, were carried out throughout the dam lifetime, which means a huge amount of resources spent in this activity.

Fig. 1. Downstream face of Alto Ceira dam and laser scanning inspection.

Fig. 2. Traditional and unassisted surveying of cracks

3.1 Methodology used in the project

Cracking is certainly one of the most important deterioration signals noticeable exclusively by visual inspections in concrete dams. 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. A spatial uncertainty better than 10 cm, for the absolute positioning of the cracks, is considered as sufficient for structural safety evaluation. Thus, the main challenge is focused on the resolution of the image rather than on its metric quality.

As a full coverage of the dam downstream face was required, three stations have been setup for the laser scanner. Each station had three different tilting positions of the scanner head. Every position produced a cloud of points (nine point clouds in total) 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. 3. Eight of these reflectors had their co-ordinates determined by tachometric 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 parameterized to get the co-ordinates of one point every tenth of arc degree on both rotational axes. The camera body was equipped with a cone having 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 of its surroundings during 6 hours.

3.2 Processing and vectorization

To process the data collected on site in one single day will require 5 days of a skilled person back 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. The total number of points after filtering was 1191563 for a 3 cm parameterized cube.

A second phase deals with mesh generation (triangulation) of the filtered point cloud, image undistortioning and finally the fusion of the undistorted images with the mesh (texturing).

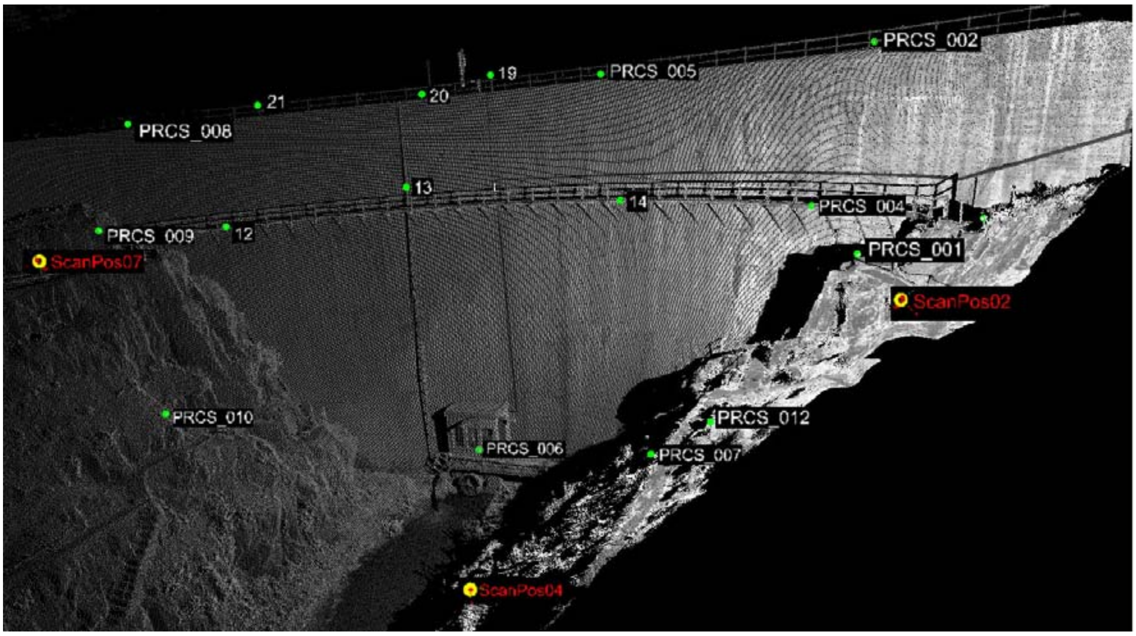

Fig. 3. Laser intensity 3D model of Alto Ceira dam downstream face, layout of stations and retro-reflector targets

Table I – Number of points measured on the dam downstream face and surroundings, measured and used retro-reflectors and empirical average accuracy of scanned targets for every scanning position

Position	Measured retro-reflectors	Used retro-reflectors	Standard deviations (m)	Measured points (millions)
1	18	18	0,019	1.487
2	18	18	0,014	1.852
3	13	12	0,016	2.755
4	16	16	0,014	1.620
5	16	16	0,016	1.125
6	8	8	0,015	1.401
7	10	10	0,013	1.049
8	16	12	0,020	1.045
9	12	9	0,020	1.170

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. Three surfaces, instead of a single one, were used for the normal projection of the synthetic imagery. These are the so-called ortoimages and they were concatenated in a single mosaic that looks like a regular photo but with scale all over its extension.

These three phases were accomplished with Riscan Pro Version 1.2.1.beta25 Riegl software. The final step was the vectorisation heads up and on top of the ortomosaic of the occurrences in a conventional CAD software, namely Microstation V8 (Bentley) or AutoCad 2004 (AutoDesk), Fig. 4. The vectorisation was done using layers, graphic characteristics and colours according to the inspection data catalogue. The information was then imported to ArcMap V9 (ESRI).

To handle the output information data the vectorised data was converted into different Feature Classes in a Personal Geodatabase and using the ArcObjects framework from ESRI, an application in Visual Basic .NET was developed.

The final result of the vetorisation, of the whole downstream face of the dam, is illustrated in Fig. 5.

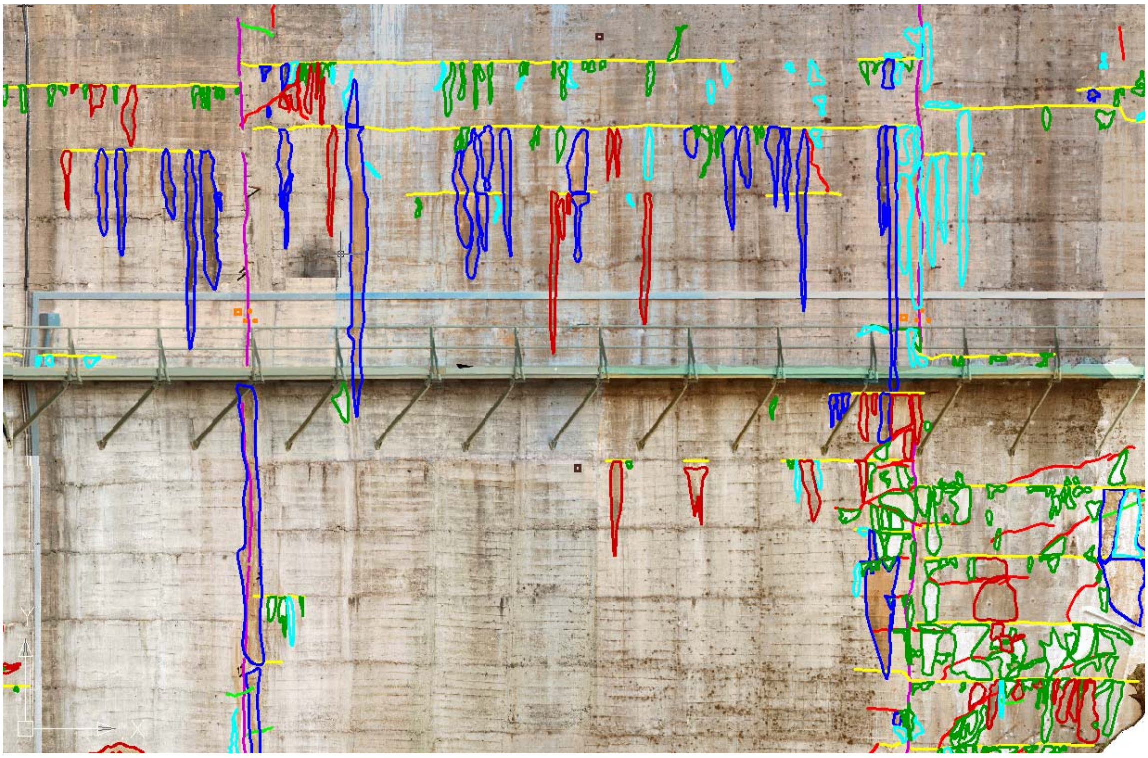

Fig. 4. Ortoimages as a base map for heads up vectorisation of identifiable features

3.3 Output framework

Visual inspection techniques are the primary methods used to evaluate the condition of many concrete structures, such as bridges, dams, tunnels, for instance. However, concerning concrete dams, nowadays, the common practice is to provide the structure with a specific monitoring system. Old dams, such as Alto Ceira, originally were not instrumented, but for the last few years they have been equipped with monitoring systems to support safety requirements and to fulfil the requirements of recent regulations. Despite the existence of a monitoring system, visual inspection is still an activity of paramount importance, as many deterioration signs are detectable only through an accurate visual inspection. In many cases, the analysis of numerical results might show the existence of a deterioration process, for instance the swelling process, which requires confirmation by visual inspections and specific tests. Alto Ceira dam is affected by a swelling process of considerable magnitude but with a heterogeneous development, which along with thermal variations has been causing important fissuration.

In conjunction with the development of the laser scanning and the digital image registration methodologies, a visual inspection support system was developed to handle the output data. Due to the differences in the field context of different inspections, a visual inspection support system needs to be customized in order to be used by any inspector, yet including parametric information. Moreover, the 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 – such as cracks, spalling, leaching, leakage, indicators of chemical reactions, erosion or cavitation – a damage symptom catalogue must be created. To each damage symptom a comprehensive set of descriptors must be assigned. For instance, a cracks descriptor may include geometrical parameters, such as length, continuity, orientation, opening and type (craquelet, linear, etc.), or any associated symptom such as leakage or deposits. Other descriptors, such as the estimated age of deterioration, the possible deterioration causes and the date on which the first time the symptom was detected may be included, if known.

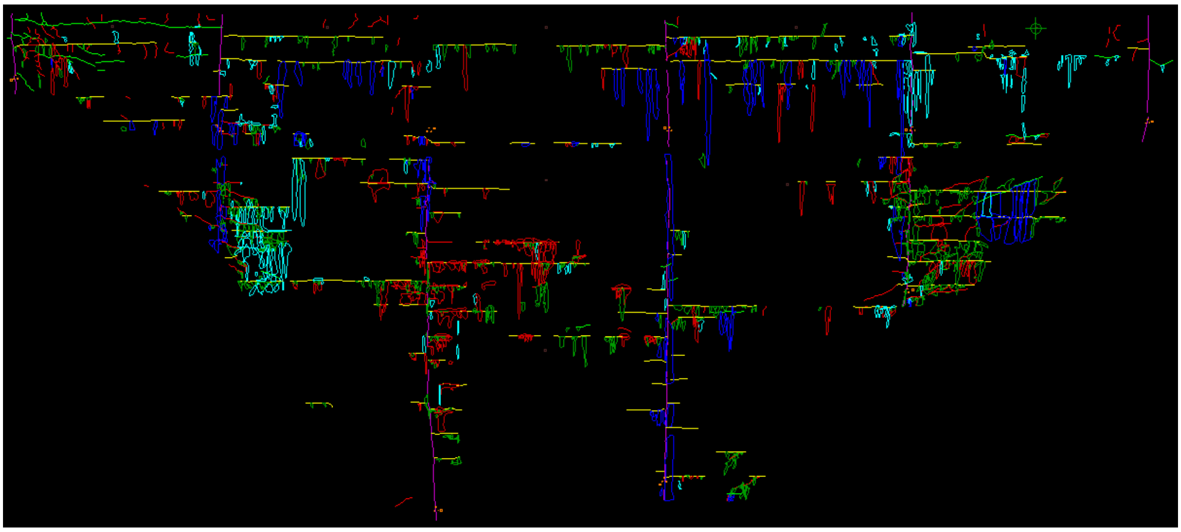

Fig. 5. Vectorisation of deterioration features such as cracks, leakage and carbonate deposits

The experimental assisted visual inspection in the above mentioned dam took place on 2005/11/24. The laser scanning was conducted by a team of 2 specialized surveying engineers and the site operation last 6 hours. Back in office, the generation of the ortoimage, the vectorisation and the codification of occurrences took around 40 hours. Fig. 6 illustrates the final result of level three codification by association of CAD points, vectors and polygons with their attributes in a data base management system (DBMS) environment. Fig. 7 shows the result of an analysis concerning a given occurrence picked up from the computer screen.

Once the deterioration is registered in the assisted visual inspection support system, it is possible to follow up the evolution between two different visual inspections through a process of imaging and descriptors comparisons, which will be very convenient to identify any new deterioration process or the evolution of old ones.

4. Conclusions

The purpose of a visual inspection is to identify deficiencies that potentially affect the safety and operation of the dam. Not only can visual inspection be a reliable way to follow up the “dam health”, but it also offer “ground truth” in case of suspected deterioration.

When compared to the conventional approach, combined laser scanning and digital image technologies provide an economic and reliable way of acquiring very quickly 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.

The fusion of both pictorial and geometric data provides the means for a high-resolution 3D electronic representation of objects justifying the use of a multi-sensor platform for this project. Further research should concentrate on how to extract and classify semi-automatically from the 3D model the most significant features according to an inspection data catalogue.

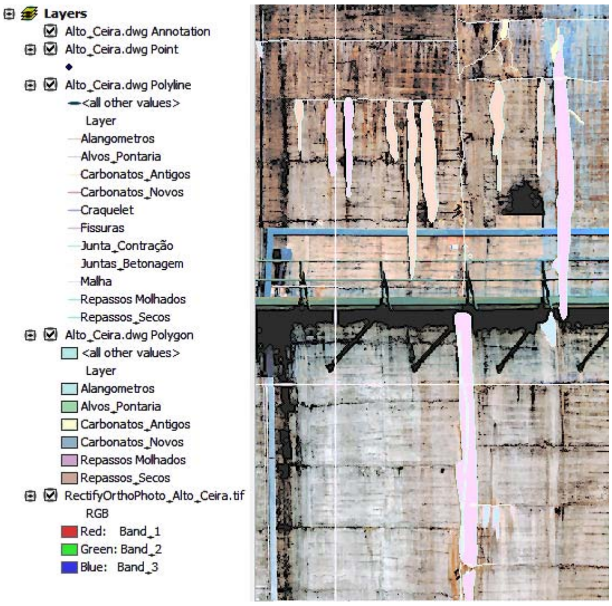

Fig. 6 CAD and DBMS technologies used to classify the occurrences in the inspection data catalogue

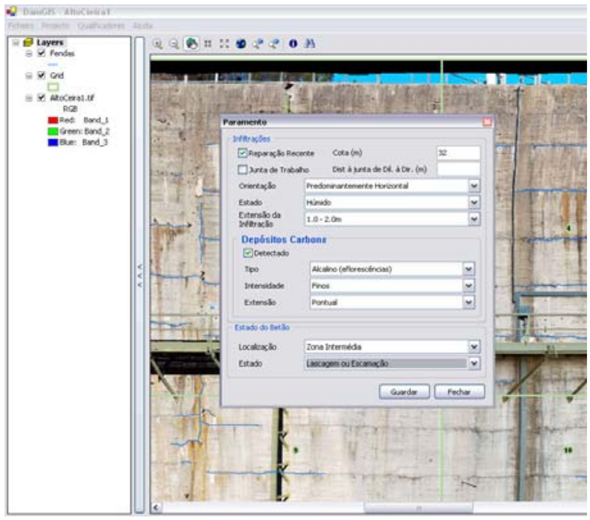

Fig. 7. Prototype of the application that handles attributes associated to the codified occurrences

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