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Design and Construction of the Real Felipe Fortress of Callao: Analysis of the Military Treatise and Layout Using Photogrammetry and GIS

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Abstract: Peru constituted the most important Viceroyalty of the Spanish Empire in South America, with the Port of Callao controlling the South Pacific trade routes. Although it was safe in its infancy, Callao suffered coastal attacks leading to its fortification. However, on 28 October 1746, an earthquake and tidal wave devastated the port, leading to its relocation and the construction of the Real Felipe Fortress of Callao, the South Pacific's most significant fortification. The fortress was based on 18th century military conceptions adapted to the specific conditions of the coastal lands of the Peruvian Viceroyalty, such as the lack of stone, the use of adobe, and the frequent earthquakes. This research sought to identify the architectural theories influencing its design, the adaptations necessary for its coastal location, and the underlying mathematical and military concepts. Photogrammetry based techniques and a geographic information system (GIS) were used for georeferencing historical planimetry, along with the analysis of historical documents. This allowed us to reconstruct the original design and make evident how European ideas were adjusted to the particularities of the American territory, thus contributing to the improvement of knowledge about Spanish military architecture in America.

Keywords: georeferencing; Viceroyalty of Peru; fortification; military building; Callao; cultural heritage

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1. Introduction

The Real Felipe Fortress, located in the Port of Callao, on the shores of the Pacific Ocean, was built after the 28 October 1746 earthquake [1].

At present, it is included in list of possible UNESCO World Heritage Sites [2], making it essential to investigate the military theories and fortification principles that guided its design.

Furthermore, a detailed analysis of the construction techniques, the arrangement of the bastions, the thickness of the walls, and other specific fortification features, revealed how it was adjusted to local conditions, innovating with the resources available at the time.

The knowledge we have generated is essential for guiding conservation and restoration, ensuring that any contemporary intervention respects the original historical principles. By stating the reasons behind its design, the techniques used and how these elements were integrated into the Spanish Empire's defensive strategy, we enrich the historical and cultural narrative of the Real Felipe Fortress.

Although there are numerous research works about the fortress, they are scattered and tend to focus on the same historical aspects. The studies of military historians such as Felipe de la Barra [3], Néstor Gambetta Bonatti [4], and Juan Manuel Zapatero López-Anaya [5] stand out. Also, the works of engineers and architects such as Alberto Regal Matienzo [6] and Víctor Pimentel Gurmendi [1] are significant, or those of journalists and historians such as Dario Arrús [7], Aníbal Gálvez [8], and Guillermo Lohmann Villena [9].

As for more recent studies, it is worth mentioning the works of Francisco Quiroz Chueca [10,11] and Michel Laguerre Kleimann [12], who investigated the defense of the port, with a particular focus on the corsair attacks. Meanwhile, Diego Celis Estrada analyzed the restorations carried out in the fortress [1] and the georeferencing of the old Port Callao, correlating the archeological remains with the current urban layout [13].

However, none of the above-mentioned studies have focused on the fortification principles influencing the fortress' design and construction.

This study researched and analyzed the military theories and fortification principles guiding the design of the fortress, reviewing historical documentation and the military treatise that inspired it. Advanced techniques such as photogrammetry were used to record its planimetry, along with geographic information systems (GIS) to georeference cartographic and historical data. The goal was to understand how European military engineering conceptions were adapted to the specific geographic and seismic challenges faced in the South American Pacific basin (Figure 1).

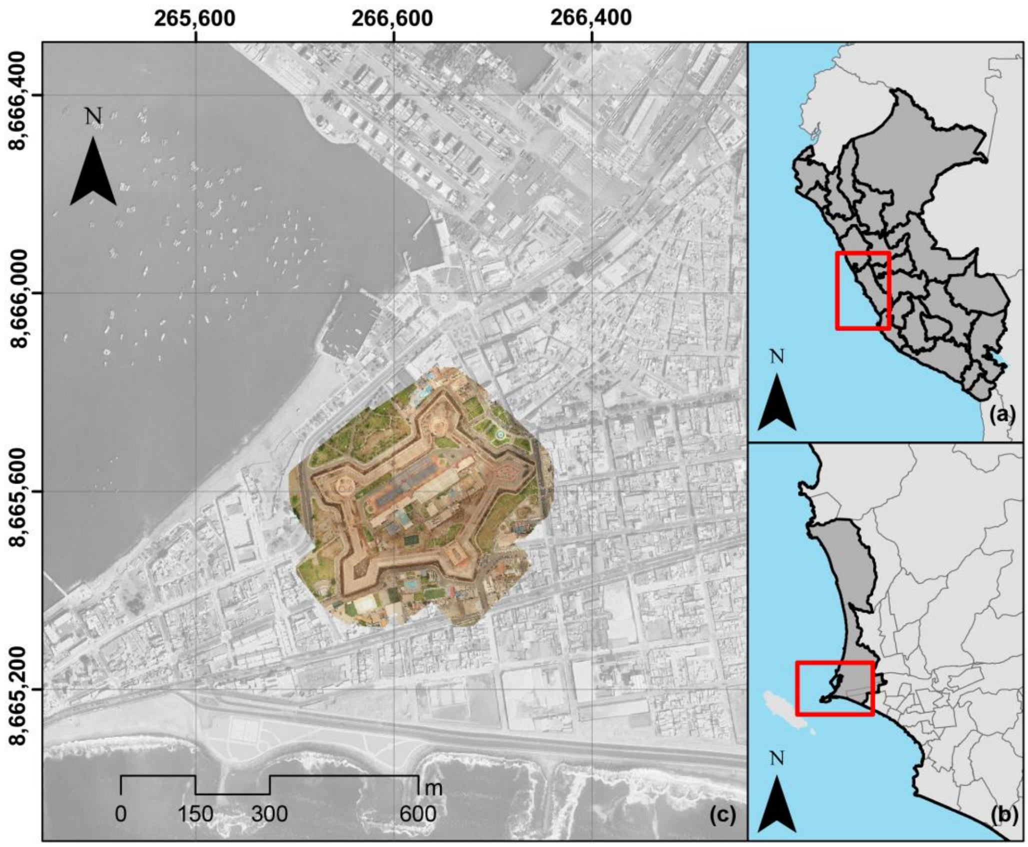

Figure 1. Location map: (**a**) Location with respect to Peru; (**b**) Location with respect to the Constitutional Province of Callao; (**c**) Location of the Real Felipe Fortress of Callao (18L 266,049.61 m E, 8,665,584.90 m S).

This methodological approach is relevant for experts from many cultural heritage related fields, such as archeology, architectural history, heritage conservation, and engineering sciences. It is also relevant from a methodological point of view, as far as photogrammetric surveying techniques and previous analyses related to resolution standards and necessary scales. The research we present not only addresses the progress made in recent years concerning the implementation of digital technologies applied to heritage studies, but also approaches the current challenges and debates around their scope, limitations, and objectives in the Ibero-American context [14].

Moreover, 3D documentation using digital photography and SfM photogrammetry with specialized software enables the recording of cultural heritage at a reasonable cost, with precision and quality. Additionally, documentation through non-invasive digital tools prevents the alteration or degradation of the elements under study, unlike many traditional techniques. Therefore, it is essential to develop a workflow methodology that minimizes the impact on heritage and produces precise and objective information [15].

2. Materials and Methods

The present research has been developed according to a four-stage methodology. First, a review of historical documentation was carried out; next, a photographic survey of the fortress was conducted; subsequently, the data were processed using photogrammetric techniques; and finally, the corresponding planimetric drawings were prepared:

2.1. First Stage: Historical Documentation Reviewing Process

This stage included the review and analysis of the historical documentation corresponding to the design and construction of the Real Felipe Fortress of Callao during the 18th century.

It is notable that the location of Callao and Lima, on the Pacific Ring of Fire, constantly exposed these cities to seismic events. On 28 October 1746, a devastating earthquake, followed by a tidal wave, completely destroyed the ancient port city of Callao [6]. This natural disaster provided the opportunity to redesign the port, focusing on relocating at-risk civilians to a safer zone and on strengthening the military defense of Callao Bay.

Faced by these circumstances, on 10 November 1746, Viceroy José Antonio Manso de Velasco commissioned the French mathematician Luis Godin, member of the Paris Academy of Sciences and Chief Cosmographer of the Viceroyalty, with the endeavor of projecting the new port city of Callao and its fortified defense [6]. A few months later, on 4 January 1747, José Amich was appointed by the Viceroy as director of the work [6]. On 18 January, the order to start digging out the trenches for the foundations of the fortress was issued, scheduling the beginning of work for the 21st of that same month. On 1 August 1747, the ceremony of the laying of the foundation stone took place, and the fortification was named Real Felipe Fortress, in honor of the recently deceased King Felipe V [6].

Thus, to complete this first stage, a search for historical documentation was carried out within the Spanish Archives Portal (PARES) (Table 1, Figure 2).

When analyzing the historical documentation found, it is noted that two fortification proposals were presented at first: one having a regular pentagonal floor plan, and a second one displaying a regular hexagonal plan.

Reviewing the written bibliography about the fortress, evidence suggests that Luis Godin issued his first report on 13 November, recommending that the most advantageous shape for the isolated fortress would be a regular hexagon [7]. However, on 23 November, Godin presented a new report in which he stated that “The fortification that the Port of Callao needs can be a regular hexagon or a pentagon as it seems best to the Superior judgment of Your Excellency” [6]. At last, the regular pentagon layout was chosen, since its construction meant optimizing land use and reducing costs [8].

Table 1. Graphic documentation consulted at the Spanish Archives Portal (PARES).

DATE	TITLE	AUTHOR	SPANISH ARCHIVES PORTAL (PARES)	SIGNATURE
1746-12-20	"Representation of the fires for the defense of the port of Callao in one location or another of the fortress" (a)	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22520 (accessed on 8 September 2024)	MP-PERU_CHILE, 27J
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22534 (accessed on 8 September 2024)	MP-PERU_CHILE, 29J
1746-12-20	Plan of the project of the Callao fortification by the Marquis of Obando	Marquis of Obando	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22536 (accessed on 8 September 2024)	MP-PERU_CHILE, 29L
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22522 (accessed on 8 September 2024)	MP-PERU_CHILE, 27L
1746-12-20	"Delineation made and manifested by the Marquis of Obando in this port of Callao today, 20 December 1746"	Marquis of Obando	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22519 (accessed on 8 September 2024)	MP-PERU_CHILE, 27I
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22533 (accessed on 8 September 2024)	MP-PERU_CHILE, 29I
1746-12-20	"Location of the fortification with respect to the old Callao enclosure" (b)	Luis Godin?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22521 (accessed on 8 September 2024)	MP-PERU_CHILE, 27K
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22535 (accessed on 8 September 2024)	MP-PERU_CHILE, 29K

Table 1. *Cont.*

DATE	TITLE	AUTHOR	SPANISH ARCHIVES PORTAL (PARES)	SIGNATURE
1746-12-20	"The prison of Callao" (c)	Luis Godín	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22525 (accessed on 8 September 2024)	MP-PERU_CHILE, 29A
			http://pares.mcu.es://ParesBusquedas20/catalogo/description/22511 (accessed on 8 September 2024)	MP-PERU_CHILE, 27A
1746-12-20	Plan of the Callao fortification project	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22529 (accessed on 8 September 2024)	MP-PERU_CHILE, 29E
1746-12-20	Plan of the Callao fortification project (d)	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22527 (accessed on 8 September 2024)	MP-PERU_CHILE, 29C
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22513 (accessed on 8 September 2024)	MP-PERU_CHILE, 27C
1746-12-20	Plan of the Callao fortification project (e)	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22518 (accessed on 8 September 2024)	MP-PERU_CHILE, 27H
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22532 (accessed on 8 September 2024)	MP-PERU_CHILE, 29H

Table 1. *Cont.*

DATE	TITLE	AUTHOR	SPANISH ARCHIVES PORTAL (PARES)	SIGNATURE
1746-12-20	Plan and profile of the Callao fortification project	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22528 (accessed on 8 September 2024)	MP-PERU_CHILE, 29D
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22514 (accessed on 8 September 2024)	MP-PERU_CHILE, 27D
1746-12-20	Cut-view of the Callao fortification project	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22526 (accessed on 8 September 2024)	MP-PERU_CHILE, 29B
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22512 (accessed on 8 September 2024)	MP-PERU_CHILE, 27B
1746-12-20	Plan of the Callao fortification project (f)	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22530 (accessed on 8 September 2024)	MP-PERU_CHILE, 29F
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22516 (accessed on 8 September 2024)	MP-PERU_CHILE, 27F
1746-12-20	Plan and elevation of a detail of the Callao fortification project	Luis Godín?	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22517 (accessed on 8 September 2024)	MP-PERU_CHILE, 27G
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22531 (accessed on 8 September 2024)	MP-PERU_CHILE, 29G

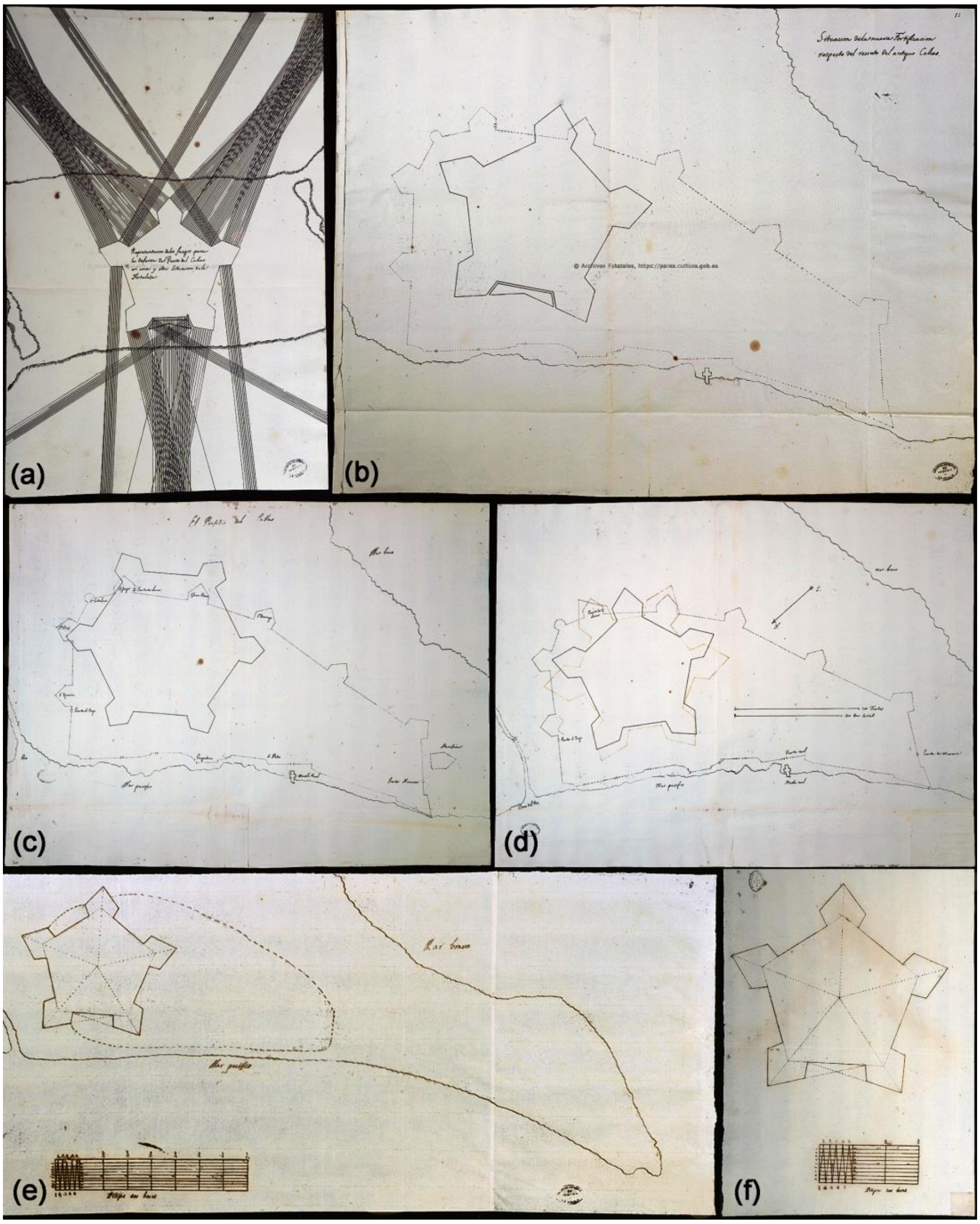

Figure 2. Graphic documentation selected from Table 1 of the Spanish Archives Portal (PARES): (**a**) "Representation of the fires for the defense of the port of Callao in one location or another of the fortress"; (**b**) "Location of the fortification with respect to the old Callao enclosure"; (**c**) "The prison of Callao"; (**d**) Plan of the Callao fortification project; (**e**) Plan of the Callao fortification project; (**f**) Plan of the Callao fortification project.

Among the historical documentation found, we highlight the report issued by José Amich, titled "Maxims and precepts that the engineer Joseph Amich took into consideration in the project of the new fortress of Callao" [16]. This document analyzes the key factors and studies of the fortress' original design, as well as the adjustments made during its construction to adapt it to unforeseen ground conditions (Table 2).

Table 2. Written documentation consulted at the Spanish Archives Portal (PARES).

DATE	TITLE	AUTHOR	SPANISH ARCHIVES PORTAL (PARES).	SIGNATURE
1749-04-15	"Maxims and precepts that the engineer Joseph Amich took into consideration in the project of the new fortress of Callao"	José Amich	http://pares.mcu.es/ParesBusquedas20/catalogo/description/22834 (accessed on 8 September 2024)	MP-PERU_CHILE, 184BIS
			http://pares.mcu.es/ParesBusquedas20/catalogo/description/22833 (accessed on 8 September 2024)	MP-PERU_CHILE, 184

For instance, it is referenced that natural phenomena significantly influenced the planning of the fortress' design and construction. Due to the earthquake risk, it was determined that the appropriate height to resist both an enemy attack and seismic movements, should be equal to 5 varas. Likewise, tidal activity was taken into account, especially the strong waves that occur during the months of December to March. This all led to the decision that the fortress should be located 100 varas from the shore and at the highest possible location to prevent the foundations from being affected [16].

As regards the ideas of fortification and the principles of European military engineering inspiring the design of the fortress, it is mentioned that for its layout, the fortification methods initially adopted were those proposed by Jacques Ozanam, whose approach was based on creating more open flanked angles without compromising the flanks. Furthermore, although this method could at first seem disadvantageous due to the greater exposure of the flanks, in the case of this fortress it was not, since its design prioritized having numerous firing points from multiple directions, which was crucial when confronting ships constantly changing their direction [16]. This reveals that the fortress was designed with a particular focus on maritime defense.

It should be noted that Jacques Ozanam (1640–1718) was a French mathematician and a member of the Paris Academy of Sciences. He was a key figure in number theory, geometry, and mechanics. Additionally, his studies on fortifications and defensive strategies established him as a prominent authority in the design of military structures, thanks to the combination of theoretical rigor and practical utility that characterized his work [17].

José Amich states that he assigned the inner side a length of 270 Castilian varas, as he assumes that 270 Castilian varas are equivalent to 120 French toises, based on his consideration that one Castilian vara equals 32 Parisian inches.

In this way, the demi-gorge was assigned 56 1/4 varas, leaving 157 1/2 varas for the curtain and 45 varas for the flanks, which resulted in 85 1/2 varas for the face of the bastion and 265 1/2 varas for the line of defense, forming a flanked angle of 81 degrees and 22 min [16].

Another determining factor in the design of the fortress was the quality of the terrain, which is indicated to be stony and unstable in nature. Because of this condition, it was decided that the foundations should have a depth and a width of 2 and 4 varas, respectively, leaving a 1/2 vara berm both outside and inside. The thickness of the wall foot was established at 3 varas, reducing its inclination at a rate of 2/5 per vara until reaching a thickness of 1 vara at the top, at a height of 5 varas at the cordon [16].

It is cited that these dimensions were considered adequate for the fortress, highlighting that the terrain did not allow for the construction of a moat since it was only 3 varas above sea level. Excavating for the moat would have required reaching a depth of at least 2 varas in addition to the further digging out necessary for the foundations of the wall, which was impossible due to the instability of the terrain and the risk of drilling below sea level [16].

Furthermore, it is emphasized that the only way to provide the fortress with a moat would have been by raising the counterscarp above the ground level and building a covered path. However, this would have required raising the wall to a minimum height of 7 varas, while increasing its thickness to guarantee its resistance, which would have considerably increased costs, since the earth necessary for the embankment, the counterscarp, and the glacis would have had to be transported from a distance of one third of a league [16].

However, it was finally determined that a moat was not needed for the fortress, as a ground attack was not anticipated due to the enemy's inability to make use of trenches. Hence, it was considered that the fortress was only susceptible of being attacked by sea [16].

Additionally, it is noted that the parapet was built with adobe, with a thickness and a height of 6 and 2 1/4 varas, respectively, in its inward side, while the embankment was designed with a 15 varas width [16].

As far as the fortress layout is concerned, although the report described a design based on a regular pentagonal plan, an unforeseen event forced to reconsider the original plan [16].

On 12 April 1747, while digging out the foundations of the bay front and eastern faces of bastion A, an unusually high tide flooded the low-lying area. This incident forced them to reconsider the layout of the new fortress, since a great extent of the land was flooded. Viceroy Manso de Velasco ordered Luis Godin to examine the terrain once again and to propose the necessary modifications to adjust the project to the new conditions. It was then decided to reduce the regular pentagon to a quasi-regular layout, considering three key factors: ensuring that the fortress stood on elevated grounds, not reducing the firing capacity towards the port area, and taking advantage of the previous excavation works [16].

Considering these factors, the original dimensions of the front facing the bay were maintained. The two collateral fronts were adjusted to 200 varas at the inward side, keeping the 108 degree angle of the polygon, as originally designed. The dimensions of the demi-gorges and flanks were adapted to the inward measurements, achieving flanked angles of 113 degrees [16].

To define the other sides of the new irregular pentagon layout, the center O of the regular pentagon was taken as a reference, and an OP distance of 90 varas was established on the largest radius of bastion D, which was used as the center of the new bastion P. The flanked angle of bastion P was drawn in a straight line to maximize its strength. From this center, the centers of the X and Z collateral bastions were delineated, and the inward sides of the PZ and PX faces were set at 231 1/3 varas, adjusting the dimensions of the flanks and demi-gorges to the main front. Thus, the new layout of the fortress resulted in an irregular pentagon [16] (Figure 3).

In addition, it was said that the fortress' profile did not undergo changes with respect to the original design, although the Z bastion and the NM curtain remained on low ground. In this section, after only digging 1 vara deep, water flooded the excavation. As a result, it was necessary to deepen the foundation by 3 varas so that the upper part was level [16].

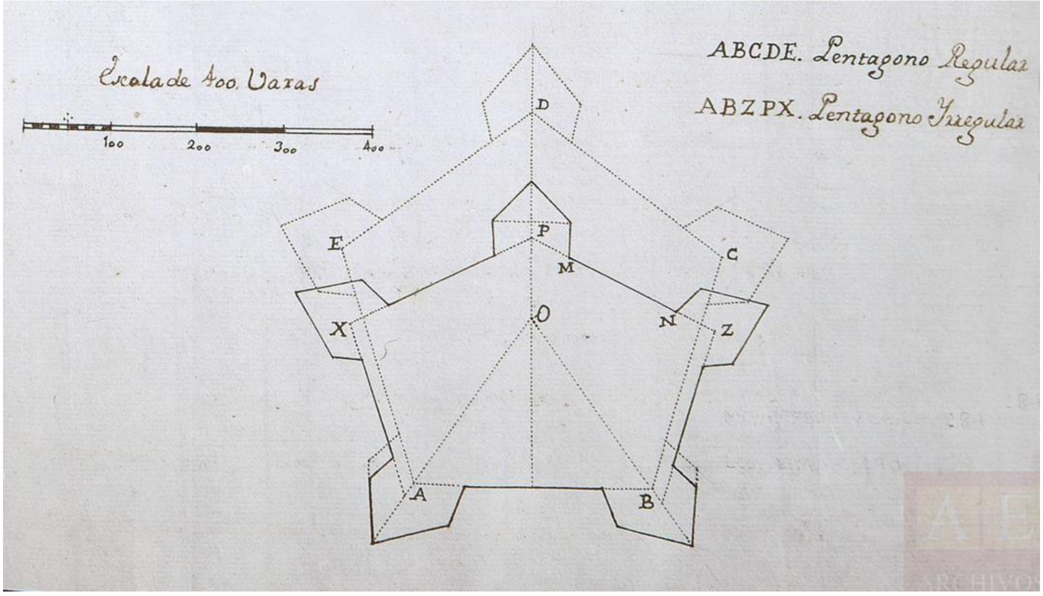

Figure 3. The original layout of the regular pentagon and the new design of the irregular pentagon, according to the report by José Amich, selected from Table 2 of the Spanish Archives Portal (PARES).

2.1.1. Jacques Ozanam

Concerning Jacques Ozanam's conceptions, his military treatise entitled "Traité de fortification: contenant les methodes anciennes et modernes pour la construction et la deffense des places, et la maniere de les attaquer, expliquée plus au long qu'elle n'a été jusques à present" was reviewed. In this treatise, Ozanam set out general fortification maxims, these being the following [18]:

1. There should not be any place in the square enclosure that is not visible and flanked by the besieged: it is essential that the entire fortress is visible and flanked to prevent the enemy from hiding, which would facilitate the taking of the enclosure.

2. The length of the line of defense should be adjusted to the range of the musket rather than to the cannon: It is preferable to adjust the line of defense to the range of the musket, as it is more efficient, accurate and economical compared to the cannon.

3. The length of the line of defense should be approximately 120 toises: the line of defense should be adjusted to the range of the musket, ideally between 100 and 150 toises, with 120 toises being the most convenient measurement, thus optimizing the costs and strength of the fortification.

4. The line of defense must end at the angle of the flank-rasant, when there is no second flank: the entire length of the flank must be used to defend the face of the opposite bastion, as this maximizes defensive effectiveness and avoids unnecessary costs, given that the face of the bastion is the most vulnerable to the enemy and can only be defended from the flank.

5. Larger flanks are better, as they also are the larger demi-gorges and larger second flanks: Larger flanks and demi-gorges improve defense, allowing for a greater number of defenders, more cannons, and best coverage of the moat and the face of the opposite bastion.

6. The flanked angle should be at least 70 degrees: The ideal flanked angle in fortification should be about 70 degrees to better resist enemy attacks. Furthermore, polygons with angles less than a right angle, such as the triangle, cannot be well fortified and are always imperfect.

7. The flank must have a covered part: a flank covered with orillons, especially round shaped, is more resistant to attacks, unlike a plain flank which is more vulnerable and is quickly destroyed in sieges.

8. The flank should not be perpendicular to either the curtain, the defense line, or the face of the bastion: The design of the flank in the fortification must find a balance between protection and functionality. The proposed method is as follows: trace the flanks from the center of the square, adjusting the dimensions of the flanks and demi-gorges according to the number of sides of the polygon, to optimize the defense without making them excessively large or small.

9. A fortified place must be equally strong on all sides, since it must dominate all the surrounding places: The fortress must be equally strong on all its sides so as not to reveal weak points.

10. The elements closest to the center of the square must always be higher than the furthest ones; the most distant and lowest elements of the fortress must be visible from the closest and highest ones, to be able to defend them and prevent the enemy from capturing them and use them as coverage.

11. It is necessary to make the preceding maxims reconciled as much as possible: in fortification, when following a maxim, it is important to balance advantages and disadvantages, so as not to weaken any part of the defense.

Regarding the layout of the regular fortifications, it is indicated that 150 toises could be assigned to the defense line, according to maxim 3; however, to achieve greater defense and be able to shoot the enemy from a closer distance and with greater precision, it is recommended that the defense line be 120 toises [18].

Respecting the fortified design of pentagonal layout, Ozanam points out that it is the most suitable for the construction of a fortress, since it allows applying most of the maxims of a good fortification. Furthermore, he recommends that the inward sides always measure 120 toises, the demi-gorges 25 toises, and the flanks 20 toises [18] (Table 3).

Table 3. Table of the angles and lines of a fortified polygon according to Jacques Ozanam.

Table of the Angles and Lines of a Fortified Polygon, from the Square to the Dodecagon, with an Inward Side of 120 Toises									
Polygons	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Angle of the center	90	72	60	51.26	45	40	36	32.44	30
Angle of the polygon	90	108	120	128.34	135	140	144	147.16	150
Flank-forming angle	14	13.1	11.53	10.36	10.2	9.21	8.44	7.5	7.22
Angle of the flank	120.58	112.59	108.7	105.7	102.28	100.39	99.16	98.32	97.38
Angle diminue	9.42	13.19	16.49	20.14	23.46	27.16	30.43	30.49	31.16
Shoulder angle	130.4	126.18	124.56	125.21	126.14	127.55	129.59	129.21	128.54
Flanking angle	160.36	153.22	146.22	139.32	132.28	125.28	118.34	118.22	117.28
Flanked angle	70.36	81.22′	86.22	88.6	87.28	85.28	82.34	85.38	97.28
Demi-gorges	24	25	26	27	28	29	30	30	30
Curtain	42	70	68	66	64	62	60	60	60
Flank	16	20	24	28	32	36	40	40	40
Great line of defense	117.3	117.5	119	120.3	122.5	126	129	127	125.4
Fase of the bastion	36.1	37.5	40.1	42.2	45.2	48.5	52.3	50	49.1
Capital	28	33.3	39.4	46.2	53.4	61.2	69.4	67.5	67.3
Little radius	84.5	102.1	120	138.2	156.5	175.2	194.1	217.5	231.5

2.1.2. Viceroy Manuel Amat Y Junyent and the Completion of the Construction of the Real Felipe Fortress of Callao

Viceroy Manuel Amat y Junyent arrived at the Port of Callao on 12 October 1761, but it was on 21 December that he made his official entry into Lima, allowing him to inspect the construction status of the fortress [1]. Upon his arrival, he found the structure fully outlined, but with serious structural deficiencies. The construction merely consisted of an outer wall whose rampart lacked the necessary solidity throughout its perimeter. For instance, the embankment intended to serve as a buttress was little more than a loosely compacted mound of earth and was excessively narrow. The wall itself had been built on shallow foundations, necessitating general underpinning to ensure its stability [19].

To address these shortcomings, a counter-wall was built to contain the embankment, thereby reinforcing the main wall and improving the fortification's solidity. Additionally, the parapet was thickened, and six ramps were constructed to facilitate the movement of artillery and the access of garrison troops. Furthermore, two circular cavaliers, each with three levels, were built on the bastions facing the bay, as well as a rectangular cavalier on the opposite bastion [6].

2.2. Second Stage: Photographic Record of the Real Felipe Fortress of Callao

This stage consisted of carrying out a detailed photographic record of the fortress' architecture and surroundings, using high-resolution aerial photographs. To guarantee precision and detail in the documentation, it was established that the photo record would have a Ground Sampling Distance (GSD) no greater than 1.69 cm/pixel, to meet a resolution of 300 dpi at a scale of 1/200, and would be georeferenced.

This GSD value meets the surveying scale and resolution requirement, according to Rodríguez-Navarro [20], has been calculated as follows

$$\text{Res} = (1\ \text{mm} \times 117.8\ \text{pixels/mm})/2000\ \text{mm} = 0.0589\ \text{pixels/mm}.$$

Calculating the inverse, the minimum necessary resolution in mm/pixel is determined:

$$\text{Res} = 1/0.0589 = 16.97\ \text{mm/pixel, or } 1.697\ \text{cm/pixel}.$$

Therefore, the photogrammetric survey of the Real Felipe Fortress of Callao was carried out using with a DJI Mavic 2 Pro quadcopter drone equipped with a 20 mega-pixel (5472 × 3648 pixels) Hasselblad L1D-20c camera and a 35 mm Format Equiva-lent: 28 mm objective.

Flight planning was conducted using PIX4Dcapture software, version 4.11.0, setting up a flight mission height at an altitude of 50 m above ground level. A double-grid flight plan was adopted, with a 70-degree camera tilt and 80% overlap between successive images. This approach allowed images to be captured with a GSD of 1.25 cm/pixel, ensuring the precision necessary to obtain a detailed 3D model of each section of the fortress while maintaining a safe flight height to avoid seabird collisions.

2.3. Third Stage: Photogrammetric Processing of the Real Felipe Fortress of Callao

Three-dimensional (3D) models of the fortress were generated from the photographic data obtained using the PIX4Dmapper software, version 4.7.5. This program employs a series of advanced techniques such as Structure from Motion (SfM), which analyzes the geometry of sets of pixels from multiple perspectives to reconstruct the 3D scene [21]; Multi-View Stereo (MVS), reconstructing the three-dimensional geometry from multiple camera images; and Bundle Block Adjustment (BBA), which adjusts the spatial positioning and orientation of images to improve the accuracy of 3D reconstruction [22].

The PIX4Dmapper software also made possible the generating of an orthomosaic of the fortress, which is a 2D orthorectified image assuring a uniform scale and adequate color balance. In addition, a Digital Surface Model (MDS) representing all the elements on the surface of the fortress was created.

In total, 3343 aerial photos georeferenced in the WGS 84/UTM zone 18L coordinate system were used, covering an area of 0.201 km^2. Each photograph had a median of 41.293 key points and 8679.11 matches per calibrated image. From these images, an orthomosaic and a Digital Surface Model (MDS) of the fortress were generated, both georeferenced with a root mean square error (RMSE) of 1.19 m on the X axis, 1.22 m on the Y axis, and 2.33 m on the Z axis. These data were exported in TIFF format, with a GSD of 1.25 cm/pixel, thus guaranteeing high resolution and precision to represent the fortress (Figure 4).

Figure 4. Three-dimensional (3D) model of the fortress generated from photographic data using PIX4Dmapper software https://www.pix4d.com/product/pix4dmapper-photogrammetry-software/ (accessed on 7 January 2025).

2.4. Fourth Stage: Planimetric Drawing

At this stage, ArcMap 10.8 software, a widely used program in the field of Geographic Information Systems (GIS) and geodatabase management developed by the Environmental Systems Research Institute, Inc. (ESRI), whose main headquarters is located in Los Angeles, California, USA. [23], was utilized. This software offers georeferencing tools, topographic analysis of the territory, and allows cartographic production [24]. Using ArcMap, it was possible to analyze the orthophoto and the Digital Surface Model (MDS) obtained with the PIX4Dmapper software [13], thus determining the location of the fortress in the geographical and topographic context of Callao, and carrying out the necessary studies for its layout.

It is necessary to clarify that, in historical documentation, length units such as French toises and Castilian varas are used. When applying the Ozanam fortification method, José Amich assumed that 120 French toises were equivalent to 270 Castilian varas [16]. However, this equivalence is not entirely accurate. Knowing that 1 French toise is equivalent to 1.949 m [25] and 1 Castilian vara to 0.835909 m [26], the degree of accuracy in the equivalence assigned by José Amich can be calculated.

Therefore, in the design of the fortress following a regular pentagonal layout, it was established that the inward sides should measure 120 toises (233.88 m), and Amich equaled this measurement to 270 varas. However, this is not an exact equivalence, achieving an accuracy of 96.50% (Table 4). Thus, when employing the Castilian vara to implement Ozanam's ideas in the fortress, it was inevitable to have a minimum margin of error due to a unit of measure discrepancy, as it was necessary to adjust the Castilian vara to the corresponding proportion of the French toise.

Table 4. Equivalence of the length units used by José Amich.

Unit	French toise	Castilian Vara	Accuracy
Equivalence	1 = 1.949 m	1 = 0.835905 m	
Design equivalence	120	270	96.50%
	233.88 m	225.69435 m	

3. Results

3.1. Geometric Reconstruction

Based on the metric data gathered in José Amich's technical report, both the original layout of the fortress' project and the readjusted project were reconstructed. The project was drawn up starting from the fact that the inward side of the regular pentagon was equivalent to 120 toises, a measurement that José Amich estimated as 270 varas. Also, the lengths of the demi-gorges, flanks, and faces of the new bastions for the readjusted project were calculated to allow their correct representation (Tables 5 and 6).

Table 5. Lines drawn according to the design report by José Amich.

	Line	Name	Vara
ORIGINALPROJECT	AB	Inward side	270
	a1b2	Curtain	157 1/2
	Aa1	Demi-gorge	56 1/4
	a1a2	Flank	45
	b2b3	Face of bastion	85 1/2
	b3	Flanked angle	81°22″
READJUSTED PROJECT	OP		90
	a3X	Inward side collaterals	200
	PX	Inward side	231 1/3
	x1	Angle of the flank	113°

Table 6. Lines calculated according to the design report by José Amich.

Inward side AB	270	Demi-gorge			Aa1	b1B
		56 1/4				
		Flank			a2a1	b2b1
		45				
		Face of bastion			a4a2	b4b2
		85 1/2				
Inward side a3X, b3Z	200	Demi-gorge			Xx1	Zz1
		(200 × 56 1/4)/270	=	41 2/3		
		Flank			x2x1	z2z1
		(200 × 45)/270	=	33 1/3		
		Face of bastion			x3x2	z3z2
		((200 × 85 1/2)/270)	=	(63 1/3) + 10		

Based on the dimensions and angles established in José Amich's design report, as well as the calculations performed, the design of the fortress was accurately represented, resulting in the following diagram (Figure 5).

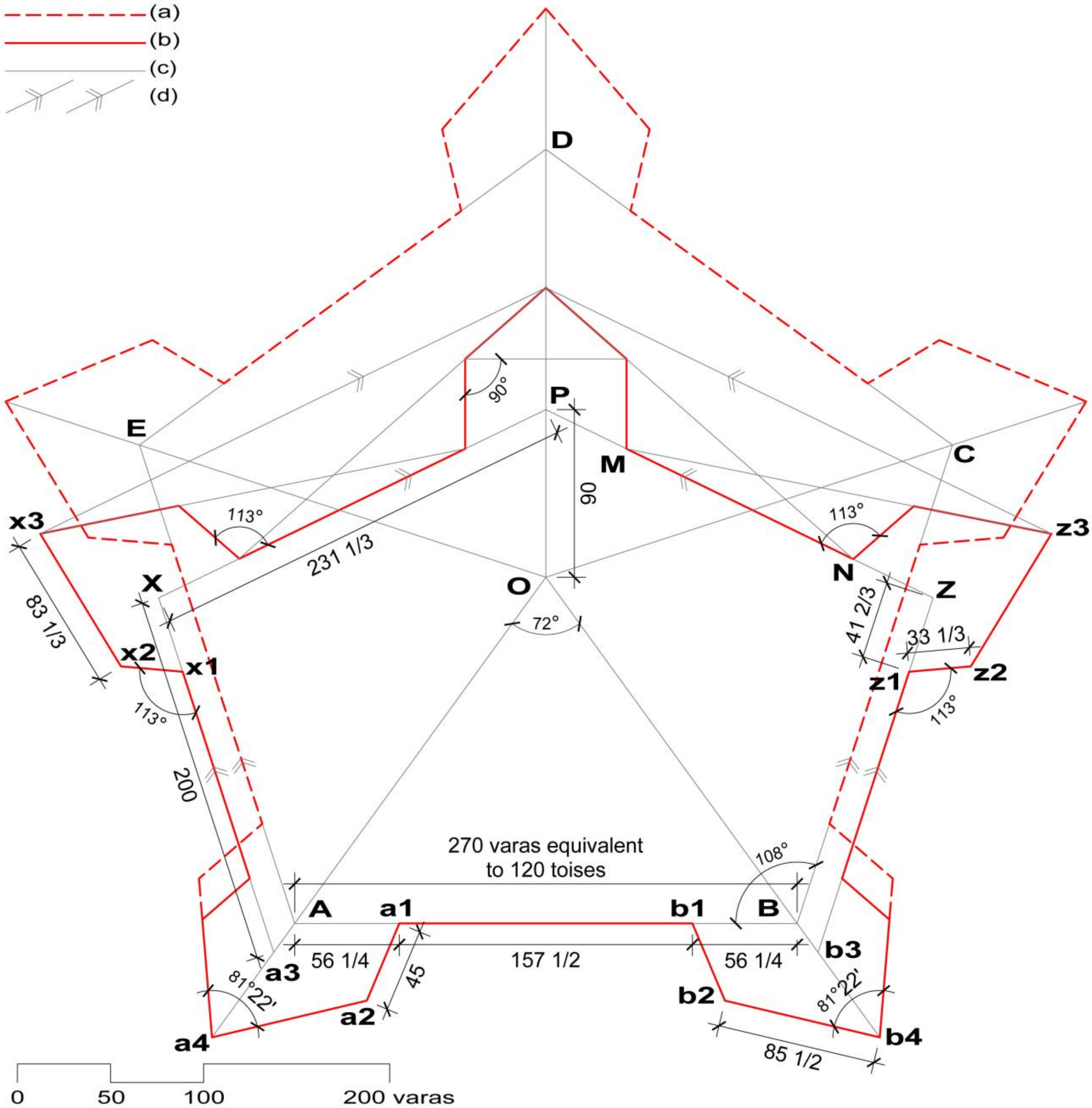

Figure 5. Layout of the Real Felipe Fortress of Callao according to the design report by José Amich: (a) Original project; (b) Readjusted project; (c) Strokes; (d) Parallel lines.

3.2. Photogrammetric Model

Thanks to the orthomosaic of the fortress, the structure could be georeferenced, which allowed projecting the layout of the fortress onto the orthographic image. This process was made possible by means of the ArcMap tool, which facilitated the georeferencing and the graphic overlay, thus achieving an accurate and detailed representation of the fortress layout within its current geographical context, as shown in the following graphic (Figure 6).

Figure 6. Layout of the fortress on the orthomosaic of the Real Felipe Fortress of Callao: (a) Original project; (b) Readjusted project; (c) Strokes.

When analyzing the current section of the wall, a certain correspondence with the original design projected by José Amich can be observed. However, the structure has undergone various transformations over time. Among these are the complementary works carried out during the viceroyalty of Manuel Amat y Junyent, such as the construction of the counter-wall, aimed at providing greater stability to the embankment [19]. Additionally, the original adobe parapet has disappeared and was rebuilt in brick during the restorations carried out in the 20th century [1] (Figure 7).

Finally, it is worth noting that this section of the wall was designed using the Castilian vara as the unit of measurement but was adapted to the proportions of the French toise proposed by José Amich [16].

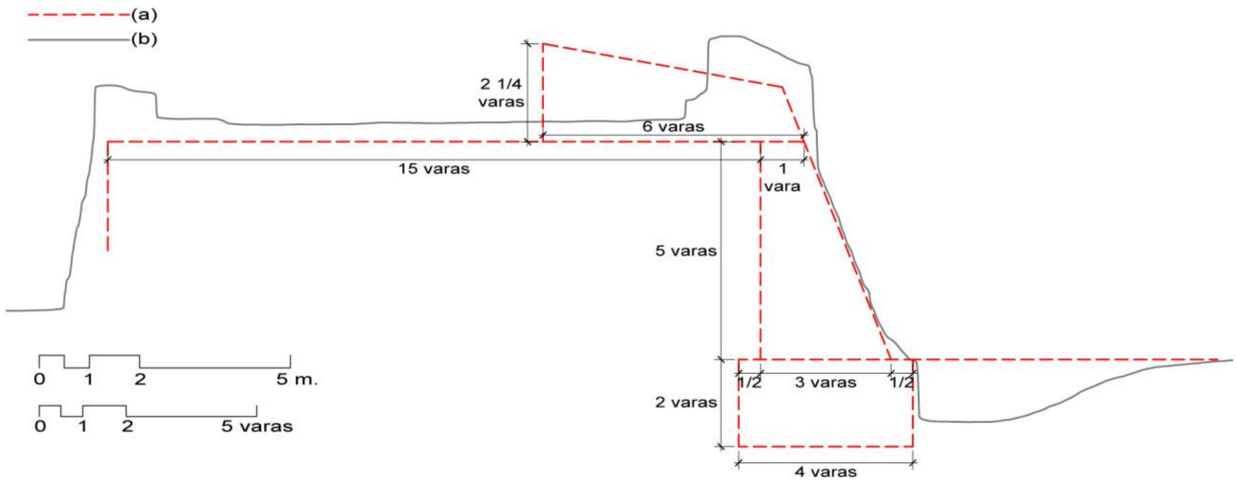

Figure 7. Section 1-1: (a) Representation of the wall according to the original design projected by José Amich; (b) Section corresponding to the wall in its current state.

3.3. Comparison Between Representations

Thanks to the orthomosaic of the Real Felipe Fortress, it is possible to calculate measurements such as the area and perimeter of the constructed fortress and compare them with the planned project, based on the reconstructed geometry derived from the metric data collected in José Amich's technical report (Table 7).

Table 7. Comparison between the built project and the layout project.

	The Real Felipe Fortress of Callao		
	Built Project	**Layout Project**	**Accuracy**
Area (m^2)	82,505.2793	81,694.9158	99.02%
Perimeter (m)	1545.4075	1558.9075	100.87%

The analysis shows a high degree of accuracy between the built and layout projects, the areas match by 99.02%, and the perimeters by 100.87%. This confirms that the Real Felipe Fortress was largely built following the specifications outlined in José Amich's technical report.

Although small discrepancies were identified, these are inherent to the construction process. In this case, the differences can mainly be attributed to the conversion of measurement units, as it was necessary to adjust the Castilian vara to the corresponding proportion of the French toise.

4. Discussion

The design of the Real Felipe Fortress of Callao stands as an outstanding example of the adaptation of European fortification theories to the local conditions of the Viceroyalty of Peru. Both the influence of Jacques Ozanam and the specific geomorphological and seismic context of the South Pacific coast played a crucial role in the conception and modification of the project. Similarly, the plans and the project report indicate that the unit of measurement used was the Castilian vara. However, it is important to highlight that José Amich had to adjust this measurement to the proportion of the French toise, determining that 270 Castilian varas were equivalent to 120 French toises, in order to adapt the project to Ozanam's ideas.

The original design, based on a regular pentagon, adopted most of Ozanam's conceptions, including principles regarding flanked angles and proportions of defense lines.

However, it introduced a variation in the length of the bastion faces, which were designed at 38 toises (equivalent to 85 1/2 Castilian varas), slightly exceeding the 37.50 toises suggested by the theorist. Nevertheless, flooding caused by extraordinary tides and soil instability necessitated adjustments to the design, transforming it into a nearly regular pentagon, relocating Bastion D to Position P, and reducing the total area to 68.85% of the original design. This adjustment preserved defensive capacity toward the port and optimized structural stability, demonstrating pragmatic adaptability.

From a technical perspective, the modifications showcased remarkable ingenuity in the use of materials and techniques. The use of adobe was key to constructing a fortress resilient to the region's frequent earthquakes, while the foundations and walls were carefully adjusted with geometric proportions to ensure stability on stony and seismic-prone terrain. Additionally, the decision to forgo a conventional moat, common in other fortifications of the time, responded to the limitations imposed by the terrain and the improbability of a land-based attack, prioritizing a functional and economical design.

The Real Felipe Fortress stands as a symbol of the dialog between European military knowledge and local challenges, demonstrating that colonial fortifications were not mere transpositions of European models but structures that integrated traditional elements with innovative solutions tailored to the territory. This adaptive approach is further supported by the analysis in the book *Techniques and Engineering in Spain II: The Century of Lights, from Engineering to New Navigation*, specifically Chapter 10, entitled "Spanish fortification in the 17th and 18th centuries: Vauban, without Vauban and against Vauban". This chapter challenges commonly accepted ideas about 17th- and 18th-century fortifications, such as the belief that Bourbon engineers exclusively implemented Vauban's theories and advanced innovations [27]. On the contrary, in this case, the direct influence of Jacques Ozanam is recognized, whose theories guided both the original layout and subsequent adjustments of the fortress.

5. Conclusions

This study on the Fortress of Real Felipe in Callao has provided insights into how European fortification theories, particularly those of Jacques Ozanam, were adapted to the geographical, seismic, and material conditions of the Viceroyalty of Peru. Through the analysis of historical documentation and the application of advanced technologies such as photogrammetry and Geographic Information Systems (GIS), the original design and modifications to the project were accurately reconstructed, highlighting the significance of military engineering in specific contexts.

The results reveal that European military concepts were not directly applied but required significant adaptations to the terrain's limitations and the available materials, such as the use of adobe and adjustments to the geometric proportions of the design. These decisions contributed to the fortress's stability in a highly seismic zone, making it an example of innovation within colonial military engineering.

Lastly, at a methodological level, we used the fortress surveying as a case study for examining the survey standards necessary for the formal analysis of large-scale defensive architecture. The area covered was 200,844 m^2, and the final resolution of the survey, of 1.25 cm/pix, has met the requirement of the necessary standard resolution according to the scale required for the study [20].

Moreover, this study contributes to understanding the dialog between European military knowledge and the demands of the local environment in Latin America, challenging the idea of a mere transposition of European models and emphasizing the adaptive and dynamic character of colonial fortifications. This approach invites the exploration of other viceregal fortifications under a similar lens, promoting comparative studies that strengthen the historical narrative of Hispanic American military architecture.

Finally, the findings contribute not only to historical knowledge but also to contemporary debates on the management and conservation of cultural heritage, underscoring the need to integrate digital methods to ensure the proper preservation of complex and significant structures. Future research could leverage the data generated in this work to simulate conservation scenarios, evaluate the structural resilience of fortifications, or develop interpretation strategies for the public, consolidating the cultural and educational value of these historic sites.

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