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3D Photogrammetry, capacity, filling time and water flow simulation of Cordoba's Mosque-Cathedral Islamic cistern

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ABSTRACT

One of the most important concerns of such a relevant city as Córdoba has always been the use and distribution of water resources. In the Mosque-Cathedral located in Córdoba (Spain), a UNESCO World Heritage Site since 1984, there is an Islamic cistern built by Almanzor around the years 999–1000 CE in the Court of Oranges of the former Mosque. In this work we aim to create an exact 3D model of this cistern. For that purpose, we have digitally reconstructed the Islamic cistern using photogrammetry techniques. Furthermore, we have documented the location and capacity of water distribution canalizations, whose initial function was to provide the cistern with water and to empty it. Finally, we have studied the cistern water capacity, calculated an estimation of its filling time and we have made a water flow simulation with a CFD (Computational Fluid Dynamics) Simulation software.

1. Introduction

1.1. Historical background

During both of the periods after the fall of the Roman Empire and the Islamic conquest (between the centuries VI and X) the original water collection and storage systems were repaired, and some of them had been in service until relatively recent times. Cisterns and waterwheels were part of the relevant transformation to the systems (Pizarro Berengena, 2012). The Mosque-Cathedral of Córdoba was not isolated in this urban landscape; rather the water resources owned by the Cathedral Chapter were heirs of the roman aqueducts. Hydraulic structures for water storage were also part of that landscape, having been used for ablutions before Islamic prayers, as in the case of the Islamic cistern (Pizarro Berengena, 2012), which is the subject of this study.

The construction of the Mosque began in the year 786 CE above the remains of the Saint Vicente Basilica, which was the most important Christian temple in the city since the V century AD. The most important expansion but with lower artistic value, was directed by Almanzor in X century; he needed more water to satisfy the needs for ablutions in the temple, this is the reason why Almanzor decided to construct the cistern in the Court of Oranges (Nieto Cumplido, 2007).

> *"Almanzor built in his courtyard the cistern with a great capacity…"* ('Idhari, 1312, 287–288 & 479 Spanish translation).

In the XVI century Ambrosio Morales described the cistern: *"The courtyard has weirdness, of those celebrated in the most beautiful buildings that have existed in the world: the courtyard is hollow under the ground where there is a large cistern with several vaults constructed with columns. The surface can be cultivated with orange trees, cypresses and other trees, which can be even compared with the Hanging Gardens of Babylon, known as one of the seven miracles of the world. In the center of the courtyard there is a nice fountain with water coming from the mountain; this water is not the same as the water described by Moor Rasis that the King Abderramen III provided for the old mosque. In addition, there are more fountains in the church. Some people believe the cistern was a dungeon for prisoners: the moors never had in their mosques the profanity of those dungeons"* (Morales, 1575, 58–59).

> *"In 967 a large Stone canal with lead piping was built (or more likely rebuilt and extended) to bring water from the mountains at the northwest of Córdoba. According to one account, it "flowed into the mosque's irrigation canals and ablution basins on the east and west sides", a description suggesting that the courtyard had at least two fountains to receive the seasonal supply provided from the roof. And so in 991-92 a very large deep cistern was excavated in the courtyard floor. This cistern was a classic Andalusia type with nine vaulted bays arranged in a square."* (Blair, Bloom, 2009).

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1.2. Technical background

The use of tridimensional technologies, and in particular the photogrammetry based on the Structured from Motion (SFM) method, allows us to check measurements with precision and, carry out multimedia projects to improve the visitor's experience, as well as to prepare and document the restoration and to make quick reproductions by means of 3D prints. Although some authors still use a traditional model in the reconstruction of excavations and monuments, the use a photogrammetry is spreading as a support to those traditional approaches (Fornos, 2012).

The use of laser scanners for the reproduction and study of monuments, sculptures and excavations (Orengo, 2013; Bennett et al., 2013; Falkingham et al., 2014) has been a more widely used methodology for the reconstruction of inner spaces (Ahmon, 2004; Rüther et al., 2009).

Subsequently, several authors improved this method of reproduction in studies using a combination of a laser scanner and close range photogrammetry techniques based on SFM (Lerma et al., 2010; Núñez et al., 2013). In this way, the precision and resolution of models are improved thanks to the use of low cost digital cameras, and the later implementation of these models in GIS software, (Torre and Benito-Calvo, 2013).

Due to the improvement in the characteristics of low cost cameras and the development of SFM software, these technologies have been widely used in several independent studies. Some authors have conducted their investigations by means of using free software such as Visual SFM (VisualSFM, 2015; Wu, 2013; Wu et al., 2011) or Python Photogrammetry Toolbox GUI 0.1 (PPG) (Arc-Team, 2015; Green et al., 2014). By contrast, other authors such as (Ducke et al., 2011; Barazzetti et al., 2011; Bevan et al., 2014; Lerma and Muir, 2014) use Agisoft's commercial Photoscan software (Agisoft, 2015).

Recently some authors have carried out investigations using CFD (Computational Fluid Dynamics) Simulation software for the calculation of the dispersion and deposition of particulate matter in historical buildings (Grau-Bové et al., 2015). Other scholars make use of CFD software for studying the ancient natural ventilation system in historical buildings, (Balocco and Grazzini, 2009). In terms of water supply, Dr Riley Snyder works on the reconstruction of water supply systems at Constantinople (Snyder and Dilaver, 2014), using GIS Software, the “CLAWS” System (Constructing the Late Antique Water Supply), and the Agent-based modelling technique. But no one makes use of CFD for water supply, water canalization or historical cisterns.

The first ground plan in which the cistern is drawn was made by Gómez Moreno (1951). In this ground plan we can observe the cistern's floor plan located at its proper place under the Court of Oranges. Nonetheless, the entry and exit of water is not included within this plan. The second plan was made in 1961 by the regional water supply organization in Córdoba, Co. (EMACSA) (Nieto Cumplido and Luca de Tena y Alvear, 1992). In this plan the cistern appears as a water tank for the fire-fighting network system of the Cathedral of Córdoba.

At the time, as the cistern was not in use, it was decided that it could work as a water tank; later, this decision was changed and at present, the cistern is dry.

Finally, the most relevant plan is that created by the conservation architect of the Cathedral of Córdoba Gabriel Ruiz Cabrero in 1981, (Fig. 1) (Nieto Cumplido and Luca de Tena y Alvear, 1992). In this plan the cistern's ground plan and its simplified elevation can be seen, with a little drawing in the superior part where the archivist Canon is seen, about to descend into the cistern. As with the other plans, the entry and exit of water are not indicated. These drawings were created using measuring tape and without the use of a topographic total station. For this reason, the drawing is very simple and does not show the inclination and differences between the different walls.

The objectives of this paper are the exact documentation of the Islamic cistern making use of photogrammetry (SFM) and a topographic total station. The second objective is the study of the entry conduits of the cistern to study which of them are the entry and exit canalization for water supply and their orientation. Finally, the third objective is the study of the water capacity and filling time, making use of a CFD simulation software inside the cistern.

2. Materials and methods

2.1. Description of the Islamic cistern’ access

The access to the Islamic cistern is difficult as there is just one entry available (Fig. 2). It has three vertical conduits, two measuring $0.72 \times 0.68\ m^2$, and, the central vertical conduit measuring $1.15 \times 0.75\ m^2$, which enables better access into the cistern. The cistern is accessed via a staircase and the floor is 10 m deep with respect to the present surface level of the Court of Oranges. The cistern is built with blocks of calcarenite stones that were filled with a lime mortar and later painted with red ocher.

The cistern is composed of nine square rooms connected by semicircular arches which form cruciform pillars, whose ceilings are formed by edge vaults. It is the same schemes that the cistern of Marmuyas (Málaga, Spain) and the Islamic cistern of the Carlos V Palace in Granada, Spain. (Pavón, 1990).

2.2. Conditions and Problematic issues

The first problem we encountered was taking our instruments down to the cistern in order to document it. Due to the difficult access, we were only able to use a spotlight to illuminate the place so as to enable us to take pictures. The spotlight used is a Walimex Pro LED 500 with 800 lx at 2 m distance and a color temperature of 6900 K; the spotlight was installed on a Mantona Dolomite 1100 tripod at a height of 130 cm throughout the study; we also used a Nikon D3200 camera and a TOPCON GTS 226 topographic station.

In the cistern, we found a certain amount of mud due to the high humidity, making it more difficult to take pictures, gather data and install the topographic station. To check the reliability of the photogrammetry technique in hostile surroundings, we decided to check its precision by taking control points with a photographic station.

To solve the lack of lighting inside the cistern, the spotlight was relocated in each room to avoid the shadows that can alter the results and introduce mistakes in the posterior data processing.

2.3. Photogrammetry

To make use of the photogrammetry technique based on the Structured from Motion method, we took 940 pictures with a Nikon D3200 camera with 24.2 megapixels and a CMOS sensor of $23.2 \times 15.4\ mm^2$. The lens used was an AF-S DX NIKKOR 18–55 mm f/3.5–5.6 G VR with a fixed focal length of 24 mm. This focal length allowed us to minimize the number of pictures, which was on average 100 per room. It also provided us with enough lighting with low image distortion. For a better division of the work and the post-processing we decided to classify data into nine modules, one for each of the cistern's rooms.

2.4. Taking control points

Once we took the pictures we needed, we conducted a topographic survey with a TOPCON GTS 226 station; despite being an old model, it has proved to be very precise in obtaining data in former works. For taking all of these control points we needed nine stations in the cistern and two more outside to establish geo-references. Overall, 500 control points were established during the topographic survey and they were then employed to check the precision of the reconstruction and to reference the space accurately.