Design of a Landmark Sign for Greenwood St Solar Array in Worcester, MA

A Major Qualifying Project Report

For the City of Worcester

Submitted to the Faculty of

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In Partial Fulfillment of the Requirements for the

Degree of Bachelor of Science

By

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Abstract

This project presents the design of a landmark sign for the Greenwood Street Solar Array that is to be commissioned by the City of Worcester. This sign will advertise the money saved through Worcester Solar to drivers on the I-146 North. For this design, the focus was placed on economic and technical feasibility for future implementation by the City of Worcester.

Acknowledgments

In completing this Major Qualifying Project, I was advised by many who deserve to be recognized. I would like to thank my advisors, Professors Mingjiang Tao and Tahar El-Korchi, for their support and guidance through the MQP process. Additionally, I would like to thank John Connelly from Honeywell Energy Services Group for assisting me with information and being my main point of contact with the City of Worcester. Their help was invaluable to the completion of this project. I would also like to thank Worcester Polytechnic Institute and John Odell and Matthew Urban with the City of Worcester for this opportunity.

Capstone Design Statement

This Major Qualifying Project focused on the design and analysis of a landmark sign at the Greenwood St Solar Array off Interstate 146 in Worcester, MA. A variety of related coursework was used for the necessary engineering work required of this Major Qualifying Project. The capstone design experience of this project is important in the transition between school and becoming a professional in engineering. This project allowed for the application of previously learned skills to aid in the design of a structure while also conforming to applicable design codes and engineering standards. The project contained structural, material, and safety design and addressed many real-world constraints including code and site restraints. Other constraints that were addressed included:

- **Health and Safety:** Structural engineering and zoning provisions also reflected health and safety requirements by following the provisions of the AISC steel construction manual and 780 CMR Massachusetts building code.
- **Environmental:** The site of this sign is on top of the capped Greenwood St Landfill. It was paramount that the signs structure and foundation did not jeopardize the integrity of the landfill's cap. The rupture of the cap could lead to hazardous waste and gases contaminating the surrounding environment. This constraint impacted the design considerations of the sign.
- **Economic:** Different structures using various materials were developed and analyzed. A cost estimate was completed to compare and contrast the feasibility of each design alternative in each area of design.
- **Constructability and Manufacturability:** This sign was designed by studying various structures to determine the best option. This was done to ensure the building's feasibility

in regards to the materials used, the cost associated with the selected materials, and the sign’s overall size, height, and layout. This ensured that the sign would be constructible in the built environment. This was done by primarily referencing the different sections of the AISC steel construction manual and 780 CMR Massachusetts building code.

- **Ethics:** As an engineer, a role of responsibility is assumed that reflects honesty and integrity. In this project, I followed the NSPE Code of Ethics. Under these ethical codes, I was dedicated to serve the interest of the public as well as my sponsors, the City of Worcester, and prioritized the health, safety and welfare of the public. I have ensured that all aspects of the proposed design meet the specifications of the AISC steel construction manual and 780 CMR Massachusetts building code.
- **Sustainability:** Sustainability is a key factor for the design of this landmark sign. It was an important design consideration to have the sign be fit last as long as the solar array is in use. The design will not need to be replaced multiple times over time, which will prevent repeated waste of materials.
- **Social:** There are currently very few people that know of the green initiatives that this City of Worcester is doing. The purpose of the sign was to bring more attention to this developing part of the City of Worcester. To do this, the sign was designed to be visible to the maximum amount of people and display a message that is simple enough to easily comprehend in a short time.

Professional Licensure Statement

A professional licensure is a certification that engineers can obtain in order to show that they are competent and have knowledge of the technical and ethical aspects that come with being an engineer. Having a professional license and the title of Professional Engineer (PE) is one of the highest achievements and engineer can have. In order to be professionally licensed, there are four qualifications that must be met. An individual must graduate from a four year university with an accredited engineering program, pass the Fundamentals of Engineering (FE) certification exam, then work under a licensed Professional Engineer for at least four years as an Engineer in Training, and lastly must pass the Practices of Engineering (PE) Exam. The PE exam must be taken in the state that the individual works in, and it is the responsibility of the individual to keep track of when to renew their license. This license grants the power to prepare, sign, seal, and submit engineering plans and designs to clients.

Having this professional license reinforces the concept that health and safety are priorities in the design process. Having a professional license helps identify that an individual has experience and knowledge of the subject matter and is qualified to come up with designs or plans. Having a PE license is a high achievement that an engineer can reach in their career and helps them to solidify their skills, knowledge, and experience.

Executive Summary

The City of Worcester, Massachusetts has recently transitioned the Greenwood St Landfill from a capped landfill to solar array. The Greenwood St Solar Array is the newest addition to Worcester's ongoing transition toward green energy to reduce expenses throughout the city. This effort is expected to save up to two million dollars on city energy expenses through current green energy projects. Most citizens in Worcester do not know about the solar array's presence on the former Greenwood St Landfill or the city's ongoing transition to green energy. The City of Worcester wants to combat this issue and inform the surrounding citizens of the solar array's presence and the contributions of the green energy projects to the city through commissioning a landmark sign to be placed on the Greenwood St Landfill.

In this project, the main concern of the design of the landmark was ensuring that the foundation does not jeopardize the integrity of the landfills cap system. The overall weight distribution of the sign was designed to not exceed the maximum bearing capacity for a given area of land. The sign was therefore designed with the use of steel reinforced concrete ballasts that will rest on top of the cap. The design of the sign's structure consisted of a steel plate display and steel beams connecting the plate to the reinforced concrete ballast. The structural design utilized knowledge of design of steel structures, design of reinforced concrete, and soil mechanics. The sign is to be visible and illuminated to the community so that drivers passing by on the MA-146 North will be able to take notice and read the sign before they have already passed the site. This sign will advertise the amount of money being saved through the city's green energy transition while maintaining cost efficiency and feasibility for the City of Worcester.

The content of the sign was determined through a meeting with the representatives of the City of Worcester and Honeywell Energy. The sign was chosen to represent the collective message of Worcester energy as a whole, and not just the Greenwood St Solar Array. In order to express the accomplishments of Worcester Energy altogether, it was decided the best representation would be through amount of dollars saved by the city. An important aspect to this decision is that the amount would change over time so the sign needed to be dynamic in that aspect. For the sign to stay up to date, the numbers would need to change in the future as more money is saved. The two ideas that seem to solve this issue was an electronic sign and a removable number strip area that is utilized in typical gas station pricing signs. Due to the high expense of electronic signs, the design for this project focuses on the use of removable number strips. This will provide the same quality of information, at a much lower cost for the city to produce.

Through online research and a site visit to the Greenwood St Solar Array, it was determined that orientating the sign towards northbound drivers on the MA-146 North would yield the maximum visibility. This is due to the curves and larger trees that block the site as a whole when driving from the south bound direction. Utilizing google maps, the approximate distance from the highway and the signs location in the south east corner of the landfill was determined. The maximum targeted viability the sign will have is around 1000 ft. This visibility affected the sizing of the letters of the sign. For maximum visibility the signs lettering ranges from 2 to 2.5 ft. high. After determining the necessary letter height for visibility, the overall size of the signs display was determined to be 14 ft. tall by 27 ft. wide.

After evaluating the size of the display, the material of the size was then selected to be 3/16th thick steel plate. Using the weight of the projected size of the sign, I was able to calculate the dead load due to the steel display. Additionally, using the wind and snow load provisions in the 780 CMR code, I was able to calculate the overall wind and snow loads that would affect the sign based off of the sites location on the wind map and the signs orientation and placement. These calculations yielded the wind load acting on the sign to be 32 psf and the snow load acting on the sign to be 50 psf. In addition, the overall wind loading was used to calculate the flexural bending moment and torsional bending moment that would be caused to the signs display and support beams. Using this dictating force, and the AISC Steel manual specifications, I was then able to determine the necessary beam weight and thickness the structure of the sign would need in order to support the display. Following the AISC methods to design steel columns, W-shaped beams were selected in order to ease connections to the display. The columns selected for the design were W14x30 steel beams. In order to connect the beams to the steel plate the two main options considered were bolted connections and welded connections. Due to difficulty and cost associated with welded connections, the design calls for bolted connections. The design calls for each column to have two rows of three 7/8ths thick bolts. For the foundation the overall allowable pressure for the landfill was 720 psf. using this value I was able to determine the necessary size of the concrete footing in order to distribute the weight across the landfills surface area to avoid damage to the cap. In addition the concrete footing was designed to have steel reinforcements in order to maintain its structure.

Once the design was set, the overall cost efficiency of the design was estimated to be about $28,500. AutoCAD drawings were made to demonstrate the design of the sign. In addition to the main design, separate designs were provided indicating how the City of Worcester could transition the main design into an electronic sign, as well as if they were to make the sign visible from both north and south directions using a double sided display. All designs and cost projections were presented to the City of Worcester and Honeywell for their future use. These designs will prove to be useful to the City of Worcester in their plans to erect a landmark sign on the Greenwood St Solar Array.

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1. Introduction

Landfills are one of the oldest methods of waste management systems in which trash is collectively gathered, compacted and buried in a site. They are well-engineered facilities that serve to help store our waste while simultaneously protecting the environment from its hazardous effects. After the typical lifespan of a landfill has run its course it has the unique opportunity to contribute back to society through becoming a new source of energy production. Once a landfill has been properly capped and closed for waste storage, it is now increasingly popular for cities to place a system of solar panels on top of the capped landfills surface to create a new source of energy for the city; creating what is known as a solar array.

The City of Worcester, Massachusetts has recently made the transition from a capped landfill to solar array with the Greenwood St Landfill. Though it was a long transformation process, the solar array was completed and had its official ceremony in August 2017. This project has led to the creation of the largest municipally owned solar array in New England with a total of 28,600 solar panels spread over 26 acres of the landfill's surface (Worcester Energy 2017). With the energy collected at the Greenwood St Solar Array in addition to the other solar projects throughout the city, Worcester is now generating about 20% of the city's energy through on site solar panels (Borrego Solar 2016).

Though this project is expected to save the city on energy expenses of up to two million dollars, most citizens in Worcester do not know about the solar array's presence on the former Greenwood St landfill. The City of Worcester wants to combat this issue and inform the surrounding citizens of the solar array's presence and energy contributions to the city through commissioning a landmark sign to be placed on the Greenwood St landfill.

In order to build the landmark sign on the landfill to advertise the solar array it needs to be designed so that the foundation of the sign does not jeopardize the integrity of the landfills cap system. The former landfill has been capped in order to seal in the leachate and natural gases from harming the environment and the public health of the surrounding communities. If this landfill cap is damaged it can lead to catastrophic outcomes of contamination to the surrounding society and environment. The sign should be visible to community so that drivers passing by the landfill will be able to take notice and read the sign before they have already passed the site. The sign will also need to be illuminated during the evening hours either through solar powered lights, or a solar powered electronic display. The overall weight distribution of the sign, plus other loading, must be designed to not exceed the maximum bearing capacity for a given area of land within the constraints of the landfill cap system. The overall design of the landmark sign must be cost efficient and feasible for the City of Worcester to have it built.

2. Background

As part of the design process, initial research in the areas related to the project is necessary to have an understanding of the factors to consider in the design. The basic concept of solar arrays and landfills such as the problems that can arise with contaminants and the landfill capping process is important background knowledge. It is also important to ensure that proper considerations are made with the stakeholders of the project in mind as well as the design restraints that will be faced in this project.

2.1 Landfills

In its conception, landfills are just designated locations, such as swamps, outside city confine for society to pile waste in rather than the street. But upon initial reflection, people realized that their waste triggered foul odors polluting the air, pests, water contamination from the waste seeping into the groundwater supply. In 1959, the American Society of Civil Engineers developed the first guidelines for creating a sanitary landfill which suggested digging separate trenches just for waste, compacting it, and covering it with soil each day to help control the odor and rodent issues (ASCE 1959).

Today, there are multiple types of landfills that are dependent of the type of waste being stored, such as municipal solid waste (MSW), construction and demolition debris, and hazardous waste to name a few. The most common type of landfill is the MSW landfill which is specifically designed to receive household waste, commercial solid waste, and non-hazardous sludge that all do not contain hazardous materials. The EPA estimates that in 2009, there were approximately

1,908 municipal solid waste landfills in the continental United States all managed by the states in which they are located. (EPA 2017)

2.1.1 Problems with Leachate and Harmful Gases

There are several issues regarding landfills, but the most harmful being contamination due to leachates and toxic gases. When it snows or rains water seeps through the landfill and trickles down through the trash, mixes with the toxic and creates a toxic liquid known as leachate. Leachates then seep into the soil causing groundwater contamination (Center for Health, Environment & Justice 2015). The harmful gases such as Methane and other toxic organic compounds can emanate from the landfill. The methane and toxic compounds create a foul smell in the air surrounding the landfill which is unfavorable to any nearby life and can be potentially dangerous for public health and the environment. These gases also enter the air and can have harmful effects on the ozone layer which can contribute to global warming. (Center for Health, Environment & Justice 2015).

In effort to combat this contamination, the EPA developed a code of federal regulations for the design, operation and maintenance of landfills. This includes specifications about the allowable locations for landfills that avoid being near fault lines, wetlands, and restricted areas. Landfills are to be lined using a geomembrane and organized into layers called cells. The geomembrane prevents leachates from seeping into the soil and causing water and soil contamination. The leachate is instead pooled at the bottom of the landfill and drained out using pipe systems. A top coat of soil is used to cover the layers of waste each day to mitigate the methane gas and another pipe system drains the gas out of the landfill. These regulations decrease the risk of contamination and therefore extend the life cycle of a landfill, causing it to be used for many years depending on its size (EPA 1988).

2.1.2 Cap Systems

Once the landfill has reached its capacity it is covered using a landfill cap that helps create a protective barrier from the waste to prevent it from contaminating its surrounding environment. Landfill caps can be a single layer to multilayer system that includes composite geosynthetic materials and layers of soil and vegetation to prevent the methane gases from escaping and polluting the air. It also reduces the amount of rain/melted snow infiltrating into landfill and encountering the buried MSW. The design of the liner cap system depends on the specific site and what the functions of the site will be. A contributing factor to the complexity of the layers is the type of climate the landfill is in. Wet climates require more complex systems due to its higher ground water content, while drier climates require less complex systems (MassDEP 2001).

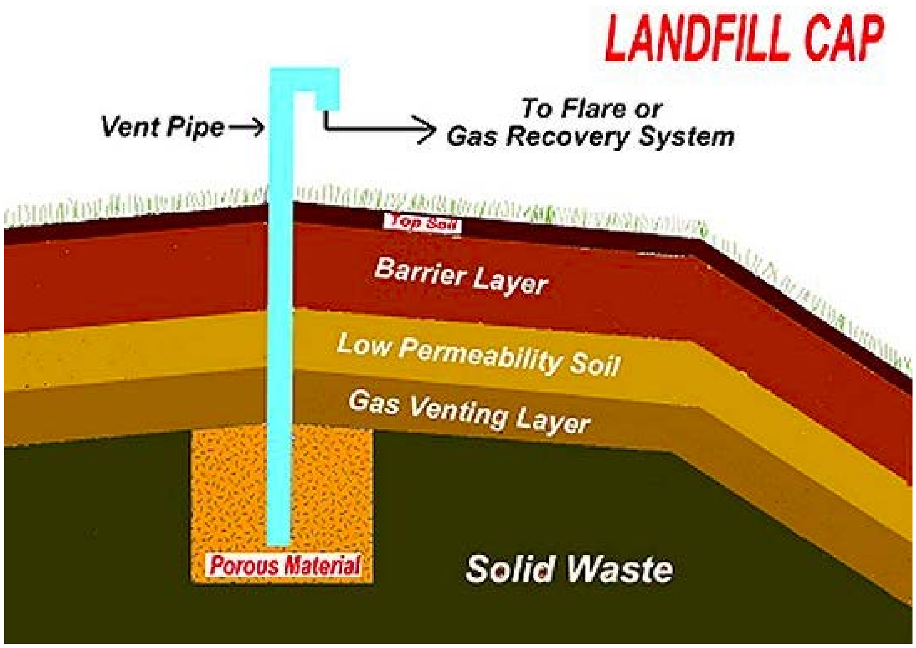

***Figure 1**: Example of a landfill cap made by the Oneida-Herkimer Solid Waste Authority (ohswa.org)*

The Massachusetts Department of Environmental Protection, or MassDEP, states that choice in materials can be essential to improve the integrity and longevity of the cap system. The materials can help provide a solid foundation layer for the cap construction as well as minimize the settlement rates of the landfill cap as a whole. However, the materials chosen cannot significantly increase the overall contamination rates of the landfill. They must be a granular, well graded, inorganic material that is easy to spread and compact to a high density (MassDEP 2001). The composite geosynthetic material used in the liner must be of both high and low permeability. The low permeability materials prevent the water from coming into contact with the waste and becoming leachate, while the high permeability materials carry away the water coming in contact with the cap (Federation Technologies Screening Technologies 2017).

2.1.3 Landfill Closure Process

The landfill closure process that landfills in the state of Massachusetts must abide by is put forth by the Massachusetts Department of Environmental Protection, also known as MassDEP. This landfill closing process requires the completion of a permit that was established in order to protect the public health, safety and environment from the harmful effects of landfills. This is done through monitoring the contamination levels that stem from a landfill and determine the criteria for what must be done in order for the proper closure of the landfill. MassDEP has created this landfill closure process in order to evaluate the landfills initial condition, select the proper tests that need to be performed on the site, design the necessary cap and additional measures, and finally implement the cap and measures needed to close the landfill. This process has four main steps that are required before the installation of the cap: the Initial Site Assessment (ISA), the Comprehensive Site Assessment (CSA), the Corrective Actions Alternative Analysis (CAAA), and the Corrective Action Design (CAD) (Massachusetts Department of Energy and Environmental Affairs 2017).

The first step of MassDEP's landfill closure process is the Initial Site Assessment (ISA). The ISA is an overview of the initial conditions of the site and the historical uses it has served. It then acts as a scope of work for the Comprehensive Site Assessment (CSA) by specifying the areas of site monitoring and evaluations that will need to be performed during the CSA. The ISA process ranges from two to four months and ends when MassDEP approves the site to move into the second phase of the process: the CSA (Massachusetts Department of Energy and Environmental Affairs).

The second step of MassDEP's landfill closure process is the Comprehensive Site Assessment (CSA). The CSA allows for the field investigation to take place at the site. For a period of one year monitoring wells are installed, samples of groundwater, surface water, soil, and sediment are taken, and the air quality is monitored for methane and other harmful organic compounds. The data collected is then presented in a qualitative risk assessment document which states the scope of work that needs to take place in the next two steps of the landfill closing process (Massachusetts Department of Energy and Environmental Affairs).

The final two steps of MassDEP's closing process involve the analyzation of data and design of the cap. During the third step, the Corrective Actions Alternative Analysis (CAAA) analyzes the data collected in the CSA and determines what type of specifications will need to be addressed in the landfills cap as well as any other additional measures that need to be taken in order to have the safe closure of the landfill. The last step, the Corrective Action Design (CAD), is the culmination of all of the past work and assessments that go into the site. In this step, the design of the landfill's cap and any other additional measures that are necessary to the landfill closure are designed for implementation. Following these steps from the MassDEP closing process, the landfill cap is assessed and additional measures are implemented; thus closing the landfill (Massachusetts Department of Energy and Environmental Affairs).

2.1.4 Life After a Landfill is Capped

In the past usually after a landfill is capped, vegetation such as grass is grown on top of the cap. Due to the low bearing capacity of the landfills cap system, the land cannot be reused for most types of traditional structures because the foundation cannot extend into the ground at risk of disturbing the landfill's cap. For this reason most landfills after their capped are just left as grassy plains that are sometimes formed to be homes for local wildlife. However, in a more recent trend as the need for renewable energy is on the rise, solar arrays are growing as a popular option for capped landfills (McDonough 2012).

2.2 Solar Arrays

A solar array is large-scale application of solar photovoltaic (PV) panels to generate clean electricity at scale which is then usually fed right into the grid. For a solar array to be successful it requires a specific type of location. The solar array needs to be in a large open area away from any foliage or infrastructures that might cast a shadow upon the PV panels, but also near enough to a city that the energy can easily be transferred and used by the citizen. (Solar Trade Association 2017).

Solar arrays allow capped landfills to serve a new sustainable purpose through solar power. According to solar-trade.org, approximately 25 acres of land are required for every 5 megawatts of installation. For every 5 megawatts installed a solar array will power 1,515 homes for a year, based on an average annual consumption of 3,300 kilowatt hours of electricity for a house, and save 2,150 tons of carbon dioxide. (Solar Trade Association 2017).

2.3 Greenwood St Landfill

The Greenwood St Landfill extends over 100 acres of land and is bordered to the north by the Intransit Container Company, to the east by the Providence/Worcester Railroad and route 146, to the south by the UBWPAD wastewater treatment plant, and to the West by the Rand Whitney Company and the former National Envelope Company Property. There are two main areas of the landfill site: the MSW landfill mound and the sewage sludge disposal area. The municipal solid waste landfill mound spans across 60 acres while the uncapped section devoted to the sewage sludge disposal spans about 30 acres (Honeywell Energy Services Group 2017). You can see the distinct properties in the map shown below.

Figure 2: *Overhead shot of overall area of the site via Google Maps*

In its conception the Greenwood St landfill was used as an active municipal sewage sludge treatment facility that accepted Worcester municipal wastewater for sludge disposal from 1899 to 1972. In April of 1973, a portion of the site was used as a municipal solid waste landfill. In June of 1985 the preparations for the landfill capping process began and it was officially capped in 1986 after MassDEP approved the cap design (Honeywell Energy Services Group 2017).

The capping system of the Greenwood St Landfill is composed of a leachate collection system, and a gas venting sand layer between the waste and the low permeable layers of the capping system. The other layers of the capping system included the low permeable soil cap layer which minimized the waste runoff infiltration, a sand drainage layer above the cap, and a top layer of dense soil and grass to help protect the capping system below. As a final part of the cap system the city tried to use soil fill to create a 5% slope on the landfill plateau, but due to time constraints in the capping process they could only create a 2% slope. The finished constructed cap was approved by MassDEP in June of 1995. However, in May 2004 due to the settlement of the waste in the landfill there was an issue with large amounts of water puddling on the landfill's cap that needed to be repaired. The final repair of the cap was completed in 2013 (Honeywell Energy Services Group 2017). The settlement rates are no longer quite as rapid as they were when the cap was first installed. The City of Worcester monitors the settlement rates through the use of monitoring wells on site (Honeywell Energy Services Group 2017).

2.3.1 From Capped Landfill to Solar Array

The City of Worcester hired Honeywell Energy Services Group to create the solar array at the Greenwood St landfill. Honeywell hired Borrego Solar to design and install the solar panels and racking systems, and Tighe and Bond for the environmental and permitting issues. Honeywell's main job is to manage the site and make sure operations run smoothly. They are in charge of making sure that all aspects of the energy contract that they signed with the City of Worcester is met. In the contract Honeywell assured that through the installation of this solar array the City of Worcester would be able to make the money they spent on the installation back within a period of about 6 years. If this stipulation is not met then Honeywell will have to pay the City of Worcester the difference of price.

The solar array was designed to have PV solar panels placed on top of 26 acres of the capped portion of the landfill. The panels and racking systems cover the majority of the plateaued portions of the landfills cap. The Greenwood St had its official ceremony in August of 2017. The solar array consists of a total of 28,600 solar panels spread over 26 acres of the capped landfills surface, making it the largest municipally owned solar array in New England. The array is estimated to have a life expectancy of about 30 years. With the energy collected at the

Greenwood St solar array it is expected to produce energy that is equivalent to powering 1,340 homes per year. In addition to the other solar projects throughout the city, Worcester is now generating about 20% of the city's energy through on site solar panels.

2.4 Stakeholders

This project is being sponsored by the City of Worcester. The Greenwood St Solar Array is owned by the municipality of the City of Worcester. The City of Worcester requested to have a landmark sign placed on the landfill in order to educate and inform the local citizens of the solar array and the green energy it is producing. The City of Worcester has hired Honeywell Energy Services Group to manage the energy being generated. This project will involve collaboration with the student and professors of Worcester Polytechnic Institute, the City of Worcester and Honeywell Energy Services Group.

The City of Worcester was the one to reach out to WPI for help with the research and design of the landmark sign for the Greenwood St Solar Array. Due to a limited budget, it was not feasible for the City of Worcester to hire an engineering firm straight away to design the sign without having a cost estimate and a detailed design plan. The potential sign, though helpful, was not a major priority for the city and they could not justify spending the money. The Job of the MQP would be to research and design a landmark sign for the Greenwood St Solar Array on behalf of the City of Worcester in order to give them a cost estimate and starting point for the design.

Honeywell, having knowledge of the university MQP program from alumni students in their staff, suggested that the City of Worcester reach out to WPI for help in the form of a MQP project. The two major contacts for this project from Honeywell were John Connelly the Project Control Specialist and Alex Horton the Project Manager.

2.5 Essential Design Requirements

In order to design the landmark sign for the Greenwood St. Solar Array there are a few essential design requirements that must be borne in mind. The two main requirements that must be taken into consideration for the design are the visibility and cost efficiency of the sign.

2.5.1 Visibility

Visibility is a very important requirement for designing the landmark sign for the Greenwood St Solar Array. If the sign is not designed with visibility in mind it will serve no purpose. The majority of citizens will need to be able to see the sign clearly and for long enough that they can properly read the information presented on the sign while they are driving by. This means that the sign must be placed in a location that is visible and gives the drivers a clear line of sight to read its information. The sign must be oriented properly to allow the citizens to have sight of the full sign without any issues of glare or being at an ill-advised angle. The letter size will need to be large enough that the drivers will be able to see it from far enough that they have enough time to read and comprehend the sign. The bigger the letter size is, the greater the distance will be for the average driver will be able to read it. This will also affect the amount of information that will be written on the sign due to the size of the letters that it will need. The content that is displayed will have to be chosen carefully to provide enough room on the sign for the words to be of the correct size.

2.5.2 Cost Efficiency

Cost efficiency is an important requirement for this design because it will determine whether the city of Worcester will deem this project to be financially feasible for it to be built. Aspects of the design that will fall under consideration of the cost of the project would be materials, and electrical components, and the construction of the sign. The materials used will have to be the most cost efficient as possible in order to make sure there is a balance between the landmark sign being long lasting and being of low cost. If materials are chosen without consideration of cost it could deem the whole project as unfeasible. Another consideration of the landmark sign design is the electrical component of the display. If the estimated cost of having a solar powered electric display ends up being extravagantly high then it too could deem the project to be unfeasible. It might be beneficial to design different scenarios: an electronic display or a standard steel display. The three are also the light fixtures to consider as well. Will the lights that illuminated the regular designed billboard be solar powered or simply be LED lights.

2.6 Essential Design Restraints

In order to design the landmark sign for the Greenwood St. Solar Array there are a few essential design restraints that must be considered. The three main restraints that must be taken into consideration for the design are the sites capacity, the building codes for the size and the electronic display.

2.6.1 Site Capacity

A site specific design restraint is the capacity of the landfills cap. The sign is to be built on top of the capped landfill and the main issue is that the integrity of the cap cannot be jeopardized in construction at risk of future contamination. This restraint will prevent the foundation of the sign from penetrating through the landfill cap system. An important aspect that will need to be factored into the design is the use of a ballast system. A ballast is a heavy material that is used to hold something down and provide stability. A typical example of a ballast used in this form of construction is a concrete or reinforced concrete block. The concrete block will serve as the foundation of the sign by providing a place for the beams to be placed in. The ballast will need to be designed with all loadings to determine its steel reinforcement and size such that the loading transferred to the cap system does not exceed the system's loading bearing capacity.

2.6.2 Building Codes for Size

In the design of the landmark sign, the aspects of the sign that will need to be adjusted in order to stay within the restraints of the code are the area of the display and the overall height of the sign. According to Chapter 31 of 780 CMR 3102.0 SIGNS in section 3102.7 Ground signs, it is specified that the structural frame of ground signs cannot be erected to a height of more than 35 feet above the ground and the overall display cannot be erected to a height of greater than 100 feet above the ground (Massachusetts State Building Code).

2.6.3 Building Codes for an Electronic Display

In respect to designing the landmark sign to have an electronic display there are restraints due to the code of how bright the sign is allowed to be. According to 700 CMR 3.17 each static display:

- Must last at least 10 seconds
- Must automatically adjust its brightness according to the natural ambient light conditions
- Must not exceed a brightness of 0.3 foot candles above ambient light, as measured using a foot candle meter at a pre-set distance.

2.7 Potential Failure Modes

The design of the landmark sign will need to account for the different types of failure modes it can possibly be subjected to. The main failure modes this design will take into account include capacity failure and failure due to loading.

2.7.1 Capacity Failure

The bearing capacity failure of the landfill cap system is the first design restraint that will impact the design. A bearing capacity is the loading limit at which the landfill's cap will be able to support without shear failure or excessive settlement. A low bearing capacity will entail distributing the weight of the sign to a concrete ballast until the weight of the sign and combination of other forces are not causing the sign to go over the bearing capacity limit. The key to this restraint is finding the right balance through the use of several beams and a concrete ballast to evenly distribute the weight and not harm the landfills cap.

2.7.2 Failure Due to Loading

Failure due to Wind loading will also be critical for the design of the landmark sign. The sign will be subjected to wind forces, and the sign must be built in respect to the wind code stipulations to withstand the wind loadings. Wind forces are categorized into different area zones dependent on the location of where the design will be built (Massachusetts State Building Code). Using the Massachusetts state building code I will estimate the force per area acting on the sign due to the location of the site.

TABLE 1611.4
REFERENCE WIND PRESSURE (POUNDS PER SQUARE FOOT)

Height above grade	Zone 1			Zone 2			Zone 3		
	Exposure			Exposure			Exposure		
H (feet)	A	B	C	A	B	C	A	B	C
0 - 50	11	12	12	11	17	17	14	21	21
50 - 100	11	12	18	11	17	24	14	21	31
100 - 150	11	16	22	14	21	29	18	26	37
150 - 200	13	18	25	17	24	33	22	30	41
200 - 250	15	20	27	20	27	36	25	34	45
250 - 300	17	22	29	22	30	39	28	37	48
300 - 400	19	25	31	25	33	42	32	41	52
400 - 500	22	28	34	29	37	46	36	46	57
500 - 600	24	30	37	33	41	49	41	51	61
600 - 700	27	33	39	36	44	52	45	55	65

Figure 3: *Table 1611.4 Reference Wind Pressure (Pounds per Square Foot) Taken from CMR 780*

The failure due to snow loading is also critical for the design of the landmark sign. Similarly to the way wind loads are classified snow loads are also separated into different levels of loading for each location. For example: Worcester has a basic snow load value of 55 psf while Blackstone has a ground snow load of 65 psf (Massachusetts State Building Code). Since the Greenwood St Landfill is in between both areas the conservative of the two values should be used in order to determine the snow loading.

Additionally, failure due to the bending caused by these loadings is a critical factor when designing the structure. The bending moment caused by the lateral forces such as the wind forces need to be addressed in the design to ensure the structure is fit to withstand it.

3. Objectives

The goal of this project are to design a landmark sign for the Greenwood St Solar Array that does not affect the integrity of the landfills cap. The sign must be being clear and visible to the drivers on Interstate 146. The design should be feasible and cost efficient in order to be replicable by the City of Worcester. I have developed 5 main objectives in order to complete these project goals. The objectives of this project are:

1. To determine the location and assess the potential visibility of the proposed sign
2. To calculate the forces that will impact the design of the proposed sign
3. To design the signs structure and concrete ballast
4. To prepare a model of the proposed design using AutoCAD
5. To analyze the cost of the proposed design

3.1 Objective 1: Determine the Location and Assess the Potential Visibility of the Proposed Sign

The first objective needed to begin this design process is to determine the signs potential location and assess that locations visibility. To complete this objective, research on the site is needed in order to avoid any areas of the site that a structure should not be placed on top of. Another key factor is maximizing the visibility of the drivers on Interstate 146. Besides the signs location, the letter size and overall sign display content and size will have an effect on the visibility as well.

3.2 Objective 2: Calculate the Forces that will Impact the Design of the Proposed Sign

The second objective needed to continue the design process is to calculate the forces and loading the sign will be subjected to. The forces of weight, wind, and snow loading will need to be calculated before the design of the structure or concrete ballast. Additionally, these forces need to also be calculated in relation to bending moments caused by the structure.

3.3 Objective 3: Design the Signs Structure and Concrete Ballast

This section will discuss using the information found in the previous two objectives to design the signs structure and concrete ballast. The tasks needed to complete this objective are to design the structure of the sign and to design the concrete ballast.

3.4 Objective 4: Create a Model of the Proposed Design Using AutoCAD

The fourth objective for this design process is to utilize the design calculations of the signs structure and foundation to create a model of the sign in AutoCAD. All designs will be displayed in a concise way that is easily understood and labeled.

3.5 Objective 5: Analyze the Cost of the Proposed Design

The fifth and final objective for this design process is to analyze the cost of the proposed design. In order to complete this objective the design of the signs structure and concrete ballast as well as the signs display will be used to calculate and analyze the cost of the sign. The cost of the amount of each material used in the design will be calculated as well as the estimated construction cost it will take to build this design. After the cost is calculated it will then be analyzed to see if there are any areas of the design that could be more cost efficient.

4. Methodology and Results

In this project there was a certain methodology used to complete these objectives. Once conducting background research on the issues that pertain to the project and developing the objectives for the project this is the steps taken to complete it.

4.1 Determine the Location and Assess the Potential Visibility

Determining the location and assessing the visibility of the sign is the first step in the design process. The location of where the sign will be placed will directly affect the target audience for the sign. This will reveal what the contents of the sign will entail and therefore how big the letters and display will need to be.

4.1.1 Location

In order to determine the visibility of the sign, the location must be selected. The first step in determining the location of the sign is to scout the site area and survey possible locations. A site visit was made to scout the area of the potential sign. This was done on November 10th 2017. I was accompanied by John Connelly from Honeywell and we toured the entire site. Upon further inspection in the south east corner of the lot we discovered there is a section down the slope that flattens out and would be a good location to have the sign be placed. I had taken several pictures while on site not only of the areas the sign would be placed.

Figure 4: *Shot taken during site tour in the area for the potential place the sign can be located.*

After narrowing down the potential location for the sign to be placed, I then double checked the location with the site drawings provided to me from Honeywell. It is important that the signs foundation and structure does not affect the landfills ventilate system. As shown in the picture below there are few obstacles the sign should avoid covering or interfering.

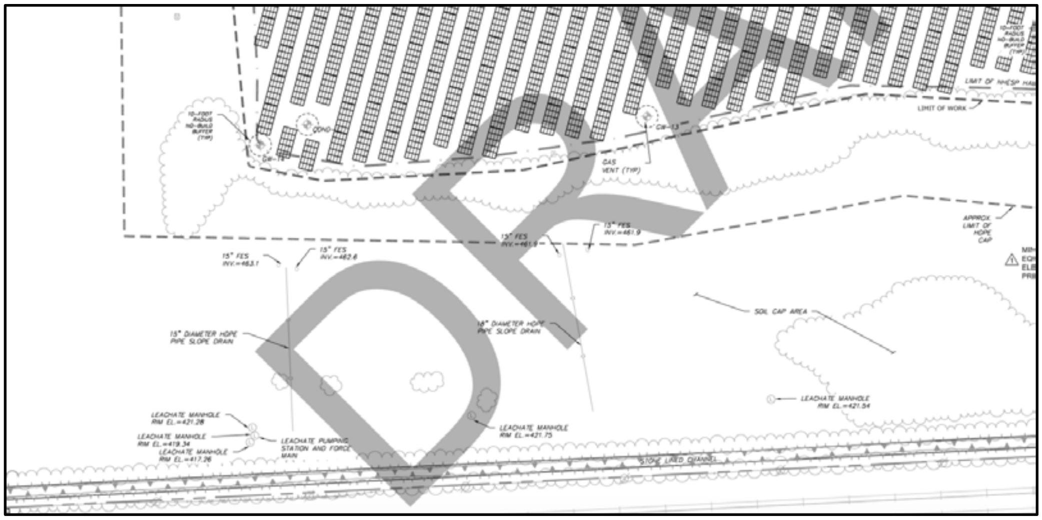

Figure 5: *Greenwood St Solar Array Layout via Honeywell Site Documents*

As you can see in the drawing of the landfills schematics, there are leachate manholes and drainage pipes along the slope of the landfill. The ideal site of the signs foundation would be to the far left of these drainage pipes and manhole areas, so it then these pipes and manholes wouldn't be an issue to the signs placement.

4.1.2 Visibility

After the location of the sign is selected, the overall visibility of the sign can be determined. It is important to assess the visibility because it affects the size and readability of the sign. In terms of visibility from Interstate 146, it seemed that the travelers headed south bound did not have a clear view of the site due to trees and a food packing building blocking the view. Additionally, the southbound lane of the interstate actually curves away from the site and therefore creates a boundary of sight from the trees. Using google maps, I was able to capture an overhead shot of the orientation of the lot in respect to the southbound portion of Interstate 146.

Figure 6: *Overhead view of Interstate 146 via Google Maps*

After this site tour, it was clear that the only viable location for the sign to be displayed would be the southeast corner of the site. Additionally, it was clear that the majority of its visibility would be to the passengers traveling on the northbound side of the interstate. Because the northbound drivers of I-146 are headed towards the city of Worcester, it will catch the eyes of people entering the city and give them a first impression of being a green and sustainable city.

To estimate the amount of visibility the sign will have, I assessed the distance from the selected location to the desired audience of drivers headed northbound on Interstate 146. I utilized the distance tool in Google Maps to estimate that distance to be between about 750-1000 feet.

Figure 7: *An overhead shot using Google Maps distance tool to estimate the distance between the proposed location of the sign and the drivers of I-146 North*

Using this distance, I was able to calculate the necessary letter size for the signs display. This was done in order to assure the signs display will be legible and effective. I estimated the minimum letter heights based off of this distance, and came up with the minimum letter height to be around 30 inches or 2.5 feet. This indicated the ideal height of the letters on the sign would need to be 2.5 feet tall.

4.1.3 Content

In order to calculate the necessary display size for the sign, the contents of the display had to be determined. To decide what the landmark sign for the solar array will say, I arranged a design proposal meeting with the City of Worcester. During this meeting, we discussed possible ideas for what the sign will say. Initially, a few options that were discussed were as follows:

- Option 1: Greenwood St. Solar Array, Est. Summer 2017, learn more at worcesterenergy.com
- Option 2: Greenwood St. Solar Array, Largest municipally owned solar array in New England, learn more at worcesterenergy.com
- Option 3: Greenwood St. Solar Array, Annually producing *live count* kwh of energy for the City of Worcester, learn more at worcesterenergy.com

These three main options were initially presented and discussed whether they would work for the signs display. Option 1 announces the solar array's presence on the former greenwood st landfill, but doesn't express how much energy or money is being made from the site, which is not ideal. Option 2 announces the achievement of the site being the largest municipally owned solar array in New England. While this is great to advertise to highlight the achievements of the City of Worcester, it is potentially subject to change in the future. Additionally, it also does not communicate how much energy or money is being saved due to the site. Option 3 displays a live count of the amount of energy the site is producing for the City of Worcester. While this option does communicate that the site is producing a large amount of energy for the city, there was a concern that kilowatt-hours is not the easiest to understand. This is also the only option that would require to be frequently updated or have an electronic display. All of the options presented displayed the name of the site, Greenwood St Solar Array, and also referred the viewers to learn more at the Worcester energy website.

Overall the discussion leaned more to prioritizing the amount of solar energy being generated by the site. However, to combat the unfamiliarity with expressing it in kilowatt-hours, it was decided that expressing the amount of dollars saved through the solar energy generated would have the best overall effect. The representatives with the City of Worcester wanted to communicate the amount of dollars saved through all Worcester Solar initiatives, and not just from the Greenwood St Solar Array. They liked the idea of the sign being updated as time progressed to increase the amount of money saved over time, so having a way to update the sign is an important aspect of the design. Lastly, the representatives of the City of Worcester liked the idea of referring the travelers viewing the sign to the Worcester energy website to learn more. In the figure below you can see an example of what the sign will convey.

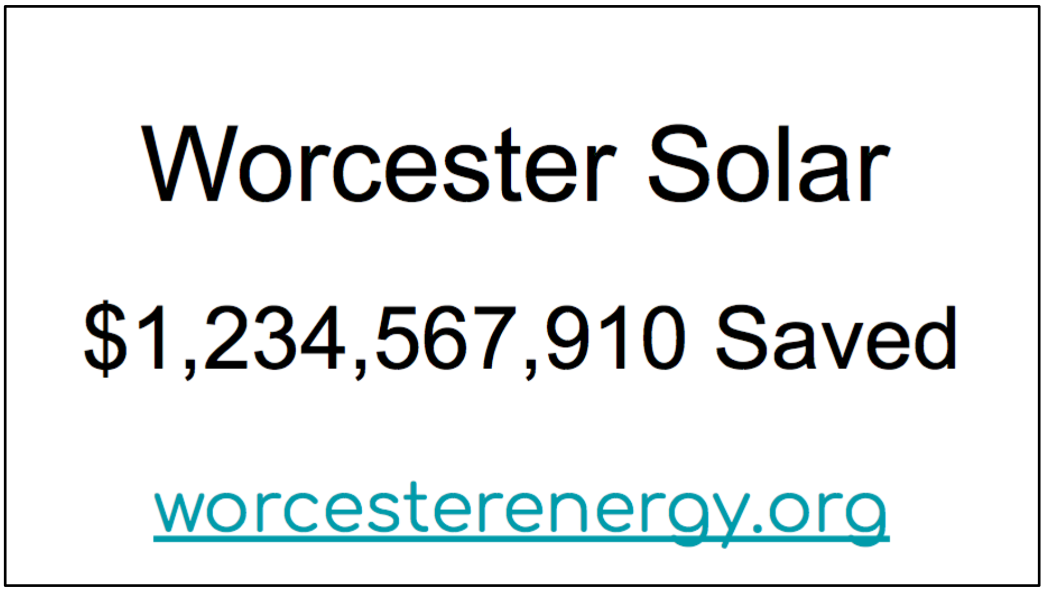

Figure 8: *An example of the current sign content display*

Using the information gathered from selecting the location and assessing the visibility of the chosen location, I was able to then determine the required size of the sign. Using the minimum text height of 2.5 feet and the chosen display content I was able to evaluate the necessary size of the sign to be 27 feet wide and 14 feet tall. This size will be adequate to allow the signs content to be seen at a maximum distance of 1000 feet. This will provide the drivers on interstate 146 ample time to read and understand the contents of the sign as they travel on their way into the city.

4.2 Calculate the Impacting Forces on the Sign

Once we have the overall location, visibility, and size of the proposed sign developed, I was able to then move to calculating the impacting forces on the sign. These main forces were dead load due to materials, wind load, and snow load. All of these forces will impact the overall design of the sign.

4.2.1 Dead Load Due to Sign Materials

In order to calculate the dead load of the sign due to its material weight, the materials must first be selected. In order to gauge input on the signs display, I met with the City of Worcester as well as John Connelly from Honeywell to discuss what they wanted from the display of the sign. Due to the interactive nature of the signs content, it was important that the sign be dynamic in its display and able to change as the total amount of money saved changes over time. The main solution that was discussed for this was an electronic or LED display. The LED Display would be more favorable that the electronic display because electronic displays prove to be harder to read and would not give off the style that the city wanted with this design. After further research into the LED display, I found that LED displays can range from $80,000 to $180,000. At this time, this would not be feasible direction to continue this design. The design needs to be affordable and cost effective so the city can actually utilize the design in the future.

Another option for the display was a steel plate display with a strip of removable numbers such as how gas station prices are advertised. This is a low cost solution to keeping up to date with the amount of money saved, without wasting a large sum of money to an electric sign. The strip would be in the middle row of the sign and would have enough room to advertise 10 digits of numbers for the cost.

After discussing this idea with the city they confirmed, that at this time, the design should not go in the direction of having an electronic display due to cost issues. They liked the idea of having this number strip be a simple solution. After this discussion I researched different steel display options. Steel signs that are commonly used on highways are typically .08" thick and made of A36 carbon steel. I selected to use a 3/16" A36 carbon steel plate. I chose to go with a thicker steel display than is typically used because the overall area of the sign is very large. I was concerned that the large wind loads that act perpendicular to the sign might deform the display if the steel wasn't thick enough to hold its shape. A 3/16" A36 carbon steel weighs approximately $7.66\ psf$. In order to calculate the deadload of the steel display plate, the weight per square foot of steel is multiplied by the area of the display.

$$DL\ of\ Steel\ Display: (7.66\ psf) * (14\ ft) * (27\ ft) = 2895.48\ lbs$$

The total weight of the steel display is 2895.48 lbs. This will be used in conjunction with the other loads to size the support beams.

4.2.2 Wind Load

The wind load that will impact the sign was calculated through use of the 780 CMR Massachusetts building code and the ASCE 7-10 codes for wind loading. Both codes were considered to ensure loading is as conservative as possible, as wind loading is a critical failure mode being considered with this design.

In the 780 CMR the wind forces are broken up into different exposure zones dependent on the amount of structures and trees surrounding the area the structure will be built

(Massachusetts State Building Code). The Greenwood St Landfill would fall under Exposure level C which is described as open level terrain with only scattered buildings, structures, trees or miscellaneous obstructions, open water, or shorelines. The county of Worcester falls under area zone 2.

According to the 780 CMR 1611.12.2 it specifies to find the wind load "for open or solid outdoor signs within the allowable ratio dimensions a wind load applied uniformly over the area of the sign and determined by the lesser of 1.2P on the projected gross area within the outside dimensions of the sign, or 1.6P on the net projected area of the sign"(Massachusetts State Building Code). The P value can be found in Table 1611.4 from the 70 CMR, seen below in figure 1.

TABLE 1611.4
REFERENCE WIND PRESSURE (POUNDS PER SQUARE FOOT)

Height above grade	Zone 1			Zone 2			Zone 3		
	Exposure			Exposure			Exposure		
H (feet)	A	B	C	A	B	C	A	B	C
0 - 50	11	12	12	11	17	17	14	21	21
50 - 100	11	12	18	11	17	24	14	21	31
100 - 150	11	16	22	14	21	29	18	26	37
150 - 200	13	18	25	17	24	33	22	30	41
200 - 250	15	20	27	20	27	36	25	34	45
250 - 300	17	22	29	22	30	39	28	37	48
300 - 400	19	25	31	25	33	42	32	41	52
400 - 500	22	28	34	29	37	46	36	46	57
500 - 600	24	30	37	33	41	49	41	51	61
600 - 700	27	33	39	36	44	52	45	55	65

Figure 9: *Table 1611.4 Reference Wind Pressure (Pounds per Square Foot) Taken from 780 CMR*

Using the corresponding zone, height and exposure category. For a sign under a height of 50ft, in zone 2, and exposure category C the reference wind pressure is 17 pounds per square foot.

Using the ASCE 7-10 codes for wind loads they utilize a calculation for the wind velocity pressure. Velocity pressure is given by factoring together the signs height off the ground, the wind directionality factor, the topographic factor, and the basic wind speed. A majority of these values were found using the standard for wind loading ASCE 7-10. Velocity pressure represents the kinetic energy per unit volume of the air flow and is the basic variable determining the wind loading on a building. The equation used for this calculation is shown below:

$$q_z = .00256(k_z)(k_{zt})(k_d)(V^2)$$

$$18.496\, psf = .00256(.85)(1)(.85)(100^2)$$

In which:

- $q_z$represents velocity pressure
- k_z Represents the velocity pressure coefficient and was found using table 29.3-1 from ASCE 7-10. This value was selected based on a height z of 15 ft or less from ground level for an exposure C structure.
- k_{zt}Represents the topographic factor found using table 26.8-1 from ASCE 7-10. This value was used based off of the design criteria set forth by Borrego Solar.
- k_d Represents the wind directionality factor and was found using Table 26.6-1 of ASCE 7-10 the wind directionality factor for a solid sign.
- V Represents the basic wind speed of the area in which the sign will reside in as stated in Fig 26.5-1C of ASCE 7-10.

Using the equation for velocity pressure found in the ASCE 7-10 wind codes, the determined velocity pressure for the sign was about 18.5 psf. This value will be used because it is more conservative than the 17 psf recommended by the 780 CMR codes. In order to determine the design force of the sign, this being the force that will act on the sign due to wind, the following equation was used:

$$F = (qz)(G)(Cf)(As)$$

$$31.8\ psf = (18.496)(.85)(1.8)(378)$$

In which:

- F represents the design force of the sign due to wind
- $q_z$represents velocity pressure
- G represents gust factor and was assumed to be a value of .85 due to its rigid structure according to ASCE 26.9.1
- C_f represents the force coefficient values found through ASCE 29.4-1 using a clearance ratio (s/h) of .33 and an aspect ratio of (B/s) of 1.93 when B=27 ft, s=14 ft, and h=42 ft
- A_s Represents the gross area of the sign. The sign as stated will be 14ft tall and 27 ft. wide with the resulting gross area of 378 psf

The overall design force due to wind was calculated to be 31.8 psf. For the design a value of 32 psf will be used.

4.2.3 Snow Load

The snow load that will impact the sign was calculated through use of the 780 CMR Massachusetts building code. Because there is not a large flat area for snow to rest upon this loading is not the most critical design load. Using the Table 1604.11 Ground Snow Loads, found in 780 CMR Chapter 16, the snow loads are given in psf by city. For Worcester, a value of 50 psf is recommended.

In order to calculate the load being acted on the sign the design force due to snow is used with the thickness and width of the signs display. Using the thickness of the signs display to be 3/16 it was then multiplied by the design force due to snow of 50psf.

$$Snow\ loading = (thickness\ of\ sign) * (design\ force\ due\ to\ snow)$$

$$.781\ lbs/linear\ ft = (3/16\ in) * (1\ ft/12in) * (50psf)$$

The overall loading due to snow per linear foot was determined to be .781 lbs/linear foot.

4.3 Designing the Structure and Foundation of the Proposed Sign

After determining the critical loading that the sign will be subjected to, I was then able to use the knowledge of steel design as well as the Structural Steel Design textbook by McCormac and Csernak to design the steel structure of the display. In the structural design of this structure I utilized the LRFD approach, which is very typical in structural design.

4.3.1 Beam Selection

In order to select the column size necessary for the structure, I first needed to determine how many columns the sign would be designed to have. Because the size of the signs display is 27 feet wide, I designed the structure to have 3 columns: one in the center and two on the edge of each side. Using three columns, I was able to determine the tributary width of each of the supports. Each side column had a tributary width of 6.75 feet and the middle column had a tributary width of 13.5 feet. The tributary width reflects how much of the display area of the sign that specific column will support. In order to find the total tributary area of each column the following equation was used:

$$(Tributary\ Width) * (Display\ Height) = Tributary\ Area$$

Using the height of the display to be 14 feet I was able to determine the total tributary area supported by each column. The tributary area of the outside columns are identical, and were calculated by multiplying the Tributary width of 6.5 feet by the height of 14 feet:

$$(6.5\ ft) * (14\ ft)\ = 91\ ft^2$$

The tributary area of the inside column was similarly calculated by multiplying the Tributary width of 13.5 feet by the height of 14 feet:

$$(13.5\ ft) * (14\ ft)\ = 189\ ft^2$$

Due to the forces acting upon the tributary areas to be the same per square foot, the amount of force each column needs to be able to withstand is dependent on the size of the tributary area. This means that the middle column will have to be sized to withstand a greater about of force because it's tributary area is much larger than the two outer columns. In order to have continuity in the design, I decided to size the middle beam and use that same beam for all three columns. The two outer columns will be over designed, but overall the structure will be more symmetrical and sturdy.

In order to size the center beam, I need to utilize the forces calculated for axial, wind, and the moment due to the wind force. The axial force was found by multiplying the combined loading of the dead and snow loads by the tributary width of the column.

$$Axial: (108\ lb/ft) * (13.5\ ft) =\ 1{,}458\ lbs$$

The force due to wind was found by multiplying the wind load by the tributary area of the column.

$$Wind: (32lbs/ft^2) * (189\ ft^2)\ = 6{,}048\ lbs$$

Due to this force acting perpendicular to the signs display, there is also a bending moment that needs to be assessed for the beam. This bending moment is found by multiplying the total force acting on the tributary area of the beam with the estimated height at the top of the sign. I used the height at the top of the sign because it is the maximum moment arm that could be possible in this case, so it is the more conservative option when evaluating for the maximum bending force. The height at the top of the sign is 29 feet, which accounts for the 14 feet of display height and 15 feet long columns.

$$Moment\ due\ to\ Wind\ force: (6048\ lb) * (29\ ft) = 175{,}392\ lb * ft\ or\ 175.39\ k * ft$$

After determining these forces, I was able to select the beam using the design tables in the AISC Steel Construction Manual and knowledge of Steel Design. This process involves comparing the beam size due to bending moment due to perpendicular wind loads and the beam size due to axial loading combination. Using the AISC table 4-1 I was able to select a W14x30 beam for the bending moment due to perpendicular wind loads.

To size the beam due to axial combination I had to use this process:

1. Determine the dead load, live load, and wind load for the tributary area of the column.

$$Loading\ Due\ to\ Axial\ Combination:$$

DL= (7.66 lb. /ft2)(14 ft.)*(13.5 ft.) =14447.74 lb.*

LL= (50 lb. /ft2)(3/16 in)*(1 ft. /12 in)*(13.5 ft.) =10.94 lb.*

WL= (32 lb. /ft2)(189 ft2) =6,048 lb.*

2. Calculate the loading on the beam: P_u= 1.2D + 1.6L or P_u= 1.4D (highest governs)

Pu = 1.4(DL=1447.74 lb.)=2.03 k*

Pu = 1.2(DL=1447.74 lb.)+1.6*(LL=10.94 lb.)+.5(WL=6048 lb.)=4.78 k*

Pu= 4.78 k governs.

3. Use table 4-1a from AISC Manual to size the beam that is sufficient for the calculated force where $\phi P_u \geq P_u$ at a column length of 15 feet.

A W8x31 beam was selected.

The lowest recommended W-shape column for axial combination loading was a W8x31 beam. However, in this case bending due to perpendicular wind loading governs with a beam size of W14x30. So in this design, the column W14x30 is now evaluated to see if it is fit for the conditions it will be under. The following process is used to determine whether the column will pass or not.

1. Obtain $\frac{r_x}{r_y}$ values from Table 4-1a of AISC Manual for the potential columns
2. Columns with lower $\frac{r_x}{r_y}$ ratios are preferred because they are boxier and more favored from a construction point of view.
3. Check Flange local buckling: $\frac{b_f}{2t_s} \leq 0.56\sqrt{\frac{E}{Fy}}$
4. Check Web local buckling: $\frac{h}{tw} \leq 3.76\sqrt{\frac{E}{Fy}}$
5. Check Slenderness: Long column: $\frac{L}{r} > 4.71\sqrt{\frac{E}{Fy}}$
6. Check $\phi P_u \geq P_u$ using $\phi P\text{u} = \phi * (F\text{cr}) * (\text{A})$
7. Column passes.

The w14x30 beam passed all of the requirements needed. For detailed calculations please see Appendix #.

4.3.2 Connections

In order to design the connections for the signs steel display to the steel W-beams, I first needed to know the forces that will be affecting these connections, as well as the size restraints on the beams. Due to the middle beam being under the largest loading, the design will focus on the middle beam and the other outside beams will be the same design in order to maintain consistency within the design. The design for these connections are based upon the ASCE Steel Construction Manual.

In design for these connections there were two main options that were considered: welded connections and bolted connections. Welded connections can be economic because it saves on cost of overall pounds of steel used, however in this case, the project is very small scale, and wouldn't really be an issue with having too much steel on site. Additionally, because the steel display is flat, and the W-beams are flat, there would be no issue with bolt connections due to shape, which is often a reason why designs call for welding. For this design, I determined bolted connections would be the best option, as it would require a smaller crew of people, and would result in the process being overall cheaper.

Once it was determined to use bolted connections for the design, the loading of the middle column was analyzed to determine how many bolts would be required. Using the following equation, and selecting a starting bolt size of 7/8in thick A490 Steel bolts, I was able to determine the strength of each bolt.

$$\phi R_n = (Fnv) * (Ab)$$

Where:

- Area of the bolt, $A_b = \frac{(\pi)*(7/8\ inch)^2}{4} = .6013\ in^2$
- Total Loading, $F_n = 84.67\ ksi$ based off of the maximum wind loading moment
- $F_{nv} = (\phi = .75) * (F_n = 84.67 ksi) = 68\ ksi$
- $\phi R_n = (\phi = .75) * (F_{nv} = 68\ ksi) * (A_b = .6013 in^2)$ =30.66k/bolt

Through this calculation I was able to determine that the overall strength of each bolt is 30.66k per bolt. Using this strength I was able to determine that there would need to be one line of 3 bolts in order to support the loading at the middle pole. In order to have a more conservative design, each pole can have 2 rows of 3 bolts. With a minimum edge distance required to be 1 1/8th inches and a spacing distance to be a minimum of 3(d_b) or three times the bolt diameter which rounds up to 3 in spacing.

The next step in the design process for the connections was to calculate the tear out capacities for the interior and exterior bolts. This was calculated using the following equation:

$$\phi R_n = (\phi = .75) * (1.2) * (L_c) * (t = 3/16\ in) * (F_u = 65\ ksi) \leq$$

$$(\phi = .75) * (2.4) * (d_b = 7/8\ in) * (t = 3/16\ in) * (F_u = 65\ ksi)$$

$$L_c exterior = (1.5\ in) - (.5)(7/8\ + 2/8) in\ =\ 1"$$

$$L_c interior = (3\ in) - (1)(7/8\ + 2/8) in\ =\ 2"$$

The lower bound of the equation represents the tear out capacities. The calculations for the tear out capacities for exterior and interior bolts are shown below:

Exterior:$\phi R_n = (.75) * 1.2(1\ in) * (3/16\ in) * (65\ ksi)\ = 10.97k$

Interior:$\phi R_n = (.75) * 1.2(2\ in) * (3/16\ in) * (65\ ksi)\ = 21.94k$

The upper bound of the equation represents the bearing capacities. The calculations for the bearing capacities for exterior and interior bolts are shown below:

$$(\phi = .75) * (2.4) * (d_b = 7/8\ in) * (t = 3/16\ in) * (F_u = 65\ ksi) = 19.19$$

Exterior:$\phi R_n = \mathbf{10.97\ k} \leq 19.19\ k$

Interior:$\phi = 21.94\ k \geq 19.19\ k$ *use the upperbound 19.19 k value.

$$T_u \leq 2(10.97\ k) + 2(19.19\ k)$$

$$\boldsymbol{T_u \leq 60.23k}$$

The total tear out is below the capacity limit, therefore the connections pass.

4.3.3 Foundation Design

In order to design the foundation the main restraints to consider was the allowable capacity of the landfills cap and not exceeding it with the combined loading.

The overall allowable capacity of the landfills cap is it cannot exceed 720psf. This information was found through the documentation provided from Honeywell. This means that the overall weight of the structure must be spread out through a foundation. The capacity and the weight were then used to determine the necessary area of the foundation.

$$\sigma soil = \frac{Loading}{area}$$

$$720\, psf\ = \frac{P_u{=}6111lb}{Area}\ \text{Area} \geq 9\ ft^2$$

Using this calculated area I then needed to determine the dimensions of how to distribute this area. Additionally, there needs to be an area much greater than the minimum needed area because the weight of the concrete has not been accounted for yet which will impact the area. Keeping this in mind, I then evaluated the structure to see how best to distribute the area. Because the beams span 27 feet across the structure the foundation needs to be enough cover for the 27 ft. long along span as well as the edges of the beams. Starting with using 29 ft. across would give a foot of foundation along the two edges of the beams. Using an area of 29 ft. by 4 ft. the area would be 116 ft^2. Then using a height of 3ft for the concrete foundation, the overall volume of the concrete ballast would be 348 ft^3. Using the weight of concrete to be about 150 lbs. per cubic foot of concrete that would estimate the ballast to weigh 52,200lbs. Utilizing the known weight of the concrete ballast into the estimated weight of the whole structure, the new weight per foot acting on the cap is:

$$\sigma = \frac{1.4(52200) + 6111\ lbs}{348\ ft^2} = 682.68\ psf$$

This is well below the allowable capacity of 720 psf., concrete ballast passes.

4.4 Create a Model of the Proposed Design Using AutoCAD

After determining the overall design of the structure, including the steel display, steel beams, and concrete ballast, I was able to create a model of the proposed design using AutoCAD. The sign will consist of an A36 Carbon steel display that spans 27 ft. wide by 14 ft. tall, 2 rows of ⅞ inch A490 steel bolts on each beam, Three W14x30 Steel beams, and a concrete ballast that is 3ft tall by 4ft wide by 29 ft. long.

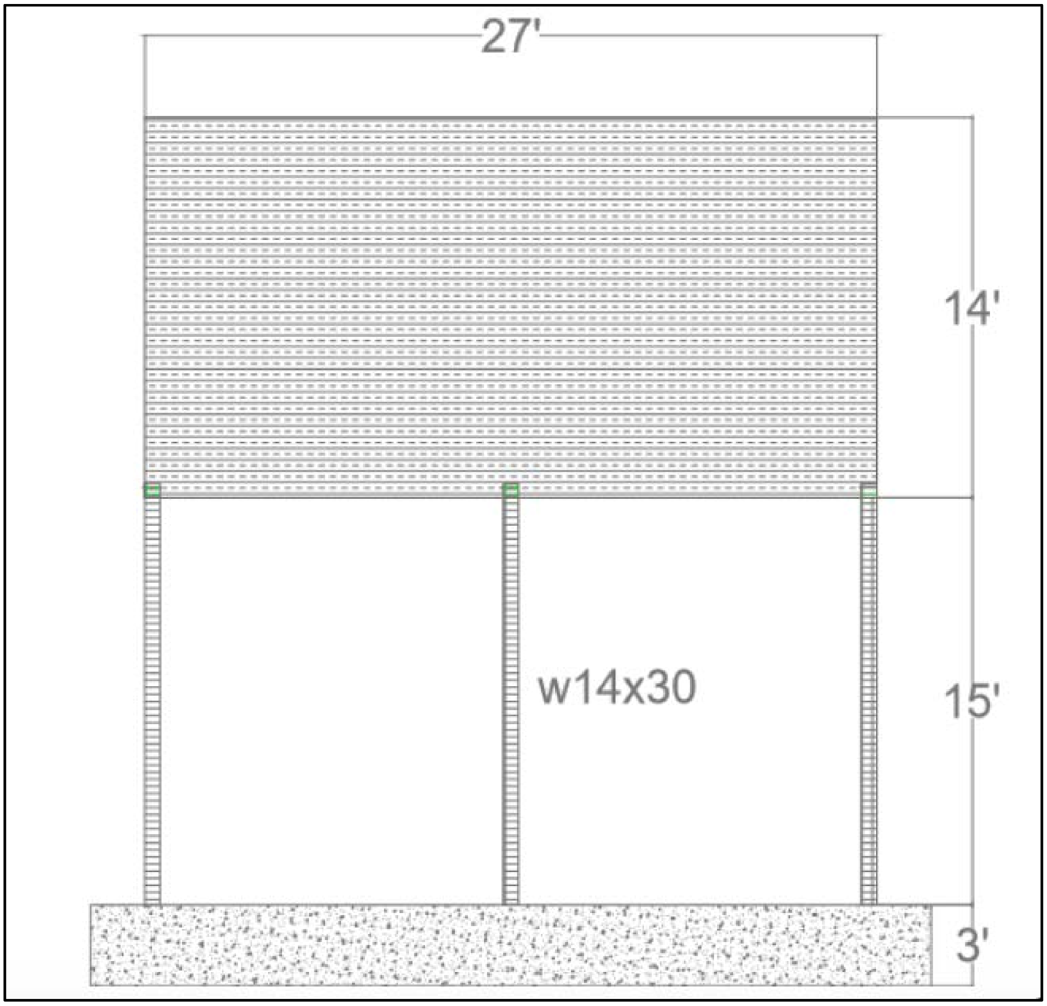

Figure 10: *AutoCAD Model of Proposed Design Structure*

4.5 Analyze the Cost of the Proposed Design

For the cost analysis of the proposed design I broke it down into material costs for two options, a steel sign and an electronic sign. For the prices, I used online retailers to estimate the material costs

Materials and Dimensions:

- Steel Plate Display - 27'x14' A36 carbon steel plate 3/16" thick
- Beams- 3 W14x30 steel beams, 15ft high
- Connections: 2 rows of 3 A490 ⅞" diameter steel bolts per each beam. In total: 18 bolts.
- Ballast- Concrete (f(c)'=50 ksi) Dimensions: 4' length x 29' wide x 3' height.

Cost Estimates:

Materials:	Rough Estimated Cost:
A36 Carbon Steel Display (27'x14'x3/16")	~ $9,000
3 W14x30 Beams 16' tall	~ $2,100
18 A40 ⅞" thick steel bolts	~ $150
Concrete pedestal (3'x29'x4')	~ $1,000
Lighting	~ $1,000
Total:	~ 13,250

The Prices were estimated using average of prices found through online retailers. Prices will fluctuate depending on the retailer. (materialsdepot.com, boltdepot.com, inchcalculator.com)

The LED Display that would be needed for this design ranges from $80,000 to $180,000 depending on the pitch of the pixels that composed the display. The overall construction cost would range depending on the projects bid but can be expected to be from $15,000 to $30,000 based on researching similar projects.

For overall costs, the steel display sign would range from $28,000 to $43,000 for material and construction costs. This is a rough estimate but can be used for future projections in feasibility of this project. The LED display sign would range from $93.3k-193.3k for material and construction costs. This is a large amount of money that would be going to a design that has a much more efficient alternative design.

5. Recommendations

For the recommended design of the sign, I recommend going with the steel display option that does not have the LED display. The LED display is very costly, and is not feasible for this project. However, if in the future the LED display does become feasible due to sponsors or extra funding, the steel display can very easily be retrofitted to have the LED display overlaid on top of it. The structure would simply need to have additional steel bolted connections in order to support the weight of the LED display.

Further recommendations for the design were presented to the City of Worcester, advising them of the key facets of the design:

- Have the sign placed on the south east corner of the site in order to have the maximum visibility of the drivers on I-146.
- In order to have dual facing sign that will target both northbound and southbound travelers on I-146 that will target people entering and leaving the city, the trees blocking the south bound should be removed.
- Opt for the steel plated design instead of the LED display.
- Later, if it becomes feasible for City of Worcester, have the steel sign be retrofitted and overlaid with an electronic display that can be updated remotely.

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Appendices

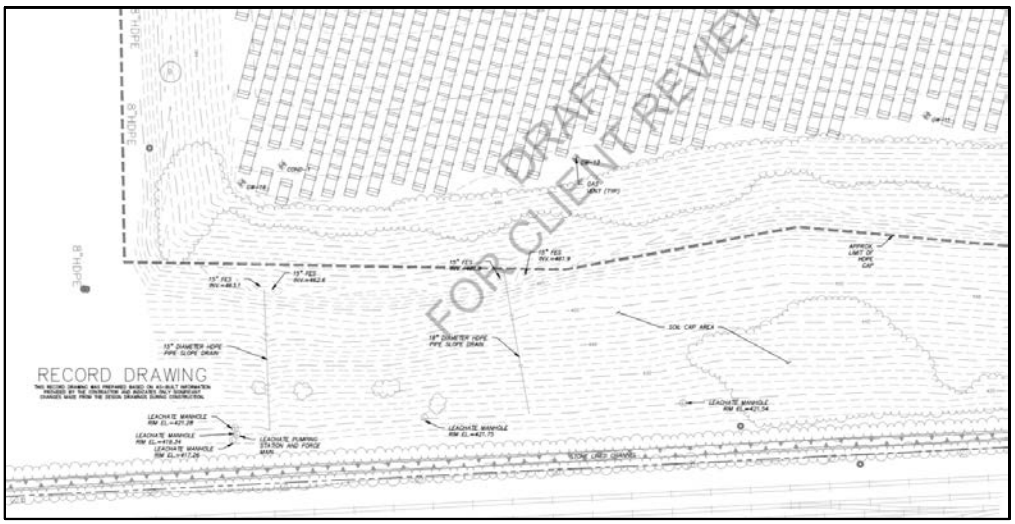
Appendix A: Pamphlet for Sign Content Meeting

Greenwood St. Solar Farm Landmark Sign
Design Concept Review Meeting

Location:

Overhead view via Google Maps.

Picture taken from site tour.

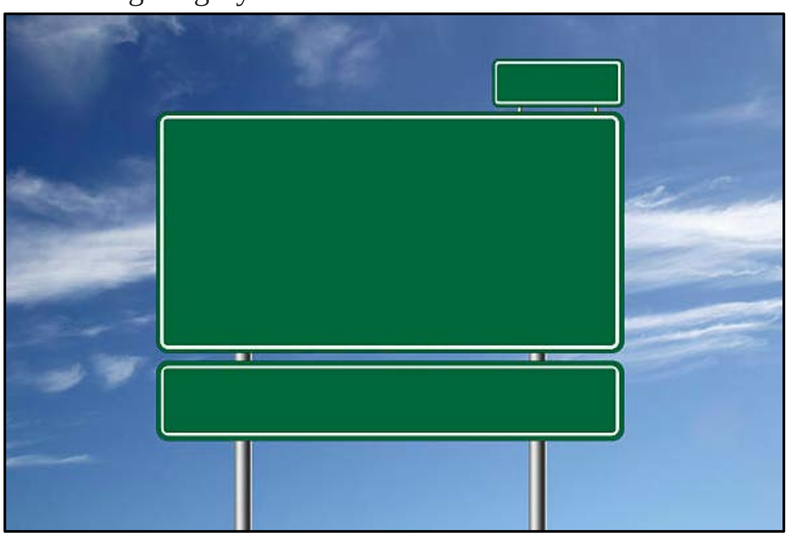


Drawing of surveyed land from Honeywell Documents

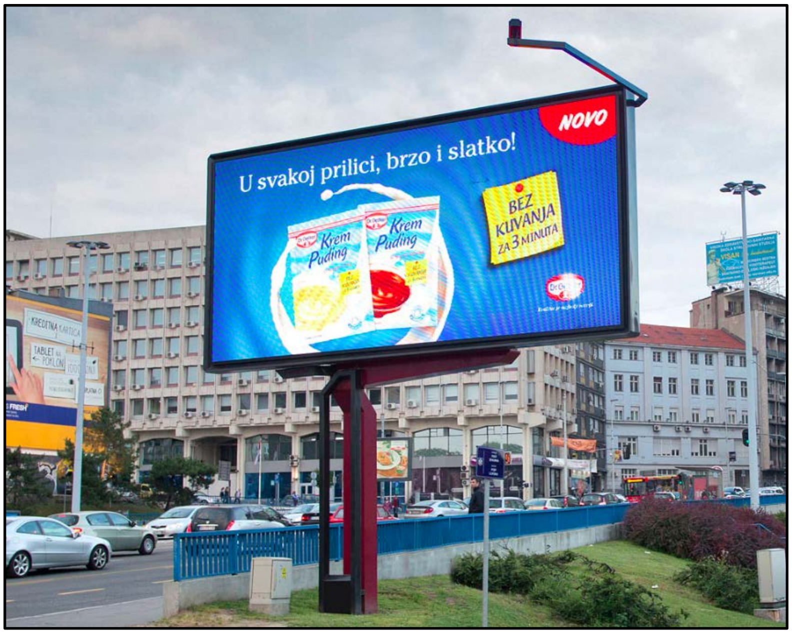
Sign Concepts:

1. Typical Vinyl Billboard
    a. Steel frame
    b. Canvas display with UV defensive paint
    c. Lighting System

2. Steel Highway Road Sign
    a. Steel Frame
    b. Steel Display
    c. Lighting System



3. Electronic Display Billboard
    a. Steel Frame
    b. LED Display



Display Content Options:

Greenwood St. Solar Farm Annually producing *livecount* kwh of energy for the City of Worcester Learn more at worcesterenergy.org	Greenwood St. Solar Farm Producing enough energy to power 1,340 homes per year. Learn more at worcesterenergy.org

1. Live count option for LED sign

Pros:

Live info being displayed

Cons:

Might not be in terms that the general public can understand

2. Homes per year energy

Pros:

Terms that public can understand

Cons:

its an average display, not interactive

3. Largest municipally owned solar Farm in N.E.

Pros:

Displays major accomplishment

Cons:

Is subject to change in future

4. Name displayed w/ year est.

Pros:

Not too much text

Cons:

Does not display any info about how much energy is being produced

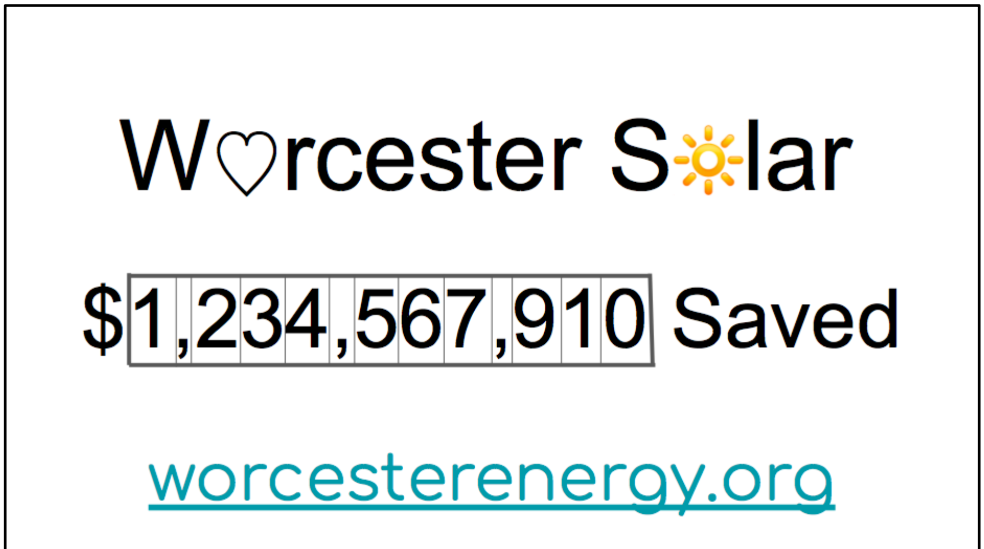
Appendix B: Pamphlet given out for final recommendations to sponsors

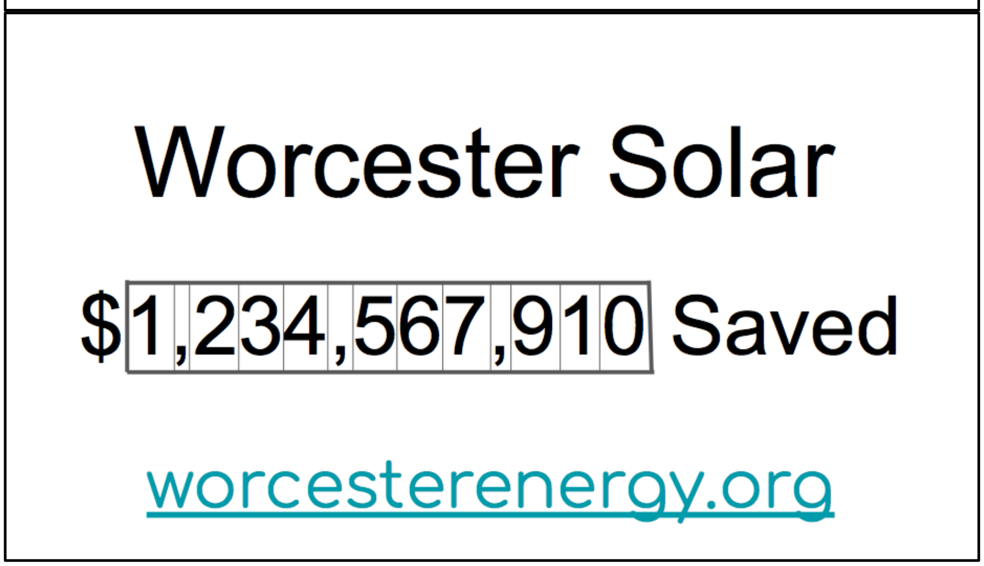
Design of a Landmark Sign for Greenwood St Solar Array in Worcester, MA

A Major Qualifying Project Completed by Cassy Rios, WPI 2018

Proposed Design Options for Landmark Sign to be placed on Site of Greenwood St Solar Array

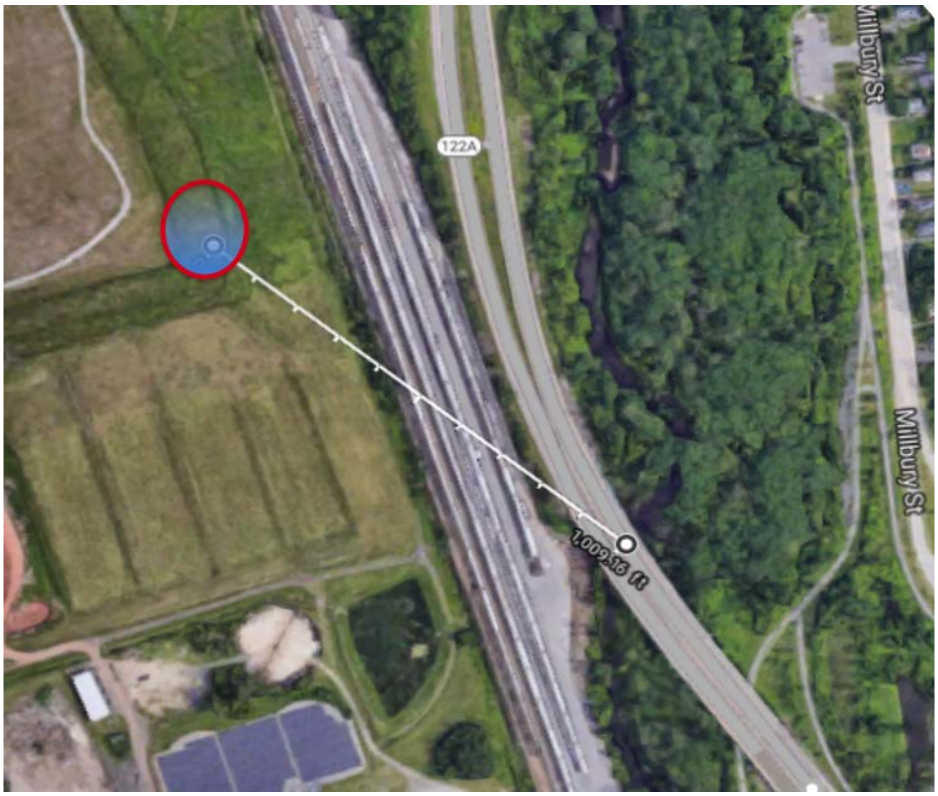
<u>Content Examples:</u>





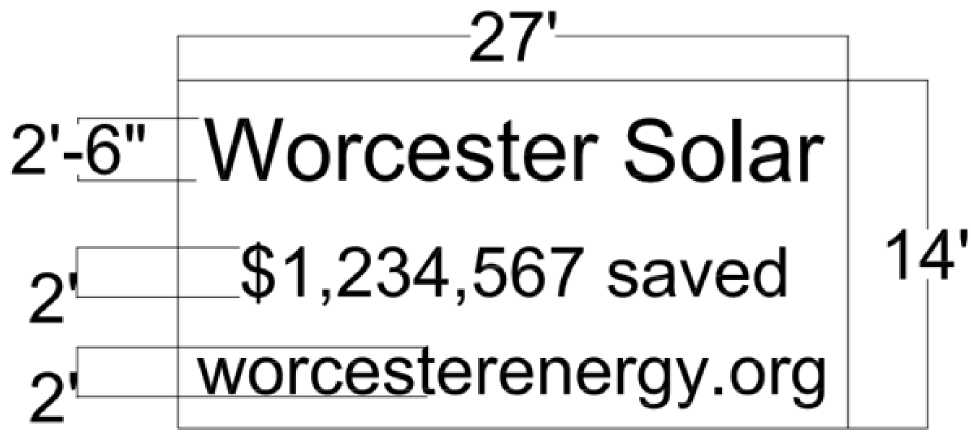
Target Visibility:

- Location of sign would be south east corner closest to I-146
- Drivers of Interstate 146 headed north into the city of Worcester.
- 1000 ft. maximum visible distance
  - Will give drivers time to read the sign as they are driving
  - When caught in traffic drivers will have time to notice the sign, see the solar panels behind it and possible look into what the City of Worcester is working on in terms of solar and green energy.



Text Height:

- Basing visibility off of 1000ft
- Letter height must be at least 2ft.
- Used 2.5ft for Worcester Solar for ease in readability

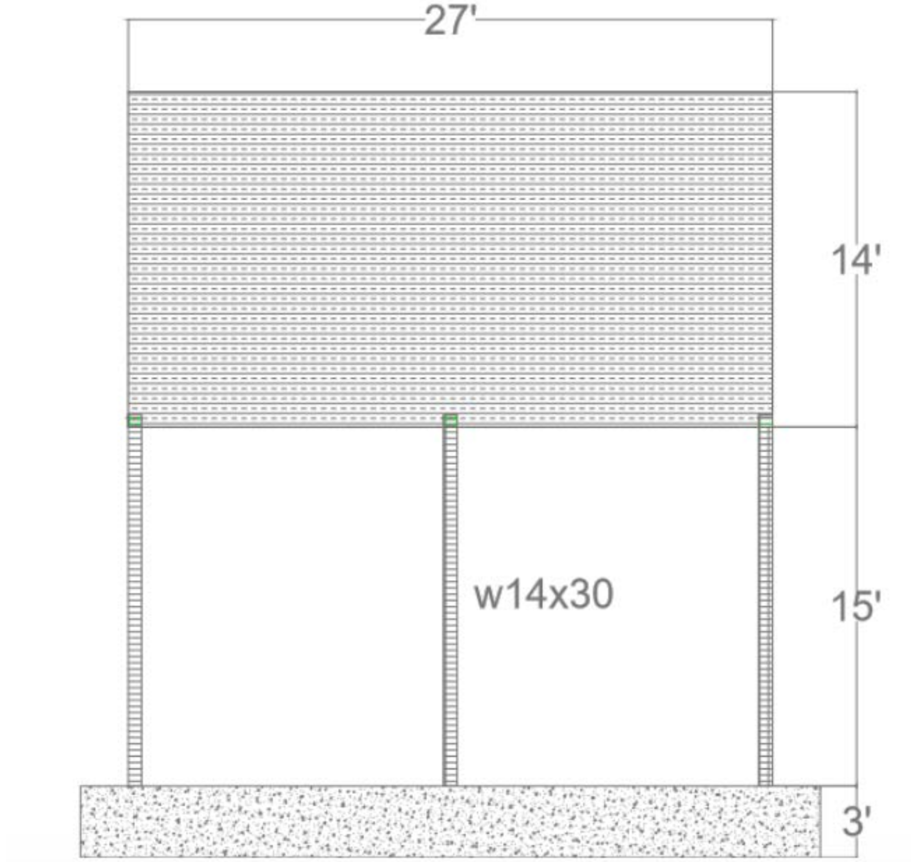


Sign Display Size:

- 27 ft. wide by 14 ft. tall to account for message to have adequate text height and visibility

Design Option 1: Steel Display with Strip of with slider display for numbers.

Design was created following the Massachusetts State Building Codes and the AISC Steel Construction Manual.



Materials and Dimensions:

- Steel Plate Display - 27’x14’ A36 carbon steel plate 3/16” thick
- Beams- 3 W14x30 steel beams, 15ft high
- Connections: 2 rows of 3 A490 ⅞” diameter steel bolts per each beam. In total: 18 bolts.
- Ballast- Concrete (f(c)’=50 ksi) Dimensions: 4’ length x 29’ wide x 3’ height.

***Total weight over distributed area does not exceed allowable capacity of the landfills cap.

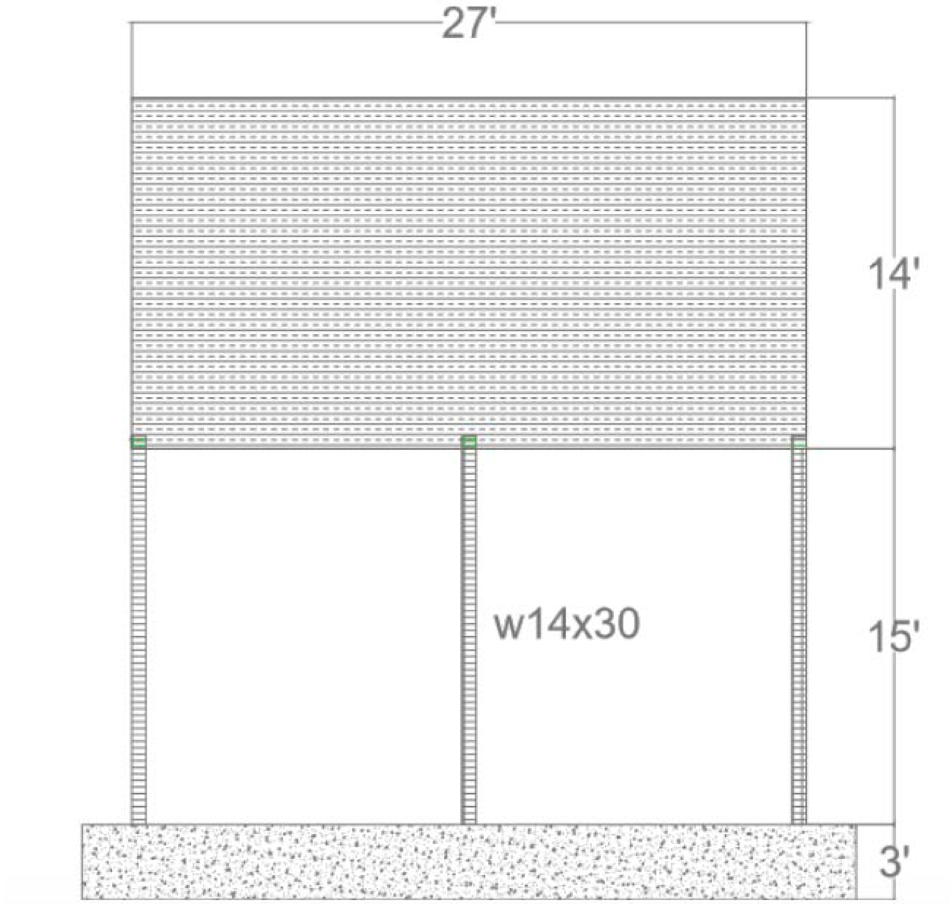
Cost Rough Estimates:

Materials:	Rough Estimated Cost:
A36 Carbon Steel Display (27’x14’x3/16”)	~ $9,000
3 W14x30 Beams 16’ tall	~ $2,100
18 A40 ⅞” thick steel bolts	~ $150
Concrete pedestal (3’x29’x4’)	~ $1,000
Lighting	~ $1,000
Total:	~ 13,250

**Prices were estimated using average of prices found through online retailers. Prices will fluctuate depending on the retailer. (materialsdepot.com, boltdepot.com, inchcalculator.com)

Design Option 2: Steel Display with LED Screen Overlay.

Design was created following the Massachusetts State Building Codes and the AISC Steel Construction Manual.



Materials and Dimensions:

- Steel Plate Display - 27’x14’ A36 carbon steel plate 3/16” thick
- LED Display 27’x14’
- Beams- 3 W14x30 steel beams, 15ft high
- Connections: 2 rows of 4 A490 ⅞” diameter steel bolts per each beam. In total: 24 bolts.
- Ballast- Concrete (f(c)’=50 ksi, 150lb/ft^3) Dimensions: 4’ length x 29’ wide x 3’ height.

***Total weight over distributed area does not exceed allowable capacity of the landfills cap.

Cost Estimates:

Materials:	Estimated Cost:
A36 Carbon Steel Display (27’x14’x3/16”)	~ $9,000
LED Display * dependent on pitch	~ $80k-180k
3 W14x30 Beams 16’ tall	~ $2,100
24 A40 ⅞” thick steel bolts	~ $200
Concrete pedestal (3’x29’x4’)	~ $1,000
Lighting -LED Strips across top of sign	~ $1,000
Total:	~$93.3k-193.3k

**Prices were estimated using average of prices found through online retailers. Prices will fluctuate depending on the retailer. (materialsdepot.com, boltdepot.com, inchcalculator.com, neoticom)

Recommendations:

- Design option #1 would be best if the LED display is not worth the cost now/ in future.
- Design option #2 would be best if the LED display is a possibility for the future.
- Main Target visibility for Northbound drivers of I-146
- Due to the limiting force being the wind load in this case, The main design is adequate for both the LED option and the non-LED option

Appendix C: Wind Loading Spreadsheet

Wind Design Force for Sign Area

Velocity Pressure:

Velocity pressure is given by factoring together the height off the ground the sign will be, the wind directionality factor, the topographic factor, and the basic wind speed. A majority of these values were found using the standard for wind loading ASCE 7-10. Velocity pressure represents the kinetic energy per unit volume of the air flow and is the basic variable determining the wind loading on a building.

$q_z = .00256(k_z)(k_{zt})(k_d)(V)^2$

q_z	Velocity Pressure	18.496	psf Calculated.
k_z	Velocity Pressure Exposure Coefficient	0.85	Based on table 29.3-1 from ASCE 7-10. This value was selected based on a height z of 15ft or less from ground level for an exposure C structure. 20ft -> .9 25ft -> .94
k_{zt}	Topographic Factor	1	Based on topographic factor from table 26.8-1 from ASCE 7-10. This value was used based off of the design criteria set forth by Borrego Solar.
k_d	Wind Directionality Factor	0.85	Based of of Table 26.6-1 of ASCE 7-10 for the wind directionality factor for a solid sign.
V	Basic Wind Speed	100	The basic windspeed of the area in which the sign will reside is 100 mph as stated in Fig26.5-1C of ASCE7-10.

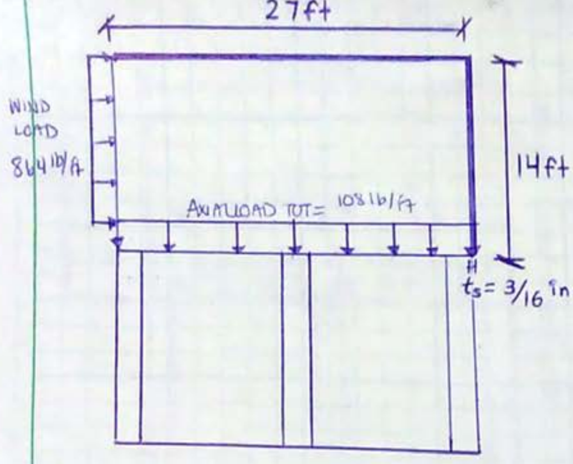
Design Force for Solid Sign:

$F=(q_z)(G)(C_f)(A_s)$

	Design Force (lbs)	10696.97664	
F	Design Force (lbs/ft of s height)	764.06976	
F	Design Force (lbs/ft^2 area)	31.83624	
q_z	Velocity Pressure (lbs/ft^2)	18.496	psf
G	Gust Factor	0.85	Assume Gust Effect Factor of .85 due to not flexible rigid structure, according to ASCE 26.9.1 The gust-effect factor for a rigid building or other structure is permitted to be taken as 0.85.
s	height of sign area (ft)	14	
C_f	Force Coefficient Values	1.8	Found through ASCE 29.4-1 using a clearence ratio (s/h) of .33 and an aspect ratio of (B/s) of 1.93 when B=27ft, s=14ft, and h=42ft
A_s	Gross Area of Solid Sign	378	This value represents the gross area of the sign. The sign as stated will be 14ft tall and 27ft wide with the resulting gross area of 378ft^2

Appendix D: Structural Calculations

MQP Structural Calculations | Cassy Rios | 1/7

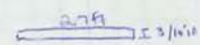


Dead Load of Steel Sign

A36 carbon steel 7.66 lb/ft²

$(7.66\ lb/ft^2) \times (14ft) = \boxed{107.24\ lb/ft}$

Snow Load applied to display



minimum flat snow roof load 35 lb/ft²

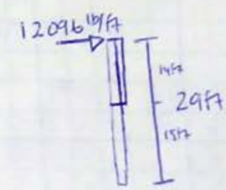
$(35\ lb/ft^2) \times [redacted] (3/16\ in \cdot \frac{1\ ft}{12\ in}) = \boxed{.547\ lb/ft}$

Combined loading in the axial direction

$(107.24\ lb/ft) + (.547\ lb/ft) = 107.79\ lb/ft$

$\boxed{108\ lb/ft}$

Wind Load



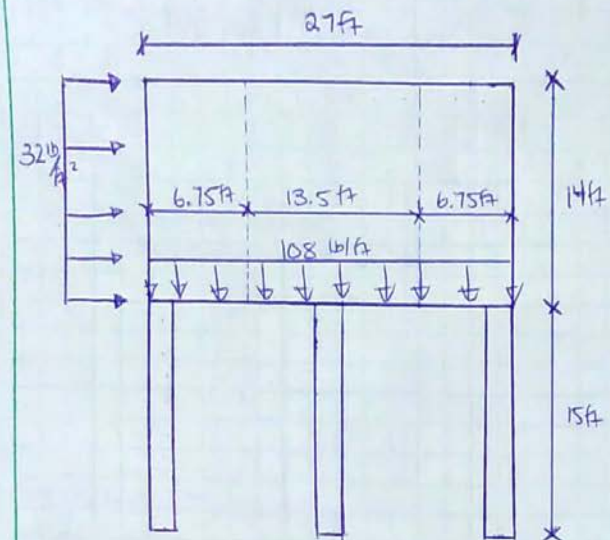
$(32\ lbs/ft^2) \times (27ft) = 864\ lb/ft$

Bending moment due to wind load

$(864\ lb/ft)\times(14ft) = 12096\ lb$ [redacted] or 12.096 K

RIOS 2/7

(12906 lb) x (29 ft) = 350.78 k·ft



The support of the sign must be able to withstand a minimum bending moment of 351 k·ft

OUTSIDE COLUMNS

AXIAL: (108 lb/ft)(6.75 ft) = 729 lb

WIND: (32 lb/ft²)(6.75 ft)(14 ft) = 3024 lb

moment: (3024 lb)(29 ft) = 87,696 lb·ft
or
87.696 k·ft

MIDDLE COLUMN

AXIAL: (108 lb/ft)(13.5 ft) = 1458 lb

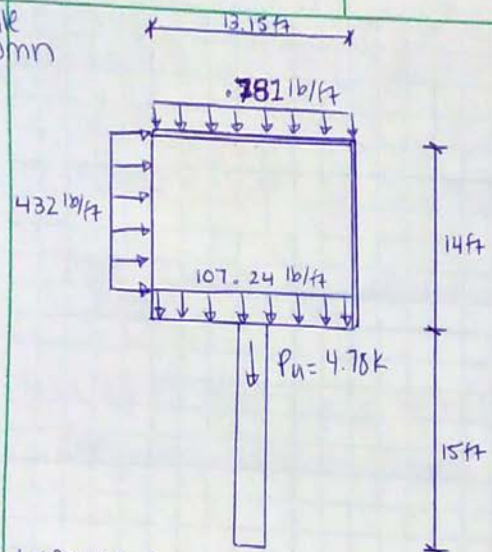
WIND: (32 lb/ft²)(13.5 ft)(14 ft) = 6048 lb

moment: (6048 lb)(29 ft) = 175,392 lb·ft
or
175.39 k·ft

Because all supports will be the same we will design around the middle column since it has the most tributary area.

DUE TO BENDING: W 14x30

middle column



LOADING DUE TO COMBINATION

Dead LOAD

$DL = (7.66\ lb/ft^2) \cdot (14ft) = 107.24\ lb/ft\ (13.5ft) = 1447.74\ lb$

$LL = (50\ lb/ft^2) \cdot (3/16") (1ft/12in) = .781\ lb/ft\ (13.5ft) = 10.9375\ lb$

$WL = (32\ lb/ft^2) \cdot (13.5ft) = 432\ lb/ft\ (14ft) = 6048\ lb$

$P_u = 1.2D + 1.6L + .5W$

$P_u = 1.2(1447.74\ lb) + 1.6(10.94\ lb) + .5(6048\ lb)$

$P_u = 4778.8\ lb$

$P_u = 4.78\ K$ w/ L of column = 15ft.

TABLE 4-1 a) FROM AISC MANUAL

THE LOWEST RECCOMMENDED W-SHAPE COLUMN WOULD BE A W8x31 which is able to suppot a 230K load for a 15ft column.

W8x31

HOWEVER, IN THIS CASE BENDING DUE WIND LOADING GOVERNS, SO the column of W14x30 is used.

W14x30

Column in compression

$\phi = .9$

(EQ E3-2) For $\frac{L}{r} \le 4.71\sqrt{\frac{E}{F_y}}$

For short to intermediate length columns $\rightarrow F_{CR} = \left[.658^{\left(\frac{F_y}{F_e}\right)}\right] \cdot F_y$

(EQ E3-3) For $\frac{L}{r} \ge 4.71\sqrt{\frac{E}{F_y}}$

For long length columns $\rightarrow F_{CR} = .877 F_e$

or

$F_{CR} = .877\left[\frac{\pi^2 E}{(L/r)^2}\right]$

Using Table 1-1 of the AISC Manual

W14x30 column

$A = 8.85 \text{ in}^2$

$r_x = 5.73 \text{ in}$

$r_y = 1.49 \text{ in}$

① Determine Slenderness

$\frac{L}{r_x} = \frac{15 ft\ (12 in/ft)}{5.73 in} = 31.41$

$\frac{L}{r_y} = \frac{15 ft\ (12 in/ft)}{1.49 in} = \boxed{120.8}$ → y-direction governs more critical. Will buckle 1st.

$4.71\sqrt{\frac{E = 29000 ksi}{50 ksi}} = 113.43$

$120.8 > 113.43 \rightarrow$ long column

$F_{cr} = .877\left[\frac{\pi^2 (29000 ksi)}{(120.8)^2}\right] = 17.2 \text{ ksi}$

$$\phi P_n = \phi (F_{cr})(A)$$
$$= (.9)(17.2\,ksi)(8.85\,in^2)$$
$$\boxed{\phi P_n = 136.998\,K}$$

W14 x 30 column PASSESS FOR BUCKLING.

CONNECTIONS

$R_u = F_u A_b$ $\phi = .75$
$F_u = F_{nt}$ or F_{nv}
A_b = normal Area of bolt.

$$A_b = \frac{\pi (7/8'')^2}{4} = \boxed{.6013\,in^2}$$

group B - Bolts A490-X

$F_n = 84\,ksi$
$\phi F_n = 63\,KSi$

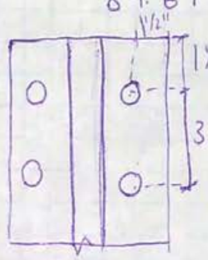
$$\phi R_n = (\phi = .75)(F_{nv} = 68\,ksi)(A_b = .6013\,in^2) = \boxed{30.66\,K/BOLT}$$

TOTAL LOADING

WIND MOMENT Affecting connection = 84.67 K·ft
AXIAL = 1.4 K

$$84.67 + 1.4 = \frac{86\,K}{30\,K} = 2.86 \rightarrow (3)$$ But, want it to be even, so

4 BOLTS/COLUMN



TOTAL CAPACITY

$$(4\,BOLTS)(30.66\,K/BOLT) = \boxed{122\,K}$$

min edge distance for 7/8" ϕ Bolt = $1\frac{1}{8}''$

spacing distance = $3d_b = 3(7/8'') = 2\frac{5}{8}''$

$\phi R_n = \phi(1.2)(L_c)(t)(F_u) \leq \phi(2.4)(d_b)(t)(F_u)$

$d_b = 7/8''$ $\quad L_{c_1} = (1\ 1/2'') - \frac{1}{2}(7/8'' + 2/8'') = 1''$ (ext)

$t = 3/16''$

$\phi = .75$ $\quad L_{c_2} = (3'') - 1(7/8'' + 2/8'') = 2''$ (int)

tearout capacities

exterior $\Rightarrow (.75)(1.2)(1'')(3/16'')(F_u = 65ksi)$

$= \boxed{10.97K}$

interior $\Rightarrow (.75)(1.2)(2'')(3/16'')(F_u = 65ksi)$

$= \boxed{21.94K}$

bearing capacities

$\phi 2.4\ d_b\ t\ F_u = (.75)(2.4)(7/8'')(3/16'')(65ksi)$

$= 19.19$ upperbound.

$T_u \leq 2(10.97k) + 2(19.19k)$

$\boxed{T_u \leq 60.23K}$ ✓

CEMENT FOUNDATION.

$\sigma_{SOIL} = \dfrac{D + L + S}{A_F}$ $\quad \sigma_{SOIL\ ALLOW} = 720$ psf

Weight of plate - 28.96 lb

3 columns @ 16 ft (30 lb/ft) = 1440 lbs

12 bolts = ~6 lbs

display extras ~ 20 lbs

total D_L = 4351.5 lbs

snowload = 14 lbs

7/7

$D_L = 4351.51$
$+ 141$

$D_L\ 4492.51$

$1.4(4492.5) = $ **6111 lbs**

$720 = \frac{6111 \text{ lbs}}{x \text{ Area}} = 8.5 \text{ ft}^2$ ← minimum

$29 \times 4 = 116 \text{ ft}^2 \geq 8.5 \text{ ft}^2$ ✓

$29 \text{ ft} \times 3 \text{ ft} \times 4 \text{ ft} = 348 \text{ ft}^3$

$348 \text{ ft}^3 (150 \text{ lb/ft}^3) = 52{,}200 \text{ lbs}$

$1.4(52{,}200) + 6111 \text{ lbs} = 73080 \text{ lbs}$

$\frac{73{,}080 \text{ lbs}}{116 \text{ ft}^2} = 682 \text{ lb/ft}^2 \leq 720 \text{ lb/ft}^2$ ✓

PASSES

Appendix E: MQP Poster