

# Restoring Mrigadayavan Palace:

## Understanding Causes of Concrete Deterioration and Determining Viable Concrete Rehabilitation Methods



### Abstract

The Mrigadayavan Palace in Cha-am, Thailand has faced the effects of deterioration on concrete structures. The project goal was to preserve and rehabilitate the damaged concrete by exploring various concrete restoration techniques and determining viable methods, as requested by the Mrigadayavan Palace Foundation, to complete a restoration project for the palace's 100th anniversary in 2024. Throughout the project, information was collected through observations, fieldwork, and research. Recommendations to address the deteriorating concrete structures came in the form of a decision tree with extensive criteria for evaluating and determining which techniques achieved the desired outcome. Additionally, web pages, QR codes, and pamphlets were produced as educational materials for visitors.

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## Concrete and the Mrigadayavan Palace

Concrete is the world's leading construction material, resulting in 4.1 billion tons being produced annually.<sup>1</sup> Concrete is favored due to its ability to last through some of the most extreme circumstances. Concrete, as we know it today, was first developed in the 1820s, though earlier formulations have been in continuous use since 126 AD, resulting in structures that still stand in 2021.<sup>2</sup>

Unfortunately, concrete does not always stand the test of time and is susceptible to natural processes that lead to its deterioration.<sup>3</sup> Adding steel reinforcement (rebar) to concrete improves its strength, specifically in the area of tension, but increases the risk of overall deterioration. Due to the metal's corrosive properties, the addition of steel into concrete became a leading cause of failure. However, due to the significant increase in strength, this type of concrete was popularized in the 1920s in Europe and globally. This

construction material was also widely used in Thailand, specifically at the Mrigadayavan Palace, a sprawling Palace in Cha-am, Thailand as shown in *Figure 1*.<sup>4</sup>



Figure 1. View of the Queen's Quarters at the Mrigadayavan Palace

Due to the Mrigadayavan Palace's coastal location, the structure's steel rebar is corroding and causing deterioration of the concrete. The Palace was built almost one hundred years ago and was not properly maintained over the years, creating a need for rehabilitation. The Palace Foundation asked the IQPISSP team to propose a method of concrete repair that will prevent

future corrosion. Through the concrete repair, these structures can be preserved or rehabilitated to fit the needs of the Palace. Concrete structures around the globe hold important cultural values and to lose them would be similar to losing part of one's heritage. Similarly, buildings hold importance to people and serve as reminders of the world's history.

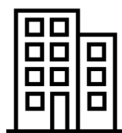
Thailand is home to many Palaces that serve as symbols of Thai culture and history, the Mrigadayavan Palace being one of them. Today, the Mrigadayavan Palace is used as a national heritage site for conservation and education for tourists.<sup>3</sup> Restoring the Mrigadayavan Palace is an important task because the Palace holds high historical values in different fields such as arts and culture, architecture, archeology, and the environment. The goal is for the Mrigadayavan Palace to be able to continue to serve as four entities simultaneously: a national heritage site, a museum, a learning center, and a foundation.<sup>4</sup>

The project's goal was to assist the Mrigadayavan Palace Foundation with the rehabilitation and

preservation of deteriorating concrete structures through assessment of the concrete columns, walkways, and ceiling tiles. We accomplished this through the following four objectives:

1. **Assess** the extent and causes of the concrete deterioration at the Mrigadayavan Palace
2. **Analyze** the applicable concrete restoration techniques based on collected data and analysis
3. **Develop** a guide with a decision tree for concrete restoration techniques for the Mrigadayavan Palace Foundation
4. **Develop** educational content on concrete deterioration and rehabilitation

### Concrete: A World Resource



In its simplest form, concrete is a construction material composed of paste and rocks. The paste is formed from cement, usually a kind known as Portland cement, and wa-

ter.<sup>4</sup> The paste is combined with small rocks, also known as aggregate, and through a chemical reaction, the paste hardens into a solid form. When newly mixed, it is easily manipulated and shaped, but once hardened it is strong and durable.<sup>4</sup> The strength and durability of concrete are achieved through tedious mixing and proportioning of the aggregates and paste. A proper ratio of cement to water is essential in the strength of the paste, which contributes to the quality of the concrete. Additionally, the water content contributes to the porosity of concrete. Porosity increases the movement of seawater and carbon dioxide through concrete. Too much porosity can cause the concrete to be weaker. High-quality concrete has a low water to cement ratio resulting in a lighter material that is easily manipulated to form structures.<sup>4</sup>

Concrete is the world's leading construction material and is seen in all aspects of daily life. Concrete is used for walkways, roads, bridges, and many more applications. The two major types of concrete used in

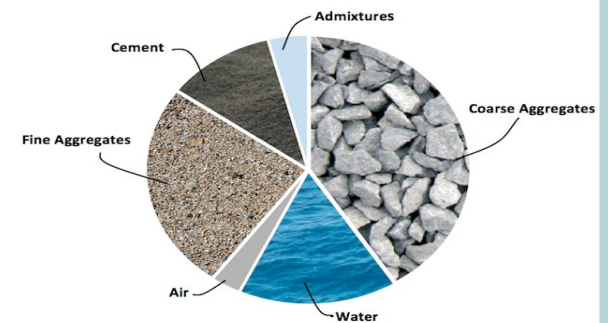


Figure 2. Concrete composition diagram<sup>7</sup>

construction and present at the Palace are plain and reinforced concrete. Reinforced concrete is embedded with steel rods, bars, and/or mesh that provide support in tension, compression, and shear stress.<sup>5</sup> Alternatively, plain concrete is strong in compression and therefore vital for concrete structures like walkways. Both concrete types are important for the Palace as each one serves a different purpose in stabilizing the structure. Once the type of concrete is chosen depending on climate and strength needs, the cement, air, water, and aggregates are combined to create the concrete. The conventional composition is 10% cement, 20% air and water, 30% sand, and 40% gravel as shown in Figure 2.<sup>6</sup>



## Concrete Deterioration and Causes



Concrete, despite its relative durability, does deteriorate over time. This can be caused by material limitations, design and construction flaws, and exposure to environmental conditions. The deterioration of concrete may result in aesthetic, functional, and/or structural problems that impact the safety and service of the structure.

The leading cause of deterioration in concrete structures is the **corrosion** of embedded metals like steel. Steel is not stable under normal atmospheric conditions. The materials in concrete create a basic environment around the steel. At this basic pH, an oxide layer forms on the steel that prevents corrosion from advancing at a fast rate, as seen in *Figure 3*. The passive layer around the steel can be ruined due to chemical reactions between the steel and environmental elements.<sup>4</sup>

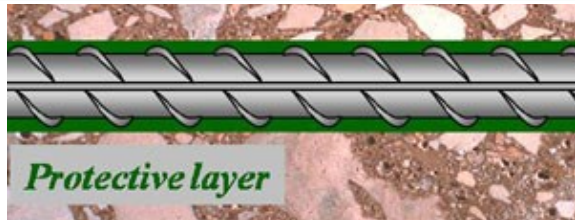


Figure 3. Protective oxide layer on steel rebar<sup>4</sup>

Ocean sea spray can cause chloride attacks which are responsible for almost 40% of failures seen in reinforced concrete structures. Concrete structures exposed to marine environments are especially at risk. Chloride ions that are present in sea spray break down the passive layer around the steel. Corrosion takes place when the chloride ions chemically react with the iron which makes up the passive layer to form iron chloride and then hydrochloric acid in the presence of water. The lack of a passive layer and higher levels of acidity open the steel up to corrosion.<sup>8</sup>

Carbonation occurs in reinforced concrete when carbon dioxide from the air penetrates the concrete and reacts with calcium hydroxide to form calcium carbonate. The reaction creates a more acidic

environment creating instability in the passive layer. This process occurs very slowly. In the presence of high humidity, carbonation occurs more quickly due to the additional water in the atmosphere. Additionally, by lowering the pH of the concrete through carbonation, more chloride ions can enter the concrete resulting in a greater amount of corrosion.<sup>8</sup>

Once the passive layer on steel-reinforced concrete is damaged by chloride attack or carbonation, steel starts to **rust**.<sup>4</sup> Through the chemical reactions between oxygen, water, and the steel rebar, rust forms. When the steel corrodes, the rust expands inside the concrete which causes further concrete cracking as seen in *Figure 4*.<sup>4</sup>



Figure 4. Rusting of steel-reinforced concrete<sup>9</sup>

**Erosion of concrete** structures can be caused by wind, water, or other environmental events. Chemical corrosion of concrete can also lead to physical erosion. Physically damaged concrete cracks, chips, and peels. A full list of physical damage of concrete is outlined in *Supplementary Materials A*. Physical damage indicates that there is underlying damage to the concrete structure.

When designing a building, its materials, mechanical systems, expected occupancy, and environmental loads are all considered in the structural calculations. In the last hundred years, engineers have started to overdesign buildings to allow for increased loads. **Overloading**, on the other hand, can cause concrete to fail and can happen for many reasons, including a **change in the use** of a structure without proper structural modifications, unintentional overloading, and other unique

scenarios. For example, wind load near the coast is often a stronger wind speed and pressure in comparison to inland areas. Due to the increased wind speed and pressure, wind loads are important to account for in the design of a coastal structure such as the Palace.<sup>4</sup>

### The Mrigadayavan Palace: A Thai Time Capsule



The Mrigadayavan Palace located in Cha-Am, Thailand was built for His Majesty King Vajiravudh (Rama VI) in 1924. Designated as a national cultural heritage site by the Fine Arts Department in 1981, the Mrigadayavan Palace serves as an

educational museum for both local and foreign visitors, with exhibitions on conservation, history, art, and culture. In 1992, Her Royal Highness Princess Bejaratana Rajasuda Sirisobha Bhannavadi founded the Mrigadayavan Palace Foundation. The Palace holds an important historical value to the Thai community around it and culturally connects them to the Royal Family. The Palace architecture is especially unique and its preservation is important to the Royal Family, the Mrigadayavan Palace Foundation, and the Fine Arts Department.<sup>3</sup> The Mrigadayavan Palace can be seen in *Figure 5*.

The Palace encompasses three groups of sixteen buildings connected by balconies and corridors, and twenty-three staircases spread out

over a three square kilometer compound.<sup>3</sup> The design of the Palace combines European architectural design and adapted it with techniques found in Thai architecture to make the Palace more suitable for Cha-Am's



Figure 5. Photo of Mrigadayavan Palace<sup>10</sup>

tropical climate.<sup>11</sup> The Palace is built using golden teak wood with concrete floors. The structure is raised on 831 concrete pillars which raise the structure one story above the ground. The raised buildings have high ceilings and walls made of plaster fretwork, interlaced decorative design, to provide good ventilation from the nearby sea breezes.

After King Rama's passing, the Palace was **abandoned** until 1965 when King Rama IX granted permission to the Naresuan Camp's Air Support Division to use the Palace grounds. At this time, the Palace had been abandoned for almost thirty-five years. The teakwood was decaying, concrete columns had failed, and the building's paint had been washed away or was peeling off. The Fine Arts Department registered the Mrigadayavan Palace as a **heritage site** in 1981 and then, with the Border Patrol Police, began a restoration effort two years later. This would be the first restoration of the Mrigadayavan Palace. The community came together and rebuilt the Palace and repainted the structure.<sup>3</sup>



Figure 6. Mrigadayavan Palace corridor with ocean

In 2013, the Palace Foundation determined it was necessary to begin the current restoration. The Palace is situated in Thailand's southern region and is exposed to high humidity and rainfall.<sup>11</sup> Its location along the beach, as seen in *Figure 6*, results in weathering that causes damage to the structure more than the typical site location would. The Mrigadayavan Palace Foundation undertook this **current restoration project** with the goal of preservation and rehabilitation by the 100th anniversary of the Palace in 2024. Ideally, the Palace would be restored to its **original state** as it

was in 1924.<sup>3</sup>

For this current restoration project, the Mrigadayavan Palace Foundation brought in architects to assist in restoring the building to be historically accurate. It was soon realized that the **roof tiles** that were placed in the first restoration effort were not historically accurate, and it is believed to be contributing to some deterioration at the Palace. The original roof tiles weighed over two kilograms and the manufactured roof tiles that were used in the first restoration were significantly heavier than the original ones. Using the heavier roofing tiles increased the loads that were acting on the structure and caused structural damage. The increased load on the concrete columns supporting the structure may have caused the columns to crack. This additional load also contributed to the cracking of the sidewalks, especially in between columns. To maintain the historical accuracy and structural safety of the structure, new tiles were manufactured to match the original tiles' style and weight.<sup>3</sup>

## Historic Conservation: Not Just for Paintings



**Historical conservation** is not only important regarding the **physical preservation** of buildings and monuments, but also as a method of **community enhancement and sustainability**. Conserving historical sites benefits local economies through increased jobs and tourism. The Delaware Division of Historical and Cultural Affairs concluded that for every \$1 million spent on rehabilitation, 14.6 jobs are created. Since conservation relies more on craftsmen than raw materials, it creates more jobs than new construction work.<sup>12</sup> In Eastern Europe, sites of historical and cultural heritage are important assets for cities' economic development. Historical sites are not season dependent and through increasing the appeal of their locations, they benefit the city's "services, infrastructures, and cultural organizations".<sup>13</sup>

**Buildings that are** not preserved are often instead demolished or fall into **disrepair**, which can then become a safety hazard, especially in the case of concrete defects.<sup>14</sup> Many important buildings and sites have been lost due to a lack of preservation and understanding of their importance. The Garrick Theater in Chicago was demolished in 1961, about 70 years after its construction, despite protests from curators and admirers of the building's unique architecture. The historical significance of the building was disregarded in favor of practicality and important culture and history connections were lost.<sup>15</sup>

**There are four standard** treatment procedures for historic buildings as outlined by the U.S. National Park Service. Preservation and rehabilitation are two applicable procedures for the Mrigadayavan Palace. The goal of **rehabilitation** is to maintain a building's historical character while still making the necessary changes or repairs in order to meet the needs of its current usage. Rehabilitation focuses on maintaining as much of the original character and

usage as possible with minimal and effective changes. In rehabilitation, the goal is to repair, not replace. The goal of **preservation** is to provide a building with ongoing maintenance and repair for whatever form the building currently takes. This method focuses on retaining a building's existing form, materials, and integrity. Any changes made over time will be preserved as part of the building's history and no new exterior additions will occur.<sup>16</sup>

## Project Approaches and Outcomes



**The goal of our** project was to explore the extent of concrete deterioration at the Mrigadayavan Palace and analyze various techniques of concrete restoration. The deterioration was determined through interviews with Palace staff as well as fieldwork and observations. The rehabilitation process and recommendations need to also take into account the cultural importance of the Palace. The variety of recommended techniques will



be adaptable to suit the Foundation's goals of both education and historical accuracy. The following approach describes how we gathered and examined the infor-

mation that was necessary to create our recommendations for the Mrigadayavan Palace. A visual representation of the approach taken can be seen in *Figure 7*.

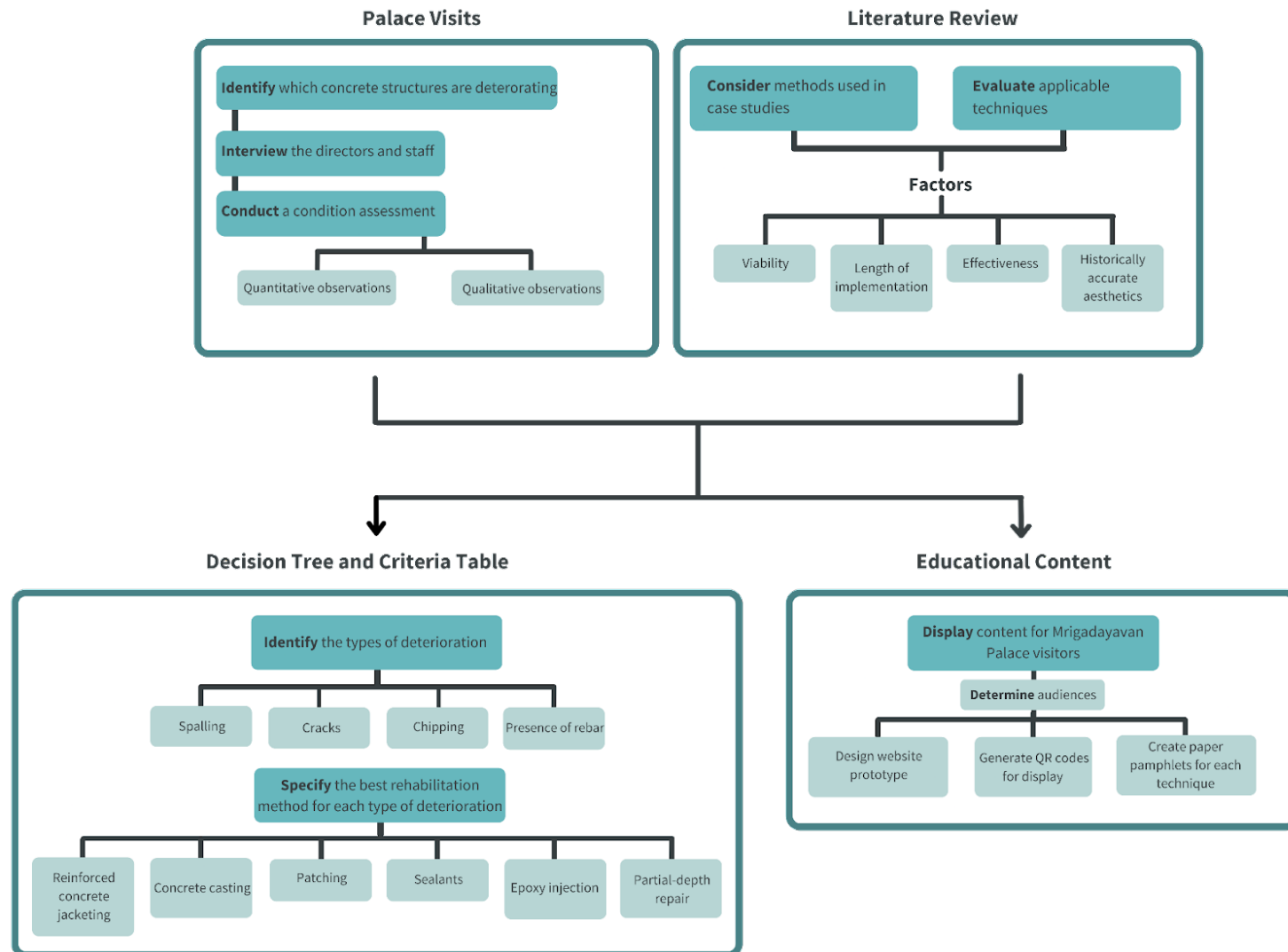


Figure 7. Methodology summary

## Concrete Corrosion: The Assessment



The project team assessed the extent of concrete corrosion and identified the causes of concrete corrosion at the Mrigadayavan Palace through discussions with the Palace Foundation staff. Additionally, empirical observations of the Palace were completed to identify the highly damaged areas. To gain a deeper understanding of the extent and the causes of the concrete corrosion, numerical data were collected as well.

**Walking interviews** with the Mrigadayavan Palace directors and staff provided general information while **semi-structured interviews** with the directors and staff provided more insightful information about concrete corrosion. The first interview was completed at the Palace by the Thai students. This provided the team with a better understanding of the extent and location of the concrete damage, and the Foundation staff's current understanding of the

causes of the deterioration. A follow-up conversation took place over Zoom with both Thai and American students. This was used to further expand the goals of the Palace Foundation regarding restoration and preservation and discuss the creation of educational content through web pages and pamphlets. The questions asked during each Palace visit are listed in *Supplementary Materials B*.



Figure 8. Examples of cracks in concrete columns at the Palace

To accurately assess the concrete corrosion, a basic **condition assessment** was performed. The team

lacked the expertise required to perform a professional condition assessment as outlined in *Supplementary Materials A*. Therefore, to make the condition assessment more manageable, the team focused on sample sections of the Palace and selected from two different building groups, the Men's Quarters (the Outer Court) and the Women's Quarters (the Inner Court). The samples were obtained through empirical observation and recording methods in the form of pictures and videos with complete annotations of their conditions. The photos and videos of all the deteriorated and corroded concrete structures were matched with their position using a map of the Palace for ease of assessment. An example of deterioration can be seen in *Figure 8*. By collecting this data, the extent of the concrete corrosion at the Mrigadayavan Palace could be seen and understood.

An **assessment of wind speed and direction** was also completed because the wind affects the deterioration of concrete structures at the Mrigadayavan Palace. The Palace is located near the coast where the

wind speed is stronger than inland areas. Data related to the wind was collected through an online platform due to the difficulty in methods and lack of equipment on-site. The specific application that the team used for gathering information is called "WINDY."<sup>17</sup> In this application, the team used a focus data set titled, "Wind Speed and Wind Direction." The timeframe for the data focused on the average of wind speed and direction from 2012 to 2021. The criteria selected have an effect on the types of cracks and the location of cracks on the concrete columns.

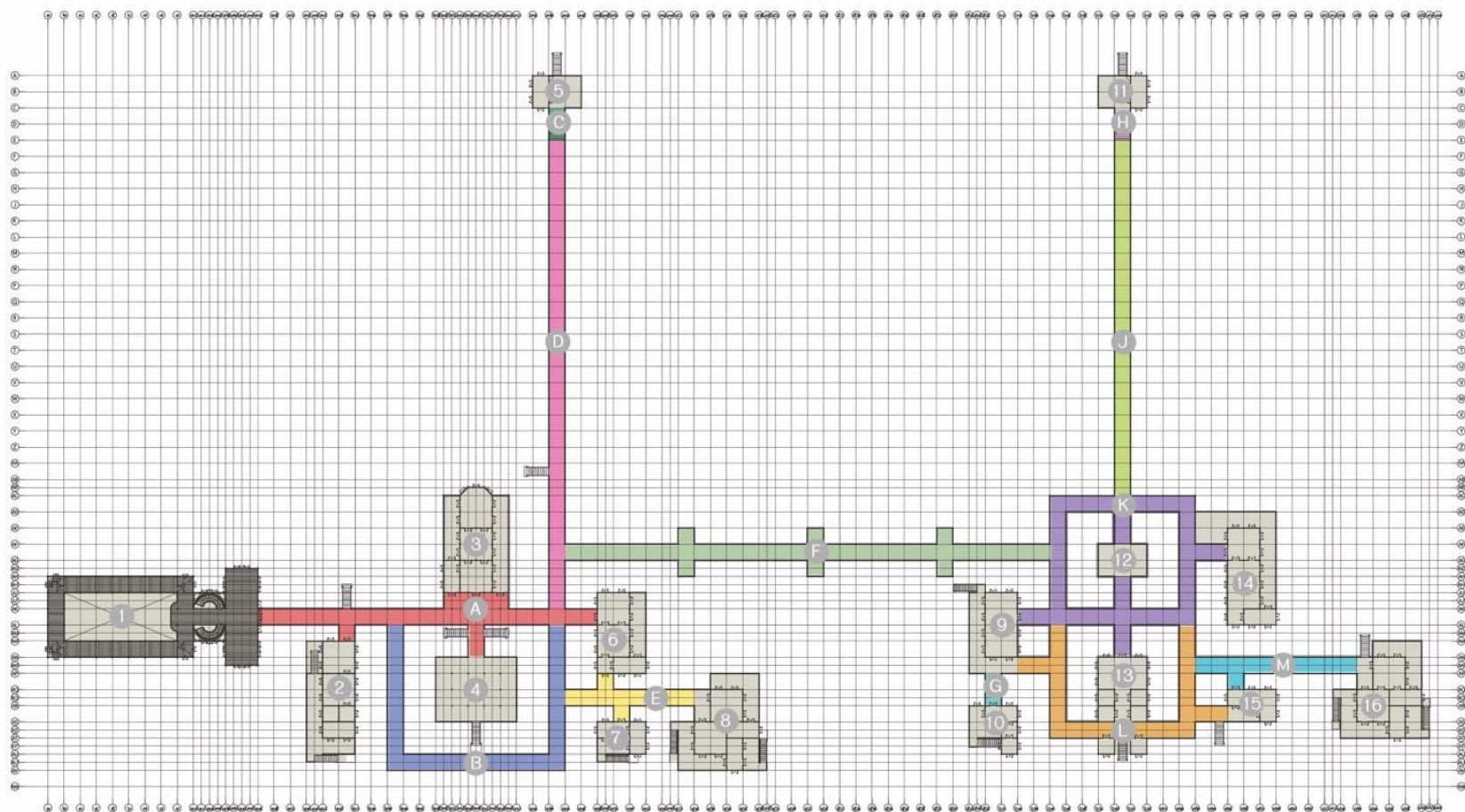
**The goal of the quantitative fieldwork** was to collect more data relating to the effect of external and internal factors on the concrete structures. The factors that our

team considered that influenced the concrete columns were ocean sea spray, previous architectural work, humidity, steel reinforcement, and wind. The Mrigadayavan Palace is divided into many different sections. The various sections contain columns with different types of cracks/spalling and degrees of corrosion. The sample set of columns was determined by dividing the Palace into three areas. See *Table 1*. There is a minimal record of all the completed renovations performed at the Palace, so the sections of the Palace needed to be selected based on known renovation times. The selected areas of the Palace correspond to color-coded locations that can be seen in the site map in *Figure 9*. The chosen areas for quantitative field-

work are a subset of the King's and Queen's quarters that were explored for the condition assessment. Each column in the selected area was analyzed with a **metal detector** to determine the extent of steel reinforcement present in the columns. A little note has to be added here that is related to the selected area. The selected areas are just a sub-group of buildings within the King's and Queen's quarters. The metal detector used, as seen in *Figure 10*, has a metal detection range of three to six centimeters and was used to scan all the columns in the sample set. Additional information related to the instrument used and more detailed explanations of the sampling methods can be seen in *Supplementary Materials C*.

**Table 1. Palace locations for metal detector testing**

Area 1	Area 2	Area 3
C. Stairs and walkway to the northern seaside room	F. The corridor connecting Men's Quarters and Women's Quarters	H. Stairs and walkway to the southern seaside room
D. Corridor connecting the northern male bathing room		J. Corridor connecting the southern seaside room
5. Front bathing room		11. North seaside room



ผังแบ่งพื้นที่พระที่นั่งพระราชวังมฤคทายวัน

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พระที่นั่ง	1 พระที่นั่งสโมสรเสวกามาตย์	7 ห้องนอนหัวหน้านมหาดเล็กห้องบรรทม	13 ห้องข้าหลวง	ทางเดินเชื่อม	A ทางเดินเชื่อมหน้าพระที่นั่งสมุทรพิมาน	G ทางเดินเชื่อมระหว่างห้องรับแขก-ห้องพักผ่อนหัว
	2 ห้องสมุทรของครุฑ	8 ห้องนอนมหาดเล็กและห้องมหาดเล็กพระอูษา	14 พระที่นั่งคชสารสาครฉายาโน		B ทางเดินเชื่อมรอบห้องเสวยฉายาโน	H บันไดและทางเดินลงห้องสรงชายทะเลด้านใต้
	3 ห้องมุขใหญ่ตรงห้องเสวย	9 ห้องรับแขก	15 ห้องข้าหลวงพระอูษา		C บันไดและทางเดินลงห้องสรงชายทะเลด้านเหนือ	J ทางเดินเชื่อมห้องสรงชายทะเลด้านใต้
	4 ห้องเสวยฉายาโน	10 ห้องพักผ่อนหัว	16 ห้องพระสุจริต		D ทางเดินเชื่อมห้องสรงชายทะเลด้านเหนือ	K ทางเดินเชื่อมรอบห้องเสวยฉายาโน
	5 ห้องสรงชายทะเลด้านเหนือ	11 ห้องสรงชายทะเลด้านเหนือ			E ทางเดินเชื่อมหน้าห้องนอนมหาดเล็กและห้องมหาดเล็กพระอูษา	L ทางเดินเชื่อมรอบห้องข้าหลวง
	6 พระที่นั่งสมุทรพิมาน	12 ห้องเสวยฉายาโน			F ทางเดินเชื่อมระหว่างพระที่นั่งฉายาโน-ฉายาโน	M ทางเดินเชื่อมหน้าห้องพระสุจริต

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Figure 9. Map of the Mrigadayavan Palace with legends



**Additional quantitative** fieldwork aspect was the creation of crack maps for different types of concrete structures at the Palace. **Crack maps** are patterns of cracks in concrete structures within a specific measurement frame. This helped the team visualize the scale of the cracks in greater detail through the total length and width measurements taken. It also assisted in visualizing and understanding the patterns of cracks that exist in the area. The sampling methodology for this technique can be seen in *Supplementary Materials D*.

**To assess the extent** of the concrete corrosion and deterioration, the collected data were carefully separated into the areas from which they were sampled. For each location within the Palace grounds, the data were further assessed by the following criteria: crack size, number of cracks, and presence of steel reinforcement. Additional visual aspects of concrete that were observed are listed in *Supplementary Materials A*.

**Potential causes** of the concrete corrosion include environmen-

tal factors, structural design, and material and casting used in prior repairs. Pictures and videos combined with the quantitative fieldwork helped produce accurate hypotheses of the causes of concrete corrosion. Additional factors, such as environmental factors, renovation time frame, and area usage history, were also identified based on interviews and literature review, and taken into consideration in the analysis of specific samples.



Figure 10. Metal detector instrument used to find steel reinforcement in columns

## Concrete Restoration Technique Analysis



**By analyzing relevant case studies,** solutions to repair and preserve the

concrete at the Palace were identified. A **literature analysis** was performed using keywords such as concrete, restoration, preservation, corrosion, rebar, steel-reinforcement, and deterioration. Some examples of rehabilitation or preservation are self-healing concrete and electrochemical techniques. Specific criteria were considered to assess the viability of different rehabilitation and preservation methods. These criteria focused on ease and time of implementation, effectiveness on varied crack sizes, aesthetics, and historical accuracy. The research was completed in detail to learn the implementation process, as well as possible limitations for each method. The final appearance of each method was compared to the materials and appearance of the historic concrete located at the Palace.

## Development of the Decision Tree



The literature review, on-site observations, and sponsor consultations provided the team with the necessary knowledge to be able to propose viable solutions for the Palace Foundation. Our recommendations come in the form of a decision tree with a supplementary criteria table and definitions page. The team took into account that particular kinds of deterioration will work best with different restoration techniques. The field observations identified the location of each type of deterioration and which restoration method can be used. These field observations and site photos were crucial for the development of visuals.

To create useful resources for the Palace Foundation, the team distributed a **survey** among the key decision-makers at the Palace, see *Supplementary Materials B*. The survey collected background infor-

mation about age, gender, position, education level, and years of employment at the Palace. It also asked about the staff's language proficiency for both English and Thai in speaking, writing, listening, and reading. The survey also included questions to understand the staff's familiarity with different methods of concrete restoration. These questions helped us to produce the deliverables at an appropriate technical level for the Palace staff since the content of this project is relatively scientific.

After analyzing the data from the interviews and literature review, a **criteria table** was developed to help the team choose the best methods for each concrete structure and related to the sponsor's goal. Furthermore, a **decision tree** was developed with the information gathered from the criteria table. The tree will be used by the staff to follow a simple decision-making process for what rehabilitation technique is best for the presented problem. Different types of rehabilitation methods can be used based on the extent and location of the deteriora-

tion. Some factors that are used to select the method included the presence of steel rebar throughout the column, type of deterioration, size of the cracks, and type of concrete structure. The decision tree includes both restorative and preservative measures for the Palace Foundation to choose from. The decision tree was created in English and then translated into Thai. A page with both photographic examples and written explanations of each branch and final method was included in *Supplementary Material G*.

## Development of Educational Content



The **educational content** was made accessible to a larger audience through a variety of educational tools. A website was created using the Origami Studio software. This software was chosen to develop the website prototype because it allowed us to build and test user interface interactions. The website was made available to visitors at the Palace through QR

codes that link to the website. The QR Codes were created in Canva and developed on information cards that were translated into both Thai and English. Additionally, paper pamphlets were created in Canva with the content being in both English and Thai.

The audience for the educational content at the Palace was determined through interviews with the Foundation staff to identify the demographic of Palace visitors. Furthermore, the Foundation staff provided information about the age range of people accessing their existing website. The age range specified helped to determine the content of the educational tools.

### Concrete Structures Are Deteriorating in Various Ways


 The Mrigadayavan Palace has experienced the effects of external and internal deterioration on concrete structures over time. Three main concrete structures are deteriorating, including concrete walkways, concrete columns, and concrete ceiling panels.



Figure 11. Photo of the Palace's Column Supported Walkways and Living Quarters<sup>18</sup>

There are a total of 831 concrete columns at the Palace, in which approximately 30% of these columns had small cracks. Approximately ten columns were severely corroded with major cracks in them. From the observations and the collected information, the possible factors that could affect the rate of corrosion and the most probable

cause of corrosion of concrete columns were discussed. The possible factors include ocean sea spray, humidity, wind, architectural deterioration, and architectural errors.

The characterization of the concrete columns and their deteriorations can be done in a few different ways. Firstly, there are two types of concrete columns at the



Palace. The first type is columns that have steel reinforcement only at the top and base of the column. The second type of column is columns that have steel reinforcement throughout the body of the column. The original type of concrete columns designed for the Palace by the original architect is the first type. However, later renovation efforts preferred the second type. An illustration differentiating the first type and second type of concrete columns can be seen in *Figure 12*.

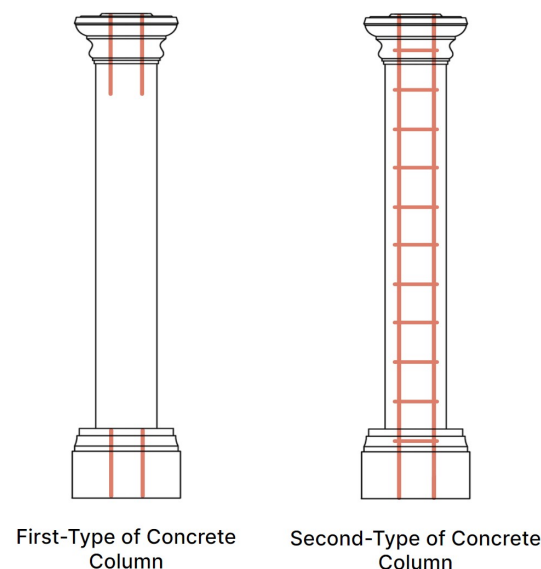


Figure 12. Illustration differentiating the first and second type of concrete columns



Figure 13. Cracks that form on the special design on top of a column

From observations, the diameter of the steel reinforcement in the concrete columns is approximately 9 to 10 millimeters. The size of the steel reinforcement that is used in the concrete columns is identical throughout the Palace. Furthermore, the steel reinforcement embedded at the top of the original concrete column was not for extra support for the whole concrete column, but it was there to support the special design that the top of the concrete column had. Any cracks or corrosion that exist on this special design would not affect the stability of the rest of the column. Cracks on the special design on top of the column can be seen in *Figure 13*.

For the characterization of cracks in concrete columns, two primary patterns of cracks were observed in the sampling areas: vertical cracks and horizontal cracks. Cracks could also form on three different locations of the concrete column. These three locations include the base, body, and top of the concrete column. An illustration that shows the locations of cracks more clearly can be seen in *Figure 14*.

The illustration in *Figure 15* is the result of the sampling methodology from the first objective which is analyzing the effect of external factors on concrete columns through the use of the metal detector and qualitative analysis. The focused sampling area can be seen in the red boxes. The illustrations contain many different symbols that refer to different types of observations. The legends of the symbol can be seen in the white box on the bottom part of the illustrations.

There are a total of six legends: **Brown square boxes** represent concrete columns that are reinforced concrete columns or columns that contain steel reinforcement



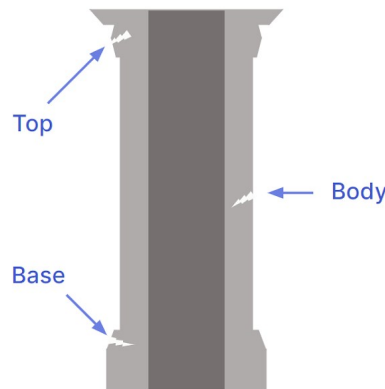


Vertical Crack



Horizontal Crack

Patterns of Cracks



Location of Cracks

Figure 14. (left) Pattern of cracks on concrete columns, (right) location of cracks on

**Circles** represent plain concrete columns or columns that only have steel reinforcement at the top and base of the columns, **Top half-filled red** boxes or circles represents concrete columns that only have cracks at the top part of the columns, **Bottom half-filled red** boxes or circles represents concrete columns that only have cracks on the base part of the columns, **Full-filled red** boxes or circles represents concrete columns that have cracks throughout the body of the column, and **Exclamation points** next to red boxes or circles represents concrete columns that contain spalling.

From the observations, the results differed significantly by sampling area. For **area one** (left-box), the **Outer Court Bathing Pavilion**, a closer

look into this area with photos of the cracks in the area can be seen in *Figure 16*. In this area, a total of sixty-six concrete columns were recorded. Fifty-nine concrete columns or 89.4% of the columns in this area had steel reinforcement throughout the body, and only seven concrete columns had steel reinforcement at the top and base of the column. This area was renovated about three years ago which makes it the most recently renovated area. Only three cracks in concrete columns were observed in this area and the pattern of cracks was all vertical. Two of them were found at the top of the column and one column had cracks in all three locations.

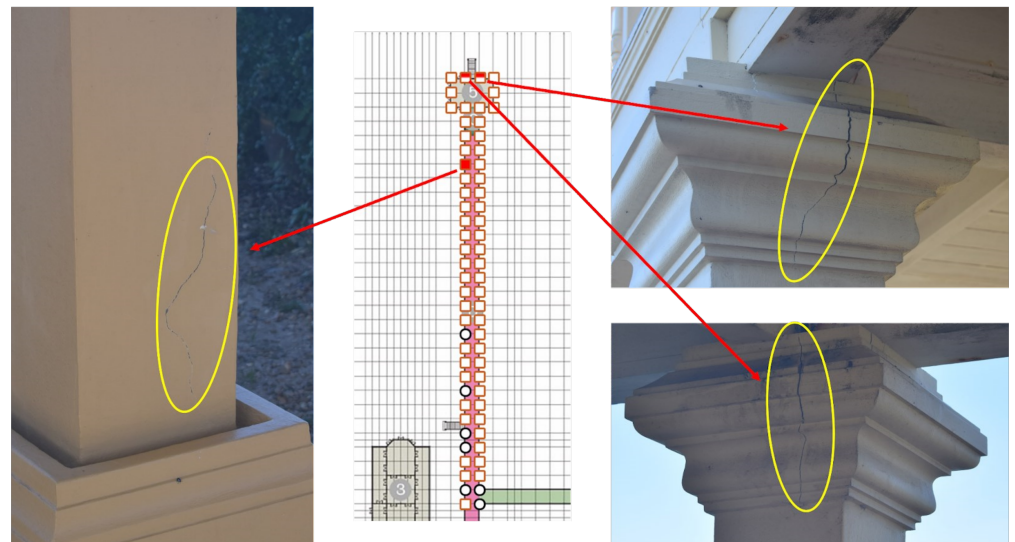


Figure 16. Area one: outer court bathing pavilion

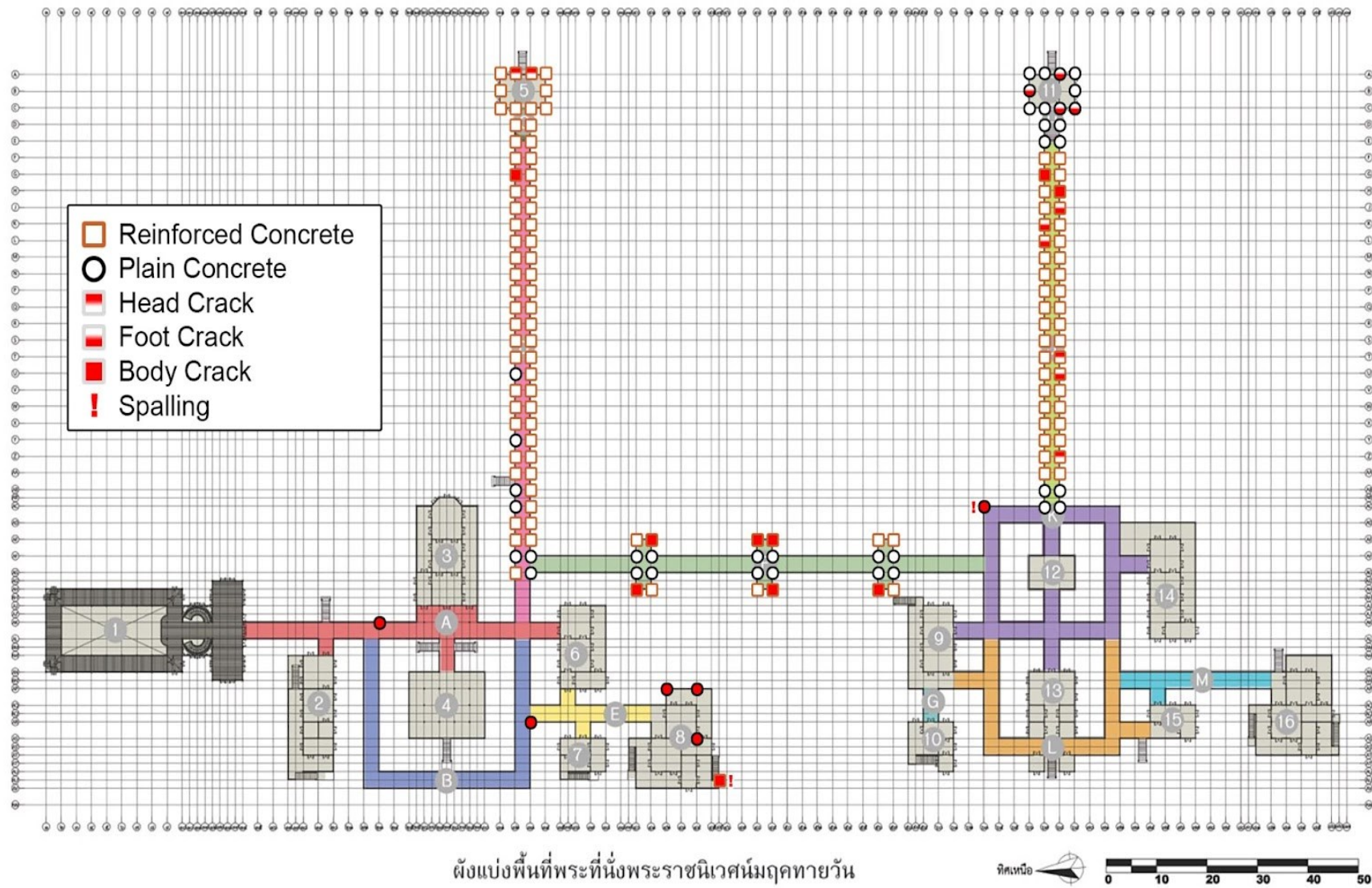


Figure 15. Illustrations of the collected data from the methodology

For area two (middle-box), the **linking corridor between the two courts**, a closer look into this area with examples of the cracks in the area can be seen in *Figure 17*. A total of twenty-four concrete columns were recorded in this area. In the recorded data, twelve concrete columns of 50% of the concrete columns had steel reinforcement throughout the body and twelve concrete columns had steel reinforcement at the top and base of the column. This area was last renovated about thirty years ago. There were six columns in this area that had cracks in all three locations and it all happened to the columns that had steel reinforcement throughout the body of the column.

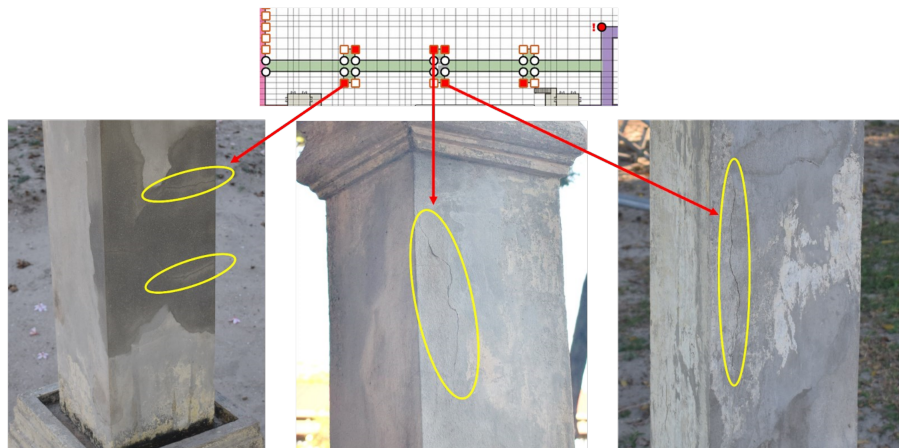


Figure 17. Area two: linking corridor between the two pavilions

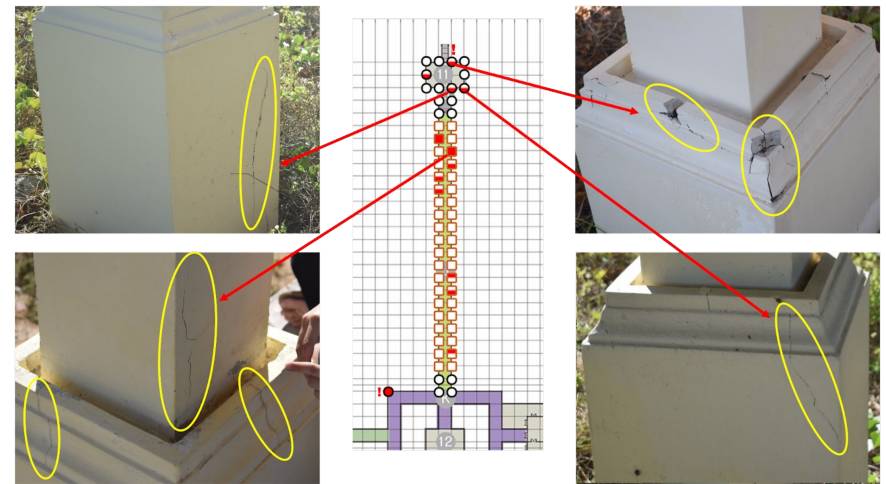


Figure 18. Area three: inner court bathing pavilion

For area three (right-box), the **Inner Court Bathing Pavilion**, a closer look into this area with examples of the cracks in the area can be seen in *Figure 18*. In this area, a total of fifty-eight concrete columns were recorded. Forty concrete columns or 69% of the concrete columns in this area had steel reinforcement throughout the body, and eighteen concrete columns had steel reinforcement at the top and base of the column. This area was renovated about thirty years ago as well. Eight columns had steel reinforcement throughout the body that had cracks in them, and four columns that had steel reinforcement at the top and base that had cracks in them. Both vertical and horizontal crack patterns were observed in this area. Most of the horizontal cracks in the sampling area can be found in this area.



## Factors Causing Cracking in Columns



For the factors that could cause concrete deterioration, **ocean sea spray** has the possibility of affecting the degree of corrosion in concrete columns. Ocean sea spray alone should not be the cause of the corrosion in concrete columns, but it could act as a catalyst that increases the rate of corrosion. Many concrete columns at the Palace contain both minor and major cracks that leave an opening for the inner steel reinforcement to be exposed to the outer environment. Therefore, the chloride ions in the sea spray could come into contact with the inner steel reinforcement. The chemical reaction generating acid that destroys the passivation layer of the reinforcement could then occur. A more detailed explanation can be seen in the background chapter in the concrete deterioration section.

The effect of humidity was analyzed through the usage of metal

detectors. The team found out that there were two types of concrete columns at the Palace: columns with steel reinforcement throughout the whole column and columns with steel reinforcement only at the top and at the base of the column. The reason that there were two different types of concrete was due to **past renovations**. Renovations in the past were done without a true understanding of the intentions of the original architect. The original architect used concrete columns with no steel reinforcement throughout the body, while the concrete columns with steel reinforcement throughout the column were used in later restoration with the idea that it is stronger and can support more load.

Based on the information that the team collected, the team observed that the concrete columns that have steel reinforcement throughout the column seem to face a more severe degree of corrosion. This effect can be seen in *Figure 15*, *16*, and *17*. In *Figure 15*, which is of area one, only concrete columns that have steel reinforcement throughout the body had cracks in

them. In *Figure 16*, which is of area two, all of the concrete columns that experience cracks in them are also columns that have steel reinforcement throughout the body as well. In *Figure 17*, which is of area three, the number of columns that have cracks was twice as much for the columns that have steel reinforcement throughout the body. This evidence, therefore, supports the hypothesis that humidity and ocean sea spray have increased the affects of steel rebar corrosion.

To be more specific, humidity is **not the cause** of cracks in concrete columns. However, the humidity was one of the main factors that increased the rate of corrosion for the steel reinforcement. Once minor cracks formed in concrete columns due to other factors, humidity from the sea and the surrounding area could seep through those small cracks. Thus, there could be rust in those reinforced steel bars which could build up and cause a more extensive cracking. Eventually, the concrete was pushed away from the steel bars, resulting in spalling of the concrete columns.



Since the Palace is situated on the seaside, an assumption was made that wind speed would relatively be stronger than normal. It could be a cause of corrosion by making the concrete column unstable because the strong wind would add parallel directional force towards the concrete structures, creating shear stress in the columns. However, after our first and second observations, this factor seemed not to be applicable and relevant. This is because it was too complex to set up a methodology to see this factor in effect. Additionally, there is also no solid evidence to prove that this factor is one of the direct causes of corrosion.

Based on collected information, the effect of wind could definitely be one of the causes of deterioration in concrete columns. The team found out that the direction and speed of the wind correlate with a specific type of crack pattern that is found in concrete columns. The specific type of crack pattern that it correlates with is the horizontal cracks that are found on the columns of buildings that have not

been recently renovated. These horizontal cracks were usually found on the opposite side of the columns that face to the shore. The location of the Palace is situated right next to the shore.

According to the “Windy” application, with the specific setting that is mentioned in the wind assessment section in objective one, the wind flows into the Palace from the shore majority of the time. An average from 2012-2021 showed that eight out of the twelve months of the year, the wind’s direction flows directly into the Palace from either the north or the south as seen in Figure 19. Only 4 of those months

showed that the wind flows in the opposite direction, which is away from the Palace. Another important finding is that the speed of the wind is also the strongest during those eight out of twelve months. Detailed graphs that contain the direction and speed of the wind with further detail can be found in *Supplementary Materials E*. This correlates with the observation that the horizontal cracks were found on the opposite side of the column that faces the shore because the prevailing winds would be able to add an additional lateral load on the concrete columns. Since the majority of the wind flows into the direction of the Palace from one side, the lateral load would be added on only one side of the Palace. Tension would be increased from only one side of the column and the other side of the column would experience a decrease of tension. The side that receives the increase in tension would be the side that forms the horizontal cracks.

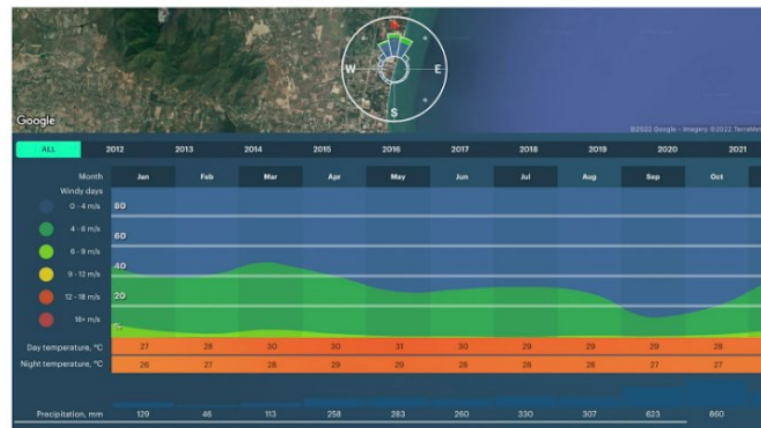


Figure 19. Detailed graph on Direction and Speed of Wind

**Architectural errors** are one of the most mentioned external factors in terms of factors that cause cracks in concrete columns. Previously, the team's assumption about the cause of corrosion in the concrete column was due to the excessive load from the heavier roof tiles. This was mentioned because, during the past restoration of the Palace, a new set of roof tiles that were about one kilogram heavier individually than the original set was used to replace the original set of roof files. However, this original assumption could be invalid. Based on consultations with Dr. Yuwarat, an architect, and the observation at the Palace, the crack patterns and corrosion that existed on the majority of the concrete columns might have been different if they were caused by the excessive load of the roof tiles. Cracks that arise from excessive load would have a specific pattern and location that is different from the cracks in the concrete columns. It would be more likely to form on the surrounding walls and the specific pattern would be deeper and wider with a slanted or diagonal pattern.

Furthermore, the cracks that existed on the concrete columns were merely **outer surface cracks** that did not relate to or affect the stability of the concrete columns. The team made a few crack maps that contain detailed dimensions of cracks on concrete columns. The dimensions that were measured and drawn on the crack map also showed that these cracks are not

that lengthy. Based on observation, the cracks on the columns were mostly on the surface and were very shallow in depth. An example of the crack map of cracks on the concrete columns can be seen below in *Figure 20*. This specific crack map only shows the dimension of length. The width was not measured because it was too small to get an accurate measurement.

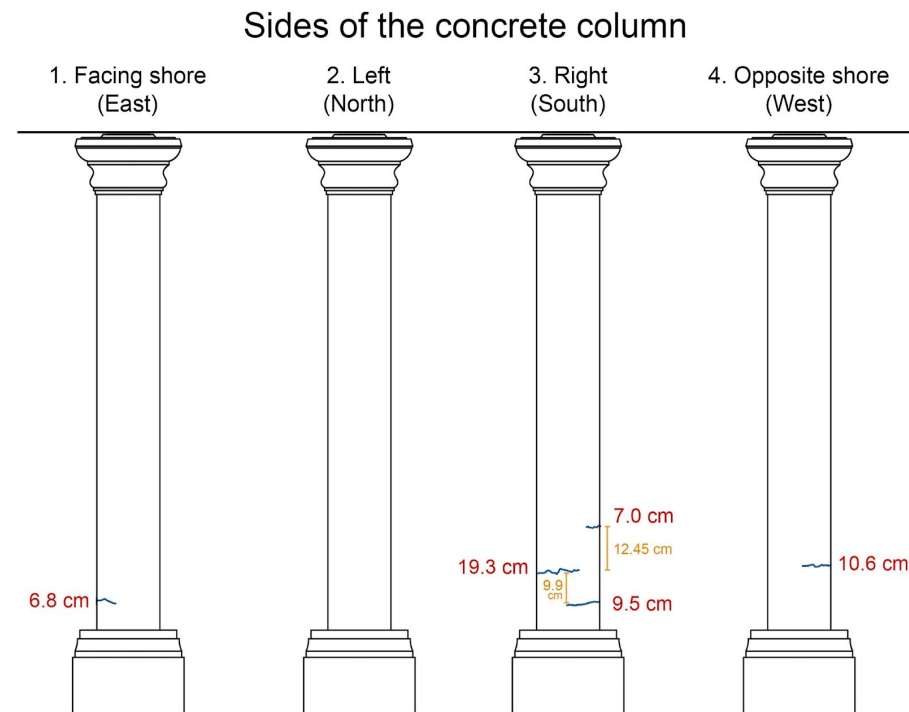


Figure 20. Example of a crack map on concrete columns with length

The outer surface of the concrete column is the additional patched concrete layer that was added to the main column. The cause of the cracks in the outer surface of the concrete column could not be stated with confidence yet, but some possible causes would be the instability of the upper wooden structure that sits on top of the concrete columns which is mentioned in detail previously. Another possible cause was that the outer surface/ additional patched layer was not applied well enough, as there was an insufficient surface area for the additional patched layer to hold on to the core of the column. This hypothesis was put together based on observing the educational columns that the Palace put on display. The additional patched layer could be seen to be very thin, and no materials were put in between the patched layer and the core of the column to increase the adhesion. Therefore, minor cracks could start forming on the surface and easily let moisture seep in and cause further corrosion, as illustrated in *Figure 21*.

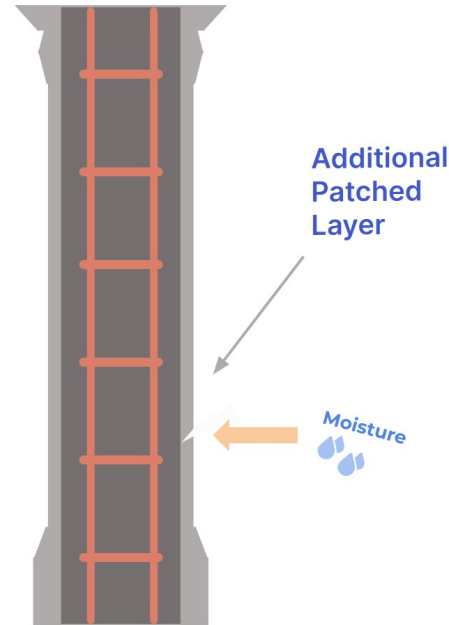
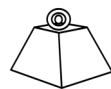


Figure 21. Illustration of the additional patched layer of concrete on the reinforced concrete column

### Palace Walkways Face Heavy Loads



The walkways on the ground floor of the Mrigadayavan Palace were made of concrete which has no steel reinforcement inside. There were no expansion joints presented in the concrete walkways. Cracks on

the concrete walkways or concrete floor base were observed to be mainly on the surface. The areas with the most deterioration problems were in the Samutphiman, section 6, and Pisansakorn, section 14, as seen in the map in *Figure 9*. The majority of the cracks were mostly near or between the concrete columns. Some cracks on the concrete floor extended from one column across to the other columns as shown in *Figure 22*.



Figure 22. Cracks in the concrete walkway between two columns

According to the Palace staff, there was no major structural renovation on the concrete walkways since the first construction in 1924.

Small-scale repair processes happened throughout the years, as walkways showed some signs of minor repairs. The timeline of the repairs is uncertain due to the lack of past restoration records. Nevertheless, differences in concrete color on the walkways in *Figure 23* showed that the concrete patching technique had been done in the past restorations. When cracks occurred on the concrete walkway, the new concrete paste would be used to patch up on the surface.



Figure 23. Signs of the difference in concrete colors in the concrete walkways

The Palace staff suggested that the installation of new **heavier roof tiles** could be one factor that might contribute to walkway cracking since the new tiles increased the

load onto the column and the floor. This could be stated as another hypothesis that the new roof tiles were not uniformly distributed and therefore caused unequal loading between different columns. This could cause the concrete walkways in each region to receive different amounts of loading force from above and form cracks.

The absence of expansion joints was another factor that could cause the cracks. The cracks in walkways were most visible near the concrete column because these areas are more highly constrained by the presence of the concrete columns. Therefore, the concrete walkways experienced more compressive loads because there is no room for expansion. This expansion could be due to heat from the climate and load.<sup>19</sup> Areas on the concrete walkways that are further away from the concrete columns can expand easier into the surrounding ground. Clear evidence showing that this type of crack was due to the absence of expansion joints was the number of cracks present in the corridor to the Outer Court Bathing Pavilion. Ninety

percent of the concrete walkway in between columns showed a crack from one side to the other. Since the Palace would not be having the concrete walkways renovated, the installation of expansion joints would not be possible.

### Ceiling Tiles: Concrete vs Wood Beams



Other than the deterioration in the concrete walkways and columns, cracks and discoloration were also observed in the concrete ceiling panels. These concrete ceiling panels are found above every wooden walkway in the Palace. The panel placement in one area of the Palace can be seen in *Figure 24*.



Figure 24. Photo of King's Dining Pavilion at the Mrigadayavan Palace



The panels are a modular grid system of three meters by three meters, each module has nine individual panels of various dimensions and painted designs. These panels were then painted and have never been restored. Within each of the nine panels in each grid, there is steel reinforcement in each panel. Using the metal detector to scan for the existence of the steel reinforcement, the team discovered that the pattern of the inner steel reinforcement was a four-by-four metal bar grid. These steel-reinforced ceiling panels have been supported by wooden frames and are held up by a complex truss system in the roof. From the observations, a minor crack at the edge of the concrete ceiling panels was observed on the displayed ceiling panel *Figure 25*.



Figure 25. Concrete crack due to uneven weight distribution of wood framework

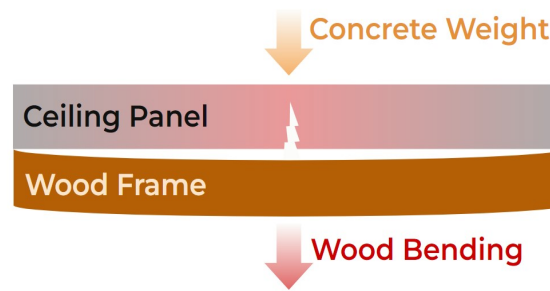


Figure 26. Schematic explanation of the crack in the concrete ceiling panel

**Architectural errors and deterioration** played a major role in causing **cracks** on the concrete ceiling panels. After discussion with the Palace Foundation, it was determined that the cracks on the concrete ceiling panels were caused by the instability of the wood framework. As time passes, the wood framework that supports the weight of the concrete panels bends. This creates an uneven weight distribution of concrete panels onto the wood framework. The arched part of the wood framework could support less weight of the concrete pane causing concrete ceiling panels to crack in the middle area between two edges as explained by *Figure 26*.

The effect of roof leakage is one of the main causes of corrosion for concrete ceiling panels. Roof leakage damaged both the appearance and physical state of the concrete. As the ceiling panels are made out of gray concrete which contains high breathability and permeability, it allowed water and vapor to seep through from the leaks in the roof. *Figure 27* shows pale marks with a droplet-like shape on the surface. These **stains** are caused by water that came in through the roof and seeped through the concrete panel and formed drops on the lower side of the panel. These droplet stains resulted in an unappealing appearance.



Figure 27. Pale marks with a droplet-like shape on the surface of a ceiling panel

Even though most of the cracks are relatively small, roof leakage is also one factor that could cause the cracks to grow larger and more intense. The degree of cracks in concrete ceiling panels at their highest point in buildings contains leakage in the roof. This is due to water that leaks through the roof and acts as a catalyst that speeds up the process of steel reinforcement corrosion. However, the effect of roof leakage would not play a part if there were no cracks contained.

Aside from the cracks, another aspect that was affected was the discoloration. The concrete ceiling panel itself contained the inner steel reinforcement inside to support the structure. The **inner steel reinforcement** is a four-by-four metal bar block, which correlates with the pattern of discoloration on the panels. As shown in *Figure 28*, rust from the steel rods created a mark on the panels in a yellow-like color plus sign mark which correlated with the steel reinforcement pattern, in *Figure 29*, as observed by using the metal detector. Over time, humidity causes rust on the steel rods. Rust on the

steel affected both the appearance of the concrete panels and their physical state in terms of cracks.



Figure 28. Plus sign marks with a yellow-like color due to rust on the steel rods



Figure 29. Steel reinforcement pattern in a ceiling panel

## Decision Tree and Supplemental Table



Repairs to the concrete damage at the Mrigadaya-van Palace may take the form of preservation, restoration, or rehabilitation; these terms are defined in *Table 2*. Based on our discussions with the sponsor, we determined that rehabilitation and preservation strategies are best aligned with the Foundation's goals. The foundation staff plans to use new technologies to repair concrete structures in the Palace and have expressed their interest in keeping the repairs visible or even leaving some damage visible to serve as an educational component. This finding seems to match the work done in rehabilitation and preservation rather than restoration.

The recommendations developed to meet the goals of the Palace Foundation are presented in the form of the decision tree with a supplemental criteria table. The decision tree, *Figure 30*, categorizes the deterioration until one restoration method is presented.

The supplemental criteria table, *Supplementary Materials F*, is a compilation of the overall analysis of the various restoration methods. The first two criteria are ease of implementation and implementation time based on the availability of the materials and level of expertise needed. Longevity is also an important criterion to prevent potential issues in the future regarding the concrete and its maintenance. Based on discussion with the Palace Foundation, aesthetics is an important aspect to consider when making recommendations. Maintaining historical accuracy is a key-value; however, visual differences in concrete

aesthetics are also important for educational purposes. The last criterion considered is crack size to suggest the most effective restoration method regarding different sizes and types of cracks.

Some of the recommended techniques that will be implemented to restore the concrete at the Palace include jacketing, sealants, and partial depth repair. Jacketing of concrete is a method that reinforces columns with steel rebar by adding a layer of concrete reinforced by longitudinal steel reinforcements and traversing steel ties around the original column in the form of a jacket. Sealants are plastics or other poly-

mers applied in cracks or over surfaces to serve as protection against water and chemical attacks. Partial depth repair involves the removal of small areas of deteriorated concrete found in only the top half of a walkway slab followed by the insertion of compressible material between the new concrete and the old and then the subsequent application of patching material to the area. Further definitions and descriptions of all the recommended restoration techniques, as well as other terms established on the decision tree, can be found in *Supplementary Material G*.

Table 2. Definition of some conservation terminologies

Term	Definition
Preservation (n.)	the act or process of applying measures necessary to sustain the existing form, integrity, and materials of a historic property
Restoration (n.)	the process of returning a building to its former state
Rehabilitation (n.)	the act or process of making possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features which convey its historical, cultural, or architectural values

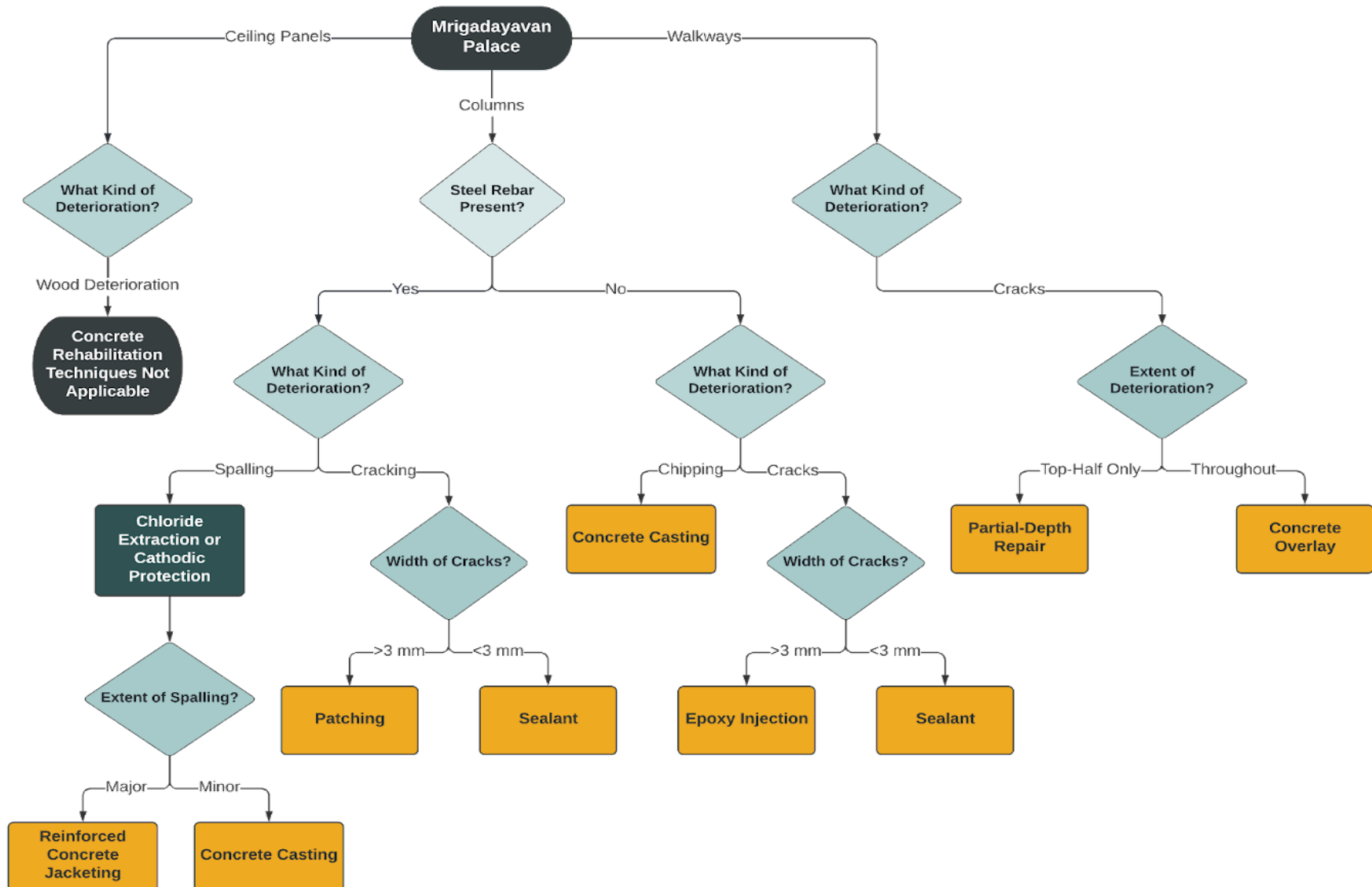
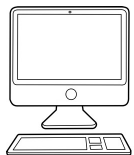


Figure 30. Decision tree for concrete restoration recommendations



Overall, the team learned that regardless of restoration method, implementing concrete matching and a prevention technique will be beneficial in accommodating the sponsor's goal of keeping the original structures and maintaining historical accuracy. Concrete matching will maintain historical accuracy in terms of appearance and ensure consistent strength and permeability in the concrete. The process of concrete matching is explained in *Supplementary Materials H*. Additionally, through the literature reviews, the team found that the presence of steel reinforcement in the concrete requires a preventative measure of either cathodic protection or chloride extraction. This must be done for all structures with reinforced concrete before any additional restorations and for all preservation.

### Website and Pamphlets Design



The team proposed that information collected about concrete deterioration and rehabilitation

methods be displayed on the Palace website. A webpage was prototyped for the Palace Foundation using the Origami Studio software. This software was utilized to build and test user interface interactions. A full-page design was included in the final deliverables as a suggestion for formatting and information to add to the website. Details and images on the degrees of deterioration such as different-sized cracks, spalling, and corrosion are also included. Under each of the types of deterioration, methods of rehabilitation are explained.

In the development of the webpage, it was important to consider the target audience. The Mrigadayavan Palace Foundation currently expects that the visitors to the website would be the same demographic that visits the site, an age range of college to adults. Overall, this means that there will be a more mature audience. The concrete restoration page is accessible through the Palace Foundation's primary website. In order to make the information more accessible and relevant to the Palace visitors, the team pro-

poses the placement of QR (quick response) codes in high foot traffic areas around the Palace grounds where rehabilitation has been implemented. An example of this QR code poster can be found in *Supplementary Materials I*. The team also designed paper pamphlets to be included at each QR code station for visitors without cellular data or who may be unfamiliar with the use of a QR code. Each pamphlet includes the information that is included on the respective webpage for the nearby restoration. An example pamphlet can be found in *Supplementary Materials J*.

### Conclusion and Discussion

The Mrigadayavan Palace Foundation tasked the team with developing a plan to repair the concrete structures at the Palace. Interviews were conducted with the Palace Directors to determine how suggested concrete rehabilitation techniques could support the aesthetic, historical, and cultural goals of the Palace Foundation. These goals include preserving and rehabilitating

the damaged concrete through a variety of restoration techniques. Site visits provided evidence that the concrete deterioration was focused on columns, ceiling tiles, and walkways. Through extensive research and analysis of the concrete structures at the Palace, the team developed recommendations that were provided through a decision tree seen in *Figure 30*. The team used extensive criteria to evaluate and determine which techniques achieved the desired outcome outlined by the Palace Foundation. In addition to the decision tree, the team developed web pages to be added to the current Mrigadayavan Palace website as well as QR codes and pamphlets to be placed around the Palace. This material was designed to provide educational material for those visiting the Palace and to learn more about the historical restoration of concrete structures. With concrete being the leading construction material in the world, its deterioration is inevitable. The project introduces the idea that important historical concrete architecture can be preserved and restored for years to

come. Through the completed research and deliverables, readers can become more engaged with the idea of concrete as a construction material.

### Our Recommendations and Implementation Plan

This section contains a summary of the group's recommendations to the Mrigadayavan Palace Foundation for the deteriorating concrete structures. It includes the recommended restoration techniques for concrete columns, walkways, and ceiling tiles, an educational tool through a webpage, visual aids to be presented around the Palace, and future areas of research.

The project team recommends the Palace Foundation implement the rehabilitation techniques for the concrete structures based on the developed decision tree. There are many different aspects of concrete restoration that should be considered when repairing structures at the Palace. The restoration techniques consider criteria such as ease and time of implementation, availa-

bility of materials, aesthetics, historical accuracy, and longevity. All the recommended solutions have been thoroughly researched and considered based on the developed criteria. It is highly recommended that the Palace Foundation pay special attention to the concrete columns, especially those with exposed steel reinforcement, as these repairs will require the most amount of time. Due to the approaching centennial anniversary and opening date only two years away, the Palace Foundation should prioritize repouring the concrete walkways as well.

We recommend that the Foundation implement an additional web page on the conservation tab of the website related to the occurring restorations for each type of structure: concrete columns, walkways, and ceiling tiles. The Mrigadayavan Palace website includes information related to history, conservation, architecture, visitation, engagement, and support of the Palace. Displaying the webpage information curated would be beneficial to those who experience concrete deterioration at their homes and businesses. Those

who experience a similar climate and structures made of similar materials could benefit from easily accessible content related to concrete restoration. This can also bring to light the deterioration of concrete in the world as concrete is a prominent worldwide construction material.

The Mrigadayavan Palace Foundation should also consider the placement of additional information related to concrete restoration at the Palace. It is recommended that the Palace place QR codes near the concrete structures to be scanned to enhance the information related to these structures. The supplemental QR codes would direct the visitor to the specific portion of the implemented Palace website to provide more information and educational materials related to how the restoration was completed. The QR codes are easily accessible for those with internet access and can be viewed after leaving the Palace. For those who do not have internet access or are unfamiliar with the technology, it is also recommended that pamphlets be distributed to supplement the visitor experience. The

pamphlets would provide an overview of concrete restoration and rehabilitation that has occurred at the Palace. This information could be brought back to homes and businesses to amplify the problem of concrete deterioration and how to rehabilitate structures.

The Palace Foundation should expand on the educational components delivered from this project. In the process of repairing the deteriorating structures, the Palace Foundation could provide demonstrations of the techniques used to help visitors better understand what goes into the rehabilitation of historic structures. The QR codes and pamphlets distributed could provide supplemental information for hands-on demonstrations for visitors.

We recommend that the Mrigadayavan Palace Foundation further explores the fungus and rot development on wooden frame-works. The wooden structures at the Palace are deteriorating from poor drainage of excess water. This has caused the development of rot and fungus which has caused the concrete ceiling tiles to lose proper sup-

port. Expanded research into this aspect of deterioration at the Palace will help the Foundation achieve their goal of full restoration by the centennial anniversary in 2024.



**Thank You**

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