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STRUCTURAL WEAKNESS OF THE TWENTY EYES AQUEDUCT IN THE WADI OF CARCAUZ (ALMERIA, SPAIN)

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ABSTRACT:

The Twenty Eyes Aqueduct is a work of hydraulic engineering with several centuries of history. In the present work, the innovative Cloud-to-BIM-to-FEM methodology is applied, capable of converting BIM models, generated from point clouds, into finite element models. The point cloud was obtained using UAV photogrammetry, carrying out a 3D survey of the current state of the aqueduct and its surroundings. The point cloud obtained has served as the basis for the generation of an HBIM model that accurately represents the geometry of the aqueduct (Cloud-to-BIM). The HBIM model has been transformed into a finite element model that respects the uniqueness of the monument without excessive geometric simplifications (BIM-to-FEM). The structural analysis of the FEM model has been able to evaluate the instability conditions of the assembly in the event of an earthquake, although it does behave adequately in the face of wind actions.

1. INTRODUCTION

The Twenty Eyes Aqueduct is a work of hydraulic engineering with several centuries of history that will soon be declared an Asset of Cultural Interest (BIC, Bien de Interés Cultural). The geometric irregularities, the heterogeneity of its materials or its accessibility, pose a challenge for the structural simulation of this type of monuments. However, recent advances in photogrammetry based on images captured by unmanned aerial vehicles (UAV), the development of integrated BIM (Building Information Modelling) models and the improved computational performance of current computers to simulate the structural behaviour of complex constructions, greatly facilitate the work of reconstruction, protection and conservation of our heritage. Thanks to the combination of current computers and photogrammetry, we can use images captured at different heights and using different angles (Fernández-Hernandez et al., 2014), to obtain 3D models based on point clouds obtained from these images. Numerous computer applications allow this process to be carried out, even if the photographs were taken with conventional cameras. This transformation is possible thanks to a low-cost technique called Structure from Motion (SfM), which has its origins in the field of computer visualisation, capable of transforming a 2D object to 3D with just a few photographs from different viewpoints (Tomás et al., 2016). The SfM algorithm provides a point cloud that represents the object under study, as well as the position and orientation of the photographs taken by the camera. Once the dense point cloud or 3D mesh of the complex under study is available, it will serve as the basis for the development of the BIM model. BIM is a collaborative working methodology for the creation and management of a building or civil engineering work during its life cycle. Its objective is to centralise all the project information in a digital information model created by all its agents, reducing time and resources in the design, construction and management of the asset, as well as minimising errors (Azhar, 2011). When we use BIM methodology to digitise existing information about artistic or historical works of heritage value, we refer to this method as Historic Building Information Model (HBIM). However, the application of this methodology to the field of heritage reconstruction depends on the peculiarities of each building, due to the irregularities it may present in its morphology and the elements that make it up. One difficulty to overcome is that the conventional parametric objects existing by default in BIM software cannot be used, and it is necessary to create new libraries of parametric objects, with the consequent investment in time that this requires. This process is called "Cloud-to-BIM" or "Scan-to-BIM" and allows a realistic reconstruction and visualisation of the modelled building to be obtained (Angelini et al., 2017; Martínez-Carricondo et al., 2021; Rodríguez-Moreno et al., 2016). One of the main challenges currently presented in relation to the 3D digital modelling of our heritage is to be able to simulate the structural behaviour of the building by means of finite element models (FEM). The process of transforming a BIM or HBIM model into a structural finite element model is called "BIM-to-FEM" (Barazzetti et al., 2015; Bassier et al., 2016). The aim of this work is to develop, from a point cloud obtained with UAV photogrammetry, an HBIM model of the Twenty Eyes Aqueduct in the wadi of Carcauz, located between the municipalities of Felix and Vícar (Almería), which in turn serves to obtain a FEM finite element model that allows a broad analysis of its structural behaviour, as well as to lay the foundation stone for the study of future rehabilitation and conservation interventions.

2. MATERIALS AND METHODS

2.1 Study Site

The Twenty Eyes Aqueduct is a hydraulic structure situated in the wadi of Carcauz. It is located on the southern slopes of the

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Sierra de Gádor in southeastern Spain, in the province of Almería, on the border between the municipalities of Vícar and Felix. Figure 1 shows the location of the aqueduct.

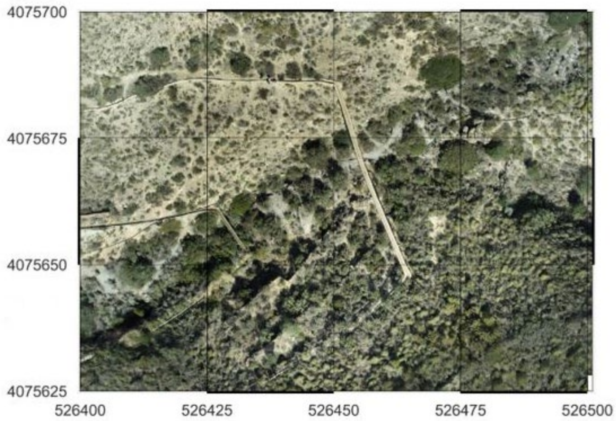

Figure 1. Location of the aqueduct

2.2 Structural description

The aqueduct has a length of 42 m and a maximum height of 9.50 m above the bed of the tributary. It can maintain the level of the water at a practically constant height of 370.8 m above sea level. The name of this aqueduct derives from the 20 arches in its elevation. The base and foundations are the limestone rocky outcrops of the ravine and it has three levels and 20 vaults formed by semicircular arches. The water from the stream flows through the vertical wall of the aqueduct through the arch located on the first level, right in the centre of the construction. Figure 2 shows the current state of conservation of the aqueduct.

Figure 2. Current state of conservation of the aqueduct

2.3 Obtaining point clouds using photogrammetric techniques

2.3.1 Control targets for geo-referencing photogrammetric products: In order to accurately georeference the photogrammetric project and to be able to evaluate the accuracy obtained, a traditional topographic survey was carried out using a Global Navigation Satellite System (GNSS), materialising a total of 14 targets distributed throughout the study area. These targets consisted of A3 format targets (420 mm x 297 mm) divided into 4 quadrants, two in orange and two in black. The 3D coordinates of these targets have been measured by means of a GNSS receiver working in RTK (Real Time Kinematic) mode and receiving differential corrections from a base located at the north end of the aqueduct.

2.3.2 Image acquisition: The images used in this work were taken from a DJI Phantom 4 RTK UAV drone with 4 rotors. This UAV is equipped with a GPS and GLONASS navigation system. In addition, it is equipped with a front, rear and bottom vision system that allows it to detect surfaces with a defined pattern and adequate illumination, and to avoid obstacles with a range between 0.2 and 7m. The Phantom 4 RGB camera is equipped with a 20 megapixel (5472 x 3648) 1-inch sensor and has a manually adjustable aperture from F2.8 to F11. The lens has a fixed focal length of 8.8 mm and a FOV of 84°. The photogrammetric flight was planned and executed autonomously with the DJI GS RTK application. This application allows the execution of double-grid 3D photogrammetric flights, which guarantees the acquisition of photographs from different points of view and inclination of the object to be studied. The flight was planned at a height of 40 metres from the take-off point (located on the north side of the aqueduct) with an equivalent Ground Sample Distance (GSD) of 1.22 cm/pix and consisted of a total of 315 photographs. In order to achieve better accuracy in the photogrammetric project, the flight was configured to take both zenith and oblique images at an angle of 45º. According to the flight altitude, the speed of the UAV and the light conditions at the time of the flight, the shutter speed was adjusted to minimise the blurring effect on the images taken. The camera was triggered every 2 seconds and the flight speed was set to obtain 70% longitudinal and transverse overlaps. Figure 3 shows the flight path followed by the drone.

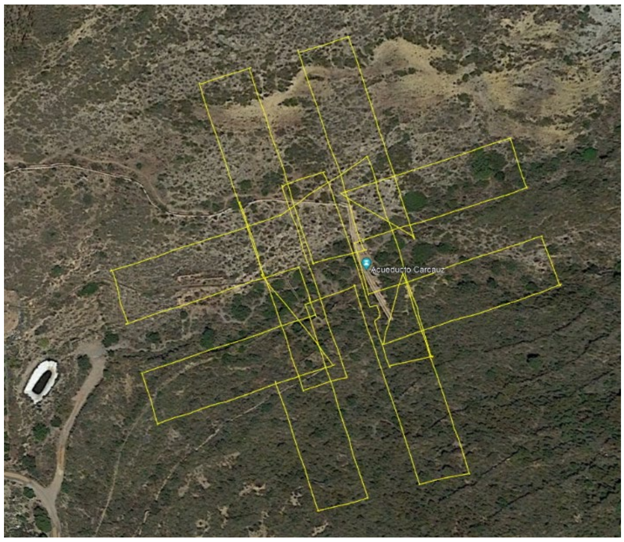

Figure 3. Flight path followed by the drone

2.3.3 Photogrammetric process: The photogrammetric process was carried out using Agisoft Metashape Professional© version 1.8.2 software. This software, based on the SfM algorithm, performs the photogrammetric process in several steps. First, all photographs have been aligned by identifying and matching homologous points between photographs. During the execution of this process, the software estimates the internal and external parameters for camera calibration, including non-linear radial distortions, starting with the camera's focal length value (value obtained from the EXIF data of the photographs). For this study, this step was carried out by adjusting the accuracy of this step to the medium level. Once finished, the program obtains a sparse point cloud with the geometry of the aqueduct environment, the individual position of the cameras, their orientation and an estimation of the camera calibration parameters. From the geolocation data of the photographs taken by the drone, the resulting point cloud is directly georeferenced. However, this georeferencing is of low accuracy and the use of ground control points (GCP) is required to improve it. At least 3 control points will be necessary to improve this accuracy (Agüera-Vega et al., 2017), increasing it by taking a higher number of control points. Of the 14 targets established in the fieldwork, 7 of them (odd numbers) will be used as GCPs, and the other 7 (even numbers) will serve as quality check points (CPs) of the work carried out, thus georeferencing the point cloud in the ETRS89 datum and UTM Huso 30N projection. Once the ground control points to be used are indicated to the software, the camera calibration model is re-optimised and the obtained sparse point cloud is re-adjusted. The sparse point cloud is then densified by creating a dense point cloud with 11,779,429 points, manually eliminating any anomalous points that may have appeared in the model. The result is a dense point cloud with a high degree of detail. After a process of classification of the point cloud, only those belonging to the aqueduct are exported in .las format.

2.4 HBIM model from the point cloud

The BIM modelling of the aqueduct has been carried out in Autodesk Revit 2022, one of the most widely used BIM software in the world. The Cloud-to-BIM process requires the use of an auxiliary software called Autodesk ReCap, which allows the interconnection between Agisoft Metashape and Autodesk Revit 2022 software. Firstly, it is necessary to import the dense point cloud obtained through UAV photogrammetry into Autodesk ReCap in .las format, which contains the point cloud classified as an aqueduct, in order to subsequently convert the project to .rcs format, which is a point cloud format readable by Autodesk Revit. Figure 4 shows the point cloud imported into Autodesk Revit.

Figure 4. Point cloud imported into Autodesk Revit

This point cloud has been used as a guide and reference for the parametric model of the aqueduct. Autodesk Revit does not have an automatic mechanism for recognising geometries, but it allows for the generation of elements with which to model the aqueduct. As the aim of this paper is to obtain a finite element model for the structural analysis of the aqueduct, it will be sufficient to reach a 3D representation level between Grades 1 and 2 (Chiabrando et al., 2017). If we refer to the LOD (Level of Development) of our BIM model, we can set it between levels LOD200 and LOD300, according to the terms coined by the American Institute of Architecture (AIA). This option is based on modelling the aqueduct by means of a structural wall with a constant thickness of 0.90 m (adopting a thickness that leaves us on the safety side for the subsequent structural analysis). Once the structural wall has been created, taking as a reference the plan layout of the aqueduct, we proceed to the opening of the eyes of the aqueduct by means of the empty and cutting shapes tool in order to subtract the "eyes of the aqueduct" from the main modelled volume. This ensures good interoperability between the parametric objects of the BIM model and their transformation into finite element shells to be used in the structural calculation software.

2.5 From BIM modelling to FEM

The FEM is a numerical approximation method that starts from the well-known Matrix Method, elevating it from a "discrete" to a "continuous" mode. The accuracy of the FEM model will depend on the size and shape of the elements in which the part is discretized. The FEM is mathematically more complex than other linear methods such as the matrix method. Fortunately there are numerous softwares capable of generating and solving the numerical equations involved in this method in a short time. For the present work, the SAP2000 software developed by Computers & Structures, INC. was used. The first step is to transform the HBIM model into a 3D model with geometric elements readable by SAP2000. For this project, due to the linear nature of the structure, it has been decided to model it using 2D shells type elements (instead of solid 3D elements), the main advantages of which are the minimization of the calculation times of the structure and the simplification of the stress analysis of the structure. To generate the FEM model, the AutoCad 3D software had to be used as an auxiliary tool. In this way, the aqueduct was divided into 10 sections in order to achieve a discretization in "shells" elements that will ensure the correct structural analysis later. Figure 5 shows the model imported into SAP2000. In order to limit the number of elements that make up the model, the average mesh size has been set to a value of less than 0.50 m, ensuring a good quality of the results obtained.

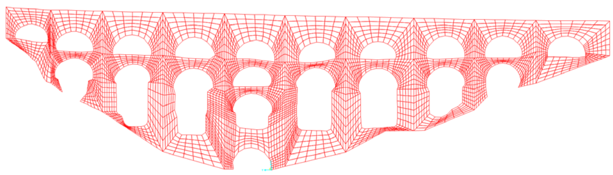

Figure 5. Model imported into SAP2000

2.5.1 Characteristics of the materials: The Twenty Eyes Aqueduct is a masonry structure built using a set of stone pieces joined together and set with mortar. The properties of the masonry depend to a large extent on the properties of its constituent parts: the stone pieces and the mortar, which on occasions may not exist. According to (Martín Caro, 2001), the specific weight of limestone is between 20 and 26 kN/m³. However, the specific weight of the composite material of the masonry will be given by the weight of the components weighted by their respective proportions in volume. Bearing in mind that in stone masonry constructions the volume of mortar is much lower than that of stone, we can estimate that the specific weight of the whole will be 20 kN/m³, adopting a conservative value. The modulus of elasticity (E_b) of limestone is between 17,000 and 76,000 N/mm² and has a Poisson's ratio between 0.15 and 0.20. In the case of lime mortar, a modulus of elasticity (E_m) of between 400 and 2000 N/mm² and a Poisson′s ratio of 0.2 is considered. The deformability of the masonry is largely due to its less rigid component: the mortar. It is, however, interesting to know the modulus of elasticity of the pieces, since the ratio of stiffness between pieces and mortar is a parameter that determines the behaviour of the composite material, a task that presents a certain complexity. An indicative value of the longitudinal deformation modulus (E) of the part−mortar assembly is expressed in equation 1.

$$E=0,50 * E_b=0,5 * 17000\ N/mm^2=8500\ N/mm^2 \quad (1)$$

A coefficient of Poisson of 0.15 shall be adopted for the whole of the masonry.

2.5.2 Structural loads: Permanent loads have been taken into account due to the specific weight of the masonry at a value of 20 kn/m^3, variable wind loads with a value of $W_e \approx 1.00$ kN/m^2, acting on both facades in one direction for the "Wind +" scenario and in the opposite direction for the "Wind -" scenario, and the accidental action of seismic activity.

2.5.3 Combination of loads: The load hypotheses taken into consideration are formed by combining the calculation values of the actions whose action may be simultaneous (concomitant actions), according to the general criteria prescribed in the Technical Building Code, both for Ultimate Limit States and Serviceability Limit States.

2.5.4 Boundary conditions: According to the field visit and the visual inspection of the aqueduct foundations, it was determined that the aqueduct rests directly on the rocky outcrops that can be seen in the riverbed, and that a continuous footing, also made of masonry, could have been laid at those points in the valley where there was a superficial layer of fill. According to what has been observed, the support conditions of the base of the aqueduct are intermediate between a simple support and an embedment. Since a large part of the aqueduct wall is inserted in the limestone rock massif, it seems reasonable that for the level of study to be achieved in the present investigation, contour conditions are adopted along the entire lower edge of the aqueduct model simulating an embedded support

3. RESULTS

3.1 Results of the photogrammetric process

The photogrammetric process yielded an error in X of 1.34 cm, in Y of 2.90 cm and in Z of 1.50 cm, giving a combined total error of 3.53 cm.

3.2 Results of the HBIM modelling

Figure 6 shows the model created in Autodesk Revit 2022 according to the methodology described in the previous section.

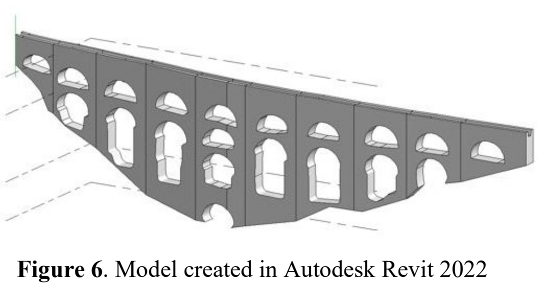

Figure 6. Model created in Autodesk Revit 2022

3.3 Results of the structural calculation

The final model used in the structural analysis is composed of 4,627 points and 4,170 area or shell elements. In this first analysis, a study of the stability of the assembly in the event of overturning and sliding has been carried out. The stability of the construction is determined by means of the coefficients of safety against overturning (CSV) and sliding (CSD), considering that the assembly behaves as a rigid solid. The following reactions have been obtained from the calculation model in SAP2000: the overall Z-reaction due to the self-weight of the aqueduct is 2979.4 kN, the overall reaction in X (axis perpendicular to the aqueduct wall) due to the wind effect is 163.3 kN, the overall reaction in X (perpendicular to the aqueduct wall) due to the effect of the earthquake is 447.9 kN. A coefficient of friction between the ground and the structure of μ = 0.55 is estimated, and an average height of the centre of gravity of each section of the aqueduct of h=3.40 m has been determined (position at which the forces resulting from wind and earthquake are applied for the purposes of the stability checks). In addition, the average thickness of the aqueduct wall is 0.90 m.

For the most unfavourable stability combination where wind action is involved, a CSV=2.41 and a CSD=10.03 values were obtained.

However, for the worst-case stability combination where earthquake action is involved, a CSV=0.88 and a CSD=3.66 values were obtained.

From the analysis of the stability against external actions acting on the aqueduct, it can be deduced that the structure of the aqueduct is stable against gravitational actions and variables such as wind, both in terms of overturning and sliding. However, in the event of a seismic event, its overturning stability would be compromised. According to the criteria set out in the CTE of the Ministry of Housing, the value of the overturning safety coefficient (CSV) must be greater than 2, while the sliding safety coefficient (CSD) must exceed the value of 1.5. Therefore, if we look at the results obtained, the CSV in the event of seismic actions is 0.88, a value even lower than the unit and far from the coefficient set by the CTE. This situation opens the door to new research to study the different reinforcement alternatives that can be undertaken on this monument in order to ensure its stability in the face of any combination established by the current regulations.

A study of stresses and deformations in the structure will be carried out in future advances of this research. For an in-depth analysis of the behaviour of the section under compressive and tensile stresses, the implementation of a model that takes into account the non-linear behaviour of the structure is recommended, a complex analysis that is beyond the scope of this work. However, this opens up another possible line of continuity for this research, since in order to correctly analyse the tensile and resistant behaviour of the masonry in the presence of the moments and shear forces acting on it, it would be advisable to generate a finite element model that takes into account the aforementioned non-linear behaviour of the masonry. Additionally, results with a higher degree of accuracy could also be determined by analysing the structure with 3D or "solid" finite elements (Molins Borrel et al., 2000).

4. CONCLUSIONS

The Cloud-to-BIM-to-FEM methodology allows the generation of BIM and FEM models of architectural and engineering works with low cost, flexibility and high quality results. This makes it an essential tool for the reconstruction, protection and conservation of our historical heritage. The process of generating the HBIM model has kept the final objective of the work in mind at all times, without unjustified simplifications, and has led to a reliable representation of the aqueduct. Future developments will require the implementation of advanced functions to automate the conversion from BIM to FEM models. Currently existing BIM-to-FEM solutions can only be applied to regular buildings with very standardised layouts. The structural analysis of the FEM model has been able to evaluate the instability conditions of the building in the event of an earthquake, although it does behave adequately in the event of wind.

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