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Case Study

Non-destructive assessment of a buried rainwater cistern at the *Carthusian Monastery* '*Vall de Crist*' (Spain, 14th century) derived by microgravimetric 2D modelling

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Abstract

The microgravity method is one of the geophysical tools used in engineering and environmental and archaeological researches, where the detection of subsurface cavities or buried structures is essential. In this study, this technique has been revealed to be an efficient and respectful tool for use in Cultural Heritage restoration studies, such as those carried out in the restoration of historical sites in which the elements to be examined are beneath a shallow coating of material. Therefore, the aim of this microgravimetric survey is to define the exact position and dimensions of a subsurface structure (rainwater cistern) through microgravity response of the medium.

For this purpose, the subsurface structure of *San Gerónimo* Cloister of the *Vall de Crist* Carthursian Monastery (14th century) has been researched. This monastery was known to be the largest Carthusian Monastery in the region of Valencia (Spain) and one of the most remarkable of the ancient *Corona de Aragón*. A rectangular grid of microgravity measurement station points was designed to cover the entire surface of the cloister. In addition, a microgravimetric profile was acquired along a hillside close to the Carthusian buildings in order to obtain the density value of the medium.

The study was performed using a LaCoste&Romberg D203 gravimeter to detect and to map the shallow subsurface rainwater cistern that probably exits beneath it. This gravimeter has a sensitivity of approximately 1 μgal (μgal = 1.10^{-8} ms^{-2}) and an accuracy of 3–5 μgal for relative gravity measurements.

Two contour maps were calculated (observed gravity and Bouguer gravity values) in order to improve the interpretation results. On these maps we can observe the shape of the body that is causing the perturbation in gravity values. And what is more, it led us to deduce that the central area of the cavity is deeper than the border area. In addition, we can asses that the cavity is 8 m wide and 12 m long, and is symmetrical along its longitudinal axis, but not along its transversal axis.

Also, a microgravimetric inversion was performed and the subsurface is split into 7 prisms and the depth and height of each is to be estimated separately. As a result of this inversion we can estimate that the ceiling of the cistern is located about 1 m under the cloister pavement and the cistern floor at a depth of 4 m. The cistern is slightly inclined towards one of its edges by about 20 cm.

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Finally, the 2D modelling derived by microgravimetric data has allowed us to determinate the shape, dimensions and location of the cistern accurately. In addition we have calculated the cistern capacity (288 m^3, that is, 2880 Hl). This capacity was quite enough for the water necessities of 13 monks who lived there permanently, even for making it through the drought periods frequent in this kind of Mediterranean areas.

Keywords: Microgravimetry; Cultural heritage; Restoration and maintenance; Carthusian Monastery '*Vall de Crist*'; Bouguer gravity anomalies; 2D modelling

1. Introduction

Microgravimetry is one of the most appropriate techniques for the study of small areas of interest in Cultural Heritage, Archaeology, and even Engineering, such us the detection of subsurface cavities, the mapping of buried structures, etc. [1–3].

This technique consists of measuring the gravity field variation in the surface. The main goal of these measurements is to locate structures whose mass has a higher or lower density as compared to that of the surrounding masses. The mass (density) distribution causes gravity to vary from the expected value as the measurement position changes. These variations are expressed as gravity anomalies, the mapping of which gives us insight into the structure of the subsurface.

A microgravimetry research study was conducted in the *Vall de Crist* Carthusian Monastery (Castellon, Spain) in order to detect and map a shallow subsurface rainwater cistern that could probably be beneath *San Gerónimo* Cloister. The difficulties involved in drilling or doing excavations on the cloister pavement area made it necessary to employ a non-aggressive prospecting technique such as microgravimetry.

This study seeks to make a contribution toward understanding the shape and dimensions of the rainwater cistern. For this purpose a qualitative interpretation has been performed from the gravity maps and in addition, the gravity values obtained were used to carry out the modelling of the anomalous body for the purpose of inferring its exact dimensions.

2. Experimental section

2.1. Site description

The *Vall de Crist* Monastery (14th c.) is known to be the largest Carthusian Monastery in the Valencian region and one of the most remarkable of the ancient *Corona de Aragón* (Fig. 1a). This Carthusian Monastery was the fifth to be founded on the Iberian Peninsula and the second in the Kingdom of Valencia after *Porta Coeli* (Valencia, Spain, 13th c.).

The Monastery was founded in 1385 by *Infante Martín el Humano* in the times of King *Pedro II el Ceremonios*. However, the life of the monastery was reduced to 450 years as a consequence of the final expulsion of the monks in 1835. It has not been reoccupied by any monk since then [4]. The construction of the *Vall de Crist* Monastery took place over the course of five different building periods spanning from 1358 through to the 18th century.

Carthusian Monasteries always have a minor cloister, which is named in this case *San Gerónimo* Cloister (20 m long and rectangular shape). It is documented that beneath the cloister there lies a big cavity that was used as a rainwater cistern (Fig. 1b). It is not clear when it was built, although it is assumed to date to the epoch during which the Carthusian Monastery was founded [5].

2.2. Survey details and field procedures

In this study, microgravimetric measurements using a LaCoste&Romberg (LCR) D203 spring gravimeter, with

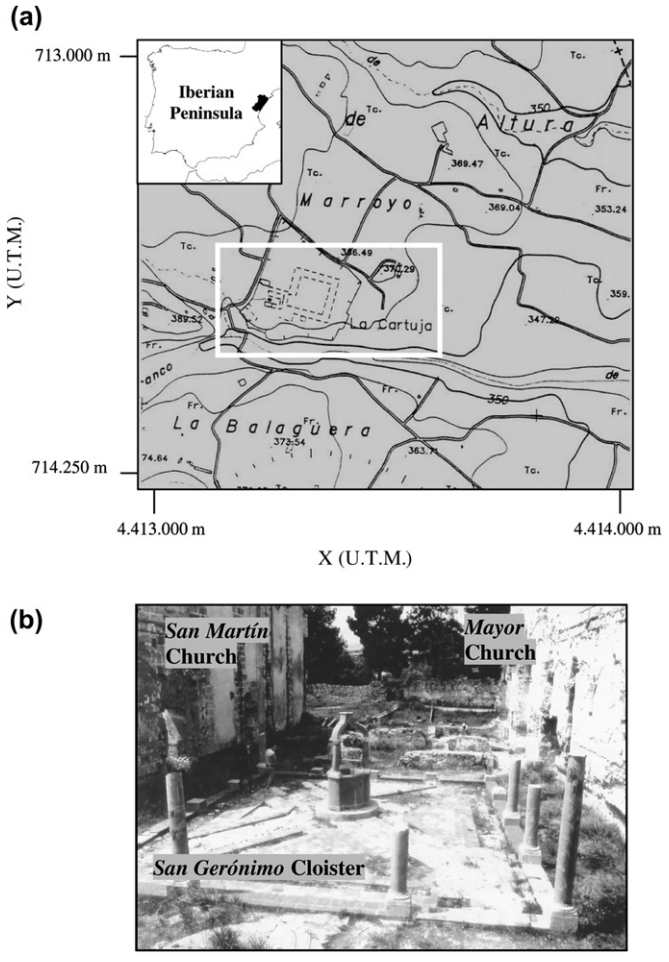

Fig. 1. (a) Topographic site map showing the location of the *Vall de Crist* monastery complex (*Consellería de Medi Ambient*, *Generalitat Valenciana*, Sheet number 640, 1–4). (b) Panoramic view of *Mayor* Church, *San Martín* Church and *San Gerónimo* Cloister.