# Climate Change, Conflict, And Heritage Preservation in Al-Qahira Citadel.

**AHRC IAA_Climate change, conflict, and heritage preservation in Al-Qahira Citadel**

When cultural heritage becomes the last line of defence against accelerating climate change and protracted conflicts, the need for cross-disciplinary applied research becomes more urgent than ever. It is from this premise that the present research project emerged, supported by the Arts and Humanities Research Council (AHRC) through the Impact Acceleration Account (IAA) at the University of the West of England (UWE), in partnership with Heritage for Peace, to offer a model that brings together the empowerment of younger generations and the protection of endangered heritage sites such as Al-Qahira Citadel in Taiz.

The project is grounded in a multidisciplinary approach that places cultural heritage at the heart of the interaction between accelerating climatic transformations and protracted conflict contexts. In the Yemeni context, the threat facing heritage sites is no longer limited to the direct destruction caused by war, but has been exacerbated by increasing climatic factors, including loss of soil moisture, changes in rainfall patterns, rising temperatures, and the growth of uncontrolled vegetation; all of these factors contribute to accelerating the deterioration of the architectural fabric of historic sites and undermining their long-term sustainability.

Accordingly, this project was conceived not only as a conventional academic study, but as an applied educational and capacity-building programme that combines the production of scientific knowledge with its practical deployment in the field of cultural heritage conservation. The project's philosophy was based on enabling final-year students in the Department of Architecture – heritage track – to acquire the analytical tools and scientific methodologies needed to understand climate-change risks, anticipate their impacts, and develop data-driven, field-informed response strategies.

The project was implemented by an international and local multidisciplinary team. The Science Communication Unit at the University of the West of England (UWE), led by Professor Lisa Mol, undertook academic supervision and science-communication support, ensuring that The research narrative was clear and accessible to both academic and non-academic audiences. This took place in partnership with Heritage for Peace, led by Dr Isber Sabrine- the Spanish Research Center-, which contributed its expertise in heritage protection in conflict settings and in formulating the methodological and ethical framework of the project. Architect Mariam Abdulalitfe provided technical and research support, particularly in the fields of digital documentation, geographic information systems (GIS), architectural analysis, and academic writing.

At the local level, the General Authority for Antiquities and Museums – Taiz Branch assumed responsibility for field coordination and practical implementation, represented by Mr Ramzi Al-Dulaimi and architect Belal AL_Makash. They ensured that research activities were aligned with site-management priorities, institutional conservation requirements, and the local context of Al-Qahira Citadel, while Bilal trained students in digital documentation and non-destructive techniques.

Within this institutional framework, seven young heritage professionals were selected through a competitive process, in cooperation with the General Authority for Antiquities and the University of Taiz, to participate as funded research fellows in the project. This group comprised Ahmed, Osama, Diaa, Hanan, Heba, Anas, and Ali, who played a pivotal role in field documentation, data collection, and environmental and structural analysis, as well as in preparing and drafting the scholarly studies included in this book.

Through this integration of impact-oriented funding, applied education, and multidisciplinary research, the project offers a practical model for how scientific research can be harnessed to strengthen the resilience of cultural heritage in contexts of conflict and climate change. The studies presented in this book are both scientific and educational outputs; they reflect a participatory knowledge trajectory and contribute to developing sustainable practices for heritage protection in Yemen and in comparable conflict-affected regions.

## Research and methodological framework of the project

The project adopted an applied research framework that combines scientific analysis and fieldwork, drawing on multidisciplinary methodologies that integrate climate science, architecture, cultural heritage conservation, and geographic information systems (GIS). Al-Qahira Castle in the city of Taiz was used as a living field laboratory for the application of these methodologies, as it is a heritage site simultaneously affected by the impacts of armed conflict and rapidly changing environmental conditions.

The research work focused on moving from a general description of risks to data-driven analysis, enabling an understanding of deterioration mechanisms, the identification of zones of vulnerability, and the linkage of these zones to climatic, structural, and environmental factors. This approach made it possible to develop applied knowledge that can be directly used in conservation policies, management plans, and strategies for adapting to climate change.

### Research projects and scientific studies

This book presents the outcomes of five integrated research projects carried out by the research fellows between March 2025 and January 2026, which were developed and formulated as fully documented scholarly studies. These projects addressed different dimensions of the impact of climate change on cultural heritage within a defined spatial and temporal framework, focusing on Al-Qahira Citadel, and include:

1. First project: Documentation of threatened tangible and intangible heritage, with an analysis of the impact of climate change on the water structures associated with the castle, as vital elements in the site's historical system.
2. Second project: Photogrammetric analysis of the distribution of architectural damage and identification of risk areas linked to the accelerated deterioration of stonework in the north-eastern tower.
3. Third project: Study of the impact of climate change on the structural stability of the western tower by correlating the physical properties of materials with surrounding environmental factors.
4. Fourth project: Analysis of changes in vegetation cover and their direct and indirect effects on the architectural and structural safety of the castle.
5. Fifth project: Enhancement of community awareness regarding the impacts of climate change on cultural heritage in the city of Taiz, as a key component in sustaining conservation and protection efforts.

These studies were completed within a cumulative research trajectory that encompassed fieldwork, damage analysis and documentation, followed by scholarly writing, reflecting a methodological and epistemic development among the funded student-researchers.

### Training and capacity-building programmes

Professional and scientific capacity-building formed a central pillar in the project design, through the implementation of an integrated training programme aimed at equipping young researchers with modern applied research tools and linking theoretical knowledge with field practice. The training programmes included the following:

First: Geographic Information Systems (GIS) and spatial analysis

- A training course in KoboToolbox and QGIS, delivered by ASOR, focusing on the collection and spatial analysis of field data.
- An advanced QGIS course delivered by architect Maryam Abdel Latif, covering advanced spatial analysis and the production of thematic maps related to climate risks.

Second: Digital documentation and non-destructive techniques

- Practical training in photogrammetry and the use of drones to document architectural damage and analyse temporal changes.
- Practical application of Proceq Bambino and Protimeter devices to measure material hardness and moisture levels, linking the results to structural and environmental analysis.

Third: Architectural surveying and site management

- Specialised training by the General Authority for Antiquities and Museums on preparing daily site-work reports, enhancing

- administrative and technical documentation skills.
- A course in architectural surveying of heritage sites, with field applications inside Al-Qahira Citadel.

Scientific and applied value of the work
This book does more than present research findings; it documents an integrated educational and research trajectory that links scientific knowledge, local capacity-building, and practical application at a heritage site affected by conflict and climate change. The studies it contains offer a model of how impact-oriented research funding can be transformed into effective tools for strengthening the sustainability of cultural heritage and supporting new generations of professionals in this sector.

**Project 1.**

# Documentation of tangible and intangible heritage in danger from the impact of climate change on water structures: Al-Qahira Citadel, Taiz.


## Abstract

This study addresses the documentation of the water system in Al-Qahira Citadel in the city of Taiz as an essential component of the city's architectural and archaeological heritage, and an advanced model of traditional water engineering in the Yemeni highlands. The study aims to document the elements of this system, analyze its architectural and structural characteristics, clarify its operational mechanisms, and assess its current state in light of environmental, urban, and climatic transformations.

The study adopted an integrated methodology that combined field documentation with precise architectural surveying of the water system components within the citadel and its surroundings, including water channels, pools, cisterns, and conveyance paths, alongside analyzing traditional building materials and techniques, particularly Qudad, and its role in protecting and ensuring the sustainability of water structures. The methodology also included conducting interviews with local sources and archaeology specialists, and reviewing historical sources and previous studies related to the history of the citadel and its water system.

The analysis focused on tracing the historical evolution of the system, studying its relationship with the citadel's urban structure, assessing its structural and functional condition, and monitoring manifestations of decay and disappearance resulting from neglect, lack of maintenance, and modern urban interventions, in addition to analyzing the decline of intangible heritage associated with traditional practices of the water system.

The study results show that the water system in Al-Qahira Citadel represents an integrated architectural system reflecting advanced local engineering knowledge based on exploiting topography and local materials, and confirming the pivotal importance of Qudad in Yemeni architecture. The study concludes with the necessity of adopting an archaeological and architectural approach to conserve this system, based on scientific documentation, specialized restoration, and the revival of traditional techniques, ensuring the preservation of its heritage value and its sustainability in the contemporary context.


## Research Problem

The fundamental problem lies in the deterioration of the historical water system of Al-Qahira Citadel due to natural and human factors; climate change and water scarcity have led to the drying of channels and the damage of the insulating "Qudad" material, alongside random urban encroachment that has obliterated the features of historical water channels. This crisis has been deepened by the physical destruction left by wars, leading to the disintegration of the system's hydraulic and functional connectivity and the loss of its efficiency in water storage and management. On the other hand, the system suffers from the disappearance of associated intangible heritage, as local knowledge and craft skills necessary for traditional maintenance and management have vanished due to social transformations and conflicts. This cognitive rupture between generations leads to a loss of collective memory regarding the operation of this heritage system, placing the research before the challenge of establishing a comprehensive scientific strategy to revive and conserve this physical and cultural legacy under current conditions.

## 1. Introduction

Al-Qahira Citadel in the city of Taiz is one of the most prominent historical and architectural landmarks in Yemen, combining defensive, functional, and aesthetic dimensions, with water serving as a critical element for the sustainability of life within it across the ages. This hydraulic dimension was not merely a daily necessity but represented a strategic foundation in the citadel's design and urban planning, prompting Yemeni civilizations, particularly during the Ayyubid and Rasulid eras, to develop advanced engineering solutions to convey water from Mount Sabir into the citadel through an integrated system of water channels, pools, and cisterns.

This system was distinguished by its high capacity to adapt to rugged mountainous terrain through the use of cone-shaped pottery pipes buried in the rocks, as shown in Figure (9), and the design of pools and cisterns with precise slopes that ensure the natural flow of water and its purification from impurities. An intelligent drainage system was also established to protect foundations from moisture and repurpose drained water for irrigating agricultural terraces within and around the citadel, reflecting a comprehensive vision for water resource management within a sustainable environmental and economic framework. Qudad material, with its insulating and climate-resistant properties, contributed to enhancing the sustainability of these water and architectural structures over long centuries, becoming a fundamental element of Yemeni engineering heritage.

Alongside the physical dimension, this system was linked to a rich intangible heritage that formed the cognitive and social framework for its management and continuity, represented in inherited local knowledge regarding the organization of water distribution, the maintenance of channels and cisterns, the process of preparing Qudad, and the social norms that regulated the protection of water sources and ensured equitable benefit.

However, this water system, as an early model of sustainable engineering, faces increasing challenges today due to modern climate change, particularly recurrent droughts that have led to receding water levels and decreased availability, as well as the disappearance of intangible heritage due to the rupture of knowledge transfer between generations, the decline of traditional craftsmen, the impact of conflicts and social transformations, and the absence of systematic documentation for these expertise. These challenges underscore the importance of this research, which seeks to document and analyze the water system in Al-Qahira Citadel in both its tangible and intangible aspects and link them to contemporary environmental changes, aiming to highlight its historical and engineering value and inspire sustainable solutions that can contribute to addressing the water crisis and climate change in the present and future.

## 2. Research Methodology

This study relies on a methodology for documenting and analyzing the water system in Al-Qahira Citadel as one of the fundamental elements of the citadel's defensive and urban structure, addressing its physical deterioration and the decline of its associated intangible heritage. The elements of the water system within the citadel and its surroundings were treated as a case study, given their historical importance and vital role in the site's sustainability through the ages.

Accordingly, the study is based on field documentation and analysis of the water system elements, including water channels, cisterns, and water conveyance and storage networks, supported by visual and descriptive documentation works. This is combined with a historical analysis of ancient sources and previous studies to understand the evolution of this system and its operational mechanisms. The current structural and functional condition of these elements was analyzed, monitoring manifestations of decay and their causes, whether resulting from neglect or environmental and climatic factors.

In the same context, the study addressed the documentation of traditional practices and technical knowledge associated with the water system, analyzing the manifestations of decline in the related intangible heritage. Furthermore, the impact of climate change on the efficiency and sustainability of the historical water system was studied, along with its repercussions on both tangible and intangible components, aiming to reach a comprehensive assessment that supports the formulation of results and recommendations contributing to the preservation of this heritage within a framework of sustainable conservation.

## 3. Documenting and Analyzing

### 3.1 First: Documenting and Analyzing the Elements of The Historical Water System in Al-Qahira Citadel and Its Surroundings.

Direct field documentation at Al-Qahira Citadel involved conducting comprehensive field surveys of all water system elements within the citadel and its vicinity, including water channels, pools, and conveyance pipes, in addition to the water source (water spring) shown in Figure (1), located near the citadel on the surrounding slopes. The location of each element in the water system was identified, documenting its current condition and determining the spatial relationships between the various components of the system.

Figure (1):The image shows the water spring in Mount Sabir.

Figure (2): The image shows the collection basin in Mount Sabir near the water spring, connected to it by an open water channel.

Figure (3):The images show remains of water channels in Mount Sabir.

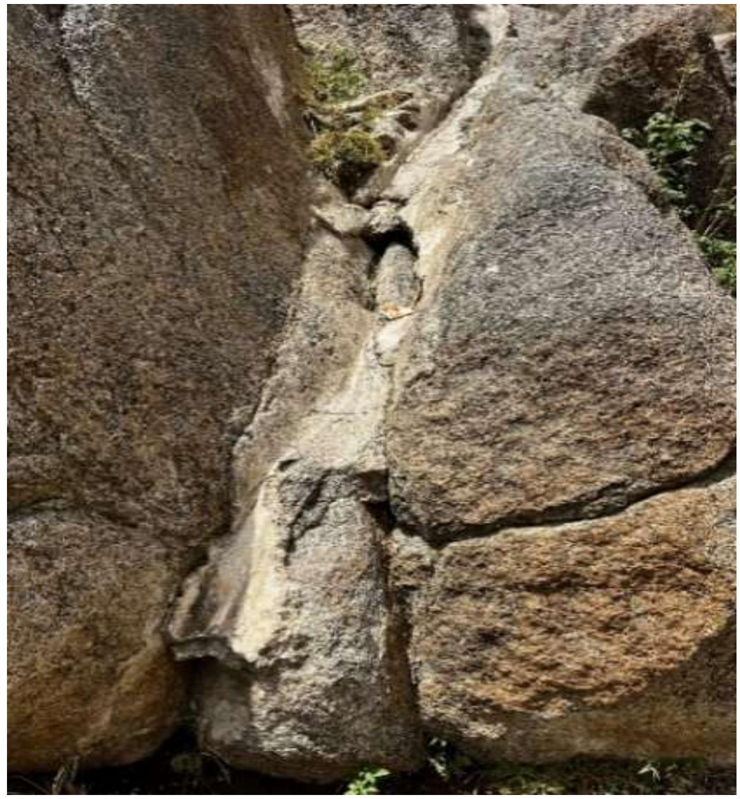

Figure (4): The images show remains of water channels in Mount Sabir responsible for conveying water to the residents in the areas adjacent to the citadel.

The traditional water system associated with Al-Qahira Citadel relied on a deliberate hydraulic sequence starting from water springs on the slopes of Mount Sabir, where water flows through open channels designed with calculated natural slopes that allow for unobstructed conveyance from the spring to a primary collection point consisting of a carefully constructed basin. As shown in Figure (2) and Figure (5), this basin is situated at an elevation higher than that of Al-Qahira Citadel. This elevated position plays a pivotal role in the system, acting as an intermediate reservoir to regulate flow and ensure continuous water supply. From this basin, networks of channels originate, including cone-shaped pottery pipes connected using a "male and female" interlocking method, as shown in Figure (9).

These pipes are tightly fixed and buried within rock masses and mountain soil, then coated with Qudad to provide protection against mechanical pressures from rocks and stones and to limit deterioration and climatic factors. These pipes were installed according to precise, calculated slopes to ensure smooth flow and prevent water backflow or stagnation. The transfer of water from the collection basin to the cisterns in Al-Qahira Citadel depends entirely on the principle of hydraulic head difference, where the natural differences between the higher elevation (water spring and collection basin) and the lower elevation (citadel cisterns) generate self-induced natural pressure that pushes the water automatically without the need for any artificial propulsion. This system reflects a clear integration between geographical knowledge and traditional hydraulic engineering, confirming the ability of ancient builders to employ laws of natural flow to ensure the sustainability of water supplies and their effective management within the defensive and urban framework of Al-Qahira Citadel.

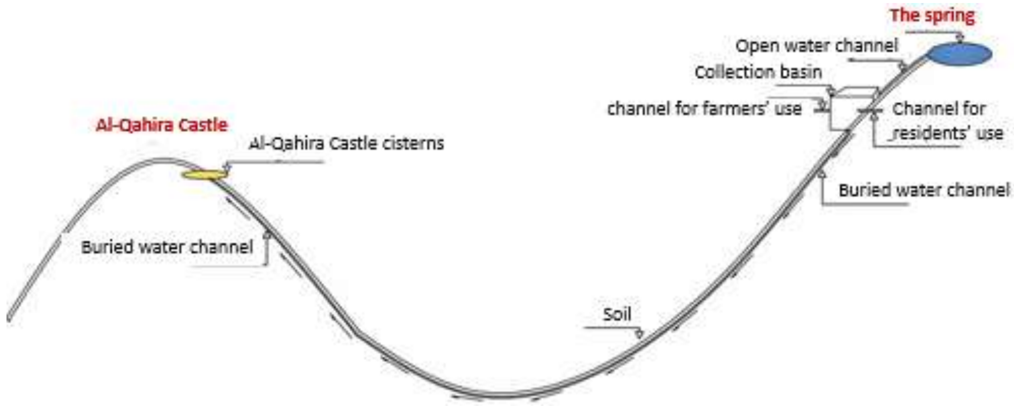


Figure (5): The sketch illustrates the conveyance of water from the spring in Mount Sabir to the collection basin, and its subsequent distribution to the citadel and surrounding areas.

### 3.1.1 Explanation Of the Water System Elements from The Water Spring to The Al-Qahira Citadel Cisterns:

#### 3.1.1.1 Architectural survey of the water system in Al-Qahira Citadel

A precise architectural and engineering survey was conducted for all elements of the water system within Al-Qahira Citadel and its surroundings, including water channels, pools, drinking water reservoirs, and water conveyance pipes. Manual measurements and field engineering survey tools were utilized to ensure the accuracy of the documentation.

Water Source (The Water Spring): The primary supply source, located at a high elevation on the slope of Mount Sabir, surrounded by a stone structure to protect it from mountainous terrain hazards and rockslides, as shown in Figure (6).

Figure (6):The image shows the water spring in Mount Sabir.

The Open Water Channel: It is directly connected to the water spring and functions to convey water from the spring to the collection basin; it is constructed with slight slopes to prevent stagnation or loss and features raised edges that protect the water from leaking outside the channel. It was built using local stones and coated with Qudad to protect it from mechanical impacts caused by rocks and stones, and to mitigate deterioration factors and climatic effects, as shown in Figure (7).


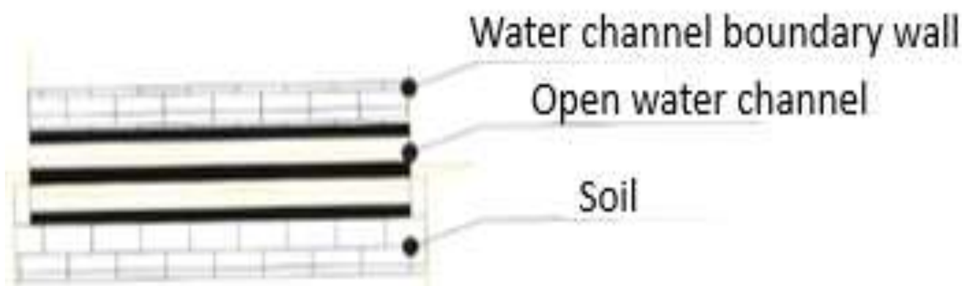


Figure (7) :The image shows the remains of water channels in Mount Sabir according to the architectural vestiges, and on the right shows plan of the open water channels.

<u>The Collection Basin (Intermediate Tank):</u> A pivotal element in the system, constructed from local stones and coated with Qudad on both the interior and exterior to withstand water pressure; it is located at an elevation lower than the water spring and higher than Al-Qahira Citadel, functioning to regulate flow, allow for the sedimentation of impurities, and generate a hydraulic head difference, as shown in Figure (8).


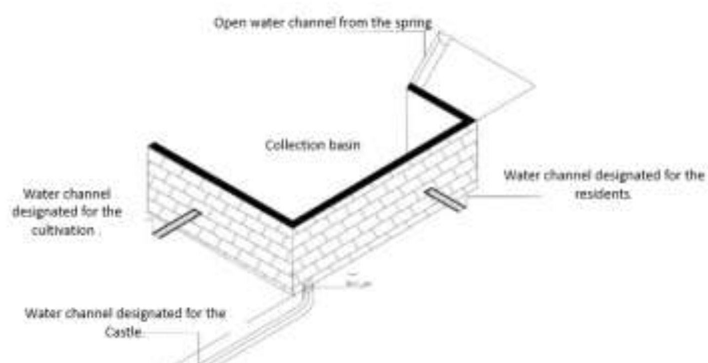


Figure (8) : The image shows the collection basin and the water channels branching from it; the plan on the right clarifies the collection basin and its diverging water channels.

<u>Buried Water Channels:</u> These consist of pottery pipes (male/female) designed in a conical shape to ensure tightness and prevent water loss; they are buried within the mountain and covered with Qudad to protect them from pressure and impact, laid with very precise slopes that ensure water flow to the citadel, as shown in Figure (9).

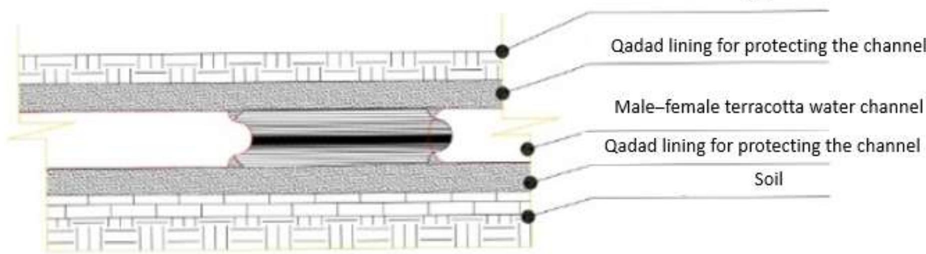


Figure (9): The image shows the image shows the plan of the buried water channel and its interlocking method according to specialists at the General Authority for Antiquities.

Drinking Water Tank: There are two drinking water reservoirs in the citadel carved into the rock and covered from above; they receive a portion of the water flowing from the collection basin, as shown in Figure (10).

Figure (10): The image shows the drinking water reservoir; the yellow arrow represents the water inlet from the channels for filling the reservoir, while the blue arrow represents the overflow outlet from the reservoir via buried channels.

### 3.1.1.2 Architectural Characteristics of a pool within Al-Qahira Citadel (Pools and Water Tank):

the pools and drinking water reservoirs were designed in rectangular or semi-square shapes to maximize storage capacity and minimize evaporation loss, as well as to facilitate construction and maintenance processes. According to observations from traditional craftsmen specializing in heritage construction, these shapes were preferred for providing structural stability and balanced distribution of water pressure on the walls. Some pools were built using local stones bonded with traditional mortar, while others were carved directly into natural rock and subsequently coated with a layer of Qudad.

The pools in Al-Qahira Citadel receive water flowing solely by the principle of elevation head (from higher to lower) without the use of propulsion means; the water is distributed to the pools via internal channels and filtration basins, as the citadel contains four primary pools:

**The Palace Pool:** Located at the highest peak within the citadel, adjacent to the Emirate Palace, this pool was carved into the rock. According to field surveys and measurements by the General Authority for Antiquities and Museums, Taiz branch, the length of this pool is approximately 10 meters and its width is 10 meters, while its depth reaches 5.5 meters, with a storage capacity estimated at about 550,000 liters of water. It is constructed from stone and lined with a layer of Qudad, as shown in Figure (11).

Figure (11) on the right the image shows the Palace Pool in the citadel, 2025; an aerial photograph of the citadel shows the location of the Palace Pool.

**<u>The Fortress Pool:</u>** located in the northwestern part of the citadel's fortress, measuring 22.7 meters in length and 11.6 meters in width with a depth of 7 meters. It accommodates approximately 1,843,240 liters, is carved into the rock, and built from stones and baked bricks Yagur stone with Qudad, as shown in Figure (12).

Figure (12): On the right, the image shows the location of the Fortress Pool within the citadel, highlighted in blue; on the left, a close-up image of the Fortress Pool, 2011.

**<u>The Western Pool:</u>** Located in the lower part of Al-Qahira Citadel, specifically on the western side; its length is 41.3 meters, its width is 9.5 meters, and its average depth is 2.5 meters. It accommodates approximately 980,875 liters and is built of stone coated with Qudad, as shown in Figure (13).


Figure No. (13): The image shows the location of the Western Pool within the citadel highlighted in blue; a close-up image of the Western Pool, 2025.

**The Eastern Pool of the Citadel:** It is located to the east of the citadel, measuring 14.6 meters in length and 5.3 meters in width, with a depth of 5.3 meters. It accommodates approximately 518,446 liters and is built of stone coated with Qudad, as shown in Figure (14).


Figure No. (14): The image shows the location of the Eastern Pool within the citadel highlighted in blue; a close-up image of the Eastern Pool, 2025.

### 3.1.1.3 Photographic Documentation of The Water System in Al-Qahira Citadel and Its Surroundings:

Photographic analysis and documentation were conducted for all elements of the traditional water system within Al-Qahira Citadel and its immediate vicinity, including pools, cisterns, water channels, conveyance pipes, and filtration basins, as well as visible and vanished flow paths. The documentation relied on high-resolution digital photography using drones, capturing elements from multiple angles to highlight structural characteristics, construction material details—particularly Qudad layers—and stone paving patterns.

The photographic documentation also focused on recording various manifestations of decay, such as cracks, detachments, surface erosion, and traces of moisture and salts, in addition to documenting modern human interventions that affected water channel paths or obliterated parts of them. Visual comparisons between similar elements assisted in identifying stages of deterioration and linking them to environmental, climatic, and structural factors.

Regarding the missing or vanished parts of the water system, reliance was placed on photographing foundation remains, traces of buried channels, and variations in soil color or regularity that indicate ancient water paths. Sites identified by elderly members of the local community as parts of water channels or distribution points were also documented, contributing to the reconstruction of the historical spatial layout of the water system.

Figure (15): The image shows the water channels of the citadel in good condition before the war, 2011.

Figure (16): The image shows the water filters before reaching the pool, 2025.

Figure (17): The image shows the thickness of the Qudad used in coating the water channels of the citadel, 2025.

Figure (18): The image shows the deterioration of Qudad material from the water channel due to climate change (drought), 2025

Figure (19): The image shows the deterioration of Qudad material from the water channel due to war, revealing the stones and baked bricks (yajour) used in construction, 2025.

Figure (21): The image shows the deterioration of Qudad material from the water channel due to climate change (drought), 2025.

Figure (22): The image shows the deterioration of Qudad material and the collapse of parts of the pool wall due to climate change (drought) and conflicts, 2025.

Figure (23): The image shows the appearance of salts on the citadel walls due to the blockage of drainage pipes for some water channels and drains in the citadel caused by the conflict, 2025.

### 3.1.1.4 Documentation using Geographic Information Systems (GIS)

Spatial analysis was conducted using QGIS software, incorporating digital layers that identify the locations of pools, drinking water reservoirs, and existing water channels, alongside virtual layers for the vanished parts of the water system, as shown in Figure (24). The locations of these elements were inferred based on a set of indicators, including field evidence, oral accounts provided by specialists from the General Authority for Antiquities and Museums – Taiz branch, and analysis of natural slope directions and topographic elevation levels.

Analytical diagrams of potential water flow paths were also prepared, highlighting mechanisms for exploiting natural elevation differences to supply the citadel and the old city with water. QGIS maps and the accompanying spatial database contributed to clarifying disconnection points in water channel paths and monitoring modern urban interventions, allowing for a deeper understanding of the evolution and decline of the historical water system over time.

These outputs formed a reference spatial database that can be relied upon in the future for restoration and rehabilitation works, as well as in preparing scientific scenarios for reviving parts of the traditional water system, in line with the principles of accurate documentation and spatial analysis.

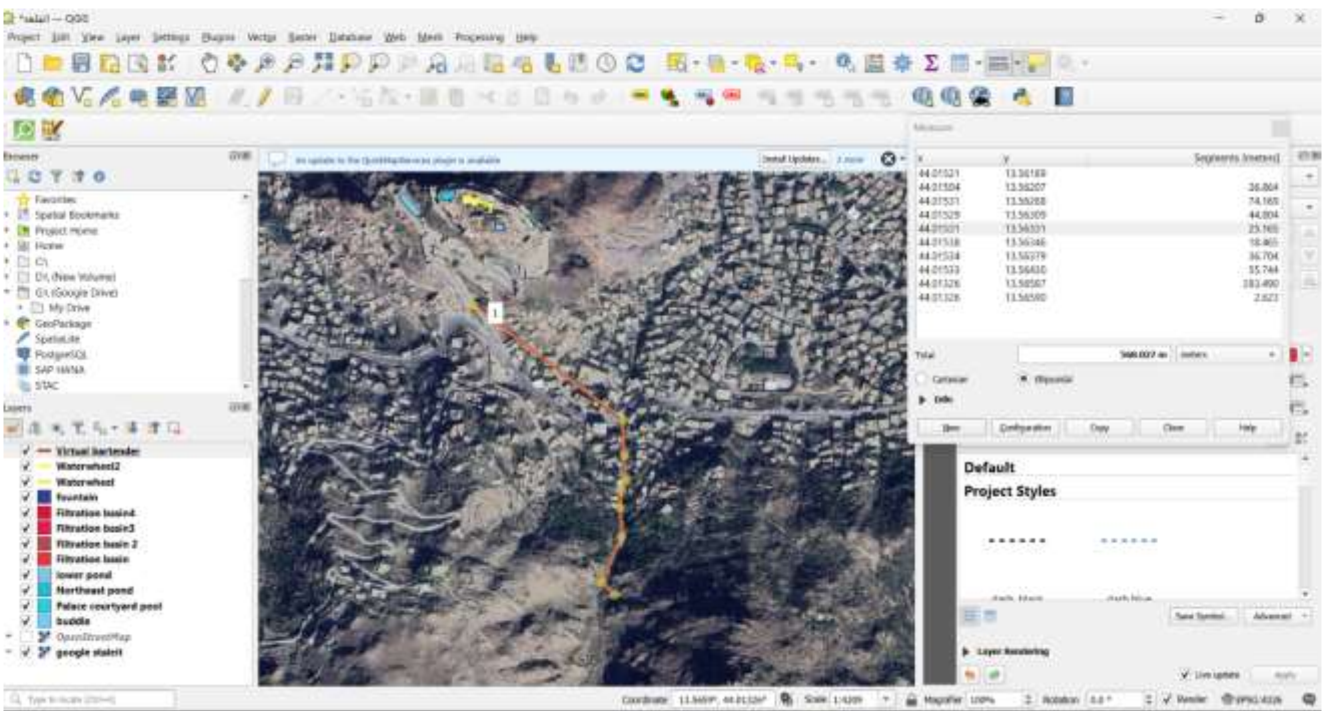


Figure (24): The image shows Digital layers identify the locations of pools, drinking water reservoirs, and existing water channels, alongside virtual layers for the vanished parts of the water system.

## 3.2 Second : Documenting the Intangible Heritage Associated with The Water System in Al-Qahira Citadel

The documentation of the intangible heritage associated with the traditional water system in Al-Qahira Citadel included conducting interviews with archaeological specialists at the Taiz Antiquities Authority and with traditional craftsmen who possessed direct experience or inherited knowledge of water management and facility maintenance. These interviews aimed to collect oral information regarding methods of organizing and distributing water within the citadel, mechanisms for controlling its flow, and the various roles of usage during successive historical periods, especially during times of drought or siege.

### 3.2.1 Architectural and hydraulic techniques for constructing the traditional water system in the historical Al-Qahira Citadel and its surroundings:

Distribution of pools and their relationship to the hydraulic head:

The pools and water reservoirs in Al-Qahira Citadel are a pivotal element of the citadel's historical water system, as they were constructed to secure water needs during both peace and siege, reflecting advanced engineering awareness of water resource management in mountainous environments. Archaeology specialists confirm, based on architectural analysis and building stratification, that the selection of sites for these pools resulted from conscious planning that considered the topographical and hydraulic characteristics of the site.

Self-flow mechanism:

The pools were distributed within the architectural fabric of the citadel at levels relatively lower than the path of the pipes coming from the collection basins, allowing them to be self-fed based on the hydraulic head difference without the need for artificial lifting means. Oral accounts from elderly residents of the area indicate that this system was known locally as a "self-running system," where water reached the pools continuously as long as supply was available from the highlands.

Construction techniques and building materials:

Qudad material played a fundamental role in preventing water leakage and preserving it for long periods, which is confirmed by local craftsmen who inherited the techniques of its preparation and application across generations. It was observed that the thickness of the Qudad layer varies depending on the pool's location and the nature of the water pressure exerted on it, reflecting a precise understanding of water behavior within structures. Furthermore, the execution of floors and walls considered slight slopes to help direct sediments toward specific points to facilitate periodic cleaning and maintenance—practices mentioned by the elderly as part of the circulated practical knowledge related to water management.

Defensive and social function of the water system:

The importance of these pools and drinking water reservoirs was not limited to water storage; they formed a strategic element in the citadel's defensive system, enabling it to withstand long periods of siege. According to oral accounts from the local community, these pools met the daily needs of the residents and the military garrison, including water for drinking, cooking, cleaning, and perhaps ritual uses, which reinforces the vital role of these facilities within an integrated system combining architectural and hydraulic engineering with defensive function.

### 3.2.2 Tangible and intangible dimensions of the system:

This integrated system, reflects a profound understanding of the relationship between geography and traditional hydraulic engineering; it confirms the ability of ancient builders—as described by local craftsmen—to employ the laws of natural flow and accumulated expertise to ensure the sustainability of water supplies and their effective management within the defensive and urban framework of Al-Qahira Citadel and its associated city.

Conveying surplus water to the Old City of Taiz:

In addition to supplying the citadel with its water needs, field evidence and local accounts indicate the existence of a complementary technique for conveying surplus water from the citadel's cisterns to the Old City; this water was drained through open channels extending from the citadel toward the residential clusters below, benefiting from the natural elevation differences. According to residents' testimonies, this system contributed to meeting the population's water needs, particularly during periods of scarcity, reflecting the citadel's role not only as a defensive facility but as a vital center for managing water resources and serving the surrounding urban fabric, as shown in Figure (24).


Figure (25): The drawing on the right how the citadel and the city were supplied with water via water channels (Source: The Book of Ain al-Dam'a: The Old City by Jamil al-Abyadh); the image on the left illustrates the current situation, 2025.

Materials used in constructing the water system in the citadel:

The water system in Al-Qahira Citadel relied on local and traditional building materials carefully selected to harmonize with the mountainous nature of the site and the defensive and hydraulic functions of the facility, reflecting the evolution of engineering knowledge across successive Islamic eras.

Natural Stone (Granite stone):

Granite stone is the primary material used in constructing pools, cisterns, open channels, and the load-bearing walls of water facilities. Local mountain granite extracted from the vicinity of the citadel and Mount Sabir was utilized, characterized by its relative hardness and ability to withstand loads and water pressure. The stone was laid in a deliberate manner in relatively regular courses within pools and cisterns, with attention given to minimizing internal gaps to reduce water permeability.

Figure (25): The image shows the natural stone material used in the construction of the Palace Pool.

## Qudad (Hydraulic Lime Mortar):

Qudad represents the most important traditional material in the water system and is a critical element in achieving waterproofing. It consists of a mixture of slaked lime, volcanic ash or lava (scoria), natural additives, and water, applied in multiple layers. Qudad was used for lining pools and cisterns, encasing water channels, and insulating the joints between stones. Qudad is characterized by its high resistance to water leakage and salts, and its durability under continuous exposure to moisture, making it an ideal material for water facilities in Al-Qahira Citadel.

Methods and techniques for preparing and applying Qudad in the construction of water systems:

Traditional Qudad is prepared through several precise steps that ensure it attains the hardness and durability required for architectural works, particularly in historical buildings and water systems. The process begins with calcining limestone at temperatures reaching 1000∘C to produce quicklime, which is then slaked with water to become usable lime (noura). Subsequently, the resulting lime is mixed with volcanic stone (gravel) in a specific ratio of 3:2 to obtain a cohesive mixture.

The mixture is then left to ferment for several weeks until it is ready for use and acquires the necessary strength and flexibility. During application, Qudad is placed on surfaces with a thickness ranging between 6 and 7 centimeters; the surface is then smoothed using a smooth stone to achieve a uniform finish and is subsequently coated with animal fat to saturate the material and increase its resistance to weather elements and water, as shown in Figure (26).

(1) begins by sprinkling a little water on the Qudad and leaving it to react with the water for some time.

(2) Then, the worker turns over the Qudad and breaks down any parts that did not disintegrate during the water reaction.

(3) Qudad material after the slaking process.

(4) After completing the slaking process, the lime (nora) is sieved and cleaned of damaged and unusable stones

(5) Then, the lime (nora) undergoes a fermentation process with water for 2 to 4 weeks, during which the mixture is tamped daily by the workers' feet

(6) The **Qudad** material in its final form is now ready for use

(7) The image shows the process of applying the Qudad tamping/burnishing material to fill cracks and smooth the surface

Figure (26): the seven processes of preparing Qudad material

Fired bricks :

utilized in the construction of traditional water channels due to their ease of molding and consistent dimensions, which allowed for the precise calibration of channel slopes and gradients to ensure unobstructed water flow. These bricks were also used to build the walls of cisterns carved into rock, with the water-contact surfaces coated in layers of Qudad to ensure effective waterproofing. This application demonstrates an advanced engineering awareness of integrating material properties with functional requirements in traditional hydraulic systems, achieving long-term durability and sustainability.

## 3.3 Third: Analysis of The Current Structural and Functional Condition of The Traditional Water System and Documentation of Degradation Patterns in The Al-Qahira Citadel.

General condition of the system:

Field inspections and historical evidence show that the water system in Al-Qahira Citadel was originally a highly efficient, integrated system that relied on collecting water from the highlands, storing it in pools and cisterns, and then distributing it within the Citadel and potentially to the old city via water channels. However, the current situation indicates that this system no longer functions as an integrated unit; instead, it has become a group of scattered elements suffering from varying degrees of degradation, with most having lost their original function.

### 3.3.1 Structural Condition Assessment:

#### 3.3.1.1 Pools and Cisterns:

Pools and cisterns suffer from several problems that have affected their efficiency and function over time, as structural cracks , as shown in Figure (27) of varying widths have appeared in the walls and floors, contributing to the weakening of their general structure. It was also noted that parts of the qudad layer have been lost or have degraded in several places as shown in Figure (28), leading to water leakage, especially during rainfall. Additionally, stones and binding mortar have undergone erosion as shown in Figure (29), particularly in areas most exposed to continuous moisture. The accumulation of sediment and dust inside some pools has also increased the pressure on the floors, exacerbating signs of damage and negatively affecting their structural integrity

Figure (27): The image shows cracks and voids in the cistern walls.

Figure (28): The image shows the deterioration of the qudad material

Figure (29): The image shows the accumulation of dust and sediment in the pools

Figure (30): The image shows erosion and visible salts on the citadel wall.

**3.3.1.2 Channels and Conduits:**

The channels and conduits have suffered significant damage that led to the decline of their functional role, with extensive parts of them having disappeared as shown in Figure (31), particularly in areas located outside the citadel's perimeter, as shown in Figure (7).The remaining channels suffer from clear blockages due to the accumulation of dust and rock collapses, which hindered the movement of water within them. This has resulted in the loss of functional connectivity between the collection, storage, and drainage elements, thereby disrupting the water system in general. Regarding general stability, some water elements were affected by the instability of the rocky slopes upon which the citadel stands, which reflected negatively on their structural integrity. Indicators of localized weakness in the foundations have also appeared as a result of water leakage and the absence of periodic maintenance, which increases the likelihood of worsening damage in the future.

**3.3.1.3 Evaluation of the Functional and Hydraulic Condition:**

The evaluation of the functional and hydraulic condition of the system shows a clear deterioration in its performance, as the function of organized water storage has almost completely ceased, and the structures are no longer able to perform their primary role as in the past. The continuous flow of water, which originally relied on natural head differences, has also disappeared, leading to the disruption of water movement within the system. Additionally, the level control systems and overflow drains have failed, which increases the risk of water accumulation within the structures and the potential structural damage this may cause. As a result of these combined problems, the system has lost its historical role in supporting the water needs of the Citadel and the surrounding city, and its functional impact, which formed a fundamental element in the sustainability of the site throughout the ages, has declined.

Figure (31): Remains of a conduit destroyed by rock collapses.

**3.3.1.4 Factors leading to deterioration according to specialists at the General Organization of Antiquities:**

The deterioration of the water system is attributed to a group of interrelated factors, primarily the absence of periodic maintenance that ensured its continued operation and functional efficiency. The loss of traditional knowledge and skills associated with water management and the maintenance of *qudad* material has also contributed to deepening patterns of damage, resulting from reliance on inappropriate practices or the neglect of authentic historical techniques. Additionally, direct and indirect damage resulting from armed conflict caused significant losses to the elements of the system, both at the structural and functional levels. Climate changes, particularly the increased intensity of flash floods, have heightened pressure on the water structures and weakened their drainage and control capacities. Furthermore, the disappearance of customary systems that regulated water use and distribution led to the loss of the social and administrative framework that maintained the sustainability of this system over long periods.

**3.3.1.5 Analysis of the decline and disappearance of intangible heritage associated with the water system in Al-Qahira Citadel :**

Despite the vital role that traditional practices, knowledge, and customary systems played in ensuring the sustainability of the Citadel's water system over many centuries, this expertise currently face grave challenges that have contributed to their gradual decline or disappearance. Foremost among these challenges is the interruption of knowledge transfer between generations, as the number of elders and specialized artisans in the maintenance of conduits, pools, and cisterns has dwindled, and traditional learning methods based on daily practice and direct apprenticeship within the local community have ceased. The lack of interest in documenting oral knowledge, by both researchers and official bodies, has also led to the loss of a large portion of the expertise accumulated over time.

In addition, social and economic shifts have contributed to deepening this decline, as the migration of residents from areas surrounding the Citadel—whether due to conflicts or in search of better economic opportunities in major cities—has emptied the local community of the holders of this knowledge. The trend toward using modern water management systems has also reduced the need for traditional practices, making them less attractive to continue and preserve. This has been accompanied by a clear decline in community participation in the maintenance of water structures, an element that was historically essential to the sustainability of the water system.

Furthermore, armed conflict has had a direct impact on accelerating the disappearance of these practices, as water structures suffered severe physical damage that led to the cessation of many traditional activities related to their maintenance and operation, in addition to the loss of some traditional tools and the destruction of vital sites within the water system. Added to this is the absence of systematic documentation, as there are no written records or accurate maps illustrating the technical and social practices associated with water management, along with weak local awareness of the importance of intangible heritage, which has contributed to the erosion of community memory and the loss of a significant aspect of inherited traditional knowledge.

### 3.4 Impact of Climate Change on The Water System in Al-Qahira Citadel and Its Associated Intangible Heritage

Climate change in recent decades has caused a deep imbalance in the water resources that fed the traditional system, as decreased seasonal rainfall contributed to the decline in the recharge of springs that historically formed the main water source in highland areas like Taiz. With increasing temperatures, evaporation rates rose significantly, weakening the efficiency of traditional water collection methods such as conduits, pools, and cisterns. This imbalance in the water budget, as confirmed by modern watershed models, reflected directly on the continuity of flow upon which the Citadel's water system relied to ensure its operation and sustainability.

This impact extended to the physical elements of the system, where the decline in water flow led to a large number of conduits and channels falling out of service, transforming from active vital elements into abandoned structures threatened by backfilling and collapse. Long periods of drought also caused the drying of cisterns and pools, causing them to lose their primary function and making them susceptible to sediment accumulation and the appearance of cracks. Conversely, sudden heavy rainfall resulting from climate fluctuations led to violent surface runoff that contributed to the erosion of soil surrounding the channels, and the alteration or disappearance of some ancient conduit paths, in addition to creating unbalanced pressures on the walls of pools and reservoirs.

Regarding the heritage architecture associated with water, the sharp alternation between periods of drought and moisture contributed to repeated expansion and contraction in the walls of water structures. This climatic behavior weakened the traditional insulation layers made of qudad and negatively affected the binding mortar and local stones, particularly in exposed parts. This resulted in the appearance of cracks, layer separation, and water leakages that accelerated the pace of deterioration of the historical structures within the Citadel.

These effects were not limited to the physical aspect but also extended to the intangible heritage associated with the water system. The decline in water availability led to many traditional practices losing their functional meaning, such as conduit maintenance, periodic cleaning of cisterns, and the management of water distribution according to local customs. The disappearance of water springs and conduits also led to the cessation of the transfer of practical knowledge associated with them between generations, while the weakened reliance on the traditional system led to a decline in the use of local terminology and traditional names for tools and water elements, threatening an important part of the cultural memory associated with the site.

### 3.4.1 Overlap between climate change and urban expansion

The overlap between climate change and urban expansion manifests as one of the most critical factors accelerating the disintegration of the traditional water system associated with the Citadel. As this system weakened due to declining water resources and irregular flow, conduits and channels lost their functional importance in the eyes of the local community and urban authorities, leaving their paths susceptible to neglect and burial. This reality facilitated unregulated urban expansion over these historical paths, where modern structures were erected without regard for the ancient hydraulic infrastructure or its historical role in shaping the urban sphere.

This gradual burial of conduit paths led to the loss of spatial memory associated with water movement within the city, as ancient flow lines are no longer legible within the urban fabric or present in the consciousness of the residents. It also contributed to the severance of the functional and historical connectivity between the Citadel and its surrounding hydraulic urban environment, whereas the Citadel once formed a central node in the water distribution and regulation network. As a result of this separation, the Citadel's social role as a center for water management and use regulation vanished, transforming it from an active space in daily life into a landmark detached from its environmental and urban system that once granted it historical and functional value.

Figure (32): The image shows urban expansion.

## Conclusion

The results of the study showed that the water system in Al-Qahira Citadel formed a highly efficient, integrated hydraulic system that relied intelligently on the natural head difference to transport water from the springs of Mount Sabir to the Citadel without the need for any artificial lifting means. This system was characterized by a precise functional sequence starting from the water sources, passing through open conduits and collection basins, then buried conduits, reaching the drinking water tanks, pools, and overflow drainage systems. This organization reflects advanced engineering knowledge of hydrology and mountainous geography, and a clear ability to employ the site's natural characteristics to serve the defensive and residential needs of the Citadel. The architectural survey also revealed that the pools and cisterns were designed with large and carefully considered capacities, indicating long-term planning to face periods of siege and drought and ensure the sustainability of the water supply.

In contrast, the study showed that the structural condition of most elements of the water system ranges between moderate and high deterioration, as structural cracks appeared in the walls and floors, with a clear deterioration or loss of the qudad insulation layers, in addition to the erosion of stones and binding mortar. The large pools and buried conduits are among the most fragile elements, due to the accumulation of previous hydraulic pressures, the effects of successive climate changes, and the absence of periodic maintenance. Field indicators also point to localized weakness in the general stability of some elements, resulting from water leakage and the erosion of the surrounding soil.

Functionally, the water system has almost completely lost its original function and no longer functions as an interconnected system capable of transporting, storing, and managing water. The continuous flow has stopped, the level control and overflow drainage systems have failed, and the system no longer has any effective role in supporting the Citadel or the old city water needs, transforming it from a vital service infrastructure into archaeological remains isolated from its historical function.

At the level of intangible heritage, the results revealed a sharp decline in traditional knowledge and practices associated with the water system, represented by the interruption of the transfer of expertise between generations, the disappearance of local terminology and technical names, and the fading of customary systems that regulated water use and maintenance. Only limited oral accounts preserved by a few elderly people and artisans remain of this knowledge, making this aspect of heritage threatened with total extinction.

Regarding external influencing factors, the study explained that climate change contributed directly to the decline in the recharge of water springs, increased evaporation rates, and accelerated the deterioration of traditional building materials, especially qudad. Simultaneously, unregulated urban expansion led to the burial of extensive parts of the conduit paths, the loss of spatial memory of the water system, and the severance of the historical relationship between the Citadel and its urban surroundings. These factors interacted together to double the severity of deterioration and place the water system in Al-Qahira Citadel at risk of long-term physical, functional, and cultural loss.

## Recommendation

The study emphasizes the need to take urgent protection measures, starting with implementing emergency structural consolidation for cracked pools and conduits threatened with collapse, aiming to limit the loss of the most fragile elements. It also highlights the importance of protecting the remaining paths of the conduits from backfilling or urban encroachments, as they are essential spatial evidence for understanding the water system. Stopping any non-specialized interventions within the elements of the water system is a necessary measure to avoid exacerbating damage resulting from unscientific restoration practices or the use of materials incompatible with the historical character.

On the level of restoration and rehabilitation, the study recommends preparing an integrated restoration plan based on respecting the original characteristics of the system, through the use of authentic traditional materials such as qudad and local stone, and involving traditional artisans with inherited practical experience. It also suggests rehabilitating selected parts of the system, such as a model pool or conduit, to implement a pilot project aimed at testing restoration methodologies and reviving part of the system as a model that can be generalized later.

Regarding the documentation of intangible heritage, there is a need to implement an urgent program to record oral accounts associated with the water system in audio and video, and to document qudad preparation techniques and traditional conduit maintenance methods. This is complemented by preparing a technical and lexicographical guide that catalogs local terminology associated with water management, contributing to preserving the technical and cultural memory associated with the system from extinction.

In the field of climate change adaptation, the study recommends integrating climate considerations within conservation and restoration plans, by improving rainwater drainage systems and protecting water elements from the effects of sudden surface runoff. It also calls for utilizing the traditional system itself as a sustainable model for water management in mountainous environments, due to the nature-adapted and long-term efficient solutions it carries.

On the administrative and legislative front, the recommendations stress the importance of including historical conduit paths within the legal protection scope of the archaeological site and strengthening institutional coordination between the Antiquities Authority, local authority, and heritage organizations. It also emphasizes the necessity of linking the protection of the water system with the urban development plans of Taiz city, ensuring that urban development projects do not conflict with the preservation of heritage values.

Finally, the study calls for supporting the research and educational dimension by encouraging specialized academic studies in traditional hydraulics and the impact of climate on heritage architecture, and including the water system of Al-Qahira Citadel within awareness, education, and living heritage programs. This approach contributes to enhancing community awareness of the system's value and ensuring the sustainability of research and conservation efforts in the long term.

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Project 2.

# Impact Of Climate Change And Armed Conflict On The Sustainability Of Historic Buildings: A Photogrammetric Analysis Of The North-Eastern Tower Of Al-Qahira Citadel


## Abstract

This study aims to assess the structural and architectural condition of the north-eastern tower of Al-Qahira Citadel in Taiz city, as one of the most important historical buildings in the citadel, through three-dimensional modelling using digital 3D imaging techniques to produce accurate engineering models of the facades, roofs, and elements of the north-eastern tower. These models are used to monitor cracks and collapses, analyse their spatial distribution, determine hazard levels, and measure rates of stone and building material erosion acceleration.
The study is based on an analysis of the tower's evolution across multiple historical periods, taking into account the differences in construction techniques and materials used during each phase, and the impact of climatic and environmental factors on its structural integrity. This approach contributes to providing an accurate scientific database that supports the assessment of the tower's current condition and helps in developing protection and preventive restoration strategies based on quantitative data, ensuring the preservation of the site's historical and architectural values and its sustainability for future generations.


## Research Problem

The north-eastern tower of Al-Qahira Citadel currently suffers from increasing structural and architectural deterioration manifested in the spread of cracks, stone erosion, damage to the binding mortar, in addition to risks of partial collapses most exposed to climatic factors. The multiplicity of historical construction phases, differences in material properties and construction methods across eras, alongside the impact of seasonal winds, rains, and thermal changes, have contributed to complicating the building's structural behavior and increasing its fragility.

The main problem lies in the absence of comprehensive and accurate scientific digital documentation that enables identifying damage locations, hazard levels, and measuring deterioration rates quantitatively and comparatively, which limits the effectiveness of traditional maintenance and restoration plans. Hence, the urgent need arises to adopt 3D imaging techniques as a scientific diagnostic tool that contributes to accurately assessing the current condition and developing well-considered interventions based on scientific foundations that ensure the preservation of the citadel's authenticity and its historical and architectural value.

## Introduction

This research relies on employing three-dimensional digital documentation techniques to produce high-precision models of the facades and surfaces of the historic building of Al-Qahira Citadel in Taiz. These models aim to document the current condition of the building, monitor locations of cracks, detachments, and partial collapses, in addition to analysing patterns of building material deterioration and their spatial distribution. These techniques also enable measuring temporal change rates in the condition of stones and architectural surfaces, determining hazard levels associated with structural stability, especially in the north-eastern tower, contributing to building an accurate reference scientific database.

This database serves as an essential tool to support decision-making for restoration and preventive protection, limit unconsidered interventions, and ensure compatibility of future maintenance works with international standards and charters for cultural heritage conservation. It also contributes to enhancing integration between scientific documentation and long-term planning for archaeological site management.

Al-Qahira Citadel in Taiz is one of the most prominent historic defensive structures in Yemen, representing a complex architectural model that reflects successive temporal layers. The citadel underwent modifications and additions during the Ayyubid, Rasulid, and Ottoman eras, and performed multiple functions throughout its history, including defensive, administrative, and residential roles. This functional multiplicity contributed to the diversity of its architectural components in terms of types of stones used, mortar properties, and different structural and architectural configurations (3).

However, the citadel currently faces serious challenges threatening its stability and safety, resulting from the interplay of two main factors. The first factor consists of mechanical and structural damage caused by armed conflicts, which resulted in partial destruction of the site's architectural structure, as is the case with many heritage structures in conflict areas (4). The second factor relates to the exacerbation of climate change impacts, where studies indicate that the site, built on rocky slopes, is directly affected by the sudden rise in rainfall rates, leading to micro rockslides, soil softening, and weakening of foundation stability (5).

Research also shows that these environments exposed to climate changes witness acceleration in erosion processes and loss of stone masses, due to changes in wind directions and thermal fluctuations. Climate change directly affects the stones used in heritage buildings by increasing evaporation rates, and the resulting salt expansion within stone pores, and the appearance of surface crumbling and delamination phenomena (5).

In particular, the extreme patterns of rainfall in Taiz city had a direct impact on the stability of the north-eastern tower of the citadel, where recent data indicate an increase in the intensity of flash floods by up to 35% during the years (2023–2024). The high-intensity water flow led to erosion of the binding mortar between stones, water infiltration into the depths of thick walls, resulting in elevated internal humidity levels and weakening of the tower's structural cohesion (6).

In general, climate change affects archaeological buildings in multiple ways, including thermal fluctuations, changes in humidity ratios, and decline in the availability of traditional raw materials, leading to manifestations of material deterioration embodied in cracking, salinization, erosion, and loss of part of the site's material and cultural value.

## Historical Background of Al-Qahira Citadel Across Different Period:

Al-Qahira Citadel in Taiz underwent stages of architectural and military development across various eras. During the Sulayhi period, it was a military barracks to protect commercial caravans coming from Mocha port, with simple fortifications consisting of non-double walls built from fragile, unhewn stones sourced from the citadel's own mountain (1).

During the period of the sultans, the citadel transformed into a formidable fortress; high double walls were constructed with thick walls reaching 2.20 m and a height approaching 20 m, along with circular and square towers distributed every 20–30 m, designed with small openings for shooting and pouring oil. Double construction techniques were used with rows of stones, internal fill, and mortar, in addition to long stone ties to increase cohesion (2).

During the Qasimi period (850–924 AH), new fortifications were added, including stepped walls linked to the wall of Taiz city, with observation towers distributed at close intervals.
In 924 AH, the citadel suffered major damage due to Ottoman shelling, after which the Ottomans restored the walls and towers and made the citadel their military headquarters.
Later, with the loss of its military function in the twentieth century, the structure deteriorated due to climatic factors, neglect, and lack of maintenance, as shown in Figure (1).

At the end of the 1990s, specifically since 1998 AD, the General Authority for Antiquities— in cooperation with local authorities—began the first restoration works in the citadel, which started with organized archaeological excavations. Actual restoration works for the citadel began within a project aimed at reviving this important historical landmark, and the initial works included extensive excavation operations to remove soil accumulations and reveal buried architectural elements. During this stage, foundations of buildings and internal palaces were discovered, and the features of the towers became clear, as shown in Figure (2).

Figure (1): The images show Al-Qahira Citadel across two different periods, Source: General Authority for Antiquities and Museums, Taiz Branch

Figure (2): Shows the internal restoration works near the northern tower of Al-Qahira Citadel, 2012, Source: General Authority for Antiquities and Museums, Taiz Branch

**Development of the Northeastern Tower:**

The tower is located northeast of the citadel fortress at a distance of thirty meters from the citadel fortress gate. The tower was built to protect the fortress from dangers in the northeastern direction. The height of the fortress is about 19.5 meters and the width is 8 meters.

- Historical Analysis of the Origin and Development of the Northeastern Tower Construction:

The first origin of the northeastern tower dates back to the period of the sultans' rule because they were the first to plan the Al-Qahira Citadel fortress, and the fortress shows a traditional Yemeni construction pattern mixed with architectural influences from Islamic civilizations in the Levant and Egypt. This tower was exposed to historical events during the Ottoman control period over Taiz city in the tenth century AH, which caused the destruction of parts of the buildings and filling the internal rooms with soil and construction debris to become a solid ground on which the Ottoman artillery was placed. After the establishment of the Yemeni Republic, the tower witnessed restorations in its structural framework and the removal of destruction debris from inside it.
From the mentioned historical sequence of the northeastern tower, it is evident that the tower's construction structure consists of different historical layers: the sultans' rule period, the Ottoman rule period, and the Republican era, which will be documented during the tower documentation works, as shown in Figure (3).

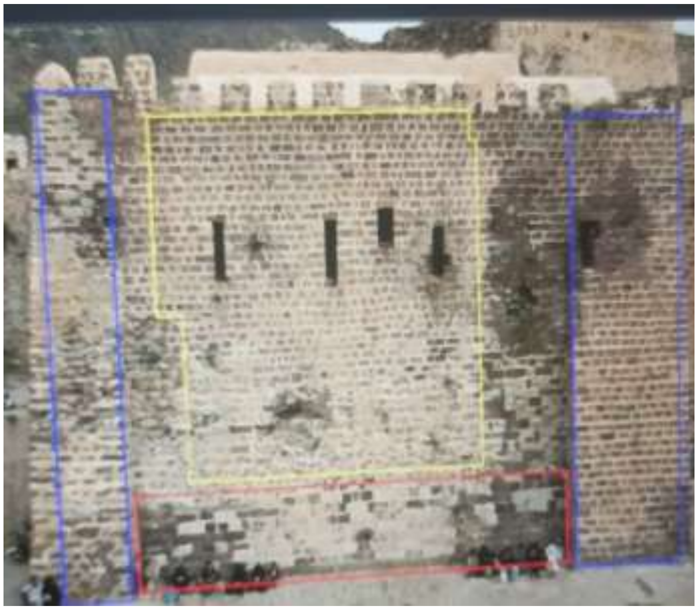



Figure (3) shows the stages of development of the northern tower construction, Source: General Authority for Antiquities and Museums, Taiz Branch

## 2. Methodology

The study adopted a descriptive-analytical applied methodology based on 3D digital documentation, architectural and structural analysis, and physical measurements of materials. Aerial photogrammetry using drones and Agisoft Metashape software produced high-precision 3D models representing the tower's current condition, alongside field visual examination documenting various deterioration manifestations.
Research tools included stone hardness measuring devices (Proceq Bambino) to assess material resistance variations, moisture meter (Protimeter) to determine moisture penetration levels in walls, plus photographic documentation, analytical tables, and comparison between stone types and traditional mortar used. The methodology was applied through comprehensive field survey, followed by 3D digital documentation, then damage classification and analysis by type and causes, linking field measurements to observed deterioration patterns. This integration formed a precise scientific database enabling current structural risk assessment and basis for conservation recommendations compatible with the monument's historical and material values.

## 3. Documentation and Structural Analysis of the Tower Using Agisoft Metashape

the three-dimensional model of the tower based on photogrammetry techniques, through processing a set of aerial images captured by a drone. The model was generated based on 173 digital images, as shown in Figure (4),which enabled accurate documentation of the current condition of the tower, analysis of damages and structural defects, monitoring of stone material deterioration manifestations, and identification of stone erosion locations, supporting the technical assessment of risk levels and structural stability.

Figure (4) shows the three-dimensional model of the northern tower using Agisoft Metashape software.

Agisoft Metashape software provides a high level of accuracy in processing digital images, as it preserves the visual and geometric characteristics of architectural surfaces as they are in reality, without distortion or excessive simplification. This accuracy enables the reliable documentation of the tower's current condition, including details of cracks, stone erosion, and mortar weakness areas, which enhances the credibility of the structural and architectural analysis.

The following images show a direct comparison between the original images captured by the drone and the resulting three-dimensional model from processing them using Agisoft Metashape software, where the high match in engineering details and the surface texture of the stones is evident, confirming the program's efficiency in producing accurate digital models that represent the architectural reality of the building with high precision, as shown in Figure (5).

(a) Original image from the drone, Northern Façade of the Tower

(b) Image extracted from the Agisoft Metashape 3D model, Northern Façade of the Tower

(a) Original image from the drone, Northern Façade of the Tower

(b) Image extracted from the Agisoft Metashape 3D model, Northern Façade of the Tower

Figure (5): Comparison between the original image taken by the drone and the resulting 3D model using Agisoft Metashape software.

## 3.1 Analysis of the External Damages of the Northern Tower:

Figure (6) An aerial photo of the general site of Al-Qahira Citadel, showing the study area of the northern tower circled in red.

### 3.1.1 Documentation and Structural Damage of the Northern Façade

The height of the northern façade of the tower is 13.33 cm, the width of the façade is 19.49 cm, and the wall thickness is 1.6 m. The tower was built with smoothed sedimentary stones and another type of untrimmed granite stones that were built in paved rows. The façade walls have rectangular openings that narrow at the front and widen at the back, which are loopholes used for shooting arrows and firing bullets, and the façade ends at the top with machicolations used for guard duties.

The facade was exposed to direct shelling by rockets or gunfire during the conflict period, which caused gaps in the walls and fragmentation and crumbling of the stones. During the past period, the facade suffered significant deterioration due to climatic changes such as heavy rains, which caused the washing away of the binding mortar inside the walls and the growth of some plants. Due to water congestion behind the walls and the absence of drainage for this water, moisture appeared, which caused erosion and deterioration of the stones. Thermal fluctuations causing contraction and expansion of traditional materials also contributed. All of this led to the erosion and damage of the traditional materials from which the tower was built, as shown in Figure (7).

The northern facade of the tower, as shown in Figure (7) a range of material deterioration manifestations, where erosion and crumbling in the stones were observed, along with the erosion of the binding mortar between the stone blocks as a result of continuous exposure to environmental factors. As shown in Figure (8), Growth of a shrub from the Mastic family was also recorded on the same facade, which is one of the plants with shallow roots that can be easily removed, and does not pose a direct threat to the structural stability of the building in its current position, but its presence indicates the availability of moisture within the stone joints, which necessitates monitoring and preventive treatment.

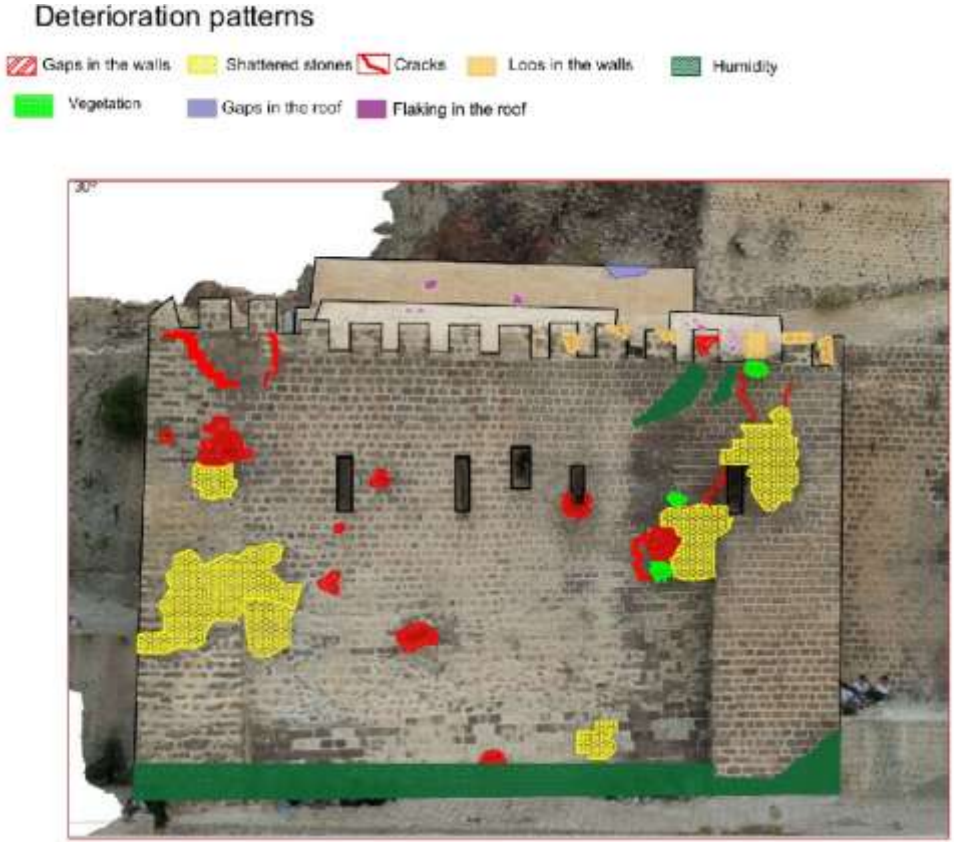



Figure (7): shows the damages on the Northern Facade of the Northern Tower.

Figure (8): Erosion and crumbling of stones and erosion of the binding mortar on the northern facade of the tower.

Figure (9): Growth of a shrub from the Mastic family on the northern facade of the tower without direct impact on structural stability.

**Table(1): Approximate Damage Rates on the Northern Facade of the Tower:**

| Type of Damage | Rea of Damage | Damage Ratio | Reason |
|---|---|---|---|
| **Chemical** | **In the middle of the northern facade** | **4%** | Climatic factors (growth of some plants) |
| **Chemical** | **north facade** | **19%** | Climatic factors (erosion of some stones due to moisture resulting from rainwater seepage inside the walls) |
| **Mechanical** | **north facade** | **85%** | Conflict factors (gaps in the walls and fragmentation and crumbling of some stone parts due to direct projectiles and gunfire) |

**Analysis of Results and Link to Climate Change:**

The results in Table(1) show significant variation in damage levels, with the highest damage recorded at 85%, resulting from mechanical factors related to armed conflicts. This type of damage directly weakens the tower's structural framework, making it more vulnerable to other external factors. The lowest damage result reached 4%, resulting from plant growth in the middle of the northern facade. Despite the small percentage, it is closely linked to climate change phenomena. Changes in temperatures and increased humidity rates provide a fertile environment for plant and algae growth on stone surfaces, leading over time to root penetration and chemical and mechanical stone crumbling.

**Cumulative Damage and Climate Impact:**

The link between damage and climate change is most evident in the average rate of 19%, resulting from stone erosion due to moisture and rainwater infiltration. The intensification of extreme weather phenomena, such as heavy irregular rains, accelerates chemical erosion processes. When these climatic factors combine with mechanical damage from conflict (gaps and shattering), the tower reaches a critical state; as gaps from projectiles act as easy passages for water and moisture to penetrate deep into the walls, doubling the speed of structural deterioration and turning minor damages into serious risks threatening the survival of the historic monument.

### 3.1.2 Documentation and Structural Damage Analysis of the Tower's Eastern Facade

The height of the facade is 13.33 m, with a width of 3 m and a wall thickness reaching 0.50 m. The wall was constructed using two types of polished and dressed sedimentary stones, along with granite stones, and was executed using a system of regular, stacked, and bonded courses. The construction fabric consists of an outer leaf and an inner leaf, separated by an internal core of small stones, in which Qadad was used as a binding mortar. The facade also contains a single wall opening.

Field inspection indicates that this facade was not subjected to direct and severe shelling compared to the northern facade, as the structural damage was limited to the collapse of some upper parts of the walls. However, the facade showed clear influence from environmental and climatic factors, as temperature fluctuations associated with climate change, along with heavy rains and water infiltration into the courses, contributed to weakening the binding mortar and its erosion from between the stones, leading to their decay and loss of cohesion. Water retention behind the walls also contributed to the appearance of moisture manifestations and salts on the stone surfaces, in addition to the growth of some plants near the facade walls, which constitutes an additional factor in accelerating deterioration processes, as shown in Figure (10).

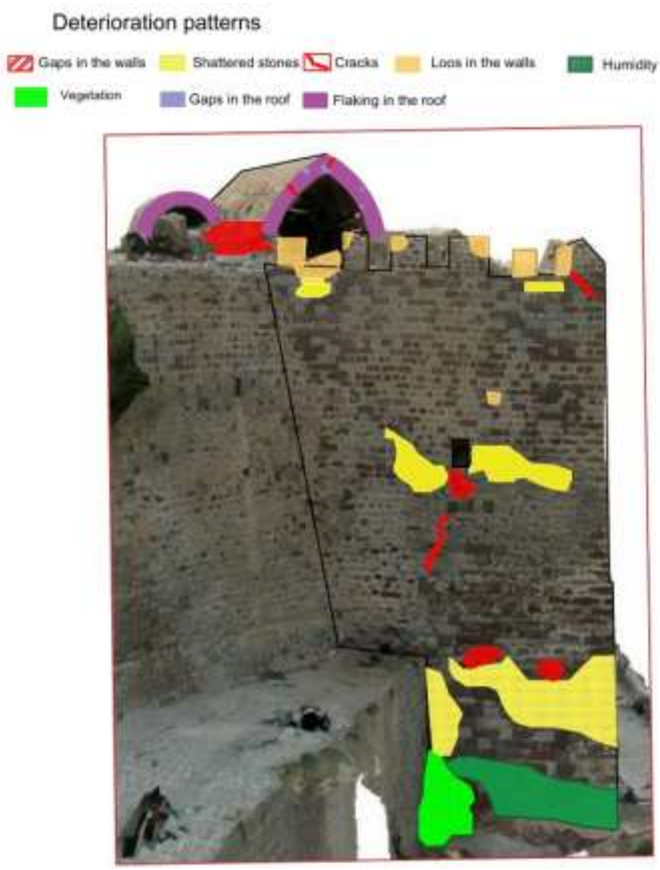



Figure (10): shows the damages on the Eastern Facade of the Northern Tower.

Figure (11): shows stone erosion

Figure (12): shows the biological and climatic factors affecting the tower

Figure (11) shows stone erosion: Over time and without periodic maintenance, construction materials are exposed to erosion due to various weather factors such as rain, wind, and temperature fluctuations. Figure (12) shows the biological and climatic factors affecting the tower: Growth of some microorganisms was observed in the low corners of the tower due to high humidity, which is considered one of the chemical damages that accelerate the crumbling of stones and change their color due to biological reactions. Also, a medium-sized tree grows near the facade foundations; it is a mountain tree that tolerates high temperatures, drought, and weather fluctuations. Although its roots extend in the soil surrounding the foundations, the level of its penetration into the structure is limited compared to other trees, but its continued presence may lead to the disintegration of some stones in the foundations, especially with the availability of moisture.

**Table(2): Approximate Damage Rates on the Eastern Facade of the Tower:**

| Type of Damage | Rea of Damage | Damage Ratio | Reason |
|---|---|---|---|
| **Chemical** | **In the middle of The Northern Facade** | **10%** | Climatic factors (growth of some plants) |
| **Chemical** | **North Facade** | **19%** | Climatic factors (erosion of some stones due to moisture resulting from rainwater seepage inside the walls) |
| **Mechanical** | **North Facade** | **30%** | Conflict factors (gaps in the walls and fragmentation and crumbling of some stone parts due to direct projectiles and gunfire) |

### 3.1.3 Documentation and Structural Damage Analysis of the Tower's Western Facade

The height of the tower's western facade is 13.33 m, with a width of 3 m and a wall thickness reaching 0.50 m. The wall was constructed using two types of polished and dressed sedimentary stones, along with granite stones, and was executed using the system of stacked and bonded courses. The construction fabric consists of an outer leaf and an inner leaf, with an internal core of small stones in between, in which Qadad was used as a binding mortar. This facade does not contain any wall openings.

Inspection shows that this facade did not represent a primary front for conflict impacts, unlike other facades more exposed to attacks, partly due to its topographically protected location and low degree of exposure to weather factors. It is also considered less vulnerable to the effects of wind and rain, as the prevailing seasonal winds in Taiz city often blow from the southwest direction, making the southern and southwestern facades the most exposed to winds and rainfall. Additionally, the limited exposure of the western facade to direct sunlight during peak daylight hours contributed to reducing expansion and contraction phenomena in construction materials, thereby limiting the development of surface cracks and the deterioration of structural materials, as shown in Figure (13).

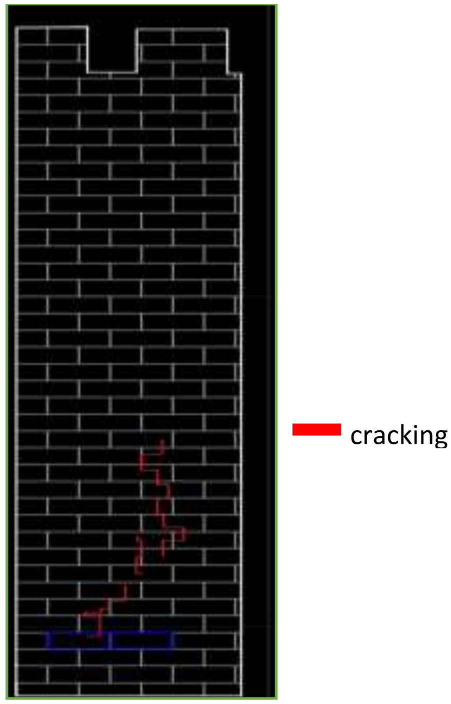



Figure (13): shows the damages on the Eastern Facade of the Northern Tower.

### 3.3.4 Documentation and Damage Analysis of the Tower Vaults (Roofs)

The northeastern tower roof is covered with barrel vaults of longitudinal shapes, constructed using traditional materials of fired red bricks and coated with a layer of Qadad material. The total area of the tower roof is approximately 134 $m^2$.

Documentation and field inspection revealed a range of damage manifestations, summarized as follows:

- Appearance of a deep vertical crack accompanied by the disintegration of wide areas of the Qadad layer in some vaults, attributed to vibrations from airstrikes and artillery shells, direct impact of intense sunlight during peak hours, and humidity from southern winds and seasonal rains, leading to repeated expansion and contraction cycles of the structural materials.
- Observation of wide gaps in one barrel vault ceiling resulting from a direct hit by a projectile, with damage exacerbated by exposure of construction materials and binding mortar to weather fluctuations and seasonal rainfall.
- Disintegration and falling of parts of the coating layers due to the combined effects of vibrations, climatic factors, artillery shells, and plant growth, where climate change contributes to weakening adhesion between layers and accelerating material erosion.
- Appearance of cracks and shattering in the tower walls at the junctions of vaults and walls, resulting from simultaneous exposure to mechanical and environmental stresses, as moisture and thermal fluctuations accelerate the deterioration of traditional materials and loss of their structural capacity.


Figure (13): shows the damages on the barrel vaults of the Northern Tower.

Figure (14): shows the presence of cracks

Figure (15): shows the plant Cenchrus setaceus

In figure (14) shows the presence of cracks, gaps, and disintegration of the Qadad material in the barrel vault ceiling due to conflict, exacerbated by climate change factors. In figure (15) shows the plant Cenchrus setaceus, a fast-growing grass that tolerates drought and heat, and its danger to the tower is high because it penetrates stone gaps and widens them. With climate change, rising temperatures, and drought, its spread increases and accelerates wall deterioration.

**Table(3): Approximate Damage Rates on the on the Barrel Vaults of the Northern Tower:**

| Type of Damage | Rea of Damage | Damage Ratio | Reason |
|---|---|---|---|
| **Chemical** | **Gable Sides** | **20%** | Climatic factors (growth of some plants) |
| **Chemical** | **North Facade** | **19%** | Climatic factors (erosion and disintegration of the roofs due to moisture resulting from rainwater seepage into the roof materials) |
| **Mechanical** | **North Facade** | **400%** | Conflict factors (gaps above the gable and fragmentation of the binding mortar layer due to direct projectiles and gunfire) |

**Table No. (4) Shows the General Analysis of the Types of Stones Used in the Construction of the Northeastern Tower in the Fortress**

| Picture | Stone Name | Type of Stone | Properties |
|---|---|---|---|
|  | Granite | Igneous rock | It is characterized by its high hardness, durability, and resistance to erosion and weather factors. It absorbs less water, making it resistant to moisture and able to withstand thermal and humidity changes. |
|  | Limestone | Sedimentary rock | It is lighter than granite and relatively resistant to erosion.It reflects heat, helping to maintain internal coolness |

## 3.2. Internal Damage Documentation

### 3.2.1 Damage Analysis

The internal walls of the tower exhibit a clear pattern of structural deterioration, manifested in the disintegration of the plaster layer and its separation from the stone surface, mortar degradation, deep cracks and gaps resulting from vibrations and shocks, in addition to the erosion and weakening of the wooden lintels supporting the openings. The main causative factors: moisture penetration and salt crystallization processes, neglect and lack of periodic maintenance, and exposure to explosions and vibrations from conflict.

### 3.2.2 Detailed Damage Analysis

**A - Disintegration of the Plaster Layer:** Extensive and intense separation of the plaster layer from the stone surface, with large sections falling off and exposing the stone surface, as shown in Figure (16).

- Moisture penetration into the wall through cracks and voids, loss of insulation.
- Transport of dissolved salts within the water solution through the pores of the mortar and plaster.

Upon water evaporation, salts crystallize inside the plaster pores and expand (salt crystallization), generating high internal pressures exceeding the adhesion strength between the plaster and stone surface. Peeling and separation of the plaster layer, mortar erosion, and exposure of the base stone surface.


Figure (16): shows the separation of the mortar layer from the stone surface.

**B. Deterioration of Construction Materials Due to Neglect and Lack of Maintenance**: Gradual erosion of building materials (mortar, clay, un-dressed stones) resulting from repeated exposure to heavy rains and humidity-laden winds, diurnal and nocturnal temperature fluctuations leading to expansion and contraction, absence of periodic maintenance and temporary repairs leading to cumulative damage.

**C. Cracks and Gaps Resulting from Conflict (Vibrations and Shells)**: The walls show cracks of multiple types, ranging from small transverse cracks to deep gaps penetrating the wall thickness, as shown in Figure (17). These gaps increase the wall's permeability and facilitate water and air penetration, easing salt transport and multiplying chemical and mechanical deterioration processes. The degree of damage ranges from transverse cracks to structural deteriorations requiring reinforcement interventions, support, and localized restoration at deep gaps.


Figure (17): shows the cracks and gaps in the internal walls.

**D. Damage to Wooden Lintels Above Openings (Doors and Windows)**: As a result of moisture penetration, wood deteriorates biologically (rotting) and due to insect activity, reducing the lintel's capacity to bear vertical loads of the stone blocks above it, leading to subsidence and secondary cracks in the walls above the lintel. These damages on the wooden lintels manifest as rotting and erosion due to the spread of termites (white ants), as shown in Figure (18). This requires assessing each lintel's condition: localized repair, partial reinforcement, or complete replacement if load-bearing capacity is lost.

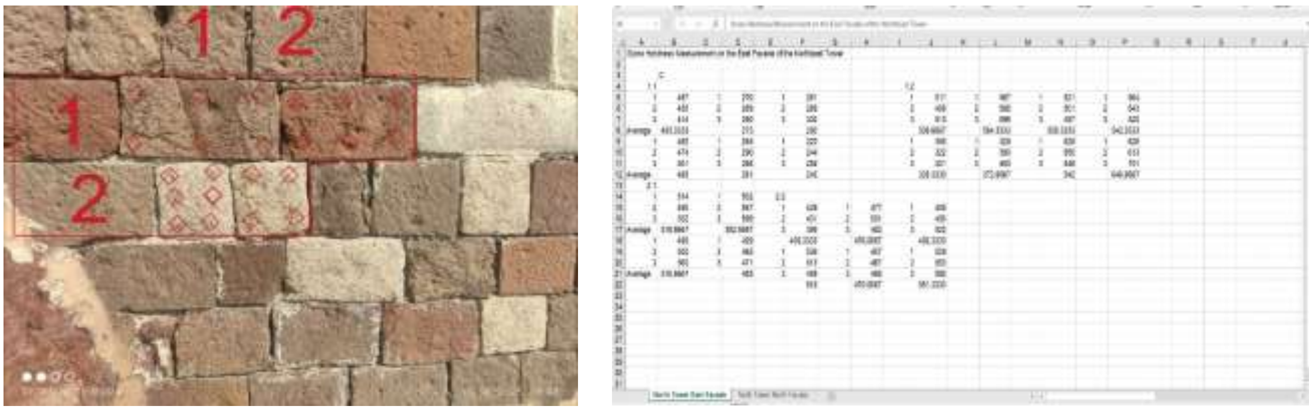

Figure (18): shows the Damage to Wooden Lintels Above Openings (Doors and Windows).

**Table No. (5) shows approximate percentages of damage in the internal walls of the northeastern tower.**

| No. | Type of Damage | Area of Damage | Cause | Percentage of Damage | Location of Damage |
|---|---|---|---|---|---|
| 1 | Chemical | 50 | Climatic factors | 20% | Inside the northeastern tower |
| 2 | Mechanical | 20.9 | Conflict factors | 13% | Inside the northeastern tower |

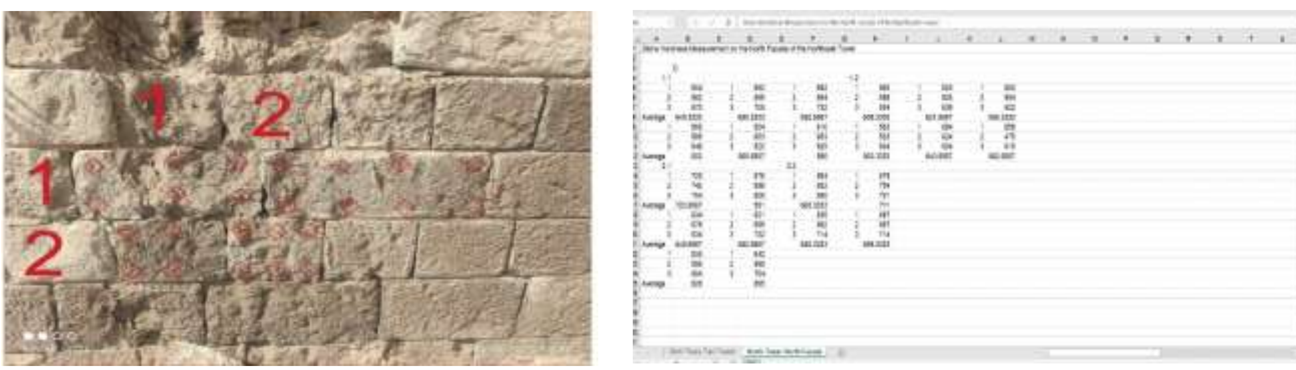
## 4. Stone Hardness Measurement: Proceq Bambino

The rebound hammer device for rock surface hardness (Proceq Bambino) was used to assess variations in stone surface hardness within the study area. The measured values were recorded and documented in the attached Excel file after conducting field measurements. Two representative areas reflecting the stone condition were selected and marked with symbols C (Figure ,19) and D (Figure ,20) on the northern and eastern facades of the tower.




(A) (B)

Figure (19): Symbol **C** on the eastern facade of the northern tower: (A) the locations of stone hardness measurements; (B) shows the Excel file.




(A) (B)

Figure (20): Symbol **D** on the northern facade of the northern tower: (A) the locations of stone hardness measurements; (B) shows the Excel file.

### 4.1 Comparison of northern and eastern façade

There is no contextual evidence to suggest that there is a notable difference in the blockwork utilised to reconstruct the tower. A direct comparison (figure 21 and table 6) suggests that the blockwork on the eastern façade is on average much harder (Leeb average is 503.8 n=270 over 16 blocks) than the northern façade (Leeb average is 420.05 n=240 over 12 blocks). Both sets of data show similar variability in the data although the eastern façade indicates a much larger spread of values indicating variable hardness between individual blocks.

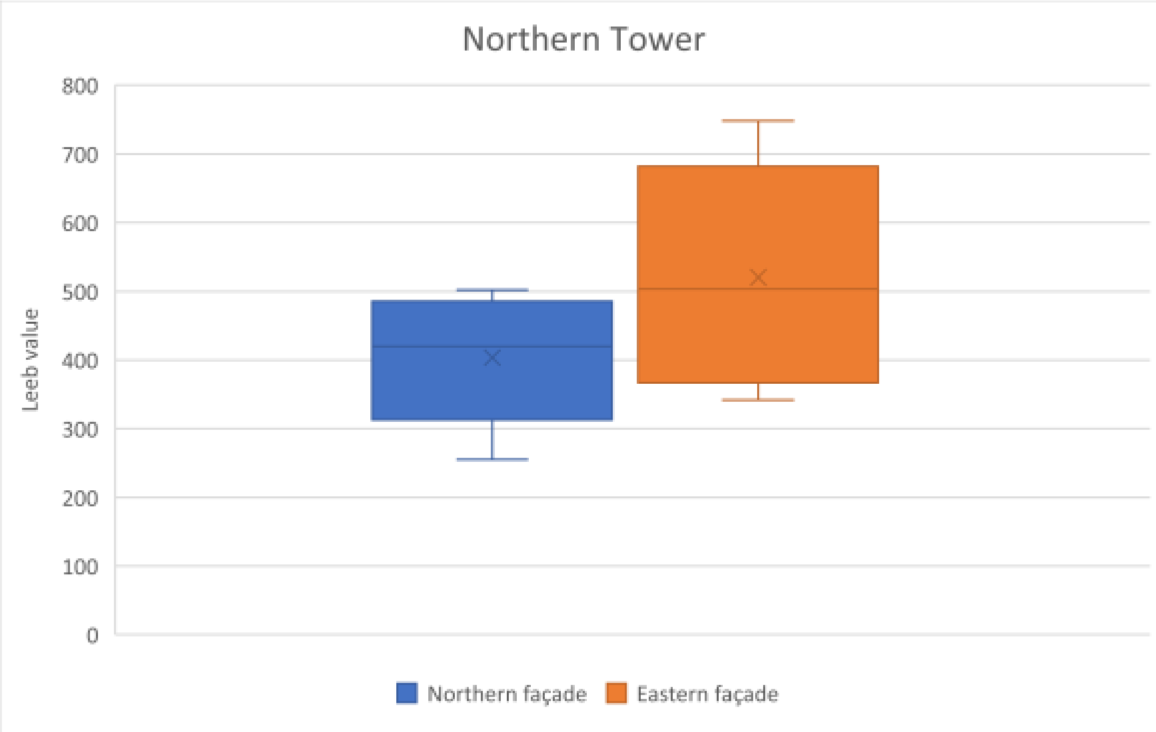


Figure (21): Comparison of northern and eastern façade mean, quartiles and maximum spread of the measurements

*Table 6: Calculated values for the northern and eastern façade*

| | Northern façade | Eastern façade |
|---|---|---|
| Min | 254.6667 | 341.6667 |
| StDev -1 | 371.0784 | 391.8743 |
| Mean | 420.0458 | 503.7778 |
| StDev+1 | 469.0132 | 615.6813 |
| Max | 502.3333 | 748.3333 |

When assessing these facades at block level, the higher average eastern façade does indeed appear to come from individual blocks, notably 1.3, 2.1, 2.2, 2.4, 3.3 and 4.4 (figure 2). These correspond directly with the very white type of stone used in the repair work. These are likely to deteriorate at a lower rate than the surrounding stones, but may also influence the movement of moisture through the wall.

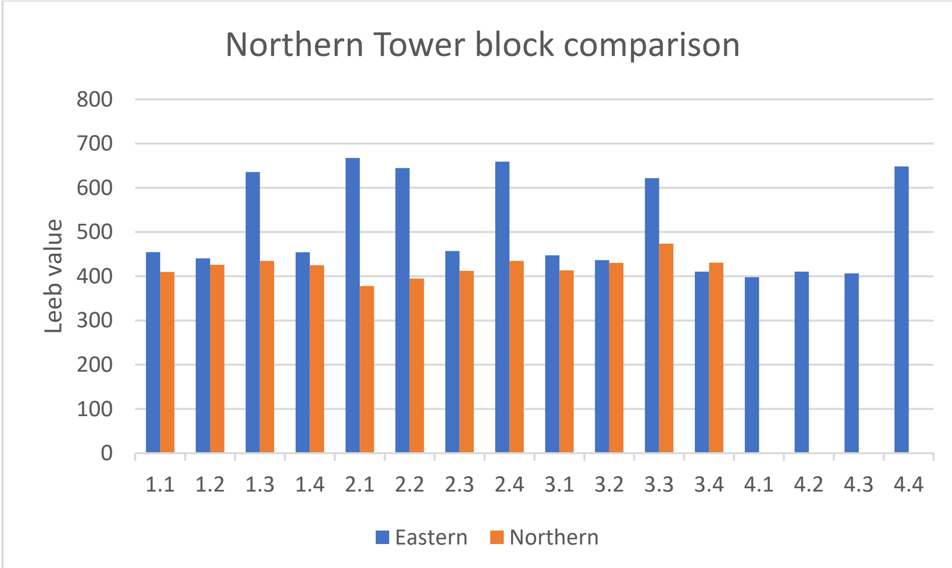
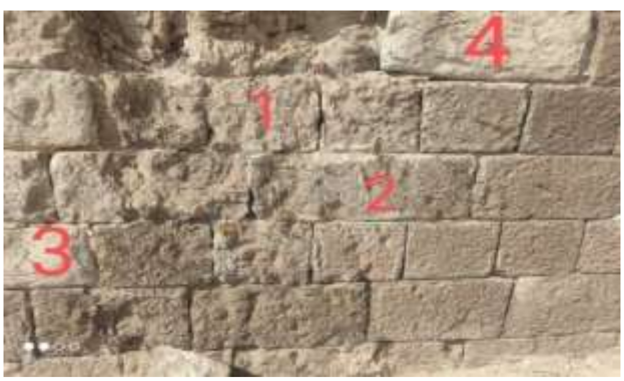



Figure (22): Individual block assessment for the northern tower, indicating selectively higher values for the lighter coloured stonework

## 5. Moisture Measurement: Protimeter

During the field inspection of the northeastern tower in Al-Qahira Citadel, moisture testing was conducted on the tower's facades. Under Engineer Bilal's supervision during training, the Protimeter moisture meter was used to determine moisture penetration levels in buildings. Training covered device operation: inserting electrodes into the material, with readings displayed on screen accompanied by color indicators (green = dry; yellow = at risk; red = wet). Readings below 10 indicate dry surface; 10-20 at risk of moisture; above 20 high moistures.




| No. | Type of Stone | Moisture Level |
|---|---|---|
| 1 | Limestone | 49 |
| 2 | Limestone | 30.4 |
| 3 | Granite | 24.1 |
| 4 | Granite | 18.9 |

Figure (23): the Protimeter moisture meter of the northern facade


| No. | Type of Stone | Moisture Level |
|---|---|---|
| 1 | Limestone | 21.2 |
| 2 | Granite | 24.6 |
| 3 | Limestone | 19.8 |
| 4 | Granite | 12.4 |
| 5 | Limestone | 24.3 |
| 6 | Granite | 21.3 |

Figure (24): the Protimeter moisture meter of the western facade

The examination revealed that granite stones are not significantly affected by moisture, while limestone stones are more susceptible to its effect, especially in the lower parts near the foundations. It was observed that stones adjacent to the foundations are more humid than the rest of the stones. The results also showed that the northern and western façades are the most exposed to moisture compared to the rest of the façades, and this is likely due to their direct exposure to atmospheric factors.

## conclusion

The study concludes that the northeastern tower of Al-Qahira Citadel faces a state of "composite structural deterioration" resulting from the interplay of mechanical factors stemming from conflict with chemical and physical factors linked to the surrounding environment. Photogrammetric analysis and 3D modeling have proven that deep gaps and cracks from direct shelling on the northern and eastern facades have disrupted the mass balance of the walls, increasing water permeability rates and accelerating erosion of stone units and binding mortar.

Physical tests revealed sharp variations in structural material responses; limestone stones and traditional mortar showed significant weakness against salt crystallization compared to hard granite stones. This binder degradation, driven by high moisture levels exceeding 20% in affected areas, led to loss of cohesion between internal and external wall layers (rendering and backing), explaining plaster layer spalling, deep vertical cracks in joints and ceilings, and wooden lintel deterioration due to biological and insect activity.

The study indicates that climate changes, manifested in sharp temperature fluctuations and intensified seasonal rains, will accelerate structural collapses without immediate intervention. Continued water infiltration through untreated gaps will amplify hydraulic pressures inside walls and exacerbate organic component erosion, placing the tower at risk of partial or total collapse, necessitating urgent preventive maintenance strategy.

In conclusion, preserving this historic landmark requires an integrated methodology starting with immediate structural intervention to address gaps, followed by a comprehensive restoration plan based on international conservation standards and material compatibility. The study recommends tackling root causes of moisture and salts, along with ongoing monitoring system, to ensure tower stability and preserve its historical authenticity as cultural heritage for future generations.

**Recommendation**

Based on field assessment, structural, and material analysis results, this study concludes the need for integrated interventions executed per clear priorities to limit deterioration manifestations and preserve the structure's historical and architectural values. Results emphasize starting with urgent interventions on northern and eastern facades and cornices, treating gaps and cracks immediately after thorough cleaning, filling with restoration mortar compatible in physical and mechanical properties with original materials, ensuring structural safety and curbing accelerated deterioration. The study recommends compatible restoration materials, especially mortar, in all intervention stages to avoid long-term material incompatibility issues exacerbating damage. Reinforcing weak walls across structure parts is essential for stability, using methods respecting heritage values and adhering to minimal reversible intervention principle.

Results indicate moisture and salts as key deterioration factors for building materials, necessitating source identification—especially in foundations and roofs—for radical treatment. Remove accumulated salts from damaged walls before re-plastering, improve water drainage, and apply suitable insulation to damp walls to limit infiltration and sustain treatments.For wooden elements, conduct comprehensive lintel assessment, replacing severely damaged ones and reinforcing partially affected with compatible materials and techniques matching original properties, preserving structural safety and historical value. Finally, adopt ongoing periodic monitoring program for the entire structure to track structural and material evolution, evaluate interventions, and ensure long-term restoration sustainability.

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**Project 3.**

# Impact Of Climate Change On The Stability Of The Western Tower: Al-Qahira Citadel


## Abstract

The study aims to assess the condition of the stones in the Western Tower and identify the natural and human factors affecting its stability, through adopting an integrated research methodology that combines field evaluation and digital analysis. Organized field visits were conducted, including documentation of deterioration manifestations using a questionnaire prepared to analyze the current condition. A high-precision three-dimensional model of the tower was created using Agisoft Metashape software based on aerial images captured by drones, while AutoCAD software was used to prepare detailed executive drawings, identify crack locations, deterioration patterns, and stone types.

To enhance the material analysis, surface moisture measurements were conducted using a Protimeter device, alongside surface hardness tests using a Proceq Bambino device on the tower's various facades, to evaluate the impact of climatic factors on the physical and mechanical properties of the stone materials. The results of this study contribute to understanding the deterioration mechanisms to which the tower is exposed, and providing a scientific basis to support intervention and conservation decisions for this heritage landmark amid complex environmental and conflict conditions.


## 1. Introduction

Al-Qahira Citadel is one of the most prominent historical landmarks in the city of Taiz, representing exceptional architectural and cultural value, as it embodies a defensive architectural model reflecting the multiple temporal layers that the city has undergone, resulting from modifications and additions during the Ayyubid, Rasulid, and Ottoman eras, along with the diversity in stone materials, types of mortar, and architectural compositions. These characteristics have led to variations in the structural behavior of the citadel's elements over time, particularly in parts exposed to direct environmental factors(1).

The Western Tower is one of the defensive elements in Al-Qahira Citadel, as it was historically used as an observation and defense tower due to its strategic location overlooking the western side of the citadel; the tower consists of two floors, with the ground floor designated as a room and storage, while the upper floor consists of a single room, and its walls are distinguished by great thickness reflecting the defensive character of the tower. With the change in the defensive function of the citadel in the present time, the Western Tower is currently used for cultural purposes where heritage exhibitions are held. However, the tower has been exposed during the recent decades to accelerated deterioration resulting from two main intertwined factors: armed conflict and climate change. Based on reports and studies issued by the Antiquities Office in Taiz city, it is evident that about 70% of the current deterioration volume in the Western Tower is due to direct conflict effects, including shelling and explosions that led to the disintegration of parts of the facades, collapse of some corners, and the appearance of deep structural cracks that directly affected the safety of the structure. In contrast, studies indicate that approximately 30% of the deterioration manifestations result from climatic factors, which contributed to accelerating the pace of structural and environmental deterioration.

Research related to historic buildings constructed on rocky slopes shows that these sites are among the most fragile structural systems, directly affected by sudden rains that lead to softening of soil layers, occurrence of micro rock slides, weakening of foundations, in addition to acceleration of erosion processes and loss of stone masses resulting from thermal changes and wind directions(2). These effects intensify in mountainous environments, such as Taiz city, which experiences noticeable thermal fluctuations between night and day, alongside irregular rainfall patterns, highlighting the importance of architectural conservation as a fundamental tool to extend the life of heritage buildings and protect them from deterioration caused by natural and human factors while ensuring the stability of their historical, cultural value, and societal role(3).

On the level of Taiz city, climate fluctuations have led to soil erosion and recurrent rockfalls, posing a direct threat to historic landmarks built in elevated locations, foremost among them Al-Qahira Citadel. Disruptions in rainfall patterns, rising humidity levels, and changes in groundwater levels have contributed to increased water absorption by stones, salt crystallization within their pores, leading to surface crumbling, delamination in stone layers, and loss of cultural value(4).

The effects of these climatic factors are clearly manifested in the Western Tower, where saturation of rocks with water during rainy seasons, followed by repeated drying, leads to successive expansion and contraction in the stone materials, accelerating the formation of cracks and disintegration of structural masses, especially at junctions of non-homogeneous materials. The absence of preventive maintenance and periodic restoration has exacerbated these effects, making the tower more vulnerable to risks of structural instability and loss of its architectural and historical value(5).

From this, this study aims to assess the current condition of the Western Tower of Al-Qahira Citadel through an integrated approach combining three-dimensional digital documentation, field inspection, structural analysis, and physical tests on stones, to identify sources of structural weakness resulting from the interplay of conflict effects and climate changes, and propose practical solutions that contribute to preserving the tower and enhancing its structural stability in the future.

In 2023, the authority took a temporary preventive measure to reinforce the Western Tower due to the appearance of clear structural weakness indicators and fear of its collapse and potential impact on visitors and residents living below the citadel. These temporary treatments consisted of implementing external reinforcement works using metal supports to stabilize and secure the damaged masses, as an emergency solution aimed at directly mitigating risks until the necessary support for restoration works becomes available.

## 2. Methodology

This study relies on a multi-method research design to examine the causes of climate change and conflict on Al-Qahira Citadel, where the Western Tower was selected as a case study due to the evident damage it has sustained in recent years.

The Western Tower has undergone deterioration due to the absence of maintenance works since the outbreak of the armed conflict, in addition to ongoing climatic impacts from 2015 to the present. From this, the study is based on field analysis of the tower's structural condition, supported by visual and measurement documentation, alongside the use of the questionnaire prepared by Dr. Lisa as a systematic assessment tool, to support the evaluation process and understand the dimensions of the problem from various aspects.

In the documentation and analytical aspect, Agisoft Metashape software was used to create a three-dimensional model of the Western Tower based on image processing, while AutoCAD software was used to prepare detailed two-dimensional drawings, facilitating the monitoring of structural problems and precise identification of crack locations and deterioration.

In addition, physical tests were conducted on the facade stones, including measuring stone hardness using the Proceq Bambino device, as well as moisture measurement tests, to assess the impact of environmental factors on the Western Tower.

## 3.Analysis and Results

This chapter presents and analyzes the results derived from field work, documentation, and physical tests conducted on the Western Tower, aiming to study the condition of the tower's stones and understand the nature of influencing factors.

Figure (1): an aerial photo of the general site of Al-Qahira Citadel, showing the study area of the Western tower circled in red.

### 3.1 Field Visit and Visual Inspection

The first phase involved conducting a field visit to the Western Tower to perform a comprehensive visual survey of its structural condition; the tower was documented from inside and outside, and the three facades (western, northern, and southern) were inspected and documented. The inspection revealed that the wall thickness is approximately 0.90 m, reflecting the defensive character of the tower. Field measurements showed that the western facade height is about 12 m with a width of approximately 8.20 m, while the northern facade height is about 10.30

m with a width of 4.25 m, and the southern facade height is about 10.70 m with a width of approximately 5.80 m. The inspection focused on monitoring visible structural deterioration manifestations. Results of the visual inspection showed variation in the degree of deterioration among the three facades, with the southern and western facades being the most damaged due to partial destruction of their upper parts, represented by loss of stone parts alongside clear cracks as shown in Figure (2,3); in contrast, the northern facade is less damaged, where collapse of the crenellated crown at the top of the southern facade was noted, along with cracks in the facade as shown in Figure (3).

Figure 2: Shows the western facade (2025)

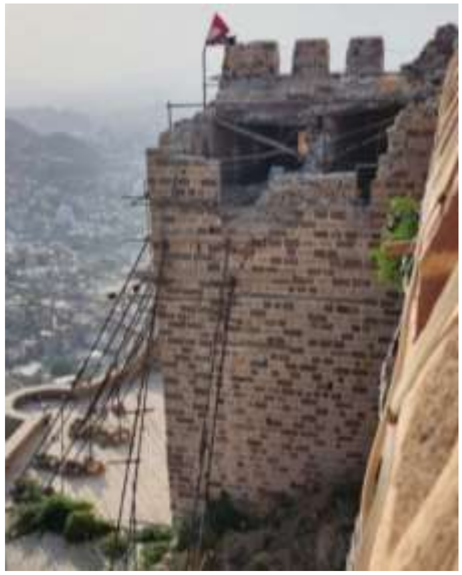

Figure 3: Shows the southern facade (2025)

Figure 4: Shows the northern facade (2025)

## 3.2 Questionnaire Results

The use of a questionnaire sent by Dr. Lisa to assess stone stability relies on a gradual scale from (0–5) to measure the degree of deterioration indicators appearing in the tower. This assessment included specific evaluation criteria for the condition of the stones, such as surface hardness, cracks, stratification, scaling, previous damage, and scratchability. Each property was studied according to a gradual scale (from 0 to 5), where level 0 represents no damage and level 5 represents the maximum stages of deterioration, such as scratching with a fingernail, a coin, or a sharp tool to estimate the level of physical cohesion.

The results of the field analysis questionnaire for the structural condition of the Western Tower showed an absence of surface hardening manifestations in the stone materials, as shown in Figure 5, where this indicator recorded a value of (0), indicating direct exposure of the structural and natural elements to environmental factors without the presence of surface protection layers.

Figure 5 also shows a close-up image illustrating that the results indicate the presence of stone cracks, as the Western Tower recorded a medium level of cracking with a value of (3), which is likely related to structural loads and the effect of accumulated moisture in the stone masses. The questionnaire results showed an absence of stratification levels in the stone used in the tower (0), indicating no clear separation along geological bedding planes. In contrast, no manifestations of scaling were observed in the tower stone (0).

Figure 5: The images show the tower facades in high resolution, illustrating the condition of the stones, 2025.

No evidence of previous damage resulting from fire, graffiti, or human interventions at the site was observed. Regarding material resistance, it was found during the field visit that the stone cannot be scratched by a fingernail or a coin, whereas it can be scratched using a sharp tool such as a knife; this indicates a medium degree of stone cohesion, with susceptibility to environmental and mechanical factors over the long term.

### 3.3 2D and 3D Modeling: Documentation, Structural, and Technical Analysis

A three-dimensional model of the tower was created using photogrammetry techniques through processing a set of aerial images captured by a drone. The model was generated based on 120 digital images, as shown in Figure (6); were used to generate an accurate three-dimensional model using Agisoft Metashape software.

Figure 6: The images, taken by drone, 2025.

The workflow was implemented in four stages: image alignment, dense point cloud generation, mesh construction, and texturing. These stages resulted in forming a clear three-dimensional model as shown in Figure (7), contributing to facilitating the structural and technical analysis process and assessing the structural condition with high accuracy. This enabled precise documentation of the tower's current condition, analysis of damages and structural defects, monitoring of stone material deterioration manifestations, identification of stone erosion locations, and support for the technical assessment of risk levels and structural stability.

Figure 7 : shows the three-dimensional model of the western tower using Agisoft Metashape software.

Through the outputs of the three-dimensional model, clear drone images were imported into AutoCAD software to prepare precise executive drawings for each facade, as shown in Figures (8-9-10), illustrating details of the tower, crack locations, erosion, and delaminations, to serve as a primary reference for restoration works and documentation of the current condition of the tower's structural stability and stone condition.

Based on the outputs of the three-dimensional documentation and facade drawings, structural and technical analysis of the tower was conducted, revealing clear heterogeneity in the construction materials used, attributed to the multiple historical construction phases and successive interventions over time. This multiplicity was reflected in the use of stones differing in their physical properties, in terms of hardness and absorption rate. Vertical and horizontal cracks, mortar erosion, weakening of the binding material, and partial deterioration of the tower's upper part due to conflict were also observed, as shown in Figures (8-9-10).

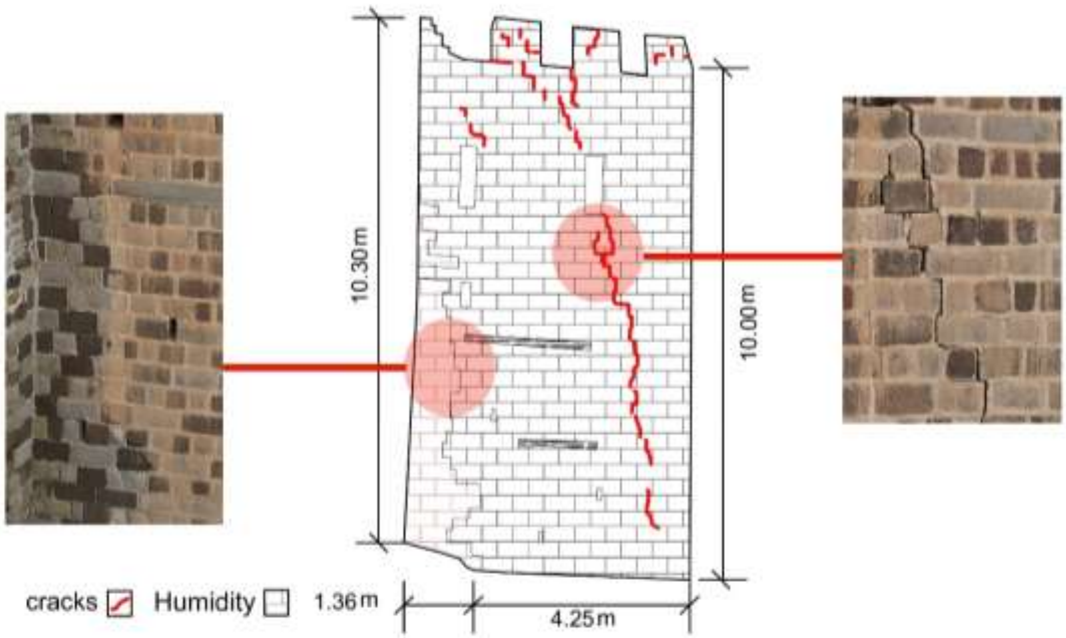


Figure 8: Shows the northern facade of the western tower

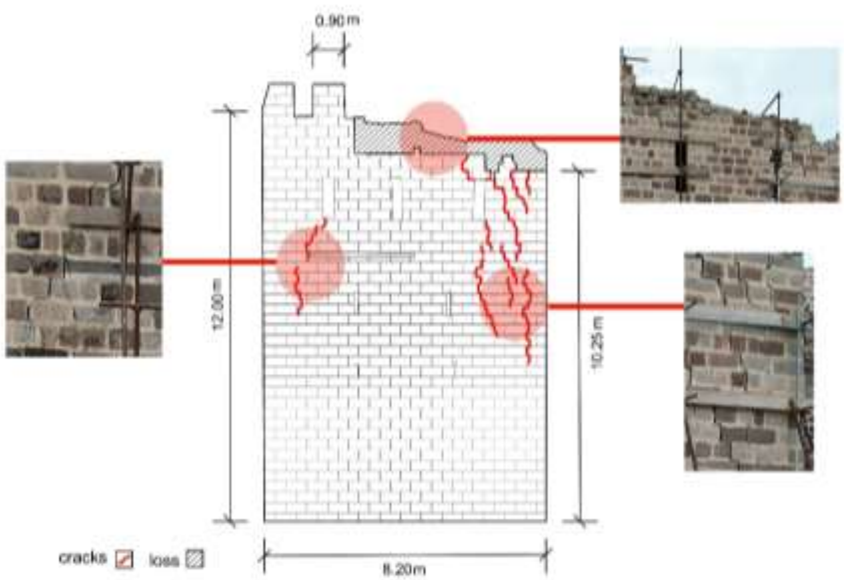


Figure 9: Shows the western facade of the West Tower

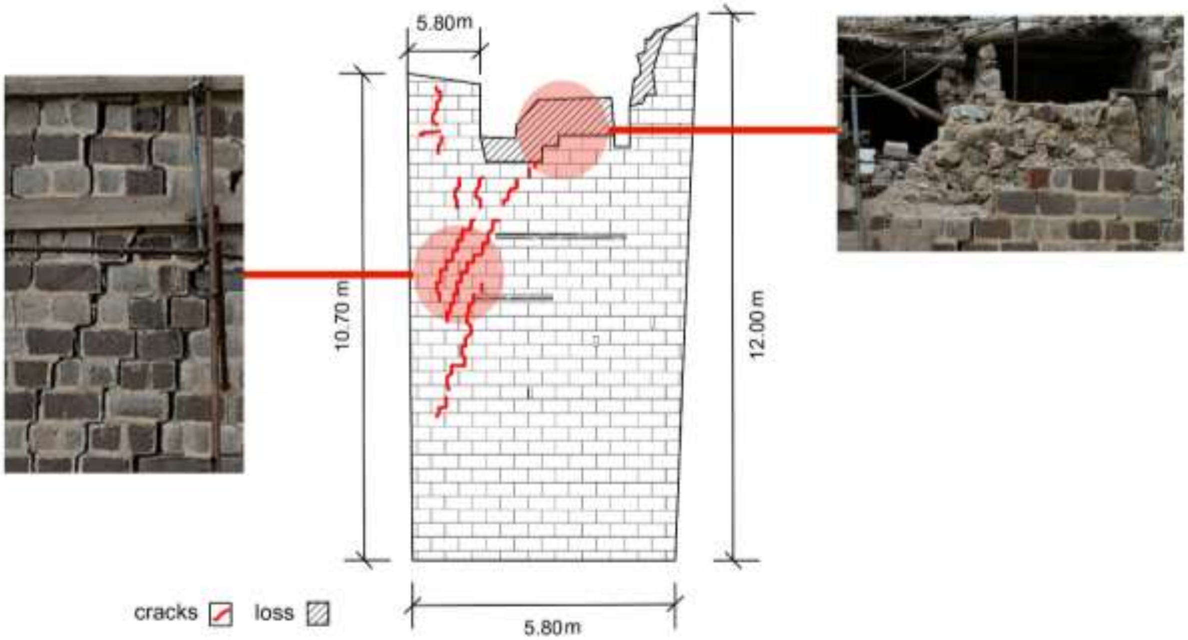


Figure 10: Shows the southern facade of the tower

### 3.4 Physical Properties of the Western Tower Stones

This phase included examining the physical properties of the stones constituting the Western Tower, with two types of field tests conducted. Measurement sites were selected on the three facades (northern, western, southern) in specific areas near the tower base, based on preliminary field observations showing stone surface erosion in these areas. A specialized structural engineer from the Antiquities Office confirmed that proximity of stones to the foundations makes them more susceptible to moisture accumulation due to rainwater infiltration, as shown in Figure (14), as well as the presence of harmful vegetation affecting structural stability, as shown in Figures (15-16).

Continuing this analysis, a study was conducted on the types of stones used in the facades, where the tower facades were drawn with identification of each stone type. The tower consists of limestone and granite stones, as shown in Figure (11), revealing that the granite stone used in the western tower facades constitutes a larger proportion compared to limestone.

Figure 11: Shows the types of stones used in the facades of the western tower

### 3.4.1 Impact of Climate Change and Conflict Damage on External and Internal Western Tower

Absence of ventilation in the tower was also observed, where reliance was limited to the presence of loopholes; although these loopholes served a military function in the past, they do not provide adequate ventilation, negatively impacting the tower's internal environment. Lack of good ventilation contributed to internal moisture accumulation, leading to delamination of plaster layers from the wall as shown in Figure (12), disintegration of ceiling plaster, and wood rot due to moisture from rainwater leakage into the building, causing its erosion as shown in Figure (13).


Figure 12: Shows the damage to the internal walls of the tower,2025


Figure 13: Shows the damage to the internal ceiling of the tower,2025

The separation of the walls in the tower due to direct artillery strikes and vibrations caused by missiles represents a major primary damage estimated at about 60-70% of the total impact. These strikes weaken the structural elements and cause cracks and fissures that allow rainwater infiltration, which subsequently contributes to increasing the damage by 30-40% through material erosion, exacerbation of separation, and mold growth, especially in the absence of rapid restoration. This contribution is expected to increase if rainfall rates rise in the future, which may lead to the collapse of the tower. There are also varying degrees of erosion severity in the Western Tower building, and a gradual scale was created as shown in Table (1), used to assess the degree of erosion in the stones along with illustrating the type of erosion.

Table (1): The table shows the assessment of the type and degree of erosion in the stones

| image | Type erosion | degrees of erosion | Notes or reasons |
|---|---|---|---|
|  | Mechanical erosion (due to direct bombardment) | 8/10 | Stones are shattered and crumbled by direct bombardment |
|  | Chemical erosion (due to moisture and salts) | 7/10 | Surface disintegration and erosion of stones due to their continuous exposure to moisture and salts |

### 3.4.2 Moisture Test (Protimeter)

Surface moisture levels of the stones were measured using a Protimeter device on the three facades (northern, southern, western) to assess the extent of stone impact from moisture. The adopted values for interpreting measurement results are based on technical standards from the Taiz Antiquities Office, where device readings below (10) indicate dry surface, values between (10–20) indicate moisture exposure, and values exceeding (20) indicate high moisture. Additionally, the analysis showed absence of an effective drainage system, leading to moisture accumulation in the stones. Figure (14-15) shows locations of moisture paths in the upper parts of the facades.

Figure 14: The photo shows stones marked in red for moisture paths on the northern façade.

Figure 15: The photo shows stones marked in red for moisture paths on the western façade.

## The Northern Façade

The measurements on the northern facade showed high moisture values recorded at most inspection points, with the highest reading of (52) in limestone, followed by other high readings in limestone stones at (45 and 45.5), values indicating very high moisture according to the adopted standards. A reading of (35) was also recorded in one location of granite stone, indicating its exposure to high moisture as well. In contrast, readings of some granite stones ranged between (12.8 – 16.6), within the medium moisture range, while limestone recorded a reading of (13.4) indicating medium moisture. These results reflect the higher capacity of limestone stones to absorb moisture compared to granite stones. Additionally, the northern facade's limited exposure to sunlight limits natural drying processes, leading to moisture retention within the stone for long periods, which increases the likelihood of deterioration in the mechanical properties of the stones.

| Number | Stone type | Humidity level |
|---|---|---|
| 1 | limestone | 52 |
| 2 | Granite stone | 35 |
| 3 | limestone | 45 |
| 4 | limestone | 45.5 |
| 5 | Granite stone | 12.8 |
| 6 | Granite stone | 16.6 |
| 7 | limestone | 13.4 |

Figure 16: the Protimeter moisture meter of the northern facade

## The Western Façade

| Number | Stone type | Humidity level |
|---|---|---|
| 1 | Granite stone | 21.7 |
| 2 | limestone | 24.6 |
| 3 | Granite stone | 12.8 |
| 4 | limestone | 25.4 |

Figure 17: the Protimeter moisture meter of the western facade

Results of measurements on the western facade showed variation in moisture levels between stone types, where limestone recorded high readings of (24.6 and 25.4), values indicating high moisture. Meanwhile, granite stones showed varying readings ranging between (12.8 – 21.7), indicating medium to high moisture. This variation is attributed to the western facade's exposure to frequent climatic changes, leading to expansion and contraction of the stones.

## The Southern Façade


Figure 18: the Protimeter moisture meter of the western facade

| Number | Stone type | Humidity level |
|---|---|---|
| 1 | Granite stone | 12 |
| 2 | limestone | 27 |
| 3 | limestone | 31 |

Results of the moisture test on the southern facade showed a relatively low reading in granite stone at (12), indicating medium moisture. In contrast, limestone recorded high readings reaching (27 and 31), values indicating high

moisture within the stones.Although the southern facade is exposed to sunlight for longer periods compared to the northern facade, contributing to reducing surface moisture levels, the measurement results confirm the continued impact of moisture on limestone stones, particularly amid increased rainfall rates and atmospheric humidity associated with climate change.

3.1 Surface Hardness Test (Proceq Bambino)
Two points (A, B) were selected for rock hardness testing, with point A chosen from the western facade and point B from the western facade.

### 3.4.3 Surface Hardness Test (Proceq Bambino)

#### 3.4.3.1 West Tower Facades

Two points (A, B) were selected for rock hardness testing, with point A chosen from the western facade and point B from the western facade.

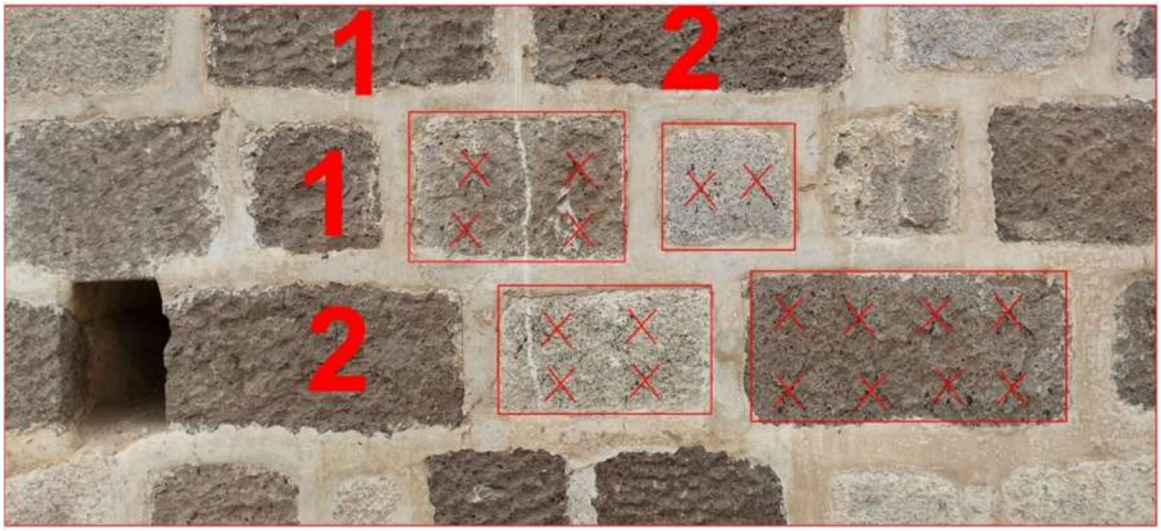


Figure 19: Shows the measurement of stone hardness in the Western Tower, western facade (A)

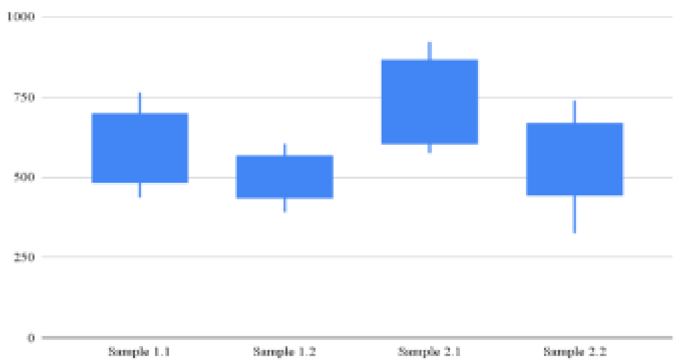


Figure 20: Shows the results of the test on the western facade A

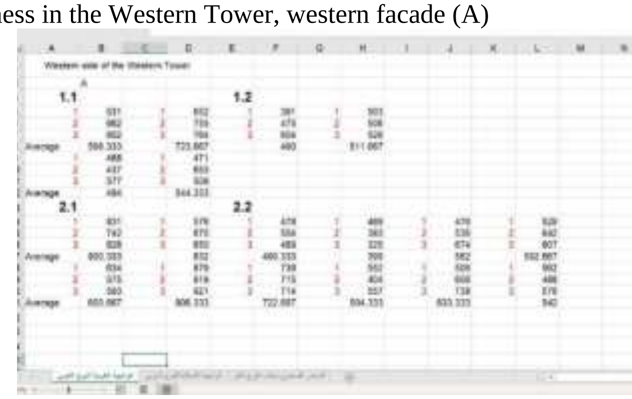


Figure 21: Shows the measurement values of the test on the western facade A

This section of the data was analyzed. Samples 1.1 and 2.2 are considered relatively good, with sample 2.2 showing higher variation toward lower values. This may indicate that stone properties in some locations have begun to deteriorate, meaning the stone structure is no longer fully cohesive as it once was, appearing in measurement results as a trend of some values decreasing. Sample 2.1 results show that it withstands weathering factors more than others, and its properties (such as cohesion/hardness or durability indicators used in the test) remain higher or less affected.

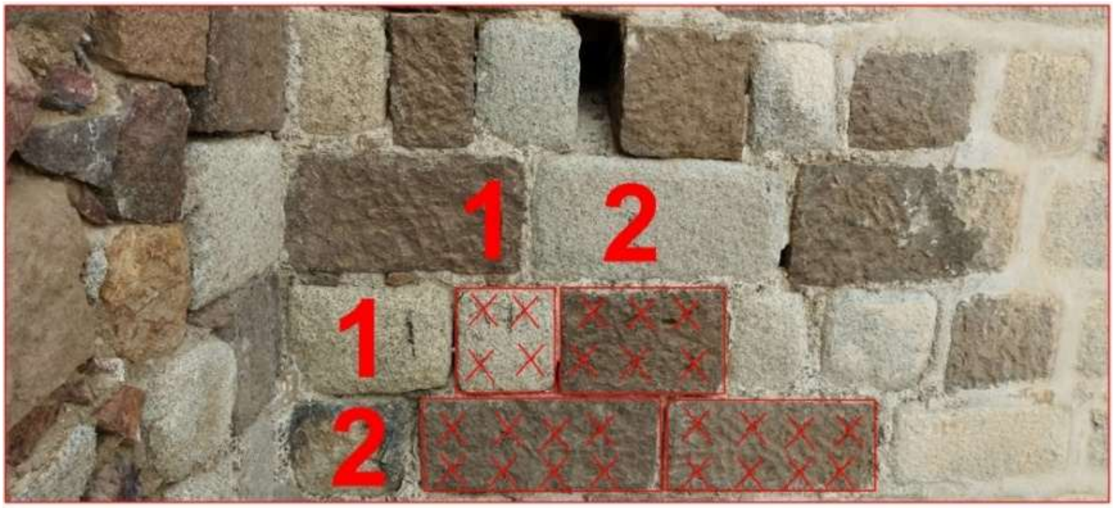


Figure 22: Shows the measurement of stone hardness in the Western Tower, northern facade (B)

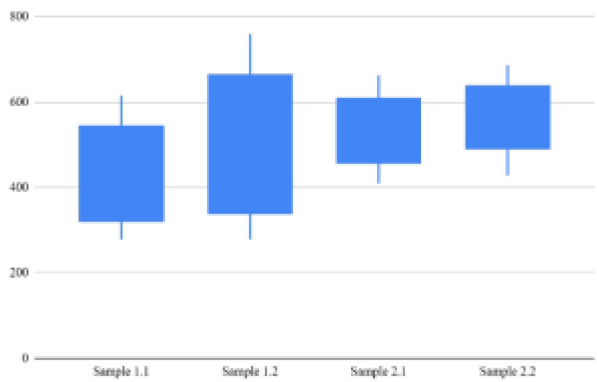


Figure 23: Shows the results of the test on the northern facade B

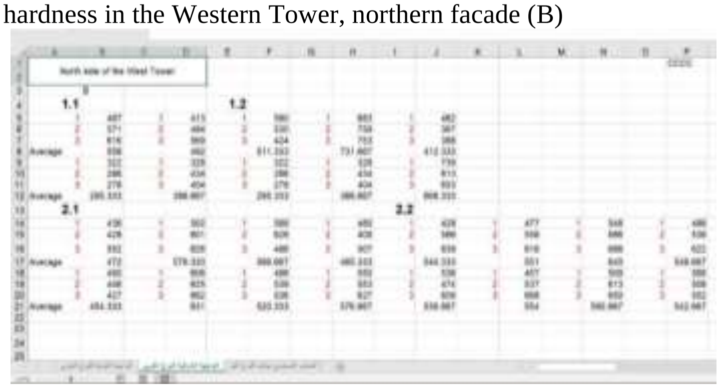

Figure 24: Shows the measurement values of the test on the northern facade B

The stones on the northern wall show a relative decrease in values by 15% (average LIP 595.4 on the western facade compared to 507.9 on the northern facade), indicating the likelihood of accelerated decay due to high moisture levels.

There is no statistically significant difference between the stones used on the northern and western façade of the West Tower (figure 25 and table 2). This is likely because the blocks that were selected for measurements were all new replacement blocks which have not been decayed over time and have not been affected by conflict damage. All blocks appear sounds with no discernible difference between blocks based on colour (figure 26).

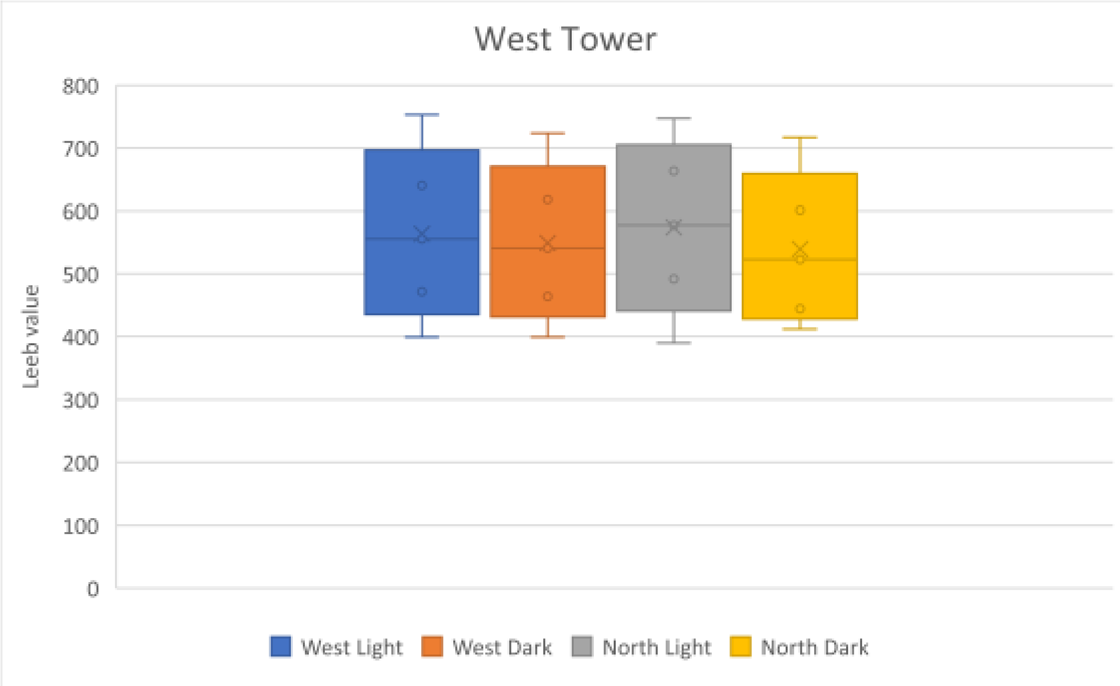


Figure 25: Comparison of light coloured stonework and dark coloured stonework, split out by façade

Table 2: Calculated values for the West Tower, split out by stone colour

| | West | West | North | North |
|---|---|---|---|---|
| | Light | Dark | Light | Dark |
| Min | 399 | 399 | 389.6667 | 411.6667 |
| StDev -1 | 471.4552 | 463.7594 | 491.9549 | 444.2971 |
| Mean | 555.8125 | 540.8274 | 577.609 | 522.78 |
| StDev+1 | 640.1698 | 617.8954 | 663.2631 | 601.2629 |
| Max | 753 | 723.6667 | 747.3333 | 717 |

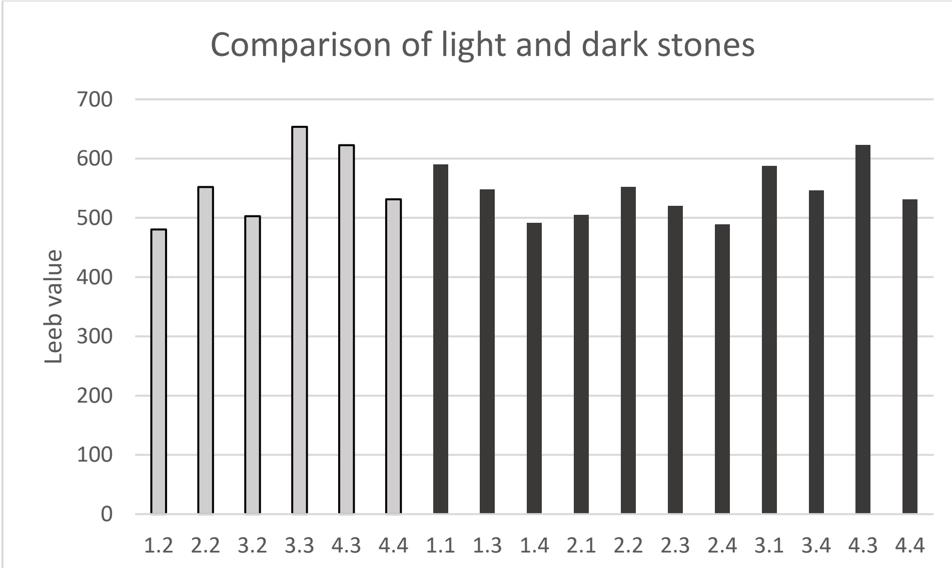

Figure 26: Plot of individual blocks, divided into light (light grey) and dark (dark grey) stones

### 3.4.3.2 Rock slope

The study of the rock slopes surrounding the western tower of the Cairo Citadel in Taiz represents an essential step toward understanding the behavior and deterioration patterns of the stones within their natural and structural context. While the research initially focused on measuring stone hardness, the field results later revealed that the condition of the rock slopes—particularly the differences between the northern and southern slopes—plays a significant role in explaining the observed rates of decay. The data show that although the mean hardness values on both slopes are comparable, the southern slope exhibits a higher rate of deterioration, reflected in greater measurement variability and a larger standard deviation. These findings suggest that environmental or structural factors, such as sunlight exposure and rainfall distribution, may influence the stability and durability of the rocks. Therefore, incorporating the study of rock slopes as an integral part of stone property analysis is crucial for a more comprehensive assessment of the citadel's current condition and its stone materials.

The data presented here show that while the mean measurement for both the northern (N=36) and southern slope (N=48) is comparable, the outcrop on the southern slope is decaying at a higher rate. This is indicated by the higher variability within the measurements as well as the larger standard deviation (figure 5 and table 3). Repeat measurements across more sites might provide more nuance.

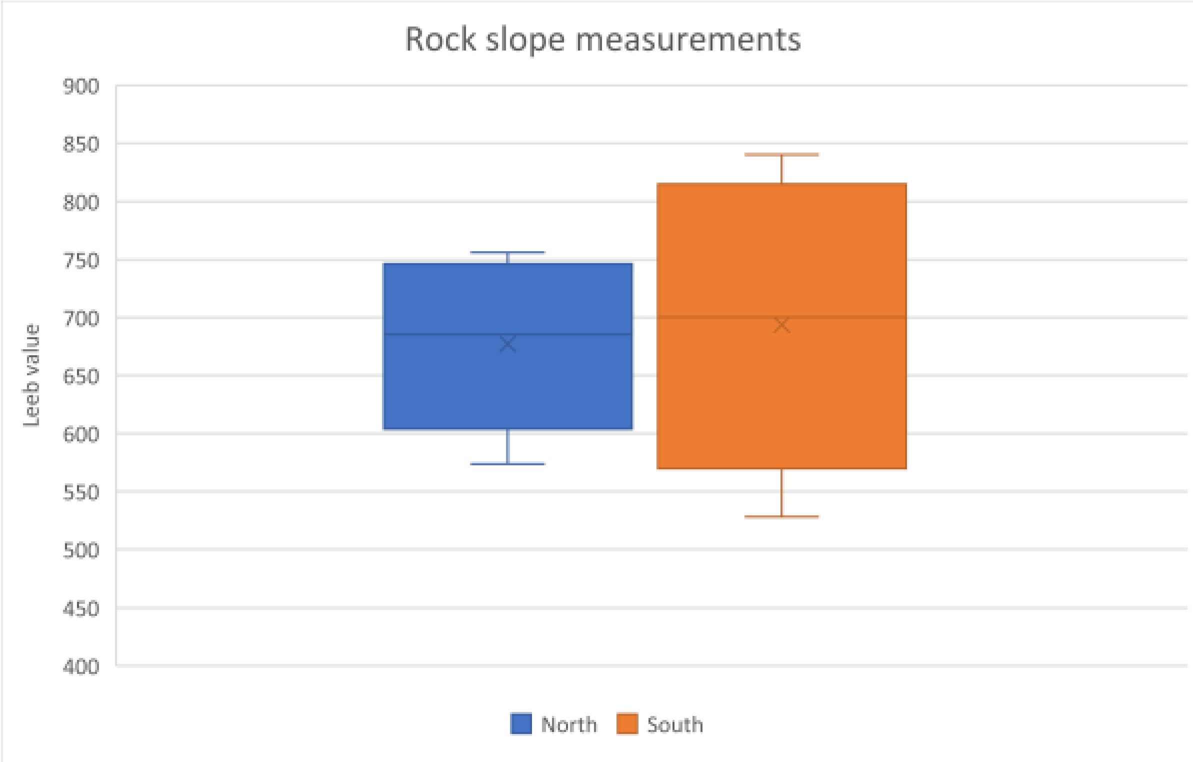

Figure 27: Comparison of measurements across outcrops on the northern and southern slopes

Table 3: Calculated values for the outcrops measured on the rock slopes

| | North | South |
|---|---|---|
| Min | 573.6667 | 528 |
| Max | 756 | 840 |
| Mean | 685.3889 | 700.3125 |
| | | |
| StDev -1 | 634.0482 | 611.4093 |
| StDev +1 | 736.7296 | 789.2157 |

## Conclusion

This study concluded that the Western Tower of Al-Qahira Citadel in Taiz city faces complex structural challenges resulting from the interaction of climate change impacts with armed conflict effects. Digital analysis and documentation using photogrammetry techniques and three-dimensional models demonstrated a close correlation between disruptions in rainfall patterns, elevated humidity levels, and accelerated physical deterioration of the tower's stones; documentation outputs (Figures 9, 10, 11) revealed critical deterioration manifested in stone material loss, binder mortar disintegration, deep structural cracks, and advanced mechanical and chemical erosion reaching a degree of 8/10 due to direct shelling and persistent moisture.

Field tests using Protimeter and Proceq Bambino devices revealed substantial variation in structural material responses; limestone stones on the northern facade recorded critically high danger levels exceeding 50, actually leading to a 15% reduction in surface hardness compared to other facades. This variation, stemming from material heterogeneity across different historical phases, indicates structural weak points making the tower more vulnerable to thermal fluctuations and cohesion loss, particularly amid inadequate ventilation and harmful vegetation growth at the base threatening foundation stability.

In addition to the structural and environmental factors identified in this study, in situ rock hardness measurements on the surrounding rock slopes provided further evidence of advanced mechanical deterioration affecting the tower's geological setting. The comparative analysis of rebound values between the northern and southern rock slopes showed that, although mean hardness values are broadly similar, the southern slope exhibits greater dispersion and a higher standard deviation, indicating more intense weathering and a faster rate of physical decay in this sector. The higher variability of hardness values on the southern slope reflects heterogeneous weathering fronts and localized zones of weakness that may evolve into larger-scale detachments if current climatic and drainage conditions persist.

Based on these findings, the study proved that the tower faces a critical future threat of accelerated mechanical erosion; continuation of current factors, such as poor water drainage, limited ventilation, increased moisture ingress, and progressive weakening of the adjacent rock slopes, may contribute to gradual loss of surface cohesion and binder material, potentially transforming existing cracks into major mass delaminations. Such developments would negatively impact the sustainability of structural elements and overall tower stability unless timely intervention occurs through integrated, sustainable restoration strategies that address both the masonry fabric and the stability of the supporting rock slopes.

## Recommendations

Based on field analysis results, physical tests, and three-dimensional documentation, the study recommends prioritizing moisture problem treatment as the most impactful factor on Western Tower stability, through improving rainwater drainage, preventing its accumulation on upper surfaces and around foundations, and removing vegetative cover near the tower base to limit soil moisture. Results also emphasize the importance of adopting restoration treatments compatible with the used stones' nature, particularly high-absorption limestone, via reinforcement with breathable materials and rehabilitating deteriorated mortar with traditional lime-based materials. The study recommends replacing temporary metal supports with permanent, studied structural solutions based on three-dimensional model outputs, alongside improving internal tower ventilation with non-invasive means to limit moisture accumulation and internal element damage. Additionally, adoption of a periodic monitoring program relying on moisture and surface hardness measurements at the same points is recommended to ensure tracking of structural condition development and evaluating treatment measure effectiveness amid ongoing climate changes.

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**Project 4.**

# Impact Of Climate Change On The Vegetation Cover And Its Reflection On The Architectural And Structural Integrity Of Al-Qahira Citadel – Taiz.


## Abstract

This research paper addresses the study of climate change impacts on the vegetation cover at Al-Qahira Citadel in Taiz Governorate, analyzing its reflections on the structural and architectural integrity of the citadel. The research relies on a descriptive-analytical methodology supported by field study, where types of vegetation cover and their distribution were monitored, and their relationship with various manifestations of deterioration in the citadel's elements was analyzed. The study concluded that climate changes contributed to an increase in the density and spread of vegetation cover, leading to the acceleration of structural decay processes. The research concludes with a set of technical and administrative recommendations aimed at mitigating these impacts and preserving the citadel as a prominent heritage landmark.


## 1. Introduction

The accelerating climate changes witnessed globally in recent decades, cultural heritage sites have become more vulnerable to increasing environmental risks that threaten their sustainability and historical value. Historical castles and forts are among the structures most affected by these changes, given the interaction of their architectural elements with the surrounding natural factors, including vegetation cover, which is directly influenced by climatic fluctuations.

Al-Qahira Citadel in Taiz Governorate is considered one of the most prominent historical landmarks in Yemen, owing to the architectural and historical value it holds, reflecting multiple stages of the city's development. Changes in climatic patterns, such as rising rates of seasonal rainfall, increasing periods of drought, and rising temperatures, have led to noticeable changes in the vegetation cover surrounding the citadel and within its perimeter, whether in terms of its density, quality, or botanical encroachment.

This change in vegetation cover contributes to direct and indirect impacts on the structural and architectural fabric of the citadel, as plant roots cause cracking in stones and traditional mortar. Furthermore, the humidity resulting from plant growth increases the rates of physical and chemical deterioration of building materials, in addition to its role in accelerating erosion processes and partial collapses in certain sensitive locations.

Based on this, this research paper seeks to study the impact of climate change on the vegetation cover at Al-Qahira Citadel in Taiz Governorate and analyze its reflections on the integrity of the citadel's architectural structure. It focuses on identifying the resulting risks and proposing scientific and practical mechanisms for the sustainable management of vegetation cover, contributing to the protection of this historical landmark and its preservation for future generations.

## 2. Literature Review

### 2.1 Climate Change and Its Impact on Heritage Sites

Climate change refers to long-term transformations in climatic elements, such as temperatures, rainfall rates, humidity levels, and frequency of drought periods. These changes have become one of the primary factors affecting heritage sites, due to their reliance on traditional building materials that are highly sensitive to climatic fluctuations.

Increased rainfall and humidity lead to water infiltration within walls, weakening the binding mortar and contributing to salt formation and stone deterioration. Continuous humidity also provides a suitable environment for the growth of plants and microorganisms. Conversely, prolonged drought periods cause shrinkage of building materials and structural cracking, with the alternation between drought and rainfall being one of the most dangerous factors that accelerate the rate of deterioration in historical buildings.

### 2.2 Vegetation Cover and Its Impact on Archaeological Buildings

Vegetation cover is one of the most prominent environmental factors affecting the integrity of archaeological buildings, including herbaceous plants, shrubs, and small trees that grow within cracks and architectural joints. The danger of these plants lies in their roots, which penetrate building elements, causing mechanical pressure that leads to stone disintegration and crack widening.

Plant growth also contributes to retaining moisture within walls, accelerating the physical and chemical deterioration of building materials. Accumulated plant debris creates a moist environment that encourages continued plant growth, making unmanaged vegetation cover a direct threat to the stability of archaeological buildings.

Numerous Arab and international studies have addressed the impact of climate change on heritage sites, with particular focus on the effect of rainfall and humidity on the deterioration of traditional building materials. Other studies have highlighted the negative role of vegetation cover in weakening the architectural structures of historical buildings, especially in mountainous and humid regions.

Reports and studies issued by international organizations concerned with heritage, such as UNESCO and ICOMOS, have indicated that climate change represents one of the main challenges facing the protection of heritage sites, emphasizing the necessity of integrating the climatic and environmental dimension into maintenance and restoration strategies. Nevertheless, applied studies linking climate change, vegetation cover, and their combined impact on heritage sites in Yemen remain limited, particularly regarding Al-Qahira Citadel in Taiz Governorate, which this study seeks to address.

### 2.3 Climate Change Impact on Vegetation at Al-Qahira Citadel: A Challenge to Natural and Historical Heritage

Climate change constitutes a direct pressure factor on vegetation cover in semi-arid mountain environments such as the environment of Al-Qahira Castle in Taiz, where climatic studies in Yemen indicate an increasing frequency of drought waves and fluctuations in rainfall amounts between periods of severe deficit and sudden intense downpours, accompanied by soil erosion and a decline in the ability of slopes to support stable vegetation cover. Environmental studies in the Yemeni highlands also show that changes in humidity patterns and temperature have historically led to shifts in the distribution of plant species, with particular sensitivity observed in species associated with ancient agricultural terraces and traditional systems for exploiting slopes.

In this context, rising temperatures and increasing drought severity contribute to weakening the growth of local perennial plant species, while allowing fast-growing herbaceous species to spread, which are often invasive and possess aggressive root systems that facilitate their penetration into cracks and construction joints within the stone fabric of historic architectural elements, thereby increasing the risk of disintegration and collapse in exposed archaeological parts. Sudden floods resulting from short, intense rainstorms also lead to uprooting surface vegetation and scouring the upper layers of the thin soils surrounding the castle, exposing the remaining roots, which accelerates the process of desertification and the loss of vegetation cover that had played a fundamental role in soil stabilization and in providing a degree of visual and environmental stability to the cultural landscape surrounding the site.

Specialized international reports indicate that heritage sites with natural value, particularly those inscribed or nominated within frameworks adopted by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and partner bodies such as the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM), have become threatened not only by the loss of their traditional building fabric, but also by changes in patterns of historical vegetation cover, which constitute part of a site's heritage value, whether as a visual backdrop to the archaeological setting or as a living record of long-term interactions between people and their local environment. In the case of Al-Qahira Castle, which was historically surrounded by green areas and cultivated terraces on the adjacent slopes, as mentioned in some recent studies and documentation projects on the castle, the increased frequency of droughts and floods in recent decades has led to a marked retreat of this vegetation cover, threatening the loss of one of the essential components of the site's historical and visual identity and turning climate change into a direct challenge to both natural and cultural heritage alike.

## 3. Methodology

This study is based on an integrated scientific methodology aimed at analyzing the impact of climate change on the vegetation cover at Al-Qahira Citadel in Taiz Governorate, and its reflections on the structural and architectural integrity of the citadel. Research methods and tools were selected to suit the nature of the study and its objectives, ensuring the attainment of accurate and reliable results.

The study relied on the descriptive-analytical methodology as the most appropriate for studying environmental and architectural phenomena in heritage sites. Through it, manifestations of prevailing climate changes at Al-Qahira Citadel were described, the state of vegetation cover and its distribution were monitored, and its relationship with various deterioration manifestations in the architectural and structural elements of the citadel was analyzed.

The field methodology was also employed through repeated field visits to the Al-Qahira Citadel site, which enabled the researcher to conduct direct on-site inspection of the current condition, identify areas of vegetation cover concentration, and record the resulting damage. This contributes to enhancing the applied aspect of the study and linking the theoretical framework to practical reality.

## 4. Analysis and Results

The study relied on a set of integrated data collection tools to achieve the research objectives, as follows:

### 4.1 Documentation of Invasive Vegetation Cover on the Structural Integrity of Architectural Elements

Through repeated field visits to the Al-Qahira Citadel site, which enabled the researcher to conduct direct condition surveys of the current site condition and identify areas of vegetation cover concentration. During these visits, nearly twenty different plant species spreading within the citadel and on its architectural and structural elements were observed and documented, including woody, shrubby, herbaceous, and climbing plants, with varying degrees of hazard ranging from low to high in terms of their impact on the structural integrity and aesthetic value of the site.

This documentation included recording the common and scientific names of the plants, describing their general characteristics, their adaptation to prevailing climatic conditions, as well as assessing the potential hazard level for each type, particularly regarding the roots' ability to penetrate stone cracks or extend near walls and foundations. Among the types documented in the field: Ashfala (Capparis cartilaginea), Bitum/Batm (Pistacia atlantica), Fig (Ficus carica), Wild Fig (Ficus cordata), Cactus/Prickly Pear (Opuntia ficus-indica), Shaikthium (Cenchrus setaceus), Hashf/Thorn Rose (Lantana viburnoides), Ghalf (Cissus rotundifolia), Sisal (Agave sisalana), Sant Al-Anbar (Vachellia farnesiana), Lavender (Lavandula dentata), Mallow (Malva parviflora), in addition to other herbaceous and creeping species with varying impacts.

This field effort contributed to forming a preliminary botanical database specific to the Al-Qahira Citadel site, supporting the scientific analysis of the study, enhancing the link between the theoretical framework and field reality, and serving as a primary reference for formulating recommendations related to vegetation cover management and mitigating its risks to historical buildings.

The problems of vegetation germination on the citadel’s architectural structure were also analyzed through studying the mechanisms of root penetration into joints and stone masonry, and its impact on mortar cohesion, stone stability, increased rates of disintegration and cracking, in addition to the role of vegetation cover in retaining moisture and accelerating physical deterioration processes of architectural elements, negatively affecting the site’s structural integrity. Herbaceous plants and small shrubs represent the most prevalent pattern, where their roots were observed penetrating cracks and joints, leading to their widening and disintegration of some stones, especially in areas suffering from weak binding mortar. The survey also revealed a clear correlation between elevated humidity levels resulting from rainwater infiltration and increased vegetation cover density, which contributed to accelerating manifestations of physical and chemical deterioration of building materials. Furthermore, the field survey revealed that soils accumulated in extensive parts of the citadel, resulting from the destruction of some buildings and blockage of water drainage channels, have formed a suitable environment for the spread of vegetation cover of various types. These soils, when mixed with moisture, act as an effective germination medium that enhances the continued growth and proliferation of plants, particularly in neglected or unmaintained areas.

This clarifies that the interaction of climatic factors with local environmental conditions within the citadel, especially humidity and soil accumulation, has directly contributed to exacerbating the vegetation cover problem and transforming it from a natural element into a real threat to the architectural and structural integrity of Al-Qahira Citadel.

Figure 1: Pictures Shows a group of herbaceous plants. Source: Researcher. Location: Al-Qahira Citadel, Taiz, 2025

Figure 2: Pictures Shows a group of shrubby plants. Source: Researcher. Location: Al-Qahira Citadel, Taiz, 2025

Figure 3: Pictures Shows a group of tree plants. Source: Researcher. Location: Al-Qahira Citadel, Taiz, 2025

### 4.2 Photographic Documentation and Supporting Techniques

Photographic documentation was used as a primary documentation tool to support the field survey, contributing to recording the current condition of Al-Qahira Citadel's elements before the study implementation and during its various stages. The photographic documentation focused on highlighting manifestations of vegetation cover spread, identifying its growth locations on walls, foundations, and architectural surfaces, in addition to documenting the resulting damage such as cracks, stone disintegration, and disintegration of traditional binding materials.

The results of the photographic documentation showed a direct relationship between vegetation cover density and the level of deterioration in architectural elements. It was observed that areas experiencing dense plant growth are the most vulnerable to cracking and elevated humidity, especially in locations near blocked water drainage channels and areas where soils accumulate.

Figure 4: Pictures showing Drone-based aerial imagery reveals the concentration of vegetation within cracks, stone joints, and moisture-prone areas, posing a risk to the structural integrity of architectural elements.

Aerial photography using the drone as a complementary tool to ground documentation, as it enabled observing the overall site view and identifying the extent of vegetation cover spread in elevated or inaccessible areas. The aerial images contributed to revealing dense plant growth atop wall crests and upper surfaces—areas that could not be accurately documented by ground photography alone—thereby enhancing the comprehensiveness and accuracy of the results.

### 4.2.1 Supporting Techniques : QGIS

Leveraging ground and aerial images, Geographic Information Systems (GIS) were used to analyze spatial data, where digital maps were prepared illustrating the spatial distribution of vegetation cover within Al-Qahira Citadel, classified by type, density, and hazard level. This was achieved by creating independent spatial layers representing observed plant locations, with each layer linked to a descriptive database (Attribute Table) containing the plant name, scientific name, plant type, structural hazard level, and visual documentation material represented by field and aerial photographs.

This analytical approach enabled direct linkage of vegetation cover locations to the condition of affected architectural elements, facilitating identification of the most vulnerable areas within the citadel, particularly at crack sites and stone joints, and regions exposed to water pooling and soil accumulation. The integration of spatial layers and descriptive data also contributed to classifying plants according to their potential impact on structural integrity, clarifying patterns of high-hazard species concentration in specific areas, as shown in Figure (6), which presents a model of vegetation distribution maps linked to the descriptive table.


Figure 5: GIS map showing the distribution of vegetation cover within Al-Qahira Citadel

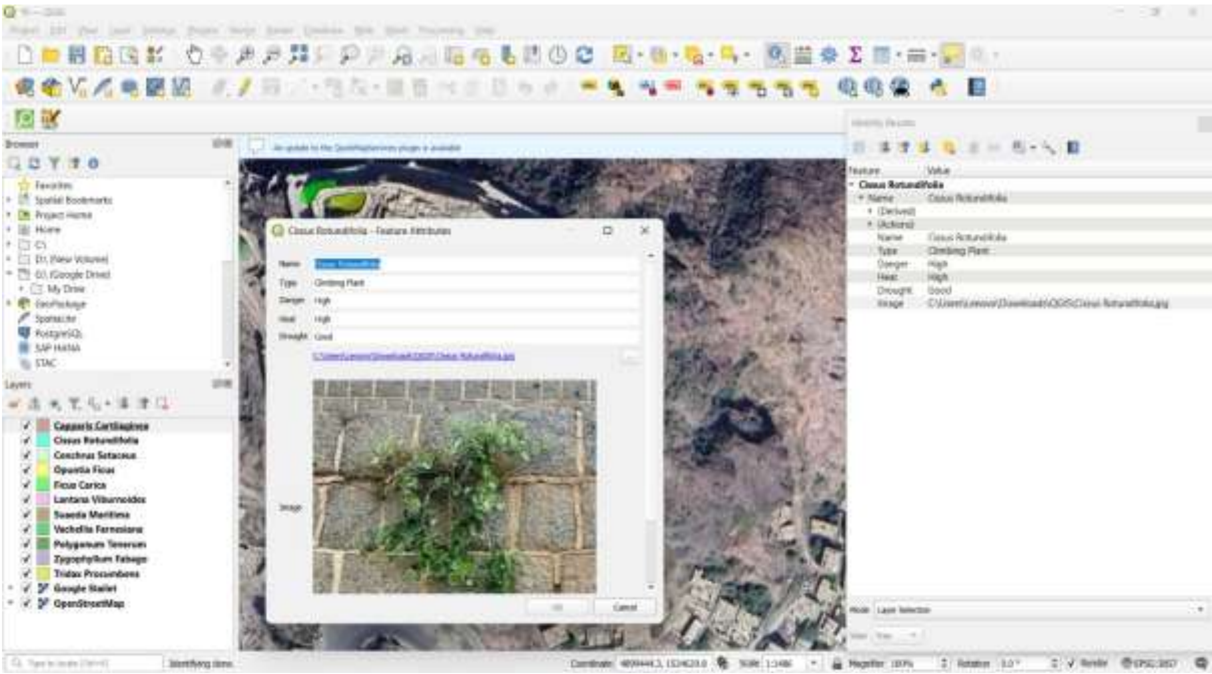


Figure 6: GIS map showing the distribution of vegetation cover within Al-Qahira Citadel, classified by type and hazard level, with spatial data linked to a descriptive table supported by documentary photographs.

### 4.3. Impact of Climate Change on Vegetation Cover at Al-Qahira Citadel and Its Reflections on Structural Integrity

Climatic data available for the Al-Qahira Citadel area in Taiz Governorate—including temperatures, annual rainfall rates, and relative humidity levels—were collected and analyzed across various climatic periods during the 20th century and the early 21st century. This analysis aims to understand the relationship between climatic changes and vegetation cover growth, and to identify environmental factors directly contributing to the deterioration of the citadel's architectural and structural elements, as it is a heritage site with high environmental sensitivity.

Studies issued by international organizations such as UNESCO and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM) indicate that climate change risks are not limited to the deterioration of stone materials but extend to include the ecosystems surrounding archaeological sites and historical vegetation patterns, which constitute an integral part of the cultural and environmental value of these sites. In this context, Al-Qahira Citadel is among the models vulnerable to climate change impacts due to its topographical location and climatic characteristics.

During the period spanning (1900–2000), the climate of Taiz Governorate was characterized by a degree of general moderation with clear spatial variations resulting from topographical diversity; mountainous regions and highlands experienced mild summers and relatively cold winters, while the western lowlands were characterized by a coastal desert climate. The annual mean temperature reached approximately 21∘C21∘C, while rainfall rates were concentrated in the summer season due to monsoons, recording an annual average of nearly 737.1 mm737.1 mm. The average relative humidity reached about 55.9%55.9%, increasing in elevated areas. These climatic conditions provided a suitable environment for the growth of seasonal plants, especially in areas that retain moisture for longer periods within the architectural fabric of the citadel.

As for the period (2000–2010), the moderate climatic character continued, particularly in mountainous areas, with relative stability in temperatures and the recording of relatively high rainfall rates, averaging about 600 mm600 mm annually, reaching nearly 1000 mm1000 mm in some mountainous regions like Mount Sabir. This rise in rainfall rates contributed to increased humidity levels following rainy seasons, which enhanced the chances of vegetation germination within cracks and stone joints, especially in areas less exposed to direct sunlight.

During the period (2010–2025), climatic data showed continued thermal moderation throughout the year with a relative extension of seasons and a decline in thermal variation; the average daily temperature during the winter season reached about 15.3∘C15.3∘C, gradually rising in the spring to 20.1∘C20.1∘C, while temperatures peaked during the summer at about 23.4∘C23.4∘C. Rainfall rates maintained an annual average of nearly 600 mm600 mm, with relative humidity levels rising after rainy seasons and its annual average stabilizing at around 55.9%55.9%. These conditions contributed to the continued growth and expansion of vegetation cover, particularly in lower architectural areas, stone joints, and soil-covered regions.

The analysis of the relationship between climatic data and vegetation distribution showed a direct correlation between elevated humidity levels and the density of plant growth within the citadel; cracked walls, joints between courses, and foundations exposed to water pooling were the sites most vulnerable to plant germination. Furthermore, periods of drought accompanied by rising temperatures led to the shrinkage of clay and lime materials used in construction, which contributed to increased cracking and facilitated the penetration of plant roots into the structural fabric. The recurrence of wetting and drying cycles contributed to accelerating the physical deterioration processes of building materials and deepening the impact of invasive vegetation cover on the structural integrity of the citadel's architectural elements.

### 4.4 Temporal Analysis of Photographic Documentation and Its Implications for Changes in Vegetation Cover

The climate change analysis was supported by conducting a temporal analysis of photographic images documented for Al-Qahira Citadel across different time periods, due to the importance of this type of documentation in tracking the development of vegetation cover and observing its dynamics within the site. Photographs taken in 2004 showed noticeable spread of vegetation cover in several parts of the citadel, reflecting the influence of prevailing environmental and climatic factors at that time in promoting plant growth, especially in architectural areas exposed to moisture accumulation.

Figure 7: A picture showing of the Al-Qahira Citadel in 2004.

Photographs taken in 2023 revealed near-complete dominance of vegetation cover over most parts of the citadel, with a clear increase in its density and spatial extent. This scene aligns with the results of climatic data analysis, which showed rising seasonal humidity levels and frequent rainfall periods, alongside the absence of routine maintenance works during that phase, contributing to the exacerbation of invasive vegetation cover within the architectural fabric of the citadel.

Figure 8: A picture showing of the Al-Qahira Citadel in 2023.

In contrast, photographs taken in 2025 showed a clear decline in vegetation cover spread, with the citadel appearing nearly free of plants, resulting from the implementation of vegetation removal works and improved site care. This temporal contrast confirms that vegetation cover spread is not linked to climatic factors alone but is directly influenced by the level of management, maintenance, and human intervention, highlighting the importance of preventive policies in protecting heritage sites.

Figure 9: A picture showing of the Al-Qahira Citadel in 2025

The study demonstrated a clear correlation between climatic changes in the Al-Qahira Citadel area and the growth and distribution of vegetation cover within the site, along with the resulting negative impacts on the architectural and structural integrity of the citadel. Climatic data analysis indicated that fluctuations in rainfall rates and rising humidity levels contributed to creating a suitable environment for plant growth, particularly in areas suffering from poor water drainage and soil accumulation.

Field surveys and photographic documentation also showed that vegetation cover is primarily concentrated in architectural cracks and joints, on lower architectural surfaces and near foundations, where plant roots—especially fast-growing species—penetrate, leading to stone disintegration, deterioration of binding materials, and increased cracking rates.

The temporal comparison of photographs (2004, 2023, 2025) revealed clear changes in vegetation cover density, peaking during the period preceding maintenance works and declining noticeably after removal and treatment interventions. Aerial photography using drones, alongside Geographic Information Systems (GIS) applications, contributed to identifying high-risk areas where plants with negative structural impacts concentrate, particularly in elevated and hard-to-access regions, in addition to creating a spatial database documenting vegetation intrusion locations and associated hazard levels.

The linkage between climatic data, temporal image analysis, and field observations confirms that climate changes accelerate the deterioration of architectural elements through repeated wetting and drying cycles, enhancing the spread of invasive vegetation cover and amplifying its negative impact on the stability of the architectural and structural elements of Al-Qahira Citadel.

### 4.5 Identification of Vegetation Cover Types and Their Impact on Architectural Structures

Field surveys reveal that the impact of vegetation cover on the structural integrity of architectural elements at Al-Qahira Citadel varies significantly depending on plant type, root characteristics, growth rate, and location within the citadel's architectural fabric. Based on this, plants can be ranked in an ascending gradient of structural hazard levels, starting with seasonal herbaceous plants, followed by shrubs, and culminating with fast-growing trees.

**First: Seasonal Herbaceous Plants (Low Hazard)**

Herbaceous plants have the least impact on structural stability due to their shallow, short-lived roots that typically do not penetrate beyond accumulated soil layers on architectural elements, as shown in Figure 8. These plants appear temporarily following rainy seasons and wither during drought periods, limiting their ability to cause direct structural damage.

However, their hazard lies in their indirect effects, as they contribute to retaining moisture on surfaces and walls, increasing the chances of water infiltration into stone joints, which accelerates erosion processes and creates a suitable environment for the growth of more hazardous shrubs and trees. Accordingly, their hazard is classified as preventive and cumulative rather than directly structural.

Figure 10: Pictures showing the growth of herbaceous plants within cracks and stone joints in the wall of Al-Qahira Citadel.

**Second: Medium-Growth Shrubs (Medium Hazard)**

Shrubs represent a transitional stage between herbaceous plants and trees, characterized by fibrous, branching roots capable of penetrating cracks and architectural joints. Field surveys showed that these roots cause the widening of existing cracks due to continuous biological pressure, weakening stone cohesion and increasing mortar disintegration rates.

The prolonged presence of shrubs without removal gradually elevates their hazard level, as their roots transform into stress points within walls and foundations. Therefore, this category is classified as medium to high structural hazard if routine treatment is neglected.

Figure 11: Pictures illustrating a growth site of shrubs on the wall of Al-Qahira Citadel, where plants appear penetrating cracks and stone joints, indicating their potential impact on the cohesion of architectural elements.

**Third: Fast-Growing Trees (Very High Hazard)**

Trees are the most destructive type of vegetation cover for architectural elements due to their deep and powerful taproots that penetrate foundations and retaining walls, exerting continuous pressure that leads to stone disintegration, separation of architectural blocks, and extensive structural cracking.

The hazard of trees increases when they grow near water storage or drainage areas or in humid depressions, where their growth accelerates and root volume increases, doubling the negative structural impact. In some cases, it was observed that the presence of trees led to localized bulging in walls and partial collapses, making them represent the highest hazard levels within the site.

Figure 12: Pictures showing tree growth within Al-Qahira Citadel near architectural elements and foundations.

## Conclusions

This study demonstrates that climate change represents a decisive factor in affecting the stability of heritage sites, as clearly manifested in the case of Al-Qahira Citadel in Taiz Governorate. The climatic and temporal analysis proved a direct correlation between fluctuations in rainfall rates and rising humidity levels on one hand, and the growth and expansion of vegetation cover within the site on the other, which contributed to the exacerbation of architectural and structural deterioration.

The results showed that vegetation cover, particularly fast-growing plants and trees, constitutes an active rather than a secondary pressure factor; roots penetrating architectural cracks and joints lead to stone disintegration and the loss of binding materials, thereby weakening the cohesion of structural elements. It also became evident that repeated wetting and drying cycles resulting from climate change contribute to accelerating these processes and increasing the vulnerability of traditional materials used in the citadel's construction.

Furthermore, the temporal comparison of photographs (2004–2023–2025) revealed that the absence of periodic preventive interventions leads to the widening and increased density of vegetation cover, whereas the implementation of regular removal and maintenance works directly results in limiting its spread and reducing its hazards. The study also confirmed the effectiveness of employing modern technologies, such as aerial photography and Geographic Information Systems (GIS), in monitoring spatial changes in vegetation cover, identifying hazard zones, and supporting decision-making in heritage site management.

Based on the above, the study affirms that addressing the impact of vegetation cover at Al-Qahira Citadel cannot be separated from understanding the site’s climatic and environmental context. Protecting the citadel and ensuring its sustainability requires adopting an integrated scientific approach that links climatic analysis, field monitoring, and well-studied technical interventions to ensure the preservation of its historical and architectural value in the long term.

## Recommendations

In light of the findings and conclusions reached by the study, the paper recommends the necessity of adopting an integrated scientific approach in dealing with the impact of climate change and vegetation cover at Al-Qahira Citadel to ensure the protection of the site and the preservation of its architectural and structural integrity in the short and long term. This includes implementing periodic and organized programs for managing and removing vegetation cover, with a focus on treating plant roots—especially fast-growing trees and shrubs—using well-studied technical methods compatible with the principles of historical building conservation.

The study also recommends improving rainwater drainage systems within the citadel, rehabilitating blocked channels, and limiting soil accumulation, given their direct role in reducing humidity levels and limiting environments suitable for vegetation growth. This measure is considered one of the most important preventive interventions contributing to the reduction of deterioration rates associated with climatic factors.

The study emphasizes the importance of adopting modern technologies, such as aerial photography using drones and Geographic Information Systems (GIS), as permanent tools for monitoring and observing vegetation cover, identifying high-risk areas, and continuously updating the site's spatial and descriptive databases to support evidence-based decision-making in heritage site management.

The paper also recommends conducting long-term climatic and environmental studies for the Al-Qahira Citadel site to forecast future climate change trends, assess their potential impact on the site, and integrate these results into maintenance and protection plans. It further stresses the need to enhance institutional coordination between authorities concerned with antiquities, restoration, and the environment to ensure the integration of efforts and standardization of work mechanisms.
Finally, the study underscores the importance of including vegetation management within the site's comprehensive management plans and raising awareness of the importance of continuous preventive maintenance as a fundamental element in ensuring the sustainability of Al-Qahira Citadel and preserving its historical and architectural value for future generations.

**Project 5.**

# Enhancing Community Awareness Of The Impact Of Climate Change On Cultural Heritage In The City Of Taiz (Al-Qahira Citadel)


## Abstract

The study aims to assess the condition of the stones in the Western Tower and identify the This study focuses on enhancing climate awareness and the impact of climate change on heritage and conflict, with particular attention to the condition of the historic Al-Qahira Citadel among teachers and students through an awareness programme that links content to the local reality, especially regarding Al-Qahira Citadel in the city of Taiz as one of the most prominent historical landmarks exposed to climatic factors. The research adopted a mixed awareness methodology through distributing a questionnaire to teachers to measure their initial knowledge level of climate issues and raising their awareness through distributing an awareness booklet on the impact of climate change on heritage and the conflict at the historic Al-Qahira Citadel, in addition to implementing an explanatory session for school students that included distributing a simplified booklet clarifying the concept of climate change and its importance, and the role of vegetation cover in protecting the climate and archaeological sites. The programme reflected a positive impact on the participants' level of understanding of the importance of preserving the environment and vegetation cover as two essential elements in protecting heritage sites such as Al-Qahira Citadel, and it also highlighted the need to develop ongoing school programmes in the field of climate awareness.


## Research Problem

The increasing climatic impacts, foremost among which is drought and the decline in the rainfall rate during recent years, and these conditions have contributed vegetation cover in the city of Taiz suffers from noticeable deterioration witnessed as a result of the to weakening plant growth, which has negatively reflected on the climatic balance. Despite the importance of the role of climate awareness in confronting challenges, the level of awareness among both teachers and students regarding the importance of vegetation cover and its relationship to climate change remains limited within schools. Hence, the implementation of an awareness programme has been proposed to contribute to enhancing teachers' and students' perception of the importance of vegetation cover and its role in protecting the environment amid the current climate changes.

## Research Question:

To what extent is the environmental awareness among teachers and students regarding vegetation cover and climate change in Taiz schools.

## Research Objectives

1. Measuring the level of awareness of students and teachers regarding vegetation cover and climate change before awareness-raising.

2. Implementing an awareness session and simplified explanation on the importance of vegetation cover and climate change.
3. Preparing and distributing a supporting educational booklet for the awareness content that focuses on climate change and vegetation cover and the effects of drought on the local environment and heritage sites (Al-Qahira Citadel).

## 1. Introduction

Climate awareness has become an urgent necessity amid accelerating climate developments and the decline of vegetation cover in many areas, which may negatively impact the environment, cultural heritage, and historical landmarks. Al-Qahira Citadel in the city of Taiz serves as an important example of sites that can be affected by the lack of climate awareness among community members, highlighting the importance of incorporating topics such as climate change and vegetation cover into educational and awareness activities.

Unlike studies addressing the direct scientific impacts of these phenomena, this research focuses on the awareness aspect and aims to develop teachers' and students' understanding of basic concepts related to climate change and the importance of vegetation cover in protecting archaeological sites and environmental stability. To achieve this, a comprehensive awareness programme was implemented, including the distribution of an educational booklet and direct explanation to students, in addition to a targeted questionnaire for teachers to assess their level of environmental awareness and link their results to the presented content.

This study seeks to highlight the vital role of educational institutions in enhancing environmental awareness and to emphasize that protecting historical sites such as Al-Qahira Citadel begins with building correct understanding among generations about the importance of the environment and vegetation cover in preserving natural and cultural heritage.

### 1.1. Climate Change

Reports from the Intergovernmental Panel on Climate Change (IPCC) indicate that climate changes are among the most prominent factors affecting natural ecosystems, as rising temperatures and declining rainfall rates contribute to increased drought periods, leading to vegetation cover deterioration, particularly in arid and semi-arid regions. These reports confirmed that recurrent drought is a clear indicator of climate change and has a direct impact on the sustainability of vegetation cover and the balance of ecosystems (IPCC, 2022).

The Food and Agriculture Organization of the United Nations (FAO) clarified that vegetation cover plays a pivotal role in protecting soil from erosion, regulating local climate, and preserving biodiversity. The organization pointed out that vegetation cover deterioration resulting from drought and climate change leads to increased desertification, negatively impacting the environment and local communities (FAO, 2020).

In the same context, United Nations Environment Programme (UNEP) reports affirmed that the impacts of climate change are not limited to natural environments only but extend to include sensitive sites and areas of environmental and cultural value, where vegetation cover deterioration or random plant growth increases risks of environmental degradation. These reports also emphasized the importance of environmental awareness as a fundamental tool to enhance local communities' understanding of the relationship between climate change and vegetation cover and to support environmental protection efforts (UNEP, 2019).

The foregoing aligns with the orientation of the current research, which focuses on environmental awareness of the importance of vegetation cover and its relationship to climate change and drought, by raising the awareness level among teachers and students regarding these issues and their impact on the local environment.

### 1.2. Brief Introduction to Al-Qahira Citadel

Al-Qahira Citadel in the city of Taiz is one of the most prominent historical and archaeological landmarks in Yemen, dating back to early Islamic periods, specifically the Sulayhid era, and then witnessing expansions and restorations during the Ayyubid and Rasulid eras. The citadel played an important political and military role due to its elevated strategic location overlooking the city of Taiz, making it a center for defense and governance, in addition to being a civilizational symbol reflecting the development of military architecture in those historical periods.

Previously, Al-Qahira Citadel and its surroundings were distinguished by a natural vegetation cover, as shown in Figure (1), including local plants and scattered trees that contributed to soil stability and erosion reduction, while adding an environmental and aesthetic character to the archaeological site. This vegetation cover played an important role in protecting the slopes surrounding the citadel from the effects of rains and floods, in addition to contributing to maintaining environmental balance in the area. However, the vegetation cover around Al-Qahira Citadel has witnessed noticeable deterioration as a result of changing climatic conditions, primarily the decline in rainfall rates, which decreased by approximately 10–15% compared to previous decades based on a study by the Antiquities and Museums Authority Office, increased drought periods, and rising temperatures. These factors have led to weakened natural plant growth and the disappearance of some species, contrasted by the appearance of random plants growing in cracks and historic walls. Human activities, such as neglect, lack of maintenance, and unplanned urban expansion, have also contributed to accelerating vegetation cover deterioration and increasing pressure on the archaeological site.

This environmental deterioration has directly reflected on the safety of the citadel, where roots of random plants have contributed to causing cracks in walls and foundations, while weakened vegetation cover has led to increased erosion rates and soil degradation, threatening the stability of the surrounding slopes. Additionally, the loss of vegetation cover has contributed to the decline in the aesthetic and natural appearance of the citadel compared to its previous state.

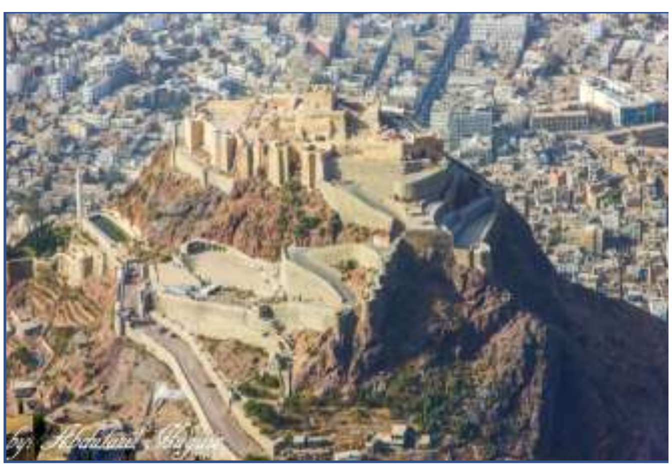


Figure No. (1): Photo showing Al-Qahira Citadel in 2014, with the spread of vegetation cover inside the citadel and on the surrounding slopes.

## 2. Methodology

This study adopted the mixed methodology, which focuses on implementing an environmental awareness programme aimed at raising the awareness level among teachers and students regarding climate change issues and vegetation cover, and linking them to the protection of heritage sites, particularly Al-Qahira Citadel in the city of Taiz.

The first phase began with collecting preliminary data through a targeted questionnaire for teachers in the targeted schools, aiming to identify the general knowledge level of environmental concepts and determine the aspects needing focus in the awareness programme.

In the second phase, educational awareness content suitable for the target group was prepared, including simplified booklets and explanatory materials addressing climate change topics, vegetation cover, and the importance of preserving the environment and historical sites, while simplifying the information and linking it to the local context. The third phase consisted of implementing the awareness programme in the field within a number of schools, through interactive explanatory sessions for students, distributing educational booklets, and opening discussion on daily environmental behaviours and their role in protecting the environment.

The fourth phase included a field visit to Al-Qahira Citadel, where a practical explanation was presented on the importance of the historical site, the traditional materials used in its construction and restoration, primarily qadad material, with clarification of its relationship to preserving the citadel and its sustainability.

## 3. Content of the Awareness Programme

A targeted questionnaire was prepared for teachers to measure their level of awareness of climate change concepts and the importance of vegetation cover Figure No.(2), as well as to learn their opinions on the current status of the citadel and appropriate environmental practices for its protection. The questionnaire covered general topics including teachers' perception of climate changes, their understanding of the role of vegetation cover in protecting the environment and historical sites, and their readiness to participate in awareness programmes.

A practical programme was also implemented in four schools in Taiz city (Iqra School, Dar al-Quran School, Al-Nibras School, and Hayel Complex School) to raise students' awareness, which included a simplified explanation of the concept of climate change, Figure No.(4), and its causes, such as greenhouse gas emissions and lack of vegetation cover, in addition to clarifying the importance of vegetation cover in protecting soil and improving the environment surrounding archaeological sites. The case of Al-Qahira Citadel was explained as a local model to link theoretical information with reality, with the presentation of photos and practical examples illustrating vegetation cover deterioration and its impact on the environment surrounding the citadel. An awareness booklet containing drawings was also distributed.

### 3.1 The Questionnaire

The questionnaire was directed to a sample of male and female teachers in four schools in Taiz city, aiming to assess their level of awareness of the importance of vegetation cover and its relationship to climate change, in addition to their perception of the impact of these factors on Al-Qahira Citadel as an important archaeological site. Teachers were selected as they are an influential group in transferring environmental knowledge and awareness to students and the community, making their awareness level an important indicator for the success of the proposed awareness programmes.

Figure No. (2): Photo showing the distribution of questionnaire forms to teachers.

Based on this, the results of the optional and essay questionnaire were analysed to obtain a clear picture of the current climate awareness level among teachers.

The questionnaire began with a question about the impact of changing climatic conditions on the environment and resources, and the results showed that the awareness rate was high at 95%. This question was asked to measure teachers' general understanding level of the climate change concept, as it forms the basis on which the rest of the research topics are built. This percentage indicates that the majority of participants perceive the general impact of climate change, indicating the presence of good preliminary environmental awareness.

The questionnaire also included a question about the role of vegetation cover in reducing climate change effects, where the awareness rate reached 90%. This question was asked to identify teachers' perception of the direct relationship between vegetation cover and environmental protection. The results indicate that teachers possess good knowledge of the importance of vegetation cover in general, but this perception remains more theoretical than practical.

Regarding the question about the potential impact of climate change on Al-Qahira Citadel, the awareness rate dropped to 55%. This question was included to link general climate concepts to the archaeological site under study. The low percentage reflects weakness in connecting climate change to its direct impact on archaeological sites, highlighting the need to enhance heritage-related environmental awareness.

A question was also asked about the positive role of plants when located in appropriate places such as the earthen slopes surrounding the citadel, where the awareness rate reached 35%. This question aimed to measure participants' understanding of the difference between beneficial and harmful vegetation cover. The low result indicates limited knowledge about managing appropriate vegetation cover for archaeological sites, rather than the mere presence of plants in general.

As for the question about the impact of strong floods and heavy rains on the slopes surrounding Al-Qahira Citadel, the awareness rate reached 65%. This question was asked to assess teachers' perception of natural risks associated with climate change, especially in mountainous areas. The results show moderate awareness of risks, but it still needs support with more detailed scientific information.

Moving to the essay questions, the responses showed that most teachers possess general knowledge of Al-Qahira Citadel's history without delving into architectural and climatic aspects, which explains the reason for asking these questions to assess the detailed knowledge level. The responses also indicated partial awareness of the damage caused by random plant growth and rising temperatures to the citadel's walls and foundations, where teachers linked this to the appearance of cracks and wall erosion.

Overall, the questionnaire results in both optional and essay forms indicate that teachers' awareness level is good in general aspects but relatively weak in specialised practical aspects related to archaeological sites. By calculating the overall average, the total awareness level can be estimated at approximately 68%-70%, confirming the need to enhance awareness programmes Figure No.3.

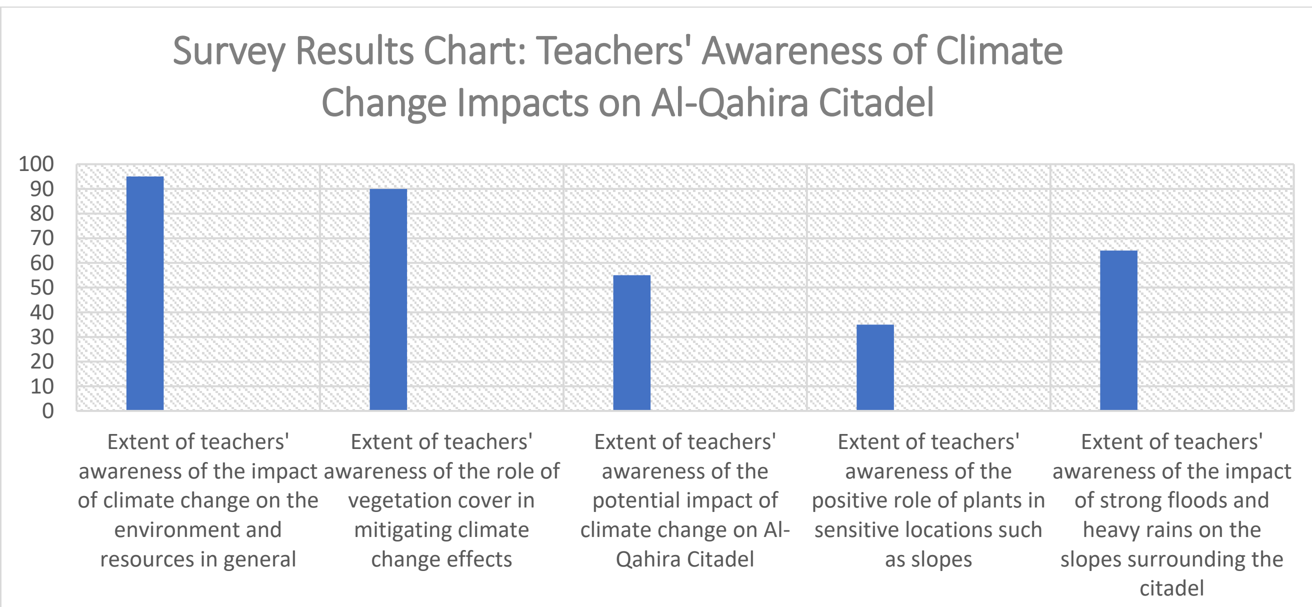



Figure3 : Survey Results Chart: Teachers' Awareness of Climate Change Impacts on Al-Qahira Citadel

### 3.2 Awareness Enhancement Activities

Preserving the local environment and historical heritage requires broad community cooperation that begins at school and relies on ongoing educational programmes and practical activities. Through implementing the proposed suggestions, the community's capacity to confront climate change effects can be enhanced, protecting natural and heritage sites for future generations.

Activities were conducted for children aged 10 to 12 years to enhance awareness of climate change impact and its effects on heritage and conflict, using a very simplified explanation suitable for children. To reinforce this, visits were made to four schools in Taiz city, lessons were explained to students, and two booklets were distributed; the first on climate change, and the second on climate change as illustrated in paragraph .




Figure No. (4): Photos showing the distribution of booklets to students during school visits.

Continuing what was explained at school, a practical visit was implemented to Al-Qahira Citadel in Taiz city to introduce students and teachers to the vegetation cover present at the citadel, where some plants contribute to protecting archaeological sites while others harm the historical components of the citadel, Figure No.(5), with a focus on qadad material, which is one of the most important traditional materials used in ancient Yemeni construction. During the visit, a detailed explanation was provided about the nature of qadad, methods of its extraction, mechanisms of its production, and reasons for its use in the citadel's restoration.


Figure No. (5): Photo documenting the field visit of school students to Al-Qahira Citadel, continuing what was explained at school, including explanation of traditional qadad material.

Within school awareness activities on the importance of vegetation cover to mitigate climate change impact, and in a simplified manner, seedlings were distributed to students, who in turn planted them in the school courtyard and cared for them through watering and tending, thereby instilling in them values of environmental responsibility and positive participation in environmental preservation, Figure No. (6).

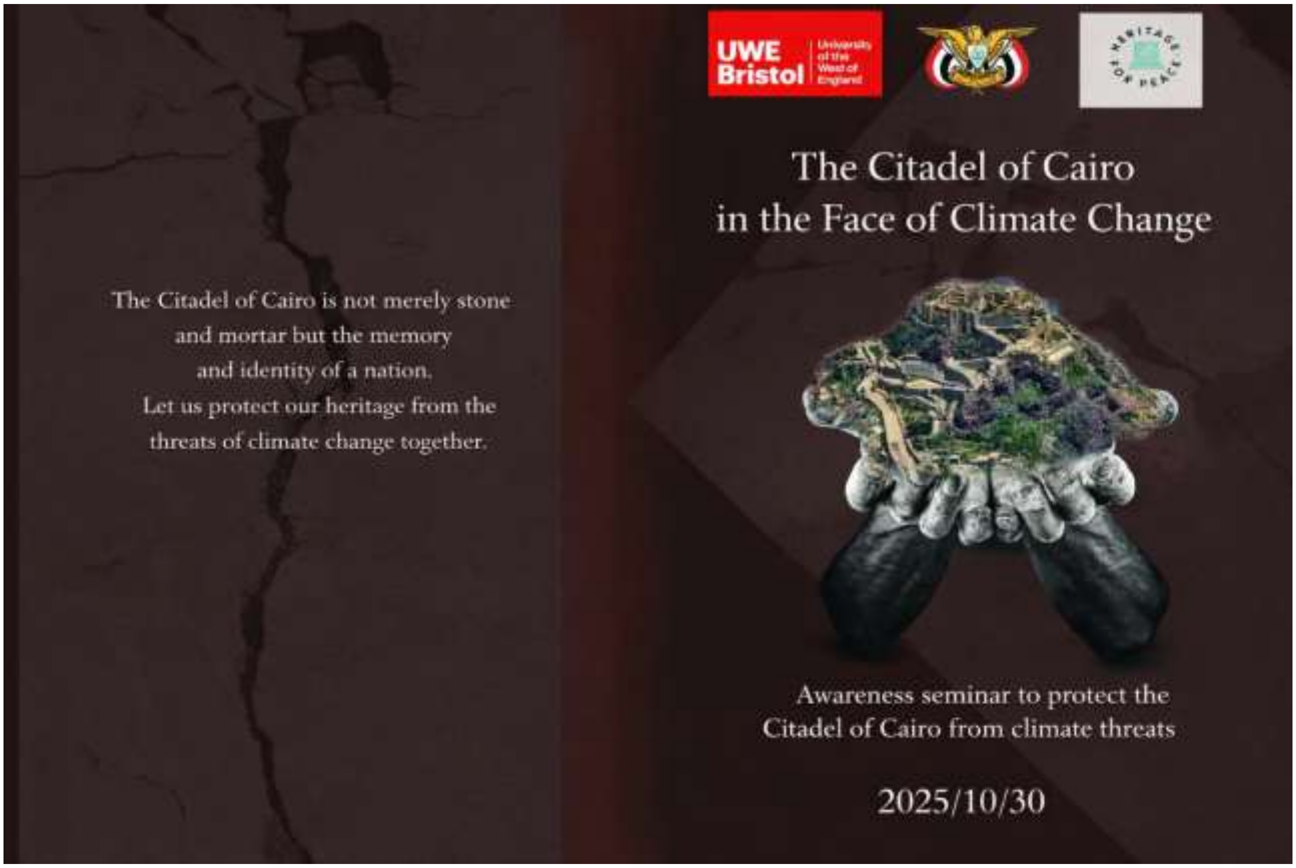
Figure No. (6): Photo showing the planting activity inside the school garden.

### 3.3 Booklet Content

As part of implementing the awareness programme, two awareness booklets were prepared for school students; the first addresses climate change Figure No. (7), while the second focuses on vegetation cover Figure No.(8) and its relationship to archaeological sites, particularly Al-Qahira Citadel in Taiz city. The content of these booklets was designed in a simplified style combining scientific information with cultural and heritage dimensions, suitable for the target age group and enhancing comprehension and interest levels.

The preparation of these booklets responded to the need for an educational awareness tool contributing to raising students' environmental awareness amid increasing climate change effects and vegetation cover deterioration, and the direct threat this poses to archaeological sites. The booklet also aims to bridge students' knowledge gap regarding climate change concepts, causes, manifestations, and impacts, linking them to the local reality and cultural heritage represented by Al-Qahira Citadel.

The first booklet includes a definition of climate change, its main causes, key manifestations, and environmental and human impacts, along with a historical overview of Al-Qahira Citadel to highlight the relationship between climate changes and the condition of archaeological sites. The second booklet addresses the concept of vegetation cover, its environmental importance, influencing factors, causes of its deterioration, and preservation methods, while spotlighting the reality of vegetation cover at Al-Qahira Citadel and its impact on the safety of historic buildings. This booklet is expected to enhance students' environmental knowledge, develop their sense of responsibility towards protecting natural and archaeological heritage, and encourage them to adopt positive behaviours contributing to vegetation cover preservation and reducing harmful environmental practices. The booklet also serves as a supporting tool for field awareness activities and helps reinforce the concepts explained during the awareness programme.


The Citadel of Cairo is not merely stone
and mortar but the memory
and identity of a nation.
Let us protect our heritage from the
threats of climate change together.
UWE Bristol University of the West of England
The Citadel of Cairo
in the Face of Climate Change
Awareness seminar to protect the
Citadel of Cairo from climate threats
2025/10/30

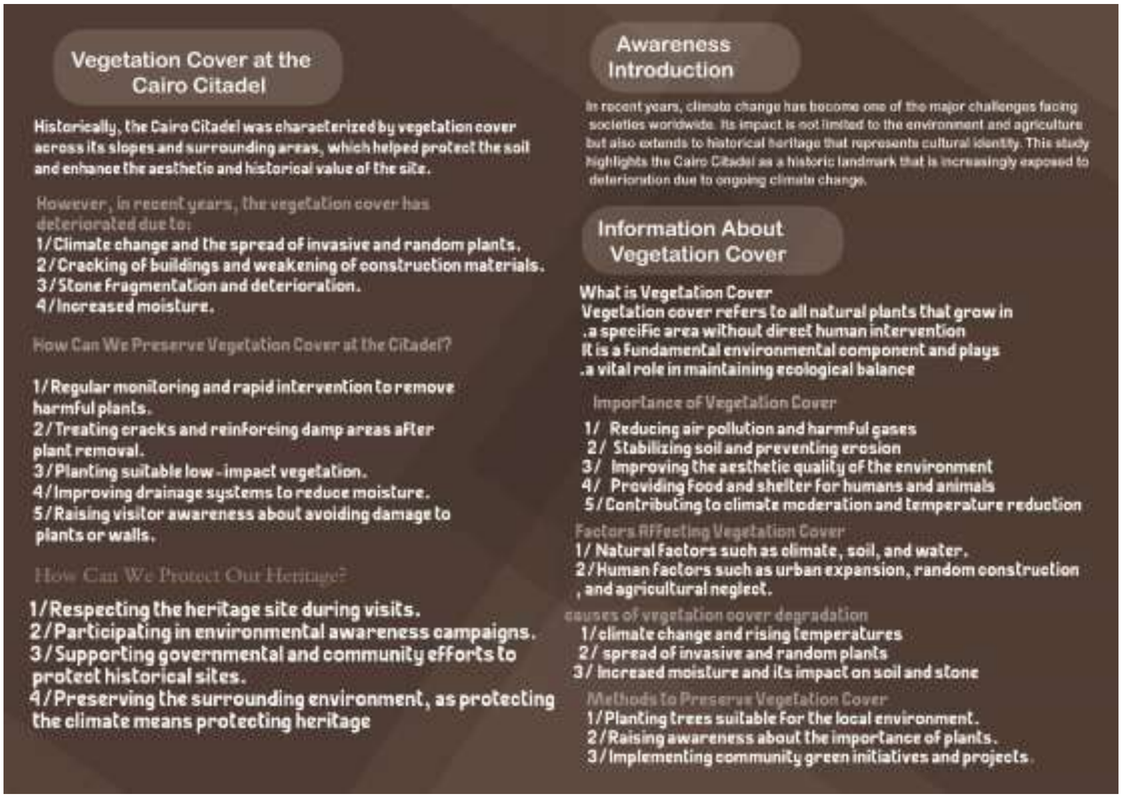



Figure No. (6): The paper addresses climate change


Figure No. (8): focuses on vegetation cover

## Conclusion

This study demonstrated that community-based educational interventions play a vital role in enhancing awareness of climate change impacts on cultural heritage, particularly in conflict-affected contexts such as the city of Taiz. Focusing on Al-Qahira Citadel as a local case study, the research revealed that while teachers and students possessed a general understanding of climate change concepts, their awareness of the specific relationship between climate change, vegetation cover, and the protection of archaeological sites was limited prior to the implementation of the awareness programme.

The questionnaire results revealed a clear gap in environmental awareness among teachers in the four surveyed schools prior to the implementation of the awareness program, particularly in linking climate change impacts to the degradation of vegetation cover surrounding Al-Qahira Citadel. Although approximately 65% of participants reported a general understanding of climate change, awareness of the protective role of vegetation in safeguarding historic sites did not exceed 70%, indicating limited specialized knowledge of local environmental–climatic interactions. Furthermore, most teachers demonstrated insufficient awareness of the effects of reduced rainfall and recurrent drought on vegetation loss and soil erosion in the citadel's surroundings.

Following the implementation of the awareness program, which included educational booklets and simplified, interactive explanations, a significant improvement in awareness levels was observed. Knowledge of climate change impacts increased to approximately 85%, alongside enhanced understanding of the importance of vegetation cover in environmental protection and heritage conservation. Participants also demonstrated improved ability to interpret observed environmental degradation in relation to climate-related factors.

These findings highlight the critical role of school-based awareness initiatives in strengthening climate literacy among educators and students. The results confirm that targeted educational interventions can effectively enhance environmental awareness and support community engagement in protecting local environments and cultural heritage. Sustaining such programs within educational institutions is therefore essential to improving long-term resilience to climate change and safeguarding heritage sites for future generations.

The implementation of the awareness programme—through educational booklets, interactive school sessions, and a field visit to Al-Qahira Citadel—proved effective in improving participants' understanding of climate change, vegetation cover, and their combined influence on heritage conservation. The programme successfully strengthened the ability of teachers and students to connect climate-related risks, such as drought and erosion, to the observed deterioration of the citadel and its surrounding environment. Moreover, the practical activities, including planting seedlings, contributed to fostering a sense of environmental responsibility and active participation among students.

Overall, the findings confirm that schools represent a key entry point for building climate and heritage awareness within local communities. Integrating simplified, context-based environmental education into school programmes can significantly enhance understanding, encourage positive environmental behaviour, and support the long-term protection of cultural heritage sites such as Al-Qahira Citadel. Sustaining and expanding similar awareness initiatives is therefore essential to strengthening community resilience to climate change and safeguarding cultural heritage for future generations.

## Recommendations

Based on the questionnaire results and field observations, a set of measures can be proposed that can contribute to enhancing climate awareness and protecting the vegetation cover around Al-Qahira Citadel, including:

1. Incorporating climate change and vegetation cover concepts into the school curriculum.
2. Organizing voluntary tree-planting campaigns around the citadel.
3. Implementing ongoing training programmes for teachers in the field of environment and climate.
4. Activating climate activities within schools such as cleaning competitions, environmental exhibitions, and planting plants in school courtyards.
5. Providing visual educational materials such as posters.
6. Coordinating between schools and environmental authorities to hold seminars and field visits.
7. Encouraging students to adopt daily environment-friendly behaviours, such as water conservation, tree preservation, and not littering.
8. Conducting periodic studies to assess the condition of vegetation cover around the citadel and monitor climate changes.

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