Design of Duxbury Boardwalk

Sponsoring Organization: Duxbury Beach Reservation

A Major Qualifying Project Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements of the Degree of Bachelor of Science in Civil Engineering

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Abstract

Two students from Worcester Polytechnic Institute, in collaboration with Duxbury Beach Reservation, worked together in this Major Qualifying Project to develop a structural design for an accessible passage that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. The project produced several distinct deliverables including a structural design and analysis, 2-D and 3-D models of the proposed design, and a cost estimate. To achieve these results, the team established existing site conditions, identified initial design criteria, analyzed the proposed structural design, and produced a final proposed package.

Executive Summary

Purpose and Goals

A pair of students from WPI worked with support from Sue MacCallum from the Duxbury Beach Reservation to create a design for an accessible passageway through the High Pines area of Duxbury Beach. The goal of this project was to develop a structural design for an accessible boardwalk that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. The team aimed to create a structural analysis of the proposed design, a 2D and 3D model of the proposed layout, and a cost estimate. To achieve this, the following objectives were developed:

1. Establish existing site conditions
2. Identify initial design criteria based on sponsor and stakeholder needs
3. Analyze the structure of the proposed design
4. Evaluate the final design package

Methods

At the beginning of the project, the team sought to understand the expectations of the sponsor as well as to understand the issues that the area faces. To achieve this, the team held a series of meetings with the sponsor, Sue MacCallum. Additionally, the team also performed extensive research and conducted a site visit. From this research and meetings, the team was able to establish design criteria and expected outcomes, which aided in guiding the project's direction. A preliminary design for a boardwalk was created based on the team's initial understanding and calculations. With this methodology, the team was able to complete their first two objectives.

The team then conducted another set of meetings with the sponsor and advisors to obtain feedback and additional information. From these meetings, the team was able to develop a more refined design and layout of the proposed boardwalk. For the selection of the layout and material choice, the team worked closely with the advisors and sponsor to find options that were both feasible and effective. Upon confirming these design choices, the team was able to perform the design calculations for the substructure and the superstructure.

Results

The product of these three objectives was the creation of the team's models, a structural analysis, a cost estimate, and a final proposed layout. The team used the structural analysis software RISA-3D to perform a structural analysis of the design of the proposed boardwalk. This helped to size the members of the boardwalk. The team then used SketchUp to create a visual representation of the boardwalk within its natural setting. The team developed a cost estimate to provide an approximation of the expenses associated with constructing a structure of this scale, including materials, labor, equipment, and other construction costs. This amounted to approximately $200,000, with $110,000 attributed to labor and construction, and $90,000 coming to materials. This cost assessment and the proposed design were then presented to the sponsor for implementation using their manufacturing techniques. These allowed the team to create and finalize a design package that also included a list of recommendations to further enhance the design of the boardwalk.

Recommendations and Conclusions

The team's final design products display the completion of the four objectives, following the defined methodology. Through the completion of this project, the team determined that there were a variety of constraints that would affect the construction of an accessible passageway and our proposed final design package would best help to solve this while mitigating the issues highlighted earlier. Designing the structure to withstand environmental impacts like storm surge and material degradation is absolutely essential. It determines whether this structure would be able to last, ensuring its enjoyment by visitors, or whether it would be a nuisance that would cause issues to both the environment and visitors.

Acknowledgments

The team would like to extend its heartfelt gratitude and thanks to everyone who played a pivotal role in the success of this project. Special thanks go to Sue MacCallum from the Duxbury Beach Reservation, whose sponsorship and regular engagement with the team significantly contributed to the project's steady progress.

We are also profoundly thankful to our academic advisors, Professor Suzanne LePage and Professor Leonard Albano. Their endorsement of the project, coupled with their wisdom and assistance, guided us through every challenge we faced.

Additionally, we appreciate the encouragement from the town of Duxbury and the Duxbury Beach Reservation. Their support inspired us to design and propose an accessible boardwalk that seeks to enhance the well-being of the community at large.

Authorship

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Capstone Design Statement

The Major Qualifying Project (MQP) is the culmination of WPI's project-based learning into a tangible capstone project. The MQP helps students to put into practice the theory of what they learned into real-life issues. In the Civil Engineering program, the MQP satisfies the capstone design requirement defined by the Accreditation Board for Engineering and Technology (ABET). The following constraints were considered by this project: economic factors, environmental aspects, social considerations, political implications, ethical concerns, health and safety aspects, constructability, and sustainability. By designing an accessible passageway for Duxbury Beach, this project fulfills the goal of the capstone design.

Economic

In evaluating the feasibility of the team's design, we took into account financial factors. Cost estimates were prepared specifically for the Duxbury beach site in accordance with the needs identified by the project sponsor. Although there was not a set budget for the project, cost minimization was a critical consideration for the design. The team looked at multiple preliminary design alternatives and determined which option best fit the needs of this project with a cost analysis. Material and labor costs were considered to best achieve a balance between quality, longevity, and affordability.

Environmental

To address environmental limitations, the team constructed the project around sensitive ecosystems such as sand dunes, beach vegetation, and Piping Plover habitats. It was important to ensure the state of the sand dunes on the site is protected from human impact. Additionally, the potential impacts of storm surges on the structure such as degradation of materials into the environment were taken into consideration.

Social

By seeking input from our community-active sponsor, we aimed to effectively address the concerns of future boardwalk users on a social level. When designing the boardwalk, our objective was to strike a balance between enhancing the user experience and minimizing disruptions to the surrounding environment and community. To ensure the seamless integration of these design considerations we actively engaged with stakeholders, particularly during the design phase which is when designers have the most flexibility to make modifications.

Ethical

This project, adhering to the American Society of Civil Engineers (ASCE) Code of Ethics, led the team to follow guidelines that ensure the creation of safe, resilient, and sustainable infrastructure. The team considered the most significant needs of the project sites, focusing on improved beach access and dune preservation.

Health and Safety

The team considered the safety of the future stakeholders. The team researched and analyzed the design to determine that it meets appropriate structural design standards and would ensure the safety of users. These standards come from sources such as the Massachusetts state buildings codes, National Design Specification (NDS) for wood construction, and the American Association of State Highway and Transportation Officials (AASHTO). Furthermore, the health of the environment was considered by selecting materials that would have minimal impact on the surrounding environment.

Constructability

The project accounted for the constructability of the passageways by assessing the needs of each location. This allowed the team to select materials that were available and feasible for implementation to current conditions on each beach.

Sustainability

The team took the use of different materials into consideration when preparing the design. The materials used and the design itself were researched so that the boardwalk has sufficient structure to prevent erosion and maintain conditions on-site. This would allow for the passageway to have more durability during events such as harsh winters and storm surges that the design would likely encounter.

Professional Licensure Statement

Professional Engineering (PE) licensure is paramount in ensuring public safety by allowing only those with proven competence and judgment to undertake the practice and responsibilities within the engineering field. Recognized as the pinnacle of professional achievement, the PE license signifies a high level of expertise and ethical standards in civil, environmental, and architectural engineering disciplines. It is essential for the preparation, signing, sealing, and submission of engineering plans for public approval. Beyond safeguarding public interest, licensure offers substantial career benefits, including advancement opportunities, potential for higher earnings, the development of a personal client base within larger firms, and avenues for self-employment.

To achieve licensure, candidates must fulfill state-specific education and experience prerequisites, including obtaining an ABET-accredited engineering degree, which streamlines the path to sitting for the required examinations. The licensure process involves passing two critical exams administered by the National Council of Examiners for Engineering and Surveying (NCEES): the Fundamentals of Engineering (FE) Exam, typically taken in the senior year of undergraduate study or shortly after graduation, and the Principles and Practice of Engineering (PE) Exam, which follows the FE exam and the completion of requisite professional experience, with the duration dependent on state requirements (e.g., four years in Massachusetts).

The FE Exam is a computer-based test offered year-round, designed to assess competency in a specific engineering discipline, including sub-disciplines for Civil Engineering such as Construction, Geotechnical, Structural, and Transportation, covering a wide range of topics to ensure breadth and depth of knowledge.

NCEES plays a crucial role in the licensure process by developing, administering, and grading the FE and PE Exams. It also offers services to support engineers in practicing across different jurisdictions, making it an essential resource for prospective licensees to understand the exam formats, requirements, and procedures for licensure in their respective states.

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FEMA: The Federal Emergency Management Agency, a U.S. government agency responsible for coordinating the response to disasters that overwhelm the local and state authorities' ability to respond, ensuring the mitigation, preparedness, response, and recovery from disasters and emergencies.

Barrier Beach: A coastal landform and a type of barrier system, consisting of a long narrow sandy island that forms offshore parallel to the mainland coast. It serves to protect the coast from the full impact of storm waves and sea level rise.

NAVD88: The North American Vertical Datum of 1988. It's a vertical control datum used for measuring elevations in the United States, Canada, and Mexico.

Bearing Capacity: This term refers to the capacity of soil to support the loads applied to the ground. It's a critical concept in the field of civil engineering, especially concerning the design and construction of foundations.

AASHTO: The American Association of State Highway and Transportation Officials. It's a standards-setting body that publishes specifications, test protocols, and guidelines used in highway design and construction in the United States.

NOAA: The NOAA stands for the National Oceanic and Atmospheric Administration. It is an American scientific agency within the United States Department of Commerce that focuses on the conditions of the oceans, major waterways, and the atmosphere. NOAA warns of dangerous weather, charts seas, guides the use and protection of ocean and coastal resources, and conducts research to provide understanding and improve stewardship of the environment.

1.0 Introduction

Boardwalks have been used in the U.S. for over a century. They have allowed people to traverse diverse terrains without impacting the local nature and fauna. Although they vary in design and size, they all function as pathways that run along a waterfront or shoreline. Recognizing the environmental and community value of such natural features, the decision to install a boardwalk in Duxbury aligns with efforts to preserve the area's natural beauty while enhancing accessibility for residents and visitors alike.

Located on the south shore of Massachusetts, Duxbury has been a long-standing beach town. Notably, Duxbury is also home to one of the many barrier beaches in Massachusetts. These large sections of deposited sediment (barrier beaches) serve as important habitats for several species of animals. In addition to this, they also act as shields to the mainland by absorbing the waves' energy. This allows for smaller storm surges and less flooding along the coast (US Department of Commerce, 2021).

Unfortunately, these barriers have been disappearing all around the world. Massachusetts, in particular, has been losing approximately 65 acres of coastal land per year due to shoreline retreat caused by sea level rise (*U.S. Geological Survey*, n.d.). Considering this, when designing a boardwalk, it is crucial to consider resilient systems that can withstand various weather conditions. Moreover, by incorporating essential design elements such as effective drainage systems, elevated sections, and durable construction materials, the detrimental effects of storm surges can be significantly reduced.

The Duxbury Beach Reservation, a local non-profit that has owned and managed 4.5 miles of the beach for the past 100 years, actively works to meet the challenges Duxbury Beach faces. The organization proactively seeks solutions to address these issues, ensuring that the beach can be enjoyed for years to come.

The goal of this project was to develop a structural design for an accessible passage that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. To achieve this goal, the team fulfilled four primary objectives: Establish existing site conditions, identify initial design criteria and design and analyze the boardwalk structure.

2.0 Background

This chapter provides the context for locating and designing the Duxbury Beach Reservation boardwalk. It introduces several key topics. These include previous designs of other boardwalks, legal issues and permitting, and accessibility factors. Also covered are sea level rise and storm surges, along with the costs of boardwalks. These topics form a foundation upon which the project is based.

2.1 Previous Work

In the spring of 2023, a previous MQP report called "Beach Access and Coastal Design" by Webster, et al. discussed the idea of constructing a parking lot beside Duxbury Beach along with a design for a boardwalk to allow access to the beach from the parking lot. The report investigated various issues that could arise from building a boardwalk in this area and factored those in to create an initial design scheme and location for the boardwalk. This initial design proposal is the foundation of this project, which is a direct continuation of their work.

2.1.1 Environment

One of the major factors that the previous team had to consider was to avoid creating a negative impact on the local environment. There were two main challenges that came from the area: avoiding the impact on sand dunes and the local wildlife. A sand dune is an accumulation of sand formed by wind, waves, and eroding sandstone, with a structure that is constantly changing and growing due to natural patterns of the wind and the coastal tide (England, 2022). Sand dunes protect the coastlines and wildlife against winds, coastal flooding, and erosion. The sand dunes absorb a lot of the impact from those factors and are therefore especially susceptible to erosion themselves. The dunes are protected and rebuilt by nature conservation groups because of how well they naturally protect the shorelines. Many animals, like Piping Plovers, use the sand dunes as their habitat because they provide protection while being near the oceans. The preliminary design of the boardwalk was made in a way where the dunes and the wildlife would face negligible negative effects on their habitat *(Webster, Colette, et al.)*.

2.1.2 Location

The location of the boardwalk and parking lot was recommended to be High Pines, a slightly wider area of the beach strip providing sufficient space to construct a parking lot. The approximate location of the proposed boardwalk can be seen in Figure 1a. The location is ideal for beach users because it is near the middle of the strip, where parking is limited. The area between the proposed parking lot and the beach is a protected area for sand dunes. This means that users cannot cross this location on foot because foot traffic may cause damage to the sand dunes. A boardwalk was proposed to allow people to use the parking lot and access the beach while not disturbing the sand dunes.

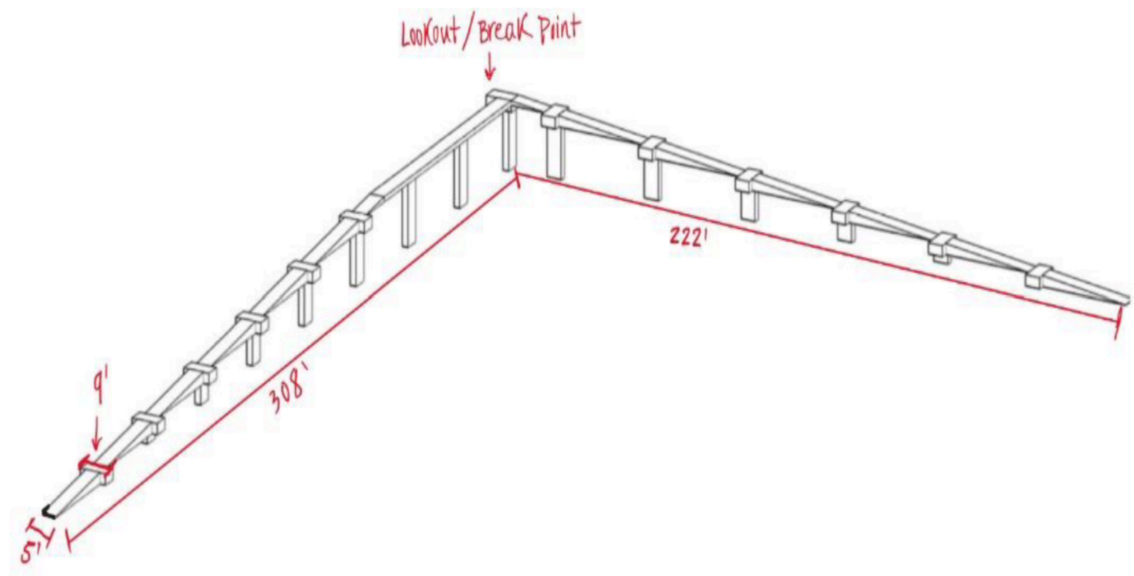
(a.) **(b.)**

Figure 1: (a) Photo displays the estimated placement of the boardwalk. (b) Photo shows where High Pines is located.

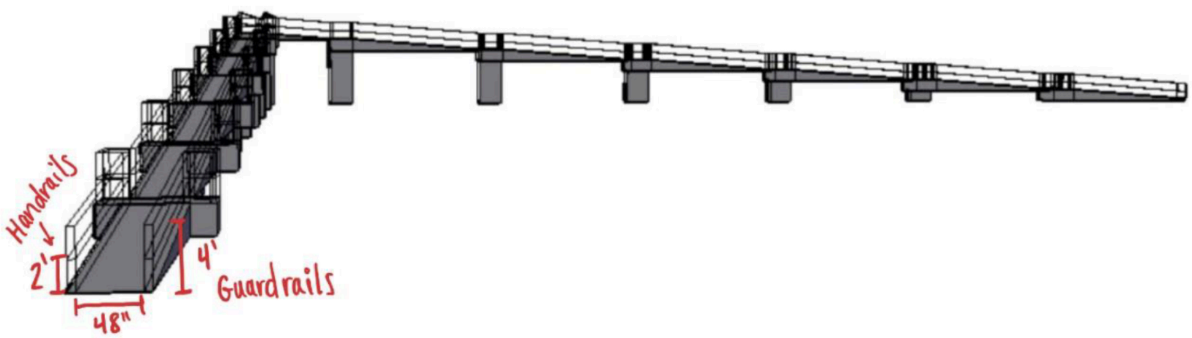
The location of this site does pose a challenge when it comes to erosion. The area is located on the coastline of Massachusetts, so winds and water are going to have a major impact when it comes to the lifespan of a boardwalk. Massachusetts experiences winters where multiple inches of snow are not uncommon, so snow loads are also a consideration for potential damage. This year's team was able to visit the site and investigate other boardwalks in the area. A similar boardwalk near the residential parking lot entrance was shown to have moderate wear from the erosion the boardwalk had experienced. It was missing pieces in some areas that were not crucial to the structure and had multiple areas that appeared to have been replaced with newer pieces of wood. This boardwalk is a reference to what can be expected of a wooden boardwalk after around 10 years of exposure to local erosion factors. The location of the proposed boardwalk will be near the ocean during high tides, and with slowly increasing sea levels and storm surges, it may be set in a vulnerable position in the future.

2.1.3 Design Choices

The purpose of the boardwalk is for people who use the High Pines parking lot to be able to access the beach. The structure also must be able to clear the sand dunes which stand at about 16.5 feet NAVD88. In addition, the design must have proper accessibility to meet ADA requirements. This means the slope of the ramp has a limit and needs to incorporate rest stops at certain intervals. The design needed to be long enough so that the proper height to clear the dunes could be achieved while not exceeding the slope limit. The result of previous work carried out by the previous MQP team can be seen in the design in Figure 2.



(a)



(b)

Figure 2: Final designs of the previous project. A basic isometric view (a) is shown with the lengths of the entire structure while the other image (b) incorporates guardrails into the picture. (Webster, Colette, et al.)

2.2 Designs of Similar Boardwalks

There is a plethora of other boardwalk designs that also serve as a good model for the planned construction of the Duxbury Boardwalk. While others may differ slightly in design and scale, they offer a view into potential design challenges and material choices.

2.2.1 Sandwich Boardwalk

One example boardwalk is located on Cape Cod in Sandwich Massachusetts. The Sandwich Boardwalk, also known as the “Plank Walk” or the “Mill Creek Foot Bridge " is a 1300-foot boardwalk that was originally constructed in 1879 (Figure 3). Since then, it has gone through many changes, including several repairs and upgrades, as well as complete reconstructions (*History of the Boardwalk | Sandwich Historical Commission*, 2021). Being along the Cape, this beach boardwalk is also exposed to similar elements such as sea salt, flash flooding, blizzards, and freezing. This gives insight into how a boardwalk would hold up in the future. In fact, the creation of the Cape Cod Canal over 100 years ago changed the natural migration of sand along the coastline and rock groins, causing more coastal erosion and beach/dune erosion in addition to more damage to the boardwalk (*Coastal Resiliency | Sandwich, MA*, n.d.).

In terms of design, the timber boardwalk framing is made up of 4x4 posts, 2x8 split pile caps, 2x6 middle stringers, 4x6 edge stringers, and Ipe decking. Similar to other boardwalks in Massachusetts, this boardwalk and dune walkway also employs pressure-treated Southern yellow pine for the timber and composite decking. With respect to existing building codes, the Sandwich Boardwalk was not meeting multiple standards since its last upgrade. The *Massachusetts State Building Code* (SBC) only requires that buildings and structures comply with the edition of the code that is in force at the time of their construction. The boardwalk's last major reconstruction was in 1992, with minor repairs conducted in 2018. Despite these efforts, several sections of the Boardwalk were nearing the end of their service life, necessitating considerable reconstruction to prevent large-scale loss. In 2021, the town of Sandwich began a comprehensive $2.3 million restoration project. Given that the renovated area would surpass 30% of the entire structure's "full and fair cash value," the Massachusetts Architectural Access Board (MAAB) required that the entire structure be upgraded to comply with current standards. The issues of non-compliance to be addressed include edge protection and ADA accessibility. Edge protection requires a guardrail for any platform in which a fall of 30 inches or greater is present. The Massachusetts Architectural Access Board (MAAB) and the American Accessibility Act (ADA), require that ramps longer than 30 feet have a maximum slope of 1:20 (Boardwalk Project | Sandwich, MA, n.d.).

Figure 3: Image of Sandwich Boardwalk. Shea, 2020; Treffeisen, n.d.

2.2.2 Plum Island

Located on the North Shore of Massachusetts, Plum Island is home to the second boardwalk that we investigated. Known as the Hellcat Boardwalk, this impressive multipath trail stretches for 1.4 miles and was constructed in the 1970s. The boardwalk consists of two distinct sections: the dune trail, which covers 0.6 miles, and the marsh trail, which spans the remaining distance.

Since the '70s this boardwalk has gone through a few changes with the most recent being in 2020. During this upgrade, the engineers opted to replace the wooded boardwalk with synthetic planks that are longer and wider than the original wood planks (Figure 4). This widening of the planks has allowed for greater accessibility for those in wheelchairs ("Hellcat Boardwalk Trail," n.d.).

Figure 4: Shows photo of the lookout on the Hellcat Boardwalk (Shea, 2020).

2.2.3 Duxbury Beach Parking Lot Boardwalk

In 2023, a boardwalk was constructed in front of the Duxbury Beach parking lot. It was completed by Duxbury Construction, and the structure showcases the type of design, aesthetic, appeal, and accessibility that the team sought to create in our proposed boardwalk (Figure 5).

The parking lot boardwalk is crafted from Eastern White Pine and Southern Yellow Pine, while its decking is mostly composed of hardwood. The framing of this boardwalk is composed of 2 in. x 10 in. joists, 3 in. x 8 in. split caps, and 4 in. x 4 in. railing posts. Despite its 80-foot length, this boardwalk demonstrates some of the specific needs, constraints, and approaches that will be necessary to meet the requirements of the area.

Different from the other boardwalks previously mentioned, this boardwalk includes a removable ramp that is designed to be detached during winter or stormy months (Figure 6). Not only does this aid the preservation of the structure, but it also addresses the potential elemental constraints of the area. However, this boardwalk is facing some issues in ensuring full compliance with ADA standards due to the constantly shifting slopes of the beachfront.

Figure 5: Image of Duxbury Parking Lot Boardwalk running over dune fence.

Figure 6: Image of the lower side of the Duxbury Parking Lot without ramp attached.

2.3 Design Criteria

Design criteria established the factors that were considered when looking at the design of the boardwalk. They served as the standard guidelines that the team had to abide by and helped to create a starting point for the project in the process. These factors can range from legal standards to environmental hazards. These were crucial in determining a final design for the boardwalk.

2.3.1 Codes and Permitting

Obtaining beach permits requires a multitude of approvals, both during the construction and reconstruction stages. These permits have a significant impact on the construction methods that can be employed and the overall duration of the project. Construction in Duxbury is subject to local building department codes and permitting, which review the design of the structure before granting approval. Table 1 summarizes the required permits for building a boardwalk in Duxbury. This permitting information was obtained from local government websites and via consultations with our project's sponsor Sue MacCallum, the Duxbury Beach Reservation Program Specialist.

Table 1. Required Permitting for Construction on Duxbury Beach

Permit	Jurisdiction	Description
Army Corp of Engineers	Federal	Regulates work done below mean low tide
Coastal Zone Management	State	Reviews possible impacts
Dept. of Environmental Protection	State	Reviews possible impacts on designated wetlands
Natural Heritage & Endangered Species Dept	State	Reviews possible impacts on state-listed/protected species
Building permit	Town of Duxbury Building Department	Reviews structure
Conservation Commission review	Local	Reviews possible impacts on designated wetland

2.3.2 Accessibility

The initial introduction of the Americans with Disabilities Act bill took place in 1988; however, it was not officially enacted into law until 1990 (*The History of ADA*, 2012). This pivotal civil rights legislation sought to combat discrimination against individuals across various domains of society, encompassing both public and private spheres. With the introduction of this law, many of these same regulations also extended to the protection of individuals' rights in public beach areas.

Accessibility normally breaks down into three categories: partially accessible; handicapped accessible; and ADA accessible. Furthermore, full ADA compliance extends to more than just ramps and elevators. The 2010 ADA standards for Accessible Design state that ADA compliance should be reflected in routes, signs, parking, mobility, reach, handrails, and restrooms (*Public Beach Access and ADA: Deciphering Disability Access for Coastal Management Programs*, n.d.).

As it currently stands, guardrails are mandated by the *Massachusetts State Building Code* (SBC) for new boardwalks, and in compliance with current regulations, guardrail heights should be at least 42 inches. Furthermore, the building code necessitates a rail system that effectively prevents any sphere with a diameter of 4" from passing through.

2.3.3 Sea Level Rise

Sea level rise is a direct result of global climate change and will have long-term consequences on our environment and communities. A significant part of climate change is global warming. Global warming has led to rising sea levels, primarily due to the melting of polar ice caps and the thermal expansion of seawater. The rate at which the sea level is rising is slowly increasing. “The global mean water level in the ocean rose by 0.14 inches (3.6 millimeters) per year from 2006–2015, which was 2.5 times the average rate of 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century (NOAA)”. This rate could continue to increase as global emissions increase. This rise will create many challenges for places near coastal regions. The graph in Figure 7 shows the changes in sea level and its overall increase since 1880.

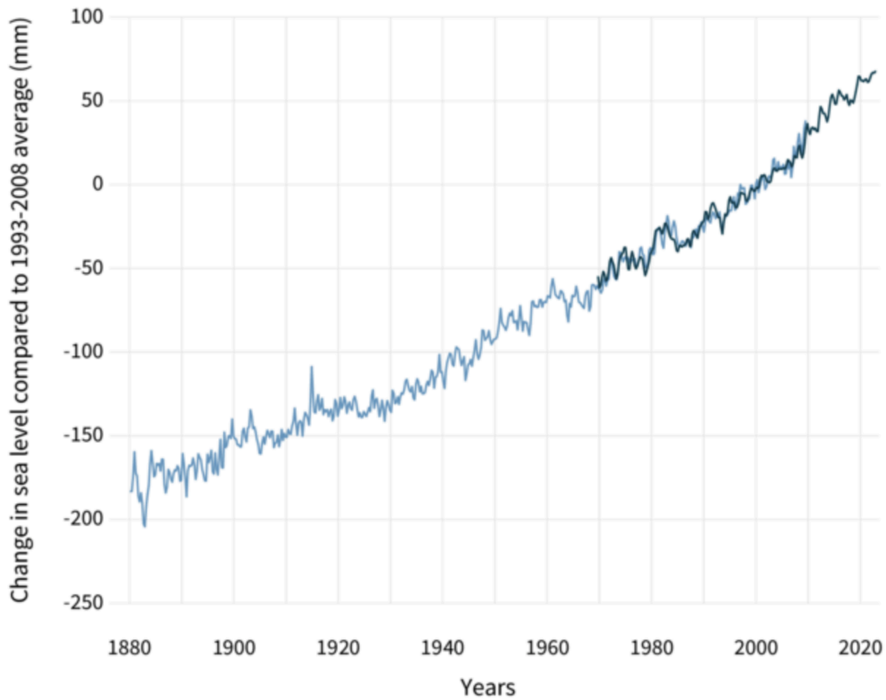


Figure 7: Graph showing the change in sea level over the years. The light blue represents historical data until 2011, and after 2011 is a predicted trend. The dark blue line represents data from the University of Hawaii which is correct to 2023. (NOAA)

Many societies around the world are located near coastal regions and will likely see a direct impact on their communities as the coastlines are progressively reshaped. Around 30 percent of the population in the United States and 8 out of 10 of the largest cities in the world are located near or on the coast (NOAA). For example, the city of Miami is predicted to be partially underwater in 30 years if nothing is done to reduce the impact of the sea. These higher water levels can allow for floods to cause more damage to communities. High tides will also make their way farther inland and take away shoreline. Structures and infrastructure, particularly in urban areas, are at risk of damage from water and erosion, making repairs costly and potentially unaffordable. Rises in sea level will not only have an impact on a community, but the local ecosystems too. The rising tides can harm the wildlife areas, such as marshes, where animals like fish live. Tides can also disrupt fisheries and introduce salt water into freshwater areas (NOAA).

To quantify the potential risk of areas to flooding Federal Emergency Agency (FEMA) has created flood maps also known as Flood insurance maps. These maps display areas of risk as zones which can denote low to high-risk flood areas. Special flood Hazard areas are deemed to be high risk. These areas are shown on flood maps as zones beginning with the letter 'A' or 'V'. In these zones, there is at least a 1 in 4 chance of flooding during a 30-year mortgage (*FEMA Flood Maps and Zones Explained | FEMA.Gov*, 2018). Non-Special Flood Hazard areas are moderate-to-low risk areas that are shown on flood maps as zones beginning with the letter 'B', 'C', or 'X'. Additionally, some flood maps include areas where there are possible but undetermined flood hazards. These areas are shown on flood maps or areas beginning with the letter 'D'. Communities often use these maps as a guide to set minimum building requirements for coastal areas and floodplains while insurance lenders typically use them to determine flood insurance requirements. For the scope of this project, these zone designations can help inform necessary design needs to withstand potential storm risk.

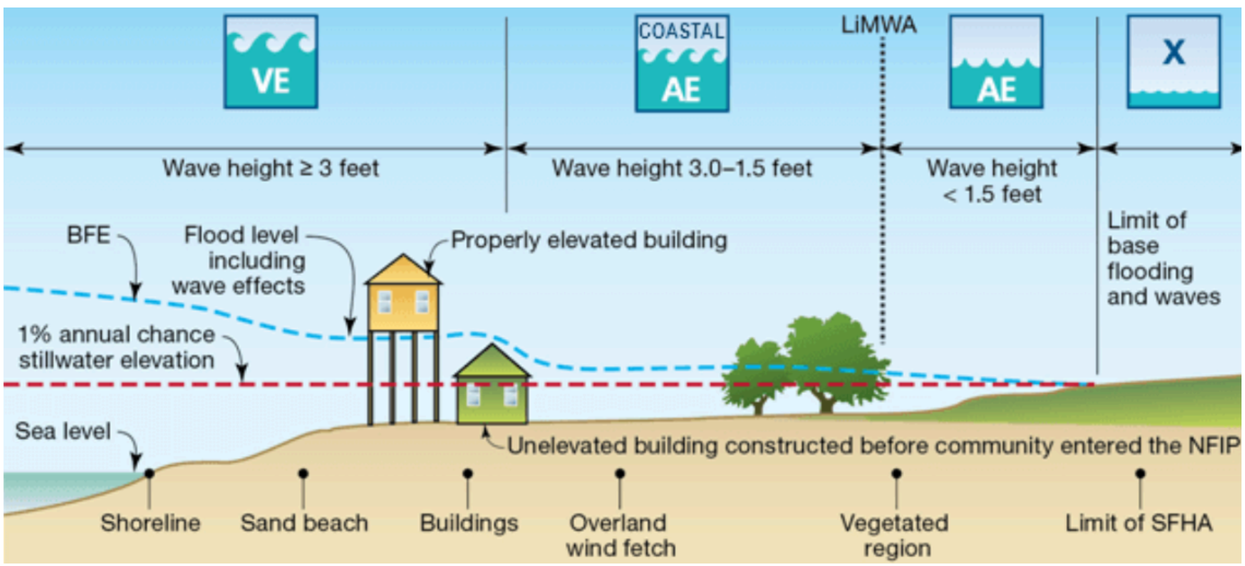


Figure 8: Image illustrates various stages of flooding in coastal areas according to FEMA Flood Zones (*CTP Webinar*, n.d.)

FEMA Flood Zone Designations				
Undetermined Risk	Low Risk	Moderate Risk	High Risk	Coastal High Risk
Increasing Risk →				
Zone D	Zones C and X (unshaded)	Zones B and X (shaded)	Zones A, AE, A1-30, AH, AO, A99	Zones V, VE, V1-30
	Non-Special Flood Hazard Area (NSFHA)		Special Flood Hazard Area (SFHA)	

Figure 9: Describes the FEMA flood zone definitions (Ernie, 2024).

2.3.4 Storm Surges

Storm surges are a challenge that most coastal regions face. A storm surge is when a water body rises far beyond the level it would be at a high tide due to an incoming storm such as a hurricane or tropical storm. The winds from these storms push water toward the shore. These storm surges can occur within hours with the help of heavy rainfall, unlike sea level rise which occurs over the span of many years. The water rise can persist for several hours or even days, and it can create a large threat to the safety of coastal communities and their infrastructure. There are many cases where the damage from the water brought by the storm surge is greater than the damage from the winds of the hurricane or tropical storm. Climate change and global warming may contribute to more intense hurricanes in the future. Angela Colbert, a scientist at NASA, predicts hurricanes will likely cause more intense rainfall and have an increased coastal flood risk due to higher storm surges caused by rising seas (Colbert, 2019). This means that the prevention or minimization of the effects of storm surges will be an important factor to consider when building along the coast. Regions that are near the coast reduce their vulnerability to storm surges by taking actions such as building seawalls and evacuating vulnerable areas.

Figure 10: Image of flooded Duxbury Parking lot post-storm surge.

Figure 11: Shows the damage caused to Sandwich Boardwalk from 2018 Storm Surge.

The water that comes with these storm surges damages structures with not only the water wearing down the materials but the sediments that the water brings along as well. A structure that is subjected to these types of conditions will experience a shorter lifespan depending on the frequency of these events (NOAA). Designs of structures can be made to reduce the impact of storm surges and sea level rise.

One method of this is to have an adjustable structure. A structure that can be adjusted could be lifted to a higher elevation to avoid damage. The elevation of the structure could also be adjusted in an instance where the level of the sand changes. Another method would be to design a boardwalk that could be easily deconstructed or have removable parts. The owner could have parts of the boardwalk that were believed to be in a potentially dangerous area disassembled and stored safely before a storm to prevent harm to the materials. A similar tactic was seen with the boardwalk already on Duxbury Beach, with the lower portion of the ramp on the beach side removed during the offseason (MacCallum, S) (Figure 12).

Figure 12: Shows the ocean-side ramp of the Duxbury Beach Parking Lot Boardwalk removed

To calculate the magnitude of these storm forces, many statistical design methods and equations are used in the field of coastal engineering. One of the most used methods in coastal engineering is the Goda method, developed by Japanese Researcher Yoshimi Goda in 1974. It is often used to design on and offshore structures to calculate breaking wave forces and their effects on structures.

2.3.5 Pricing and Costs

Cost is an aspect of the project that will have an impact in determining some decisions. Two of the main categories that need to be looked at in the construction costs are the materials used and labor costs. There will be different types of materials used for the decking, supports, handrails, and other elements of the structure. The previous MQP report recommended specific materials to use to construct the boardwalk (Webster, Colette, et al); however, the price of materials fluctuates over time, and certain materials may not be the most cost-effective anymore. Engineers who design structures want to calculate the materials that would allow for the structure to perform what it's designed to do while keeping the price as low as they can. After narrowing down the choice of materials, the cost of those materials can be looked at versus the quality and potential duration of service life. This can help determine what choice is preferred to create some possible options.

3.0 Methodology and Findings

The goal of this project was to develop a structural design for an accessible passage that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. The team aimed to balance functionality with sustainability, while also promoting environmental conservation. The following chapter delves into the team's methods and objectives, starting with establishing the existing site conditions, identifying the initial design criteria, and analyzing the proposed boardwalk's design. This comprehensive approach culminates in the evaluation of the final design package. Through research, interviews, and detailed analysis, the team was able to derive some final design recommendations, ensuring a thorough and informed decision-making process.

To complement the narrative of our boardwalk design process, the team has included a flow chart that encapsulates the journey from conception to completion (Figure 13). This visual representation is not merely an adjunct but an integral part of our documentation, mirroring the textual content of this paper. Each stage of the flow chart is deliberately aligned with the corresponding sections of the essay, providing a clear, visual guide to the evolution of our project. It delineates the various objectives that the team set, the methods that were employed, and the critical design decisions that shaped the final outcome. By referring to this flow chart, readers can gain an understanding of the team's design philosophy and process as the team navigated through varying challenges. It serves as a roadmap, guiding the reader through the process of our team's creative and analytical thinking, ensuring a coherent and comprehensive grasp of the project's lifecycle.

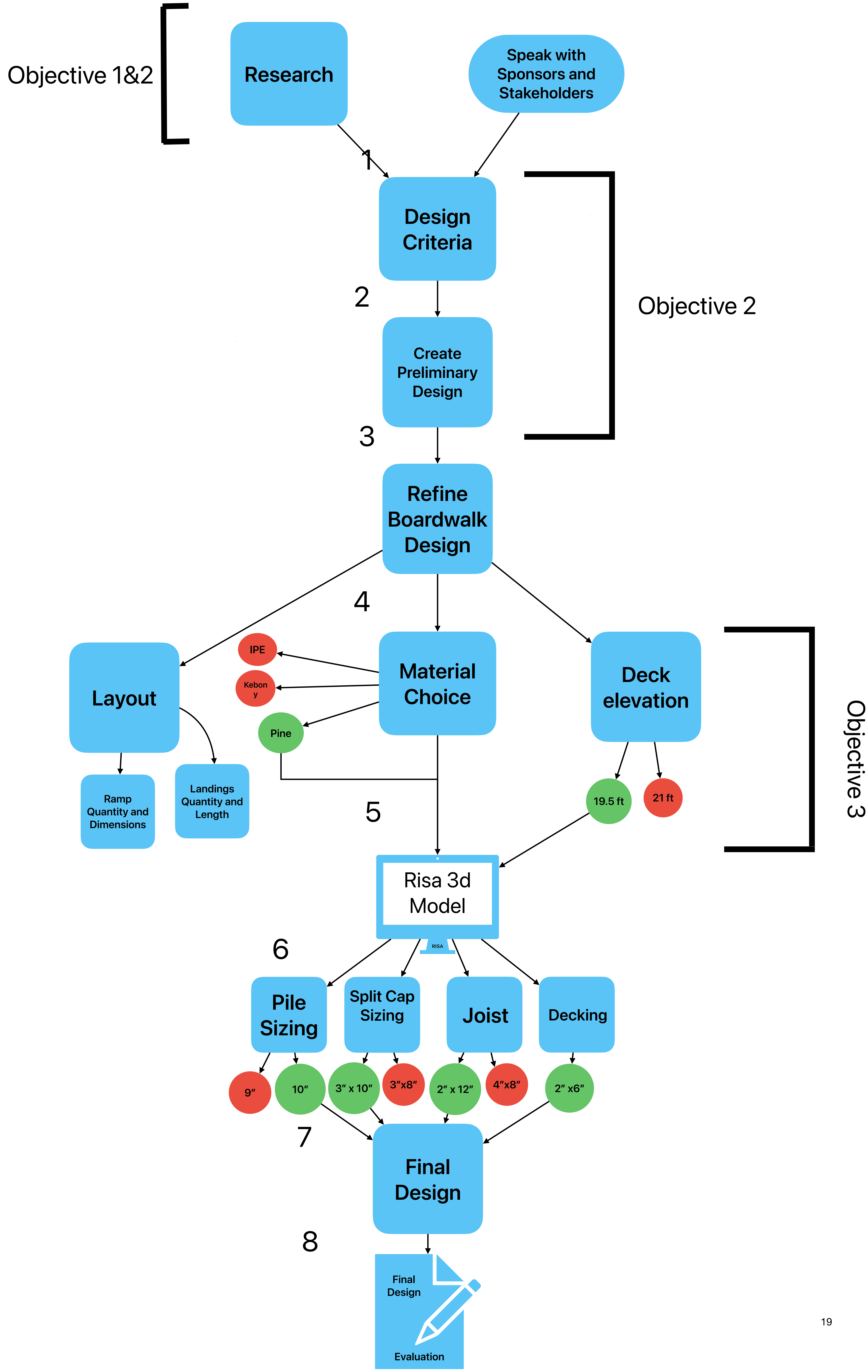


Figure 13: Shows the flowchart of the team's process.

3.1 Objective 1: Establish Existing Site Conditions

The team was able to establish the existing site conditions and constraints by collecting qualitative and quantitative data about the physical and environmental characteristics of the beach from the "Beach Access and Coastal Design" MQP report. This data included distance and slope measurements which were used to establish preliminary designs in line with the Americans with Disabilities Act (ADA)/ Architectural Access Board (AAB) requirements. The team was able to utilize USDA's SoilSurvey to obtain classification data about the different soils present at Duxbury Beach as well as their properties. To investigate the impact of the boardwalk design on the environment, the team examined both the required local and state permitting regulations. Our sponsor also provided support and guidance on additional regulations for working on the beach. With this data, the team was able to continue with the preliminary designs and calculations for the boardwalk.

Table 2: Activities and Resources for Objective 1

Activity	Resources
Examine previous boardwalk design and its solutions	Beach Accessibility: Passageway Design for Massachusetts Beaches MQP 2022
Survey the site and understand site's history	Sue MacCallum, the Duxbury Beach Reservation Program Specialist, who also serves as the co-chair of the Community Outreach Committee.
Assess dune conditions	USDA SoilSurvey website; field observations
Assess impact of structure on local wildlife and environment/ impact mitigation strategies	Permitting and conservation standards; review data from Beach Accessibility: Passageway Design for Massachusetts Beaches MQP 2022

Findings 1: Existing Site Conditions and Constraints

The team analyzed the High Pines area (Figure 14) through the use of existing local data and geographical data collection tools. From this information, we were able to calculate various environmental loads as well as other parameters that will affect the boardwalk's construction and design.

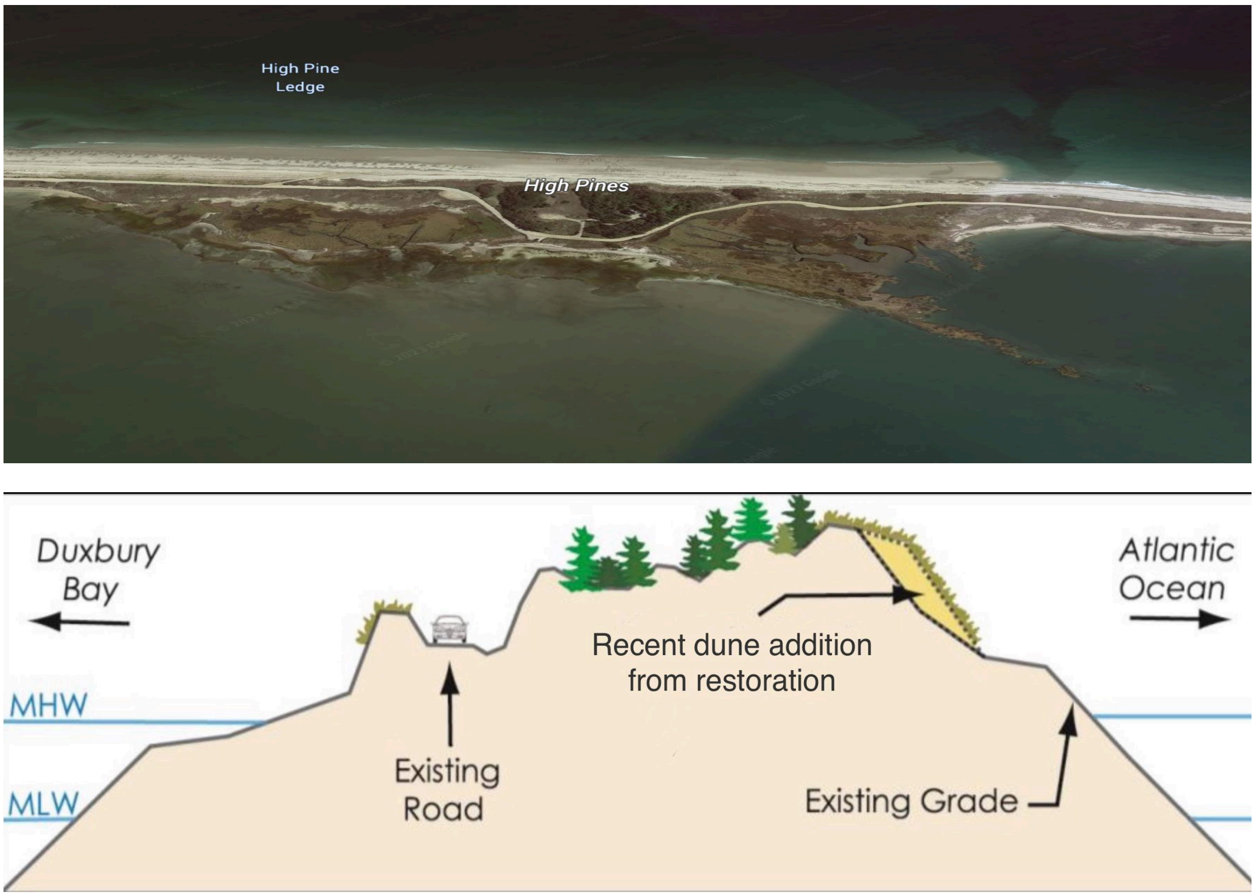


Figure 14: Aerial 3D view showing the general area of the site and a 2D cross-sectional view of the area (Woods Hole Group, n.d.).

Site's Environmental History

The High Pines area is located 1.8 miles south of the Powder Point Bridge crossing between crossovers one and two. This particular section of the beach overlies glacial till deposits of small rocks and cobble, allowing for the area to be more resistant to wave-induced erosion compared to the ribbons of sand that it's connected to (Figure 15).

Figure 15: Layout of Duxbury Beach. (*Windansea Getaway at Duxbury Beach | Duxbury, Massachusetts*, n.d.)

The High Pines area is primarily made up of two terrains. There is the forested rocky portion closer to the Atlantic side of the beach. Then there is also the salt marsh portion which lies on the bay side of Duxbury. Developing an understanding of the characteristics of these varying terrains required the use of more advanced mapping tools. Consequently, the team employed the use of geological software such as ArcMap and Google Earth to further delve into the natural topography with greater accuracy. The use of these tools along with the insights gathered from the "Coastal Processes Study and Resiliency Recommendations for Duxbury Beach and Bay" by the environmental consulting firm Woods Hole Group on Duxbury Beach, equipped the team with the additional measurements and understanding to make informed design decisions (Woods Hole Group, n.d.). Some of these measurements and information included meteorological, tide, and geological data on Duxbury Beach.

Dune Conditions

Finding accurate and current dune height measurements also presented a challenge, particularly due to the constantly changing coastal environments. The latest dune height data for the High Pines area of Duxbury Beach, dating back to 2018, indicated a measurement of 16.5

feet. Recognizing the likelihood of changes since this last assessment, the team proceeded with this figure as a provisional assumption. The team understood that an updated surveying process would be essential before the actual construction of the boardwalk, as confirmed in discussions with Sue McCallum.

Soil Conditions

Geotechnical conditions are an important consideration for the boardwalk design because they impact the stability, longevity, and overall safety of the structure. The area encompassing the project is classified as Hooksan sand, with most of the sand having an 8 to 15 percent slope except for the area near the beach which has a 3 to 8 percent slope (Figure 16). The type of soil in the project area was approximated using USDA's Web Soil Survey (Figure 17 and Table 3). Data on particle size distribution, soil classification, approximate bulk density, and other properties is provided for layers in the top 64 inches of soil. This data comes from the USDA's database and can be found in Table 3.

The soil information was used to determine its presumptive bearing capacity. The presumptive bearing capacity was found using the capacities given in Table 1806.2a of the *Massachusetts State Building Code*. Hooksan sand in this case was assumed to be closest to the material class 8 ("sands or non-plastic silty sands with little or no gravel"). The density classification for the sand was assumed to be medium-dense near the vegetated area because the sand in that area was compacted by workers for previous storage use per our interviews with Sue Maccallum. The sand around the dunes and the beach was believed to be closer to a loose classification. These assumptions gave a presumptive net bearing capacity of three tons per square foot in the vegetated area and a design capacity of one ton per square foot.

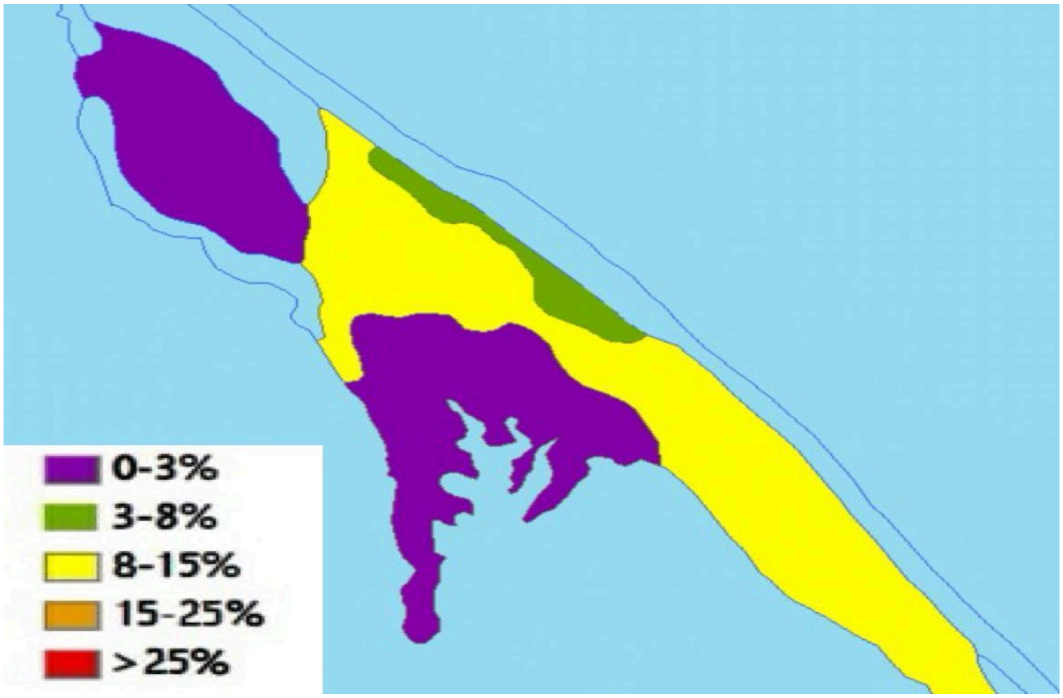


Figure 16: Slope classes of the different sections of the High Pines area from ArcMap GIS

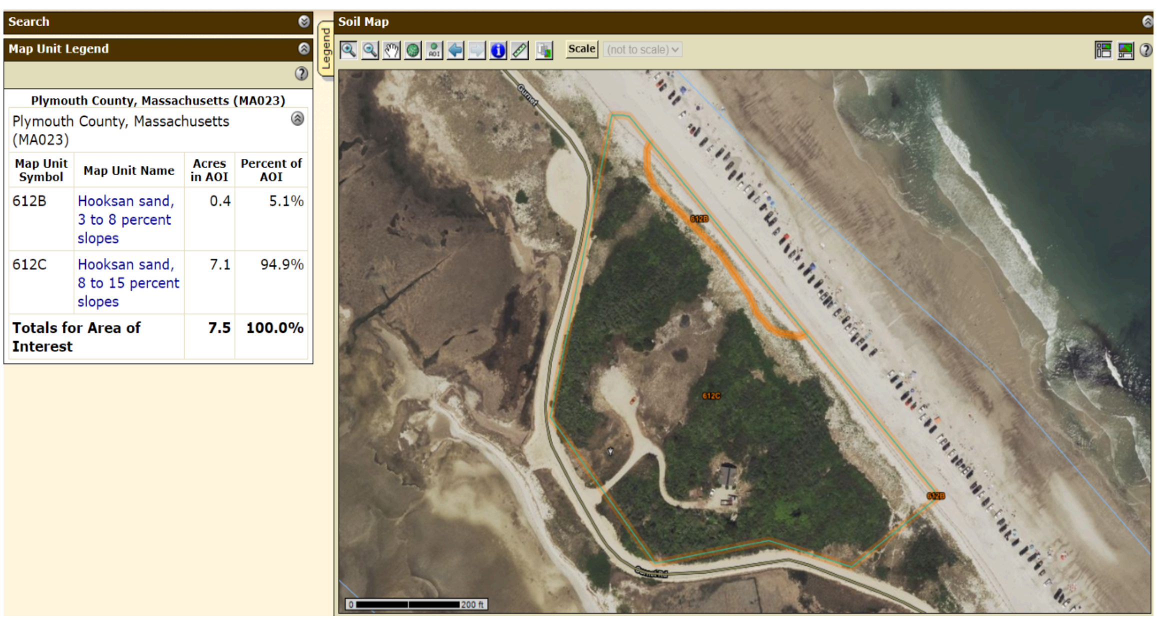


Figure 17: Aerial image of High Pines showing the soil type from USDA's Web Soil Survey.

Table 3: Properties of the soils in the High Pines area

Plymouth County, Massachusetts

Map unit symbol and soil name	Pct. of map unit	Hydrologic group	Depth	USDA texture	Classification		Pct Fragments		Percentage passing sieve number—				Liquid limit	Plasticity index
					Unified	AASHTO	>10 inches	3-10 inches	4	10	40	200		
			In				*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*	*L-R-H*
612B— Hooksan sand, 3 to 8 percent slopes														
Hooksan	80	A	0-20	Coarse sand, fine sand, sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP
			20-30	Sand, fine sand, coarse sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP
			30-64	Fine sand, coarse sand, sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP
612C— Hooksan sand, 8 to 15 percent slopes														
Hooksan	80	A	0-20	Sand, coarse sand, fine sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP
			20-30	Fine sand, coarse sand, sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP
			30-64	Fine sand, sand, coarse sand	SP	A-3	0- 0- 0	0- 0- 0	100-100-100	98-100-100	77-78-78	1- 1-1	0-0-14	NP

3.2 Objective 2: Identify Design Criteria

Before the development of the structural design and calculations, the team met with the sponsor to learn more about the site and some of the challenges in the area. Our sponsor was also able to provide us with the drawings of another recently constructed boardwalk in Duxbury. This helped the team to better anticipate the challenges and the norms when constructing a boardwalk in sandy terrain. In order to account for the potential effects of storm surges on the structural design, the team examined historical storm and meteorological data and assessed the impact on factors such as sea level rise, storm surge, erosion, and sand movement. Understanding this data allowed the team to better select materials and appropriately size structural members to resist these forces. Additionally, this would enable the team to implement various design strategies and choices to effectively mitigate the impact of these storm forces. These various design strategies would also allow the team to come up with a cost estimate for storm mitigation techniques.

Table 4: Activities and Resources for Objective 2

Activity	Resources
Establish sponsor and stakeholder needs	Interviews with sponsor to obtain preferences; conversations about some of the potential challenges and communities involved
Identify accessibility, environmental, and usage design requirements according to permitting and standards	ADA/AAB codes. Required permitting from Table 1&5
Assess sea level rise/storm surge, erosion, and sand movement	Flood risk data from FEMA website to estimate impact on coastal regions.
Identify and explore different material options and their effects on boardwalk design and cost	*AASHTO design guide for Pedestrian Bridges*, ASTM standards; materials and pricing data, *Massachusetts State Building Code*

Findings 2: Design Criteria

Sponsor and Stakeholder Needs

Designing a durable and beneficial boardwalk for the community was among our primary objectives. To achieve this, the team believed it was crucial to seek insights from a diverse range of experts, including those knowledgeable in permitting and safety standards, as well as understanding the needs it should meet for its users and the community.

To obtain information and share updates with our sponsor, Sue McCallum, the team held regular meetings which were either conducted on Zoom or in person. For these meetings, the team created slideshows to showcase the designs that the team had for the boardwalk. Sue MacCallum was able to offer feedback on topics such as material choice, design styles, potential obstacles, and many more topics. The team compiled the data into meeting minutes that were used to guide and inform the design of the boardwalk.

Accessibility, Environmental, and Usage Design Requirements

In addition to the ADA requirements, Massachusetts requires that its local Architectural Access Board (AAB) regulations also be incorporated when constructing a walkable structure. Table 5 shows the subset of elements deemed appropriate from local requirements that affect the design of footbridges.

Table 5: Architectural Access Board (AAB) Requirements

Section of AAB	Subject	Requirement
20.3	Width of an accessible route	Minimum clear width of 36 inches
20.4	Obstacles/ Turns for those in wheelchair	Obstacle must be at least 48 inches wide or clear width around obstacle must be at least 42 inches
20.5	Passing space	At least 60 by 60-inch clear

		space at intervals <= 200 feet
20.6	Protruding objects onto accessible routes	Max. protrusion 4 inches between 27 and 80 inches above floor; must not reduce clear width in any case.
20.6.3	Free-standing objects mounted on posts or pylons	Max overhang is 12 inches or less measured between 27 inches and 80 inches above the ground
20.9, 24.1	Slope and Cross-slopes	- Cross-slope and Running slopes steeper than 1:20 (5%) shall comply with all ramp regulations - Cross slopes shall not exceed 1:50 (2%)
22	Drainage	Grading and drainage shall be designed so as to minimize the pooling of water or accumulation of ice or the flow of water across boardwalk
22.2	Width of walkways	Walkway width shall not be less than 48 inches with at least 36 inches clear of unobstructed width
22.4	Level Changes	Changes in level must comply

		with regulations for changes in level greater than ½ inch
24.2, 24.2.1	Slope and rise	Ramps shall have the least slope possible. The maximum slope of a ramp shall be 1:12 (8.3%), with an exception, allowing a slope between 1:10 (10%) and 1:12 (8.3%) for a single rise of a maximum 3 inches
24.4	Landings	All ramps must have landings at their start and end
29.1	Gratings\ Floor surface	Ground and floor surfaces must be stable, firm, slip-resistant, and maintained with materials that ensure continued slip resistance.
29.2.1	Gratings\ Floor surface	Changes in level up to ¼ inch may be vertical without edge treatment.
29.2.2	Gratings\ Floor surface	Changes in level greater than ¼ inch and less than ½ inch must be beveled with a slope no greater than 1:2 (50%).
29.2.3	Gratings\ Floor surface	changes in level greater than ½ inch require a ramp, walkway, or other means of

		vertical access that complies with 521 CMR.
29.4	Gratings\ Floor surface	Grating in walking surfaces must have spaces no greater than ½ inch wide and, if elongated, must be positioned perpendicular to the direction of travel.

Based on Massachusetts AAB requirements, the team compiled the regulations they felt would be most applicable to our boardwalk design when looking at the different elements and measurements of the team's boardwalk design (Table 5). Some of these included, the bridge's walkway requiring a clear width of at least 36 inches, necessitating a total width of 52 inches to accommodate posts and/or edge buffering, based on the stipulated requirement of a 48-inch width. Furthermore, access ramps to the bridge must ensure a clear width of 48 inches between handrails, which implies an overall width requirement of 56 to 58 inches. Additionally, the maximum allowable slope of any ramp would not exceed 1:12.

Deck Height in Consideration of Sea Level Rise/Storm Surge, Erosion, and Sand Movement

The first major challenge Duxbury Beach faces relates to the rising sea levels. As climate change accelerates, the implications for this coastal region have become more of a consideration in our design. This information was factored into the design criteria as the boardwalk would have to withstand the impacts of the rising water.

Additionally, FEMA mapping shows that the High Pines area lies primarily in the AE and VE zones with a base flood elevation between +15 and +17 North American Vertical Datum (Figure 18). The salt marsh elevations on the bay side are approximately between +3 NAVD and +7 NAVD but ground elevations rise to approximately +16.5 NAVD at the crest of the dune. NAVD is a standard reference point used to measure elevations. NAVD88 is the most recent datum adopted in 1988, used in North America to provide a geodetic reference for elevations above sea level. Knowing the elevation of these areas relative to the standard datum helps in assessing their flood risk. Understanding these elevations allows the team to better design structures that are appropriately elevated to better protect against expected sea level rise and storm surges.

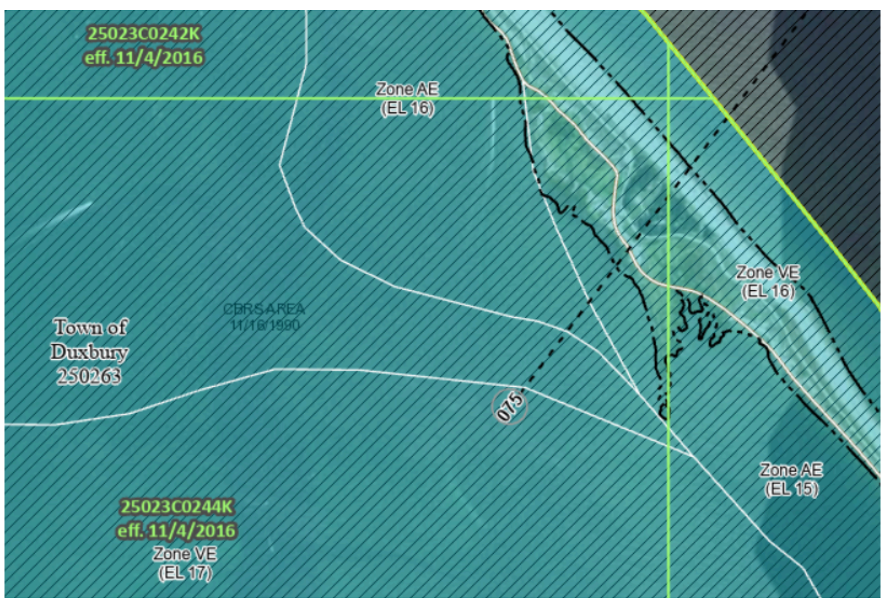


Figure 18: Different FEMA flood zones in the High Pines area (*FEMA's National Flood Hazard Layer (NFHL) Viewer*, n.d.).

To better protect against future storms, the team felt that the deck would not need to be raised significantly because the peak of the dune (which will serve as the lookout area) would almost lie entirely above the FEMA base elevation. The team also considered the impact of future sea level rise on the design of the structure and its overall lifespan. Utilizing data from FEMA, the image in Figure 19 shows the areas of the site that are at risk of annual flooding. Figure 19 also depicts the projected impact areas affected by sea level rise over a 30-year period, aligning with the expected lifespan of our design. Sea level rise over this time is expected to be around 2 to 4 feet based on FEMA prediction mapping. Including these amounts, the team opted to set the deck height to be 3 feet above the dune crest, which would give us a deck elevation of +19.5 NAVD. This elevation will allow the deck to lie completely above the base flood elevation while also mostly accounting for the projected sea level rise. Although a higher deck elevation would reduce the overall risk of damage, there were a series of potential disadvantages such as increased falling distance, impeding on the aesthetic of the area, and increased boardwalk size and cost.

Figure 19: Visual of expected sea level rise by the year 2050 (left). Image of coverage of water during annual floods at High Pines (right). Source: FEMA.

It was determined that the High Pines area experiences the most significant erosion at the base of the dunes facing the Atlantic side where the wind has the most impact on sand movement. The report also found that the bayside of the beach has experienced significant shoreline retreat over the past century due to sea level rise and erosion. While the High Pines forested area is relatively resilient to erosion, the exposed beach area experiences erosion rates between 1.5 to 2 feet per year (Woods Hole Group, n.d.).

The northeast section of the boardwalk would need to be able to withstand water damage up to 10 feet of elevation during large storms. The team created two suggestions to minimize damage on the lowest section of the boardwalk on this side. The first design would be able to allow for the section to be removable so that the material avoids the impact of the water entirely. The section would be made so workers at the beach could detach and store the section during predicted storms. This method is in use on another boardwalk on Duxbury Beach. The second suggestion would allow for a hinge design to allow the slope of the lower section to adjust. The lower section could be raised to allow for the water to pass underneath without disconnecting the entire ramp. Of the two suggestions, the former was selected to prevent the water from damaging the ramp and because there was already a similar design on the beach.

3.3 Objective 3: Analyze the Structure of the Design

With the criteria set in sections 3.1 and 3.2, the team focused on the structural analysis of the boardwalk design and determined whether modifications to the team's original design were needed. An analysis of the structure was necessary to ensure the safety and durability of the boardwalk.

Table 6: Activities and Resources for Objective 3

Activity	Resources
Confirm design goals and final structure layout	Review sponsor goals for the project. Ensure design complies with ADA standards
Selection of materials	Investigate local lumber yards for availability of sizing and types of wood. Review different types of wood to determine what wood types are available. NDS for material properties. Review similar projects such as the Sandwich and Duxbury parking lot boardwalk.
Evaluate economics of design	Nearby lumber yards' websites such as Cape Cod Lumber, BB&S Lumber, and Goodrich Lumber
Design calculations for substructure and for superstructure	AASHTO bridge and pedestrian bridge standards and references; RISA 3D; ADA/AAB requirements

The analysis includes a study of the boardwalk's entire structure with the key areas to investigate being the pillars, railing systems, and flooring of the boardwalk. To calculate the load-bearing capacity of different areas of the boardwalk, a detailed load analysis was conducted. This analysis took into account factors such as pedestrian traffic, maintenance, environmental conditions, and varying loads. Static loads were considered to accurately predict real-world conditions. Engineering properties of the materials were analyzed to ensure the dimensions of members and elements are sufficient to support the calculated loads, as opposed to merely selecting materials based on design specifications. The information on these loads for selected materials was found through various credible online sources such as the National Design Specification or NDS. This information helped determine the capacity of the boardwalk and if the proposed design needed adjustments. After the prior steps were completed, a final design was selected to be carried out.

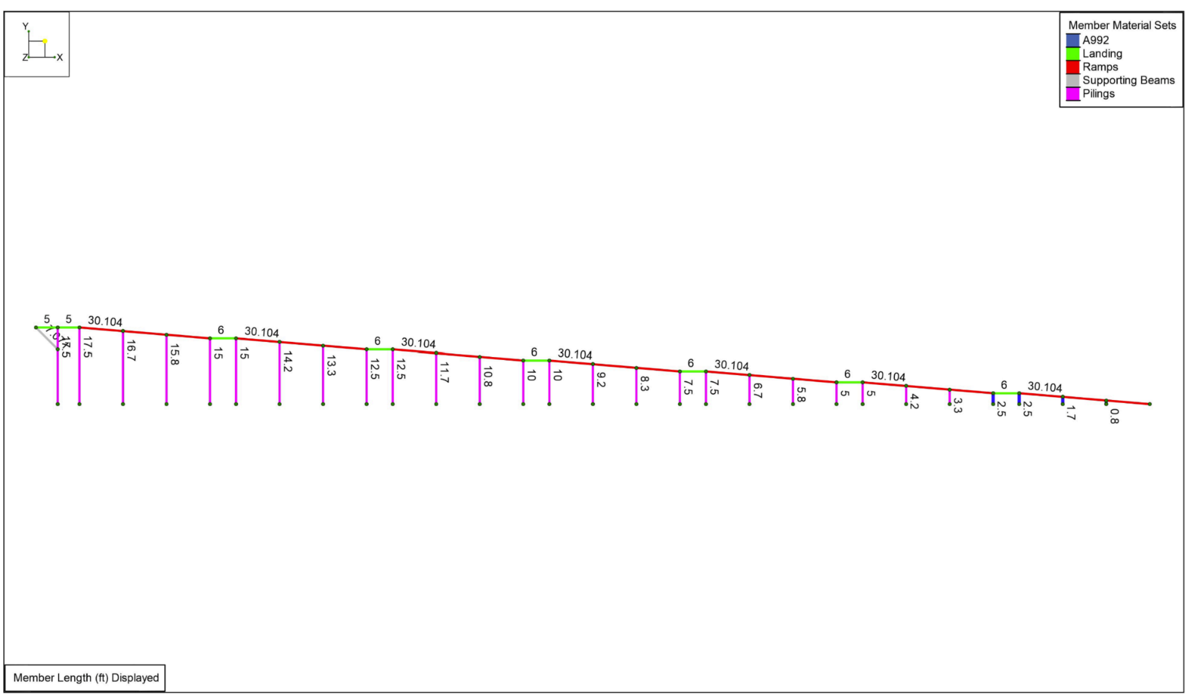
The team determined the appropriate design software to use for the boardwalk. The selection of software was based on its capabilities to replicate accurate structural modeling and load analysis. The chosen software enabled the group to make more informed decisions about the boardwalk design.

Findings 3: Development of Design and Structural Analysis

Design Goals

The design of the boardwalk was modeled from the desires of the sponsors as well as factors previously mentioned throughout the design process. The foundation of the design was taken from the previous MQP project by Webster et al. (2023) and their proposed layout of the boardwalk's location. After discussions with sponsors and visiting the site, the length of the boardwalk on the parking lot side or bay side was deemed to be too long. The elevation change was minimal for a large section of the High Pines area, so the boardwalk was not needed for the entire distance to the parking lot. This would also save money on materials and reduce labor costs. The new proposed starting point was selected based on where the elevation started to see a noticeable increase based on the site visit and elevation data from Google Earth. A pathway such as a Mobi-mat could be used to go from the parking lot to where the proposed boardwalk starts.

The new layout took the previous design and adjusted it so that it would accommodate the design criteria. The layout was made in 2D in RISA, so the boardwalk was split into two sections: the bayside and the oceanside. The layout model of the two designs can be seen in Figure 20.



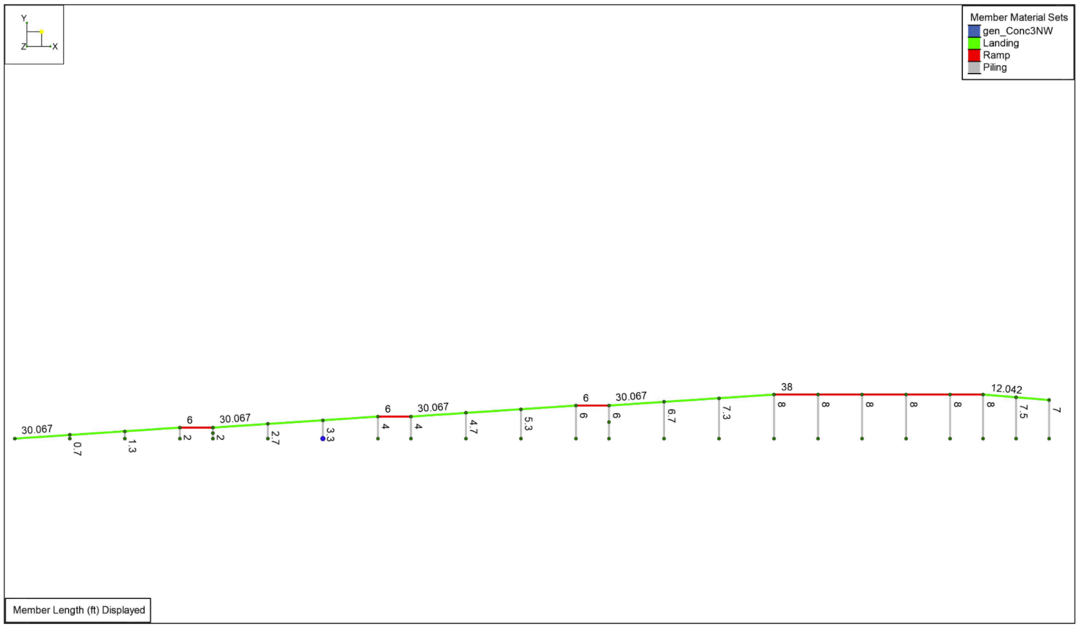


Figure 20: Two-dimensional RISA model of the boardwalk from the ocean side (top) and bayside (bottom) with dimensions of landings and ramps.

The section of the boardwalk on the bay side was modified from the original design proposed in the previous MQP report. One of the goals for the boardwalk was to be able to clear the dunes by a minimum of 2.5 feet. The 2.5-foot minimum was selected because the team wanted to ensure the boardwalk would clear the dune by a comfortable margin. To accomplish this, the boardwalk would need to rise 7.5 feet from its starting point according to the elevation data referenced. The team decided to make four ramps that each spanned 30 feet across with a 2-foot rise that started at the beginning of the boardwalk. Between each 30-foot ramp, there would be a 6-foot flat landing. ADA requires a 5-foot landing for every 30-foot ramp, but it is not recommended for sets of piling to be spaced less than 6 feet away from each other according to "Pile Design and Construction Practice" because a closer spacing will likely mean reduced capacity.

This would bring the elevation of the boardwalk to 8 feet from its starting point and 3 feet above the dune. The boardwalk would then span for a flat section of 38 feet and end with a slightly downward ramp. The ramp would run for 12 feet across and 1 foot down. This would make the total length of the boardwalk about 200 feet, which would clear the wooden fence on the beach indicating where the dune is located. The ramp on the end of the section was designed to reduce the ocean side of the boardwalk by 18 feet.

The design for the ocean side remains similar to the design proposed in the previous MQP report. There are a total of 7 ramps that start on the beach. They are 30 feet in length with a 2.5-foot rise, slightly higher than those on the bay side. This was designed in that way because the goal is to descend from the highest point as quickly as possible. There are landings between ramps that span for 6 feet long. The top of the landing will have a 5-foot by 5-foot section followed by another 5-foot by 5-foot section. The first 5-foot by 5-foot section is where the ocean-side section of the boardwalk will intersect with the bay-side section. The spacing of the support piles on this section will be less than the six-foot recommendation due to how the widths of the boardwalk sections come together as well as this section having the highest risk area of the boardwalk. This area has the largest risk due to the section having the highest elevation point on the boardwalk, with the section being almost 18 feet above the sand below. The second section of this area will support a small lookout area for beachgoers, and its elevation will be approximately 17.5 feet above the beach.

Material Selection

For the substructure, there were multiple types of footings that the team investigated. Using a mix of helical and standard wood timber piles was the most ideal when balancing cost and minimizing environmental impacts. Initially, the team had opted to use helical piles for the entire sub-structure due to their ability to resist upward forces caused by the elements. Helical piles, which are also known as screw piles, are deep foundation footings that support structures and transfer loads into the surrounding areas whether it be soil or rock. They are typically made of steel. The installation process involves rotating the pile into the ground, similar to installing a screw into wood. This allows workers to avoid soil excavation. In addition to this, the team felt that having the pile's ability to resist storm forces would lead to less future disturbance due to not having to re-excavate in order to readjust the pile. Although soil excavation is not required, the use of machinery would still be necessary to twist the piles into the soil. While this process would not trigger extra permitting outside of what is already required, the team anticipates that navigating machinery to the High Pines area of Duxbury Beach would potentially disturb the surrounding environment. For this reason, the team decided to utilize helical piles for the sections of the boardwalk most vulnerable to erosion and storm forces, particularly the lookout area of the dune. The remainder of the structure will employ traditional wooden piles. This strategy enables the team to reinforce the boardwalk's most critical sections effectively, while also minimizing expenses and environmental impact.

While the cost of lumber has largely changed post-Covid, it is much less expensive to install and maintain when compared to other construction materials such as steel or reinforced concrete. Additionally, the project's sponsor Sue MacCallum communicated that the majority of the superstructure should be constructed of wood so as to not negatively impact the environment both during its installation and during its natural decay process.

Design Loads

In the design process of the boardwalk, various loads were carefully considered to ensure structural safety. Estimated live loads, dead loads, snow loads, seismic loads, wind loads, and guardrail loads can be found in Table 7 below. The self-weight of the boardwalk depended on the weight of the types of wood and the amount used. The types of wood to be used are Yellow Pine and Ipe wood decking. The weight can slightly vary due to the variable nature of wood so these values accounted for the upper bound of the expected weight. The earthquake loads were obtained from the *Massachusetts State Building Code* (780 CMR) specifically for the town of Duxbury. Additionally, the structure accounted for ice and snow loads which were 45 psf per 780 CMR. Wind loads were set to accommodate speeds of up to 110 miles per hour. Massachusetts's building codes have Duxbury designated as Zone 3 conditions, which equated to 21 psf in this area. All of the various loads listed were factored into the final design to ensure the boardwalk is structurally safe and complies with building codes.

Table 7: Design Loads for Boardwalk

Load Type	Value of Load	Reference
Live load for pedestrian traffic	100 psf	AASHTO
Self-weight of southern yellow pine	34 pcf	BB&S Lumber
Self-weight of Ipe wood decking	70 pcf	The Wood Database
Earthquake loads	0.25 for Ss (short-term response) and 0.061 for S1 (one-second period) for town of Duxbury	*Massachusetts State Building Code* (780 CMR)
Wind loads	21 psf	*Massachusetts State Building Code* (780 CMR)
Guardrail loads	200 lbs in all directions	*Massachusetts State Building Code* (780 CMR)

4.0 Final Design

The final phase of the project consisted of conducting a thorough cost analysis. This analysis evaluated materials and their associated costs. The team researched the current market price of the materials, such as the type of wood, to give a more accurate cost estimate of the project. The total cost of materials was calculated along with the cost of shipping them to the site. The site may present some logistical challenges because of the accessibility of the site, and this factor must be considered by the sponsor and contractors when determining how to ship the materials. Another factor considered for the total cost was the price of labor. The equipment needed and laborers used for construction were estimated in the final cost of the project. These factors were added to determine the total cost of the boardwalk.

4.1 Structure of the Boardwalk

The final design of the boardwalk as well as its structural elements and weight-bearing capacity followed the applicable American Association of State Highway and Transportation Officials (AASHTO) standards. As seen in the Methods and Findings section the team's flowchart delineates the steps and processes followed in developing the structural design of the boardwalk from the initial research to the final design elements. The structural elements were chosen based on constructability and economic feasibility. The elements of the boardwalk were chosen to meet AASHTO load requirements for pedestrian walkways and the M*assachusetts State Building Code*. The sizing of these elements was also aided by the team's structural analysis in RISA-3D which gave the necessary loading values. The team created a 3D model in SketchUp of the overall design of the structure.

4.1.1 Boardwalk Layout and Structure

The final layout is shown in Figure 21. Meetings with Sue MacCallum, the team's sponsor, and advisors helped to confirm the location and layout of the boardwalk. During these meetings the team's sponsor emphasized the boardwalk's placement being a few meters ahead of the parking lot. This combined with the fact that the trees and local shrubbery took up a large portion of the available buildable area, caused the team to essentially maintain the initial placement of the boardwalk. More specifically, the flowchart in the methods and finding section better models the process that the team followed to arrive at this design configuration.

Figure 21: Final layout

The deck elevation was established as described in Findings 2 such that the deck would be set to 19.5 feet NAVD88 which is 2.5 feet above the FEMA flood zone that the boardwalk lies in. Pile depths were established to be dug 4 feet or until refusal. The team also recognized that pile depths may vary when construction comes due to the mix of traditional and helical piling. Final Elevations are illustrated in Figure 22 below. Additionally, the team created a render as seen in Figure 23 to further help illustrate what the structure would be like on the final site.

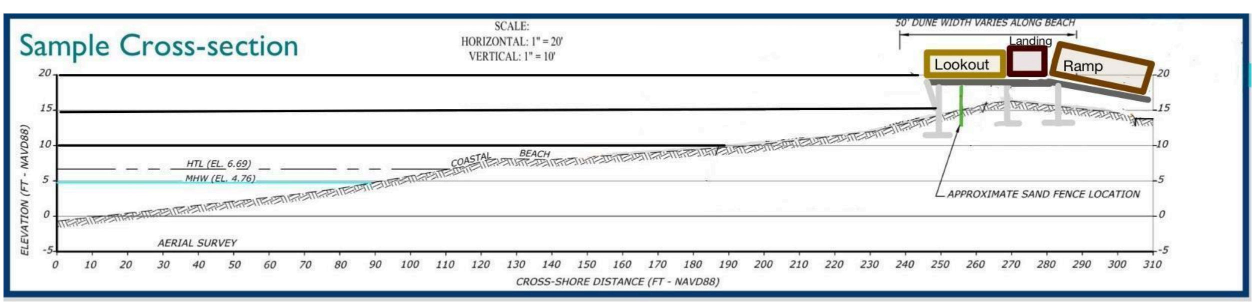


Figure 22: Elevation schematic of the final design

Figure 23: 3D Render of boardwalk on beach.

4.1.2 Ramp Structure

On the oceanside of the boardwalk, the team chose a slope of 1:12. This allowed the team to minimize the use of wood and the length of landings compared to other options that featured gentler slopes. Minimizing the amount of length on the oceanside ramps was crucial due to the more directed forces from the sea. Moreover, it was important that the team minimize the length of the bayside ramps to respect the sponsor's wish for a gap between the parking lot and the boardwalk's beginning. This resulted in the team's final proposed design on the oceanside to include 7 ramps, 6 6-foot landings, 1 5-foot landing, and 1 5-foot lookout. A 3D render of the oceanside can be seen in Figure 25.

On the bayside, the team chose a more gentle slope of 1:15. These ramps connect to the oceanside at a 90-degree angle and run perpendicularly to the ocean. The bayside of the boardwalk includes 5 ramps, 4 6-foot landings, and 4 8-foot landings. A 3D render of the bayside can be seen in Figure 24. Both ramps have a width of 5 feet

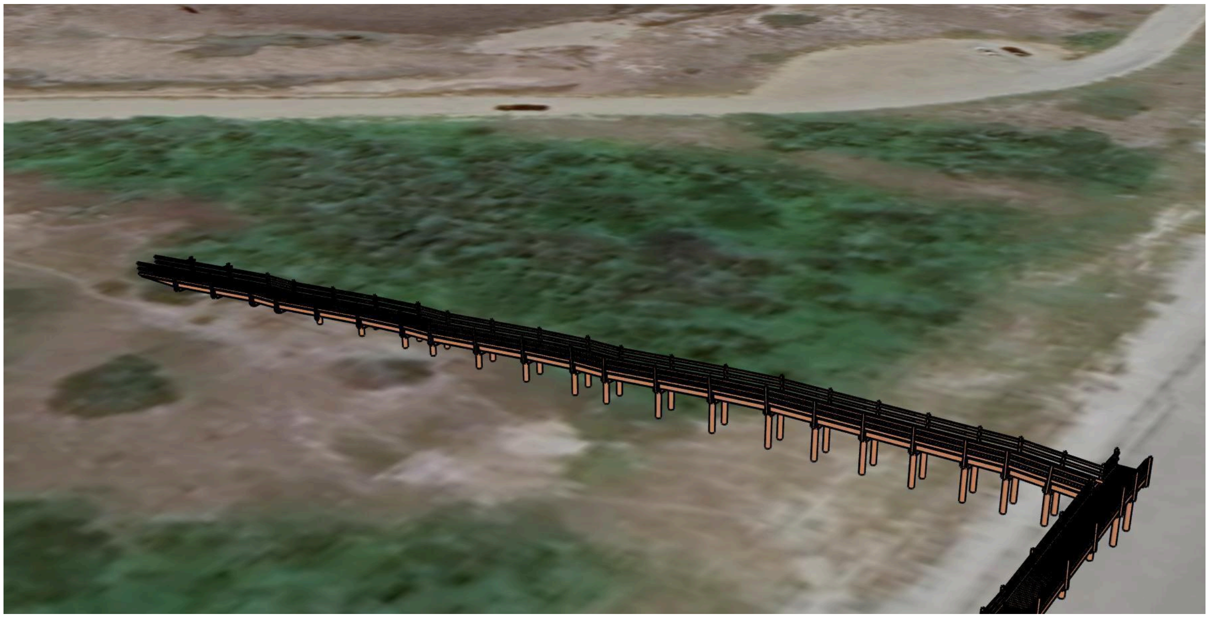


Figure 24: 3D Bayside view of boardwalk.

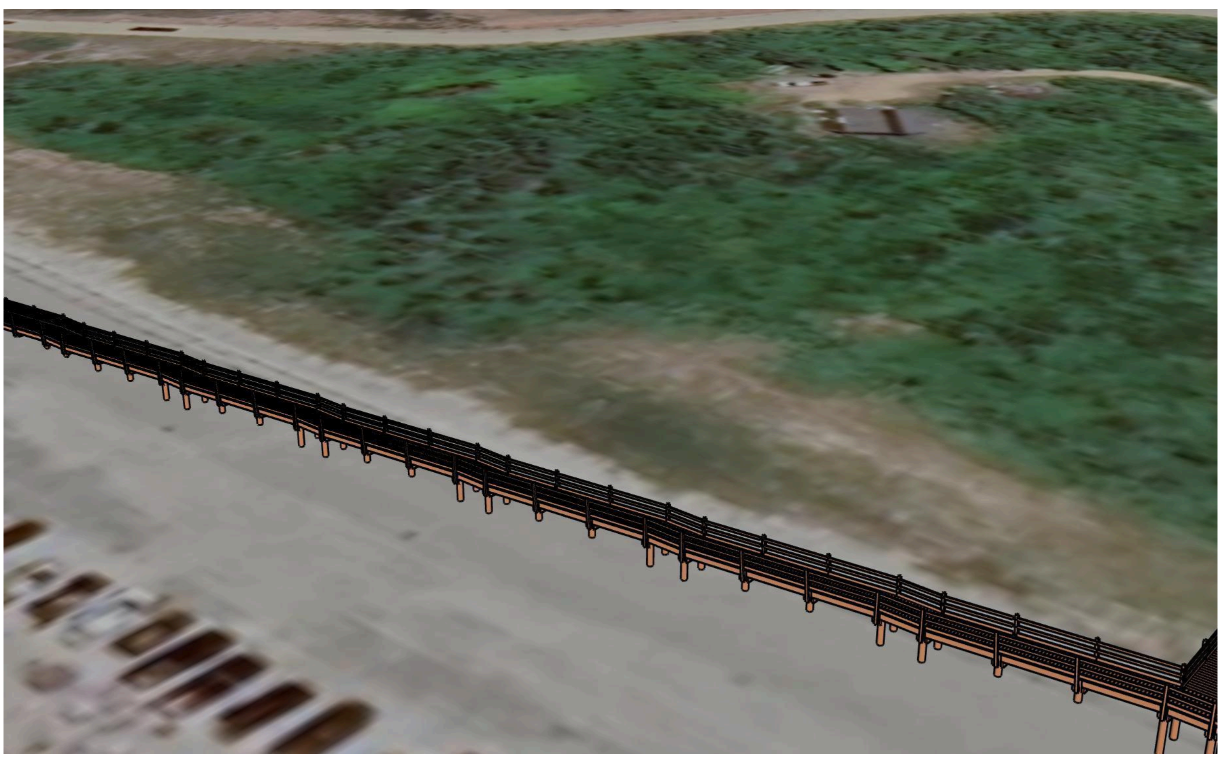


Figure 25: 3D Oceanside view of boardwalk.

4.2 Cost Estimate

The team developed a cost estimate to give our sponsor an idea of how expensive the current project would be. The sponsor can use this information to determine if the project is generally within their budget and to support future fundraising efforts. The estimated cost factors in materials needed, labor expenses, maintenance, and shipping prices. The estimate was taken from numerous sources at the current market price, so the values listed in Table 8 and Table 9 are likely to fluctuate in the future.

The anticipated lifespan of the boardwalk is 30 years. This is a commonly expected lifespan used for similar wooden structures exposed to similar environmental conditions. In that period, it is expected that the boardwalk will be subject to routine repairs due to its location and exposure to the elements. The guardrail of the structure will likely see the most deterioration because it is the least secure part of the structure. These repairs can be done by volunteer workers as the sponsor confirmed they could. The main cost of the maintenance would be the purchase of new wooden materials and shipping. A general view of the cost categories can be found in Table 8.

Table 8: Cost Categories for Estimate

Cost Category	Description	Estimated Cost
Materials	Member and connection materials for ramps and landings of boardwalk	$90,000
Labor and Construction	Piling crew, construction crew, equipment, mobilization, shipping supplies, permits	$110,000
Maintenance Plan	Repairs and replacements on structure	$2,000 annually

In summary, most of the project's costs come from expenses surrounding the piling. The purchase of the piling and installation comes out to be over half of the total project costs. Other major expenses come from the Ipe wood decking, skilled labor costs, galvanized bolts, and wood for the guardrails. A summary of each individual construction item can be found in Table 9.

Table 9: Detailed Cost Estimate Summary

Final Cost Estimate Summary			
Name of Item	**Quantity**	**Unit Price**	**Total Cost of Item**
2”x12”x12’ #1 Pressure Treated SYP	102	$33.41	$3,400.00
2”x12”x10’ #1 Pressure Treated SYP	12	$28.82	$350.00
2”x12”x8’ #1 Pressure Treated SYP	27	$21.55	$600.00
2”x12”x16’ #1 Pressure Treated SYP	3	$46.95	$140.00
2”x10”x12’ #1 Pressure Treated SYP	50	$22.41	$1,120.00
4”x4”x8’ #1 Pressure Treated SYP	2	$44.98	$100.00
2”x6”x5’ Ipe wood decking	990	$35.75	$35,400.00
10’’ diameter lumber piling	98	$300.00	$30,000.00
Piling Install Labor cost	Per pile (98)	$600.00	$80,000.00
Construction Labor Cost	-	-	$27,000.00
¾” x 14” galvanized bolts	800	$154.00 per 20-count box	$6,200.00
3” Screws	10,000	$56.30 per 350 box	$1,500.00
3x10 Pile Cap	400	$10.50	$4,200.00
2”x4”x4’ #1 Pressure Treated SYP	102	$11.35	$1,200.00
2”x6”x10’ #1 Pressure Treated SYP	102	$17.01	$1,750.00
2”x4”x10’ #1 Pressure Treated SYP	204	$14.15	$3,000.00
4”x4”x4’ #1 Pressure Treated SYP	102	$20.42	$2,100.00
Shipping costs	-	-	$2,000.00
Permits	-	-	$3,000.00
Total Estimated Cost	$203,000.00		

As stated, these costs were obtained from various companies and previous projects. The lumber, metal connections, and shipping were estimated by talking to local lumber yards through online quotes and going to speak with representatives in person. The lumber yards included Cape Cod lumber, Koopman lumber, and BB&S Lumber. The piling installation cost was estimated by researching the rates of piling installation businesses in the area and referencing that with online forums to confirm actual installation costs in the Duxbury area.

The labor cost was approximated by using the *RSMeans Construction Cost Database*. The final price includes the expected overhead in the listed cost. The labor cost was an assumption based on this information, but the value will change depending on how the sponsor decides to take on the project. The amount of people, involvement of volunteer labor, and the time to complete the project will factor into the total expected labor cost. The labor cost listed in Table 9 is based on an estimated project completion time frame and approximate hourly rates for laborers who have worked on similar projects. The use of union labor workers may be required, which would likely increase the estimated cost of the labor.

The cost of multiple items can be reduced depending on the market rate and scope of the project. Numbers were rounded up for each item, so the actual price could be lower than this estimate. The expected maintenance for this boardwalk is expected to be up to $2,000 annually, although help from volunteers can significantly reduce this cost. This cost comes from the expected maintenance of similar boardwalks in areas exposed to some harsh environmental elements. The cost itself was estimated based on the cost of maintenance for other similar boardwalks in the area.

Another significant challenge was sourcing suitable lumber within reasonable proximity, which was crucial for maintaining financial efficiency. The project's sustainability criteria necessitated finding locally available wood, avoiding the need for long-distance imports. However, this constraint substantially narrowed our options, leaving us with a limited selection of suitable wood types and sizes.

5.0 Conclusions and Recommendations

Based on the project criteria and proposed structure, the team has listed additional recommendations for the Duxbury Beach Reservation of this project regarding the construction and maintenance of the proposed bridge.

5.1 Conclusions

This project created a sustainable design to provide access for people from the proposed parking lot in High Pines to Duxbury Beach while making minimal interference with the dunes. The bridge is designed to withstand the various types of loads listed in the *Massachusetts State Building Code* while also complying with ADA standards for accessibility. To form this design, the team met with the project sponsor to discuss their goals and desires for this project. The team visited the proposed site of the boardwalk and researched similar boardwalks, including some that were local to the area. These design factors were used to create a preliminary design for the structure. The design was revised with the sponsors and changes were made where they were needed. The final layout design for the ramps, landings, and lookout point was made from these discussions and further research. Then, the structural analysis calculations were completed to determine the type and quantity of materials required. Finally, the team developed a cost estimate and models for the final selected design.

The layout for this project was split into two sections so the design could be more easily understood. The first section, which is located on the western side, otherwise known as the bay side, consists of 4 ramps with landings in between until the desired elevation is reached and then ends with a smaller ramp. The 4 ramps rise with an elevation of 2 feet and run 30 feet, and the last ramp descends 1 foot for a 12-foot run. The landings are a flat distance of 6 feet except for the landing at the highest point which runs for 38 feet. The decking of the boardwalk is planned to be made from Ipe wood with a span of 5 feet. The other parts of the structure are planned to be made from various sizes of #1 pressure-treated Southern Yellow Pine. The piling is to be round Yellow Pine with 10-inch diameters. The other section is the western, otherwise known as the ocean side, consisting of 7 ramps going to the south and a small lookout area on the northern end. The lookout area is 10 feet long with a width of feet. The sections intersect where the southern 5-foot portion of the lookout and the end of the western ramp from the bay side section will meet. From the south of this point, there will be similar ramp and landing sections as the 4 that were on the bay side, except the ramps will have a rise of 2.5 feet instead of 2 feet. The run will remain at 30 feet as well as the 6-foot landings between.

Additionally, throughout this project, the team encountered several constraints and challenges that influenced the development process of our structural analysis design. One significant issue was with the structural analysis software, RISA 3-D. The team's difficulties stemmed primarily from an inadequate level of documentation and a general underutilization of the software. RISA 3-D is predominantly tailored for steel and concrete structures, so the values for wood design, such as types of hardwood, were not given by the program. By employing a methodology similar to steel structure design but substituting loads and design values for wood, the team aimed to accurately reflect the real-world forces acting upon the structure. However, the team encountered a notable deficiency in RISA 3-D's database regarding wooden materials. This required manual input of values sourced from the National Design Specification (NDS). Despite potential discrepancies between these values and the actual characteristics of the wood used, the team deemed the approximation sufficiently accurate for our purposes.

5.2 Recommendations

5.2.1 Boardwalk Construction

The boardwalk's construction could be a challenge due to the High Pines area's location. It is recommended that the construction process for the boardwalk wait until the completion of the parking lot area is completed. This would prevent any interference and allow for the boardwalk construction crew to have more space for operation. In order to access this area, vehicles must traverse a narrow strip of land for nearly a mile and a half. This road is made of flattened dirt and sand and is located close to the water on the bay side. These conditions make the road have large bumps and can be difficult to travel across, especially for larger vehicles. The construction team may have to consider delivering the materials to High Pines using smaller vehicles depending on the conditions of the road at the time of construction. It is recommended that construction should occur when beachgoers are most infrequent, being in the fall or the spring months and the crew does not work if there are conditions that may make the road potentially dangerous to drive on.

An important part of this process is to ensure that the proper steps are taken in the construction of the boardwalk. These steps include making sure proper safety measures are put into place and all permits required are obtained for the project. For this to be done, the team recommends the consideration of hiring a construction manager to manage these steps as well as manage the construction process. This step is not required, and the cost of this hiring was not included in the final, but a construction manager will help the progress of the construction.

5.2.2 Removable Portion

Sea level rise and storm surges were a concern when designing the boardwalk. Discussions with our sponsor and data from FEMA show that the water from the ocean will reach the area for the proposed boardwalk. The waves and impact from the water can damage the wood, specifically smaller pieces of wood used to construct the ramps and landings of the boardwalk. The existing boardwalk on Duxbury Beach has had to face this issue as well. To reduce the impact of the water, a group of volunteers removes the lower section of the ramp on the beach and stores it away during the colder seasons when the beach sees less use. The boardwalk will become unusable, but this will save the ramp from environmental conditions during this time. It is recommended that the same system be implemented and that the lowest section of the ramp on the oceanside be removed during the off-season of the beach. The work can be carried out by the same volunteer workers at the same time as the other ramp is removed.

5.2.3 Path to Boardwalk

There remains a length of land on the bay side of the High Pines between the parking lot and where the boardwalk begins. The team's recommendation is to implement the use of a Mobi-mat. The Mobi-mat would be practical to lay across the sand in this area so that the boardwalk is accessible for wheelchairs and other beach items such as large coolers. The use of Mobi-mats is a common practice seen on beaches to provide accessible pathways over sand or other uneven surfaces. The setup of the Mobi-mat is simple labor that could be reasonably handled by a volunteer. The cost of a 5-foot width of Mobi-mat spanning across the expected length of 120 feet would cost around $5500 according to the Mobi-mat website.

5.2.4 Boardwalk Signage

Placing signs on the guardrails is not a required step of the construction, but they can be a low-cost and easy way to enhance the experience of the beachgoers and share knowledge of the area. These signs would be similar to the ones seen near the main parking lot of Duxbury Beach. They display information about the local wildlife in the area and other important information about Duxbury Beach. These signs can offer crucial information about the beach ecosystem and the wildlife inhabiting it so visitors can be more educated about their surroundings. Furthermore, the placement of signs on the guardrails not only educates visitors but could minimize disruption to the beach landscape, preserving its natural beauty. Signs can be placed along the guardrails of the boardwalk, possibly at the beginning, end, and lookout points of the boardwalk.

5.2.5 Boardwalk Maintenance

Upon the completion of the boardwalk's construction, the team highly recommends that a maintenance program be put into effect to ensure the longevity of this passageway. Based on reviewing other pedestrian walkway maintenance programs it is recommended that routine inspections be performed every 5 years. Moreover, emergency inspections should also be conducted as required post-storms. It is also recommended that during these inspections short and long-term repairs be identified.

Short-term repairs are recommended to be completed every 2 to 5 years. These repairs may include the replacement of bolts, the replacement of connections at splices and cross bracing, and the replacement of rotted boards. Long-term repairs may include repairs or replacement of items that have outlasted their service life. Additionally, code upgrades may also cause a need for parts of the boardwalk to be upgraded or changed.

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Appendices

Appendix A: Project Proposal

Structural Analysis of Duxbury Boardwalk

Sponsoring Organization: Duxbury Beach Reservation

Submitted to:

Advisor: Professor Leonard Albano and Suzanne LePage

A Major Qualifying Project Proposal Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

Submitted by:

Elidja Diakite

Ryan Tonry

In partial fulfillment of the requirements of the Degree of Bachelor of Science of Civil Engineering

Capstone Design Statement

The Major Qualifying Project (MQP) is the culmination of WPI's project-based learning into a tangible capstone project. The MQP helps students to put into practice the theory of what they learned into real-life issues. In the Civil Engineering program, the MQP satisfies the capstone design requirement defined by the Accreditation Board for Engineering and Technology (ABET). The following constraints are taken into account by this project: economic factors, environmental aspects, social considerations, political implications, ethical concerns, health and safety aspects, manufacturability, and sustainability. By designing accessible passageways for Duxbury Beach, this project fulfills the capstone design requirement by providing beach access.

Economic

In evaluating the feasibility of the team's design, we will take into account financial factors. Cost estimates will be prepared specifically for the Duxbury beach site in accordance with the needs identified by the team's sponsor. Material and labor costs will be considered to best achieve a balance between quality, longevity, and affordability.

Environmental

To address environmental limitations, the team will construct the project around sensitive ecosystems such as sand dunes, beach vegetation, and Piping Plover habitats. It is important to ensure the state of the sand dunes on the site is protected from human factors. The design of the boardwalk will take this into consideration in its design process.

Social

Some social concerns may be the construction of the boardwalk disturbing or interfering with the nearby residents. The selected location is far enough away from the residential homes that the construction should have little to no interference.

Ethical

This project will abide by the American Society of Civil Engineers (ASCE) Code of Ethics.

The team will follow the guidelines on ethics which lead to the creation of safe, resilient, and sustainable infrastructure. The team will consider the most significant needs of the project sites, focusing on improved beach access and dune preservation.

Health and Safety

The team will take the safety of the future stakeholders into consideration. The team will research and analyze the design to determine that the design meets ASCE standards and would ensure the safety of users. Furthermore, the health of the environment will be considered by selecting materials that would have minimal impact on the surrounding environment.

Constructability

The project will account for the constructability of the passageways by assessing the needs of each location. This will allow the team to select materials that are available and feasible for implementation to current conditions on each beach.

Sustainability

The team will take the use of different materials into consideration when looking at the design. The materials used and the design itself will be researched so that the boardwalk has sufficient structure to prevent erosion and maintain conditions on-site. This would allow for the passageway to have more durability during events such as harsh winters and storm surges that the design would likely encounter.

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1.0 Introduction

Boardwalks have been used in the U.S. for over a century. They have allowed for people to traverse diverse terrains without impacting the local nature and fauna. Although they vary in design and size, they all function as pathways that run along a waterfront or shoreline.

Located on the south shore of Massachusetts, Duxbury has been a long-standing beach town. Notably, Duxbury is also home to one of the many barrier beaches in Massachusetts. These barriers vastly contribute to the beauty and uniqueness of Duxbury Beach, but they play another critical role as well. These large sections of deposited sediment (also known as barrier islands) serve as important habitats for several species of animals. In addition to this, they also act as shields to the mainland by absorbing the waves' energy. This allows for smaller storm surges and less flooding along the coast (US Department of Commerce, 2021).

Unfortunately, these barriers have been disappearing all around the world. Massachusetts in particular has been losing approximately 65 acres of coastal land per year due to shoreline retreat caused by sea level rise. Considering this it is all the more important to maintain and protect these areas. When properly designed, boardwalks provide a convenient passageway for visitors to navigate and interact with nature without disturbing the sensitive coastal ecosystems. When designing a boardwalk, it is crucial to consider resilient systems that can withstand various weather conditions. By incorporating essential design elements such as effective drainage systems, elevated sections, and durable construction materials, the detrimental effects of storm surges can be significantly reduced. These factors not only contribute to the longevity of these vital structures but also ensure that a diverse range of individuals, including those with accessibility issues, can continue to enjoy coastal areas with ease in mind.

The Duxbury Beach Reservation, a local non-profit that has owned and managed 4.5 miles of the beach for the past 100 years, actively works to meet the challenges it faces. These challenges include beach erosion, protecting endangered species, and more. As additional challenges arise, the organization proactively seeks solutions to address these issues, ensuring that the beach can be enjoyed for years to come.

The goal of this project is to develop a structural design for an accessible passage that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. To achieve this goal, the team will fulfill four primary objectives:

- Establish existing site conditions
- Identify initial design criteria based on sponsor and stakeholder needs
- Analyze the structure
- Evaluate the final design package

This beach has long been a cultural staple in the town of Duxbury. In order to ensure the continuation of this great beach the team of WPI students will undertake to design a boardwalk that would meet the concerns of the local community and the changing landscape and climate.

2.0 Background

This chapter provides the context of the Duxbury Beach Reservation boardwalk, previous designs of other boardwalks, legal issues and permitting, accessibility factors, sea level rise and storm surges, and costs of boardwalks. These topics form a foundation upon which the project is based.

2.1 Previous Work

In the spring of 2023, a previous project called "Beach Access and Coastal Design" by Webster, Collette et al. discussed the idea of constructing a parking lot beside Duxbury Beach along with a design for a boardwalk to allow access to the beach from the parking lot. The report investigated various issues that could arise from building a boardwalk in this area and factored those in to create an initial design and location for the boardwalk. This initial design that was made is the foundation of this project, which is a direct continuation of their work.

2.1.1 Environment

One of the major factors that the previous team had to consider was to avoid having a negative impact on the local environment. There were two main challenges that came from the area, avoiding the impact on sand dunes and the local wildlife like the piping plovers. A sand dune is an accumulation of sand formed by wind, waves, and eroding sandstone, with a structure that is constantly changing and growing due to natural patterns of the wind and the coastal tide (England, 2022). Sand dunes protect the coastlines and wildlife against winds, coastal flooding, and erosion. The sand dunes absorb a lot of the impact from those factors and are therefore especially susceptible to erosion themselves. The dunes are protected and rebuilt by nature conservation groups because of how well they naturally protect the shorelines. Another environmental factor was protecting animals such as piping plovers. Many animals use the sand dunes as their habitat as they provide protection while being near the oceans. The design of the boardwalk was made in a way where the dunes and the wildlife would face negligible negative effects on their habitat.

2.1.2 Location

The location of the boardwalk and parking lot was recommended to be High Pines, a slightly wider area of the strip that allows for the space to construct a parking lot. The space is ideal for beach users as the location is near the middle of the strip, where parking is limited. The area between where the parking lot would be located and the beach is a protected area for sand dunes. This means that users cannot cross this location on foot as the foot traffic may cause damage to the sand dunes. A boardwalk was proposed to allow people to use the parking lot and access the beach while not disturbing the sand dunes. The estimated location of the boardwalk can be seen in Figure 1.

(a)

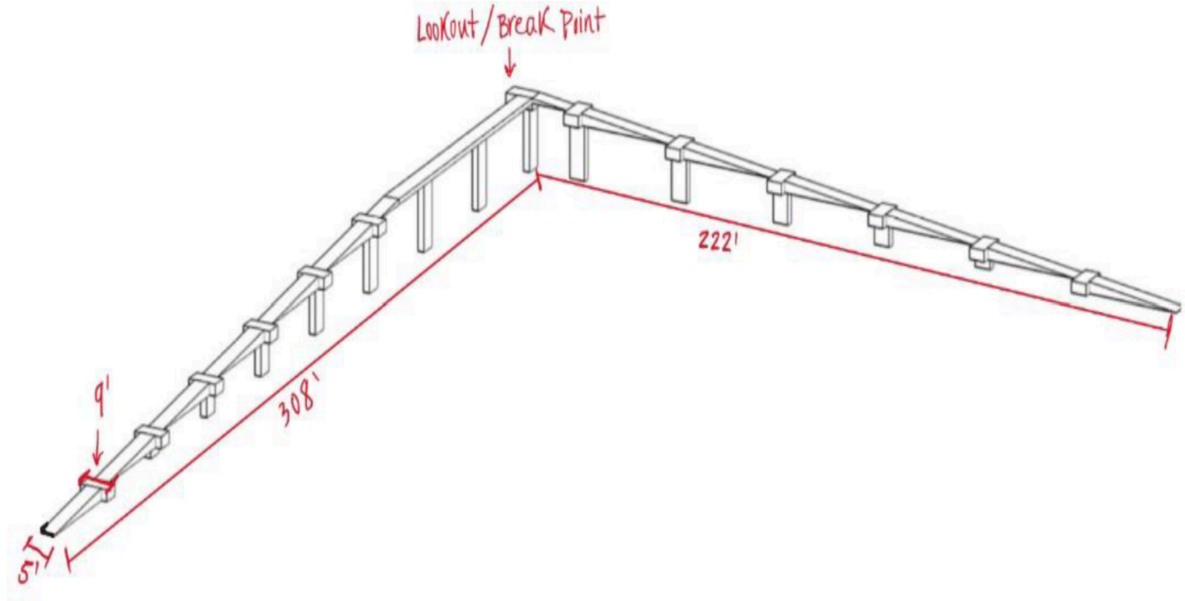
(b)

Figure 1: (a) Photo displays the estimated placement of the boardwalk. (b) Photo shows where High Pines is located.

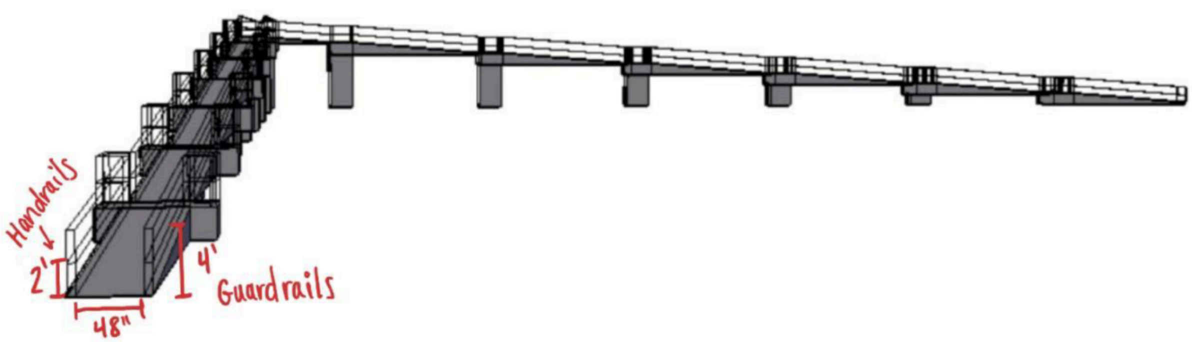
The location of this site does pose a challenge when it comes to erosion. The area is located on the coastline of Massachusetts, so winds and water are going to have a major impact when it comes to the lifespan of a boardwalk. Massachusetts experiences winters where multiple inches of snow are not uncommon, so snow loads are also a consideration for potential damage. The team was able to visit the site and investigate other boardwalks in the area. A similar boardwalk near the residential parking lot entrance was shown to have moderate wear from the erosion the boardwalk had experienced. It was missing pieces in some areas that were not crucial to the structure and had multiple areas that appeared to have been replaced with newer pieces of wood. This boardwalk is a reference to what can be expected of a wooden boardwalk after around 10 years of exposure to local erosion factors. The location of the proposed boardwalk will be near to the ocean during high tides, and with slowly increasing sea levels and storm surges, it may be set in a vulnerable position in the future.

2.1.3 Design Choices

The purpose of the boardwalk is for people who use this parking lot to be able to access the beach. The structure also must be able to clear the sand dunes which stand at about 16 feet in height. The team needed to be able to make a design with proper accessibility that will meet ADA requirements. This means the slope of the ramp has a limit and needs to incorporate rest stops at certain intervals. The design needed to be long enough so that the proper height to clear the dunes could be reached while not exceeding the slope limit. The result of their work can be seen in the design in Figure 2.



(a)



(b)

Figure 2: Final designs of the previous project. A basic isometric view (a) is shown with the lengths of the entire structure while the other image (b) incorporates guardrails into the picture.

2.2 Designs of Similar Boardwalks

There is a plethora of other boardwalk designs that also serve as a good model for the planned construction of the Duxbury Boardwalk. While others may differ slightly in design and scale, they offer a view into potential design challenges and material choices.

2.2.1 Sandwich Boardwalk

One example boardwalk is located on Cape Cod in Sandwich Massachusetts. The Sandwich Boardwalk also known as the “Plank Walk” or the “Mill Creek Foot Bridge " is a 1300-foot boardwalk that was originally constructed in 1879 (*History of the Boardwalk | Sandwich Historical Commission*, 2021). Since then it has gone through many changes including several repairs and upgrades as well as complete reconstructions. Being along the Cape, this beach boardwalk is also exposed to similar elements such as sea salt, flash flooding, blizzards, and freezing. This gives insight into how a boardwalk would hold up in the future. In fact, the creation of the Cape Cod canal over 100 years ago changed the natural migration of sand along the coastline and rock groins, causing more coastal erosion and beach/dune erosion in addition to more damage on the boardwalk (*Coastal Resiliency | Sandwich, MA*, n.d.).

In terms of design, the timber boardwalk framing is made up of 4x4 posts, 2x8 split pile caps, 2x6 middle stringers, 4x6 edge stringers, and IPE decking. Similar to other boardwalks in Massachusetts, this boardwalk and dune walkway also employ treated Southern yellow pine for the timber and composite decking. With respect to existing building codes, the Sandwich Boardwalk was failing to meet multiple standards since its last upgrade. The Massachusetts State Building Code (SBC) only requires that buildings and structures comply with the edition of the code that is in force at the time of their construction. The Boardwalk's last major reconstruction was in 1992, with minor repairs conducted in 2018. Despite these efforts, several sections of the Boardwalk are nearing the end of their service life, necessitating considerable reconstruction to prevent large-scale loss. In 2021, the town of Sandwich began a comprehensive $2.3 million restoration project. Given that the renovated area will surpass 30% of the entire structure's "full and fair cash value," the Massachusetts Architectural Access Board (MAAB) requires that the entire structure be upgraded to comply with current standards. The issues of non-compliance to be addressed include edge protection and ADA accessibility. Edge protection requires a guardrail for any platform in which a fall of 30" or greater is present. The Massachusetts Architectural Access Board (MAAB) and the American Accessibility Act (ADA), require that ramps longer than 30' have a maximum slope of 1:20 (Boardwalk Project | Sandwich, MA, n.d.).

2.2.2 Plum Island

Located on the North Shore of Massachusetts, Plum Island is home to the second boardwalk. Known as the Hellcat Boardwalk, this impressive multipath trail stretches for 1.4 miles and was constructed in the 1970s. The boardwalk consists of two distinct sections: the dune trail, which covers 0.6 miles, and the marsh trail, which spans the remaining distance.

Since the '70s this boardwalk has gone through a few changes with the most recent being in 2020. During this upgrade, the engineers opted to replace the wooded boardwalk with synthetic planks that are longer and wider than the original wood planks. This widening of the planks has allowed for greater accessibility for those in wheelchairs (“Hellcat Boardwalk Trail,” n.d.).

2.3 Design Criteria

Design criteria establishes the factors that will be considered when looking at the design of the boardwalk. They will serve as the standard guidelines that the team has to abide by and can help create a starting point for the project in the process. These factors can range from legal standards to environmental hazards. These will be crucial in determining a final design for the boardwalk.

2.3.1 Codes and Permitting

Obtaining beach permits requires a multitude of approvals, both during the construction and reconstruction stages. These permits have a significant impact on the construction methods that can be employed and the overall duration of the project. Construction in Duxbury is subject to local building department codes and permitting, which review the design of the structure before granting approval. Table 1 summarizes the required permits for building a boardwalk in Duxbury. This permitting information was obtained from local government websites and via consultations with our sponsor Sue MacCallum, the Duxbury Beach Reservation Program Specialist.

Table 1. Required Permitting for Construction on Duxbury Beach

Permit	Jurisdiction	Description
Army Corp of Engineers	Federal	Regulates work done below mean low tide
Coastal Zone Management	State	Review of possible impacts
Dept. of Environmental Protection	State	Possible impacts on designated wetlands
Natural Heritage & Endangered Species Dept	State	Possible impacts on state-listed/ protected species
Building permit	Town of Duxbury Building Department	Reviewing structure
Conservation Commission review	Local	Reviewing possible impacts on designated wetland

2.3.2 Accessibility

The initial introduction of the Americans with Disabilities Act bill took place in 1988; however, it was not officially enacted into law until 1990 (*The History of ADA*, 2012). This pivotal civil rights legislation sought to combat discrimination against individuals across various domains of society, encompassing both public and private spheres. With the introduction of this law, many of these same regulations also extended to the protection of individuals' rights in public beach areas.

Accessibility normally breaks down into three categories: partially accessible; handicapped accessible; and ADA accessible. Furthermore, full ADA compliance extends to more than just ramps and elevators. The 2010 ADA standards for Accessible Design state that

ADA compliance should be reflected in routes, signs, parking, mobility, reach, handrails, and restrooms (*Public Beach Access and ADA: Deciphering Disability Access for Coastal Management Programs*, n.d.).

As it currently stands, guardrails are mandated by the State Building Code (SBC) for new boardwalks, and in compliance with current regulations guardrail heights should be at least 42 inches. Furthermore, the building code necessitates a rail system that effectively prevents any sphere with a diameter of 4" from passing through.

2.3.3 Sea Level Rise

Sea level rise is a direct result of global climate change and will have long-term consequences on our environment and communities. A significant part of climate change is global warming. Global warming has led to the sea level increasing because one result of global warming is the melting of the polar ice caps as well as the thermal expansion of seawater in the ocean. The rate at which the sea level is rising is slowly increasing. “The global mean water level in the ocean rose by 0.14 inches (3.6 millimeters) per year from 2006–2015, which was 2.5 times the average rate of 0.06 inches (1.4 millimeters) per year throughout most of the twentieth century (NOAA)”. This rate could continue to increase as global emissions increase. This rise will create many challenges for places near coastal regions. The graph in Figure 3 shows the increase in sea level since 1880.

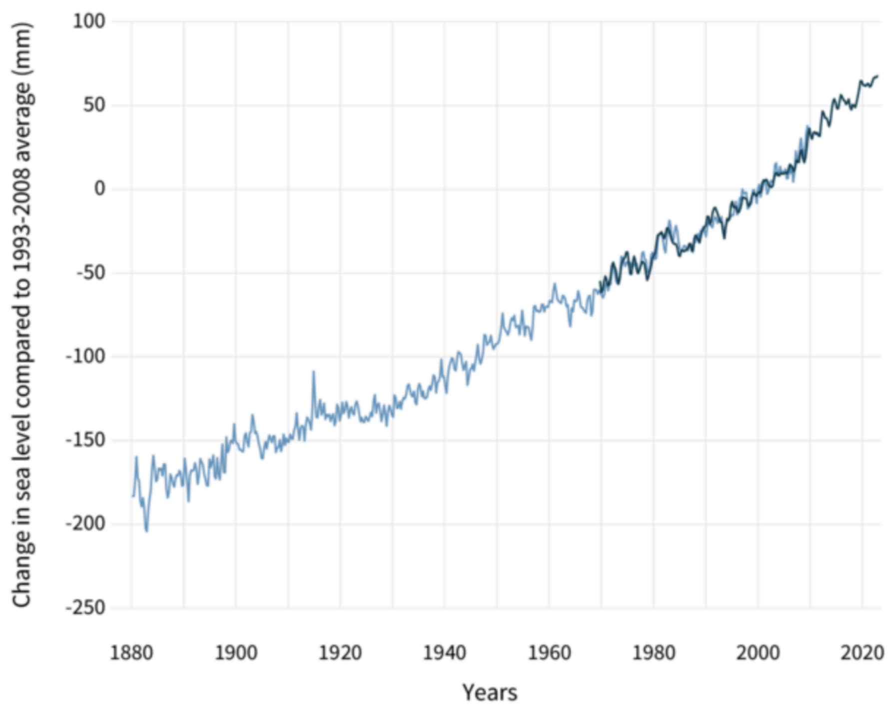


Figure 3: Graph showing the change in sea level over the years. The light blue represents historical data until 2011, and after 2011 is a predicted trend. The dark blue line represents data from the University of Hawaii which is correct to 2023. (NOAA)

Many societies around the world are located near coastal regions and will likely see a direct impact on their communities as the coastlines are progressively reshaped. Around 30 percent of the population in the United States and 8 out of 10 largest cities in the world are located near or on the coast (NOAA). The city of Miami is predicted to be partially underwater in 30 years if nothing is done to reduce the impact from the sea. These higher water levels can allow for floods to cause more damage to communities. High tides will make their way farther inland and take away shoreline. Structures and other infrastructure, especially in urban areas, will likely be damaged due to water damage and erosion. Repairing infrastructure can be very expensive and may result in damage becoming too expensive to cover. Rises in sea level will not only have an impact on a community, but the local ecosystems too. The rising tides can harm the wildlife areas, such as marshes, where animals like fish live. Tides can also disrupt fisheries and introduce salt water into freshwater areas (NOAA).

2.3.4 Storm Surges

Storm surges are a challenge that most coastal regions face. A storm surge is when a body rises far beyond the level it would be at a high tide due to an incoming storm such as a hurricane or tropical storm. The winds from these storms push water toward the shore. These storm surges can occur within hours with the help of heavy rainfall, unlike sea level rise which occurs over the span of many years. The water rise can persist for several hours or even days. They create a large threat to the safety of coastal communities and their infrastructure. There are many cases where the damage from the water brought by the storm surge is greater than the damage from the winds of the hurricane or tropical storm. Climate change and global warming may contribute to more intense hurricanes in the future. Angela Colbert, a scientist at NASA, predicts hurricanes will likely cause more intense rainfall and have an increased coastal flood risk due to higher storm surges caused by rising seas (Colbert, 2019). This means that the prevention or minimizing of the effects of storm surges will be an important factor to consider when building the coast. Regions that are near the coast reduce their vulnerability to storm surges by taking actions such as building seawalls and evacuating vulnerable areas.

The water that comes with these storm surges damages structures with not only the water wearing down the materials but the sediments that water brings along as well. A structure that experiences these types of conditions will experience a shorter lifespan depending on the frequency of these events (NOAA). Designs of structures can be made to reduce the impact of storm surges and sea level rise. One method of this is to have it be able to adjust. A structure that can be adjusted could be lifted up to a higher elevation to avoid damage. The elevation could also be adjusted in an instance where the level of the sand changes. Another method would be to design a boardwalk that could be easily deconstructed or have removable parts. The owner could have parts of the boardwalk that were believed to be in a potentially dangerous area disassembled and stored safely before a storm to prevent harm to the materials. A similar tactic was seen with the boardwalk already on the Duxbury beach, with the lower portion of the ramp on the beach side taken away during the offseason (MacCallum, S).

To calculate the magnitude of these storm forces, many statistical design methods and equations are used in the field of coastal engineering. One of the most commonly used methods in coastal engineering is the Goda method, developed by Japanese Researcher Yoshimi Goda in 1974. It is often used in the design of on and offshore structures to calculate breaking wave forces and its effects on structures.

This method considers factors such wave height, wave period, water depth, wave pressure and other wave kinematics to allow for relatively precise prediction of wave forces. While the Goda method is widely used and accepted, it does have certain constraints and limitations. The Technical standards for Port and Harbour Facilities in Japan (1980) has been employing this method for a long time, however they caution that the method may underestimate wave forces due to certain assumptions such as assuming relations between the length of waves and their height. Due to this, a safety factor of 1.2 is recommended for structure design against sliding and overturning. While this method was originally designed for caisson structures, it has and can be modified for use with many other types of elevated structures (*Breaking Wave Forces on Walls*, n.d.).

The equation for the Goda method is described as follows: “The formula predicts a maximum pressure at the still water level, $p1$, which is directly proportional to the wave height, H, and is given by the following relation:

$$p_1 = \frac{1}{2}(1 + cos\beta)(\alpha_1\lambda_1 + \alpha_2\lambda_2 cos^2\beta)\,\rho g H$$

where β is the angle of wave incidence, ϱ is the density of the water, g is the acceleration due to gravity, $\lambda 1$ and $\lambda 2$ are modification factors for structure geometry, and $\alpha 1$ and $\alpha 2$ are wave pressure coefficients” (Wiebe et al., 2014).

2.3.5 Pricing and Costs

Cost is an aspect of the project that will have an impact in determining some decisions made throughout the project. Two of the main categories that need to be looked at in the construction costs are the materials used and labor costs. There will be different types of materials used for the wood, supports, handrails, etc. The previous project report recommended specific materials to use to construct the boardwalk (Webster, Colette, et al). However, the price of materials fluctuates over time and may not be the most effective anymore. Engineers who design structures want to calculate the materials that would allow for the structure to perform what it's designed to do while keeping the price as low as they can. After narrowing down the choice of materials, the cost of those materials can be looked at versus the quality and potential duration. This can help determine what choice is preferred to create some possible options.

3.0 Methodology

The goal of this project is to develop a structural design for an accessible passage that not only withstands the impact of natural elements but also emphasizes minimal disruption to sensitive areas like dunes, wetlands, and natural habitats, all while ensuring an efficient installation process. The team aims to balance functionality with sustainability, while also promoting environmental conservation.

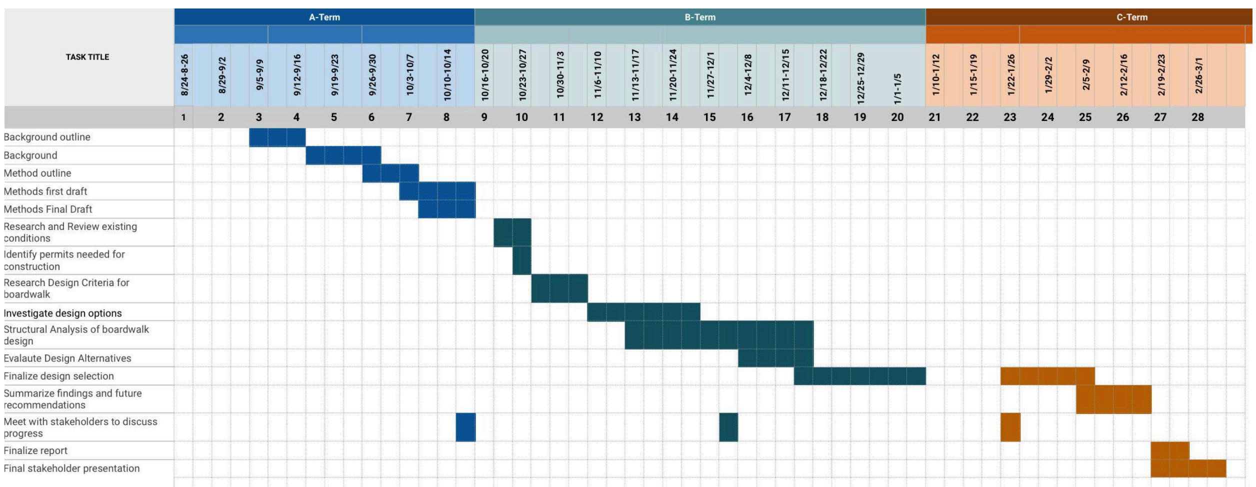


Figure 4: Gantt Chart of Methods

3.1 Establish existing site conditions

Table 2: Activities and Resources for Objective 1

Activity	Resources
Examine previous boardwalk design and its solutions	Beach Accessibility: Passageway Design for Massachusetts Beaches MQP 2022
Survey the site and understand site's history	Spoke with Sue MacCallum, the Duxbury Beach Reservation Program Specialist, who also serves as the co-chair of the Community Outreach Committee.
Assess dune conditions	USDA SoilSurvey website; field observations
Assess impact of structure on local wildlife and environment/ impact mitigation strategies	Permitting and conservation standards; review data from last year

The team will be able to establish the existing site conditions and constraints by collecting qualitative and quantitative data from the Beach Accessibility: Passageway Design for Massachusetts Beaches 2022 MQP team about the physical and environmental characteristics of the beach. This data included distance and slope measurements which allowed the team to establish preliminary designs in line with the Americans with Disabilities Act (ADA)/ Architectural Access Board (AAB) requirements. The team will be able to utilize USDA's SoilSurvey to obtain classification data about the different soils present at Duxbury Beach as well as their properties. To assess the potential impact of the boardwalk design on the environment, the team will examine both the required local and state permitting regulations. Our sponsor also provided support and guidance on additional regulations for working on the beach. With this data, the team will be able to continue with the preliminary designs and calculations for the boardwalk.

3.2 Identify Design Criteria

Table 3: Activities and Resources for Objective 2

Activity	Resources
Establish sponsor and stakeholder needs	Interviews with sponsor to obtain preferences; conversations about some of the potential challenges and communities involved
Identify accessibility, environmental, and usage design requirements according to permitting and standards	ADA/AAB codes. Required permitting from Table 1
Assess sea level rise/storm surge, erosion, and sand movement	Utilize flood risk data from FEMA website to estimate impact on coastal regions.
Identify and explore different material options and their effects on boardwalk design and cost	AASHTO load guide for Pedestrian Bridges, ASTM standards; materials and pricing data

Before the development of the team's calculations and designs, the team met with the sponsor to learn more about the site and some of the challenges in the area. Our sponsor was also able to provide us with the drawings of another recently constructed boardwalk in Duxbury. This helped the team to better anticipate the challenges and the norms when constructing a boardwalk in sandy terrain. In order to account for the potential effects of storm surges on the structural design, the team will examine historical storm and meteorological data and assess its impact on factors such as sea level rise, storm surge, erosion, and sand movement. By analyzing past storm and flood data, such as mile fetch, average wind speeds, wave periods, and wave heights, the team can gather valuable sample data to simulate the forces acting on the structure. Using a modified form of the Goda method would allow the team to perform calculations for uplift, wave, and lateral forces. This information can help assess the potential damage caused by storms and how to mitigate it. Understanding this data would allow the team to select better materials. Additionally, this would enable the team to implement various design strategies and choices during the actual construction process, effectively mitigating the impact of these storm forces.

These various design strategies would also allow the team to come up with a cost estimate for storm mitigation techniques.

3.3 Analyze the Structure

With the criteria set in sections 3.1 and 3.2, the group can begin to focus on the structural analysis of the boardwalk design and determine whether modifications to the original design are needed. An analysis of the structure is necessary to ensure the safety and durability of the boardwalk.

The analysis includes a study of the boardwalk's entire structure with the key areas to investigate being the pillars, railing systems, and flooring of the boardwalk. To calculate the load-bearing capacity of different areas of the boardwalk, a detailed load analysis will be conducted. This analysis will take into account factors such as pedestrian traffic, maintenance, environmental conditions, and varying loads. Dynamic and static loads will be considered to accurately predict real-world conditions. Design specifications will be researched for selected materials to confirm that selected materials will be able to withstand the loads calculated. The information of these loads for selected materials will be found through various credible online sources. This information will help reveal the capacity of the boardwalk and if adjustments needed to be made to the design of the boardwalk. After the prior steps are completed, a final design will be selected to be carried out.

The boardwalk will face the challenge of sea level rise and storm surges affecting the future use of the boardwalk. The team will discuss potential options for how to design a boardwalk that would be able to adapt to site conditions. The group will research methods of creating adjustable or removable areas of the structure that would allow for the boardwalk to function if the site conditions changed. The team will determine the appropriate design software to use for the boardwalk. The selection of software will be based on its capabilities to replicate accurate structural modeling and load analysis. The chosen software will enable the group to make more informed decisions about the boardwalk design.

3.4 Package Final Design

The final phase of the project will consist of conducting a thorough cost comparison analysis. This analysis will conduct an evaluation of materials and their associated costs. The team will research the current market price of the materials, such as the type of wood, to give a more accurate cost estimate of the project. The total cost of materials will be calculated along with the cost of shipping them to the site. The site may present some logistical challenges because of the accessibility of the site, and this factor will be considered when determining how to ship the materials. Another factor to consider for the total cost is the price of labor. The equipment needed and laborers used for construction will need to be estimated for the final cost of the project. These factors will be added to determine the total cost of the boardwalk.

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Appendix B: Sue MacCallum Meeting Minutes

Questions for Sue
Meeting on Nov 15, 2023

Questions:
1. Opinion of how to end the ramp section of the boardwalk
2. Expected lifespan for boardwalk (30 years?)
3. Opinions for piles: Helical vs. Timber Piles (can we can a small crane out there)
4. What do you think about our new zig zag design?

Updates:
1. Initial ideas of design
    a. Ez dock section
    b. Removable end
    c. Hinge design
2. Primary and Secondary choices for
    a. Timber
    b. Railing
3. Considering putting ramp on both ends due to sea level rise

Meeting Notes:
- Prefer removable
- Ramps don't extend very far out the beach
- How to wheelchairs onto beach, how to flatten
- Mobi mat only works if surface is already flat
- Can't move sand easily due to regulations
- Nylon weave mat and styrofoam like material 6x6 interlock are already there but are effective
- Can just use regular piling - less footprint, less expensive, less environmental interference, more equipment.
- Look into half and half piling
- Minimize design

Questions for Sue
Meeting on Nov 20, 2023

Questions:

1. Expected lifespan for boardwalk (30 years?)
2. What do you think about our new zig zag design?
3. What lumber yards were used to build the other boardwalk in Duxbury?

Updates:

- Met with Pine Point Beach Scarborough Maine beach engineer to discuss the issue of creating a level surface
- Dune elevation

Meeting Notes:

- Walkway for stairs and wheelchairs
- Mobi mats covered on windy day
- Not a lot of staff available all the time so clearing them off is a problem
- She will try to get historical data for dune height
- Lumber is usually left to the contractor
- Last contractor was duxbury construction
- No idea for expected lifespan
- Repairs are done by volunteers (small) but use contractors if bigger contract
- No metal railing sun, salt air and water wear down very fast
- Nylon would be fine material but not sure how it would face site conditions

Questions for Sue
Meeting on Jan 24, 2024

Questions:

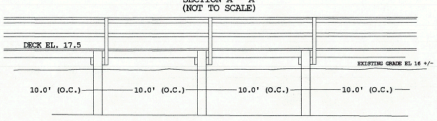
1. Flooding that happened in Duxbury, if she knows how the area in High Pines was affected ~
2. How deep piling goes into other boardwalk
3. Adding shrubbery
4. ramp increase?
5. Ada information for longer ramps ?
6. How the other boardwalk ramp looks like, how it transitions to beach ~

Meeting Notes:

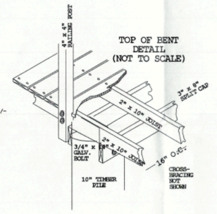
- A lot of water got pushed into the bayside due to wind, parking lot was covered
- Oceanside wasn't much of an issue
- Zoom meeting with people later on
- None of dune restoration has been done
- Not much that keeps sand from moving (sand doesn't move a lot of parking lot side, scrubs help a little but can only placed on east side)
- Cobble sand mix keeps sand at bay a little bit
- She will send piling info, helical piles may be necessary but she is concerned about how much more expensive they are
- ADA can be vague

Appendix C: Duxbury Beach parking lot Boardwalk Plan

SECTION A - A
(NOT TO SCALE)



TOP OF BENT
DETAIL
(NOT TO SCALE)



N O T E S

All framing components such as joists, stringers, posts, and rails must be made of pressure-treated wood members such as Eastern white pine or Southern yellow pine. The wood must be treated with either ACQ alkaline copper quaternary 0.60 pcf retention or CA-B copper azole 0.31 pcf retention, and should be surfaced on all four sides (S4S). The preservative treatment must adhere to AWPA standards C-3 and C-18, and contractors must use category 5A.

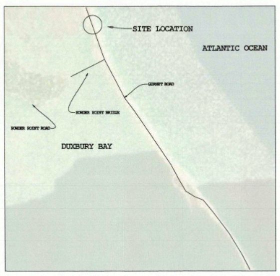
For all framing hardware, either exterior structural screws (such as Timberlok or equivalent) or hot-dipped galvanized hardware that conforms to ASTM-A153 are required.

Steel angle and flat bar components must also be hot-dipped galvanized, in compliance with ASTM-A653 and -A123.

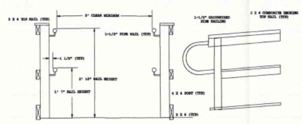
The decking must be made of hardwood that matches the existing decking, and the contractor must verify the type of hardwood before installation. The decking must be installed with a hidden fastening system, similar to the existing system, with all deck fastening screws being made of stainless steel. When screws cannot be hidden, they must be countersunk and covered with a wood plug, similar to the existing decking.

All joists that are not connected to posts or are not supported by pavement must have joist hangers installed at each end.

SITE LOCUS



PIPE RAILING DETAILS
NOT TO SCALE



COMMONWEALTH OF MASSACHUSETTS SHELDON ROBERT PHINNEY REGISTERED PROFESSIONAL LAND SURVEYOR

SHELDON ROBERT PHINNEY P.L.S DATE

COMMONWEALTH OF MASSACHUSETTS FREEMAN BOYNTON III CIVIL No. 57047 REGISTERED PROFESSIONAL ENGINEER

Feb/28/2023

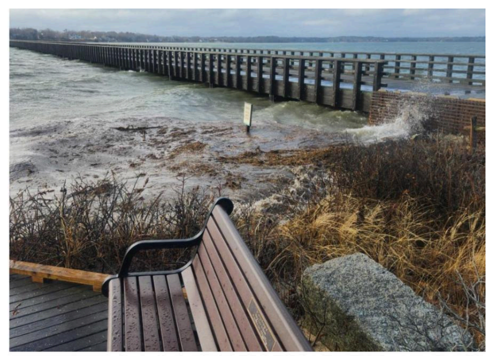
FREEMAN BOYNTON III P.E. DATE

PLAN SHOWING: PROPOSED ELEVATED BOARDWALK IN DUXBURY	
FOR: DUXBURY BEACH RESERVATION, INC.	DRAWN BY: MOHAB ELDOKLA
LOC: GURNET ROAD	DESIGN & CHECKED BY: FREEMAN BOYNTON, JR. & FREEMAN BOYNTON, III
LOT #: 145-400-000 / DATE: FEB 27 2023	REVISIONS: DESCRIPTION: DATE:

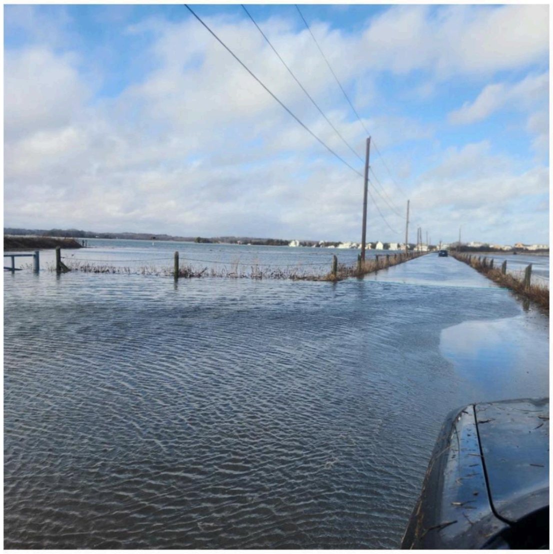
DUXBURY CONSTRUCTION, LLC.
P.O. BOX 2514 DUXBURY MASSACHUSETTS 781 934 0000

Appendix D: Site Visit + Post Storm Surge Images from Duxbury Beach

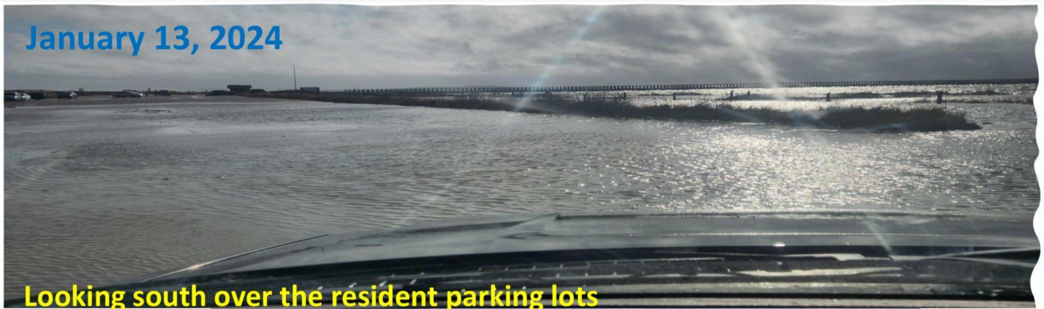

January 13, 2024



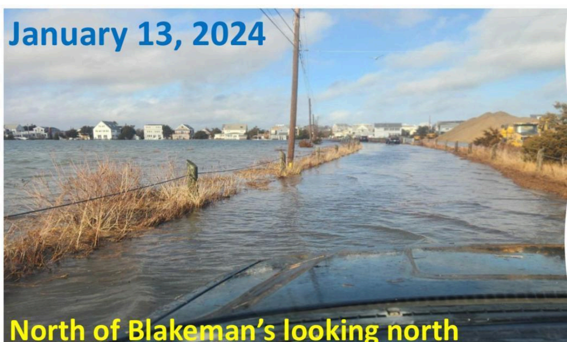
January 13, 2024



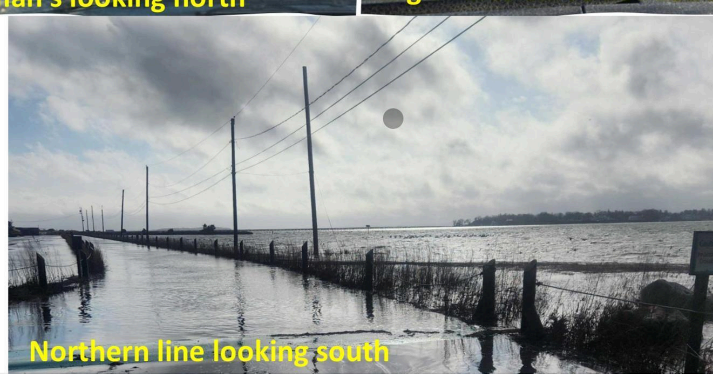
Blakeman's overflow (western) lot


January 13, 2024
Looking south over the resident parking lots

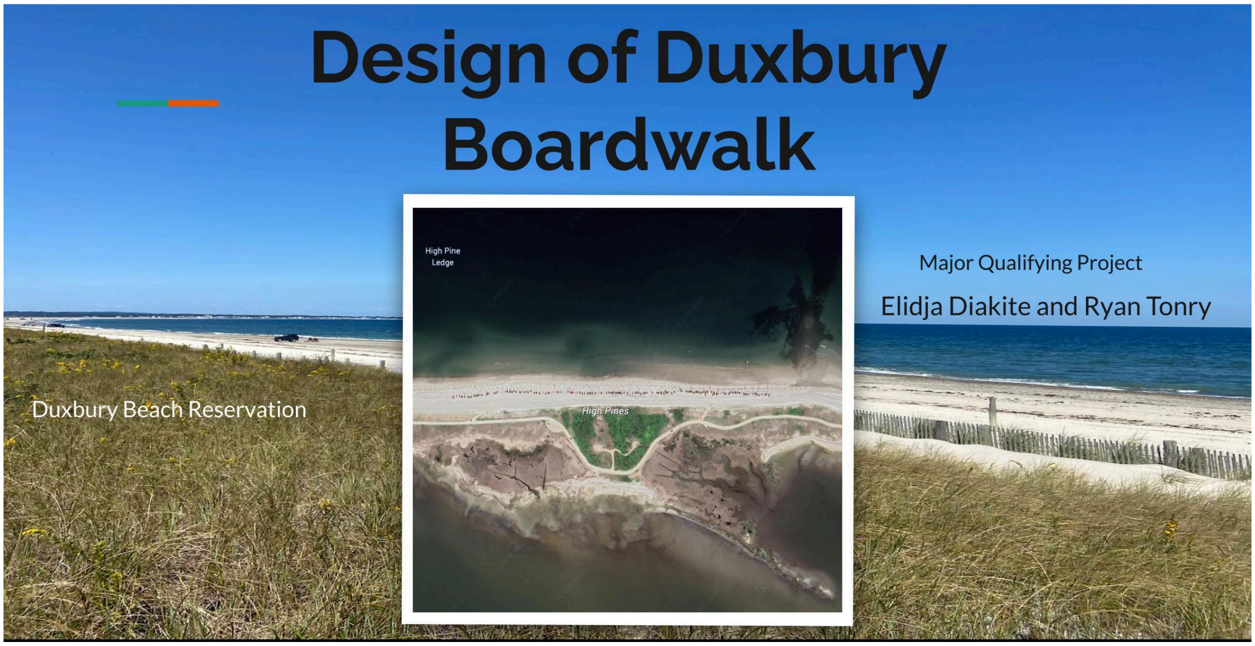

Looking northwest

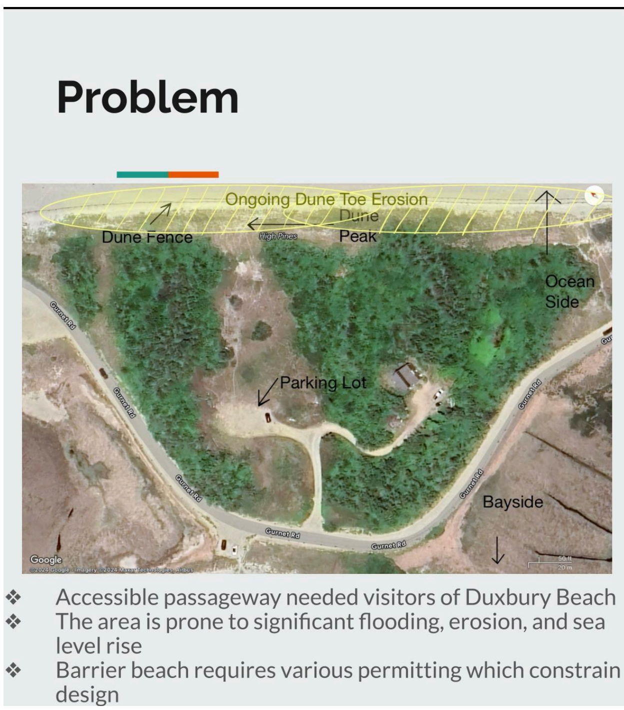

January 13, 2024
North of Blakeman’s looking north

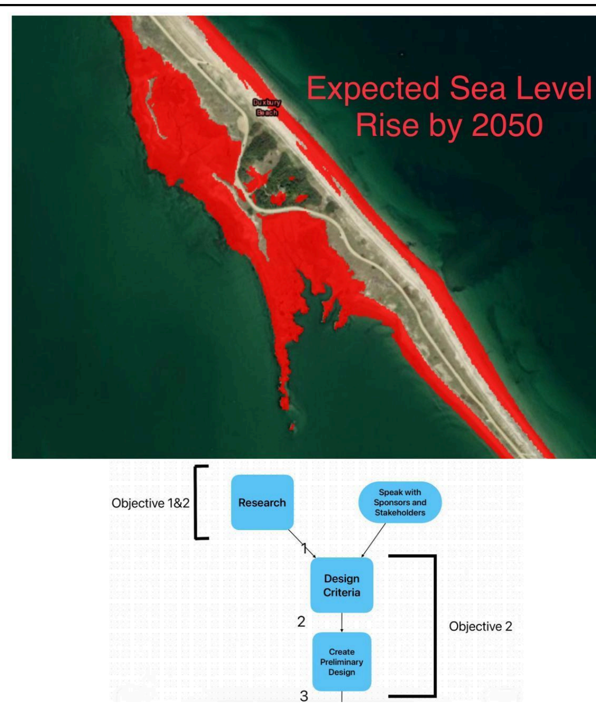

High Pines curve headed south


Northern line looking south

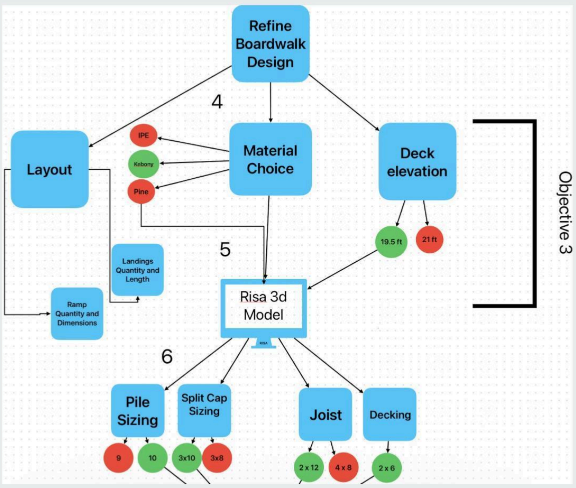
Appendix E: MQP Presentation Slides

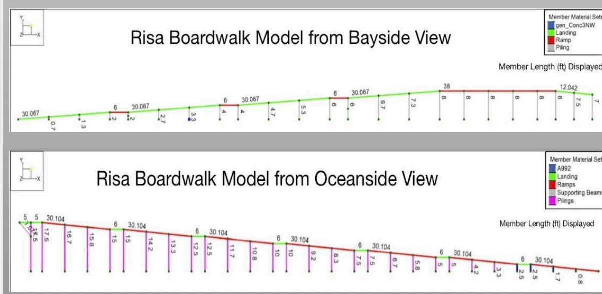






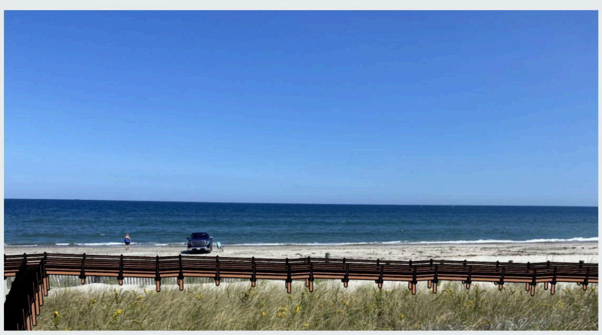
Approach

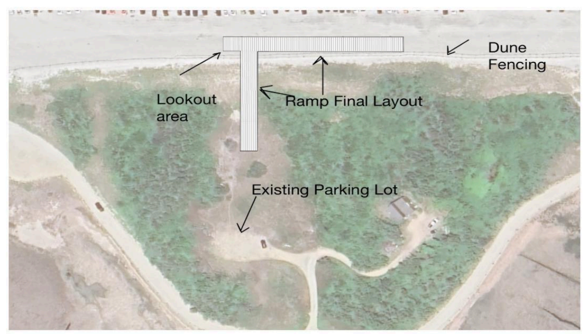




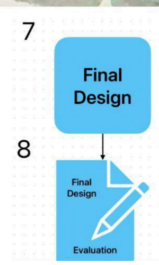
- ❖ Evaluation of site layout relative to constraints
- ❖ Boardwalk design to address environmental constraints and ADA accessibility
- ❖ Meetings with advisors and sponsors to identify additional criteria

Solution





- ❖ Initial design and drawing
- ❖ Analysis for boardwalk members
- ❖ RISA-3D and SketchUp models
- ❖ Cost estimate of $200,000



Appendix F: Final Design Drawings