ADAPTIVE COASTAL CONSTRUCTION: DESIGNING FLOATING HOMES TO RESIST HURRICANE WINDS AND STORM SURGES

by

RUSSELL ARCHER

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Husam Najm

And approved by

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ABSTRACT OF THE THESIS

ADAPTIVE COASTAL CONSTRUCTION: DESIGNING BUOYANT HOMES TO RESIST HURRICANE WINDS AND STORM SURGES

By RUSSELL ARCHER

Thesis Director:

Husam Najm

Residents in coastal communities face multiple challenges when protecting their homes. Hurricane winds and storm surges have caused widespread structural damage throughout eastern and southern communities in the United States and internationally. This reality, coupled with existing research indicating rising sea levels and increased hurricane intensity has forced coastal communities to address the issue. One strategy being implemented and continuously refined is adaptive coastal structural design.

This thesis explores adaptive coastal design techniques for residential structures, focusing on floating housing. A literature review is conducted on existing design concepts of coastal housing that explored the advantages and disadvantages of various concepts as well the challenges associated with them. The floating home structural design concept presented in this thesis includes a lightweight concrete hollow slab base and steel guideposts to resist lateral loads and prevent lateral movements of the house under an extreme flood event. The presented design concept discusses the critical factors that influence the design of the floating home components and other related factors. The design loads and load combinations applied to the floating home structure were based on a 100- year flood event with hurricane level wind forces and high storm surges following FEMA recommendations. Results of the analysis and design of the floating home structure showed that the design is feasible and sustainable in a 100-year flood event with minimum to minor structural damage.

Additionally, a life-cycle cost analysis was conducted for a 50-year period. Using estimates of construction, maintenance and insurance costs, the analysis compared the costs of floating homes built in a New Jersey coastal community to the repair and restoration costs of existing homes damaged following 100-year flood event. The results showed that the costs of floating homes were about 12% lower than the repair and restoration costs.

ACKNOWLEDGEMENTS

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Additionally, I would like to thank Dr. Carrie Ferraro for granting me access to funds to construct the floating home physical model. I would also like the thank Dr. Ferraro for coordinating the Coastal Climate Risk and Resilience Program and the numerous workshops designed to enhance the C2R2 students' perspective on numerous topics, ranging from sustainable development in Latin America and the Caribbean to proper techniques for proposal writing.

I would like to thank the all instructors and students of the Coastal Climate Risk and Resilience (C2R2) Initiative at Rutgers University for shaping my graduate studies in such a significant manner. Through C2R2 I was able to learn about the challenges faced by coastal communities first hand through interactions with stakeholders throughout New Jersey and various courses offered within the program. I was also able to explore methods in which my Civil Engineering discipline interacts with other fields such as Urban Planning and Oceanography, through numerous C2R2 electives. The C2R2 program will influence the way in which I approach engineering solutions throughout my career.

Finally, I would also like thank Chenhang Li and Kirollos Gadalla for their assistance in decorating the floating home physical model. Additionally, I would like to thank Kirollos for his assistance in with the buoyancy test we performed in the Civil Engineering Lab at Rutgers University.

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1.1 Motivation

Climate change and its effects on sea level is a concern for coastal communities. At current rates of sea level rise, many coastal areas are expected to flood repetitively [1]. In New Jersey, projections for sea level rise exist over various time scales. The Science and Technology Advisory Panel (STAP) at Rutgers University has evaluated sea level rise trends and assessed its implications for coastal stakeholders in New Jersey. Using existing projections, STAP concluded that New Jersey coastal areas are likely to experience between 0.6ft – 1.0ft of sea level rise by the year 2030, and 1.0ft- 1.8ft by 2050 [2]. Under high greenhouse gas emissions, these coastal areas are likely to see between 2.4ft and 4.5ft by the year 2100 [2].

	Central Estimate	**'Likely' Range**	**1-in-20 Chance**	**1-in-200 Chance**	**1-in-1000 Chance**
Year	*50% probability SLR meets or exceeds…*	*67% probability SLR is between…*	*5% probability SLR meets or exceeds…*	*0.5% probability SLR meets or exceeds…*	*0.1% probability SLR meets or exceeds…*
2030	0.8 ft	0.6 – 1.0 ft	1.1 ft	1.3 ft	1.5 ft
2050	1.4 ft	1.0 – 1.8 ft	2.0 ft	2.4 ft	2.8 ft
2100 Low emissions	2.3 ft	1.7 – 3.1 ft	3.8 ft	5.9 ft	8.3 ft
2100 High emissions	3.4 ft	2.4 – 4.5 ft	5.3 ft	7.2 ft	10 ft

Figure 1. Expected Sea Level Rise given greenhouse gas emissions. (Science and Technology Advisory Panel)

A 2017 CNN article discussed the threat sea level rise poses to many U.S. cities in the coming century, including major metropolitan areas such as New York, Boston, San Francisco, and Miami [3]. The statistics discussed in this article were published in a report by the Union of Concerned Scientists, who discussed the potential for these cities to experience chronic inundation; flooding occurring 26 times per year or more, disrupting daily routines and covering over 10% of the area's land [4]. To solve this challenge of chronic inundation, the group suggested that more comprehensive solutions be discovered to bring meaningful change and large-scale collaboration between stakeholders be increased [4].

In addition to chronic inundation, coastal communities are impacted by floods of greater magnitude during hurricanes. For example, storm surge levels observed during Hurricane Sandy were between 6 to 7 feet in certain parts of the Jersey Shore in 2012 [5]. Floods of this magnitude cause widespread devastation, displacing coastal residents and triggering expensive long-term recovery efforts. Figure 2 for example, displays the remnants of a home's foundation, which was ripped off its base in Mexico Beach, Florida as a result of the storm surge from Hurricane Michael in 2018.

Figure 2. Home ripped off foundation due to Hurricane Michael storm surge in Mexico Beach, Florida

One potential solution to these issues is adaptive coastal construction. Designing coastal homes that remain immune to the effects of rising waters and storm surges could be beneficial in the foreseeable future if residents elect to remain on the coast. Although numerous coastal residential design techniques exist, design strategies should be analyzed and discussed to determine their suitability and practicality given the new threats coastlines face.

This thesis explores two coastal resilient design techniques for residential structures, the elevated home and the floating home, noting the benefits and setbacks of each design type. Subsequently, the design of a specific style of floating home is explored further through structural analysis and design, seeking to evaluate its performance against hurricane force winds and storm surges. Following this, the cost of the required design is considered and weighed against its potential to reduce residential losses following 100-year flood event. A prototype of the floating home was also built to further illustrate the concept.

1.2 Literature Review

This literature review provides background information on both structural types: the elevated home and the floating home. It is divided into two sections, each discussing the history of both building strategies and their use in different regions of the world. Following this, the chapter highlights specific benefits and challenges that come alongside both structural types.

1.2.1 The Elevated Home

1.2.1.1 History & Usage

Elevated houses are built in areas vulnerable to flooding to ensure livable spaces are protected from flood damage. Permanent home elevation is not a new concept and some cities have grown on water out of necessity. Ganvie, for example, is a village built on Lake Nokoué in Benin and is home to approximately 20,000 residents [6]. The Tofinu people settled there approximately 400 years ago to escape attackers who refused to venture into the water [6]. As a result, they developed a lifestyle that revolved around water, with full markets permanently erected atop the lake where residents trade goods while in canoes [6]. The homes in Ganvie are an example of an open foundation, built with bamboo and permanently elevated on stilts [6].

Figure 3. Homes on stilts in Ganvie, Benin

Open foundations are extremely popular throughout the globe and allow water to flow under the house during a flood event. While Ganvie's homes were designed to stand permanently above a lake, many elevated homes are built on land, prepared for potential floods and storm surges. There are examples of this type of construction in the United States throughout its coastal regions.

Figure 4. Elevated house along the New Jersey coastline

Many homes on the New Jersey coastline use pile foundations along with other strategies to achieve a desired first floor elevation (Figure 4). Coastal communities in New Jersey and the rest of the United States have the option of participating in the National Flood Insurance Program (NFIP), sponsored by the Federal Emergency Management Agency (FEMA), which aims to minimize the loss of life and property due to flooding [7]. The program requires new, improved, or repaired buildings to comply with floodplain management regulations and be elevated to designated heights [7].

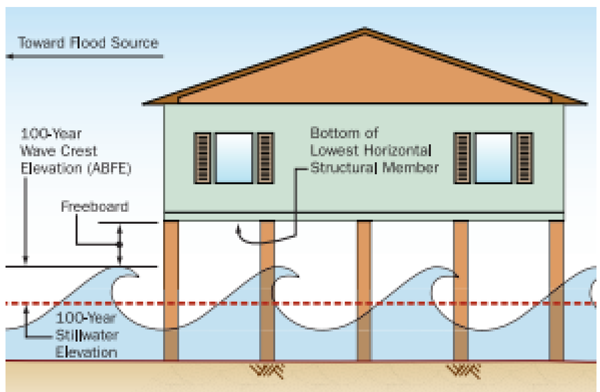

Figure 5. Elevation requirements of the National Flood Insurance Program.

1.2.2 Benefits of Elevated Structures

1.2.2.1 Flood Insurance Discounts

One advantageous aspect of elevated housing for coastal homeowners in the United States is the opportunity to receive discounted flood insurance. Ground-level structures are mandated to pay higher flood insurance rates if located within a floodplain. Coastal communities in the United States have the option of participating in the National Flood Insurance Program that mandates new homes maintain a certain level of freeboard above base flood elevation (Figure 5). The base flood elevation (BFE) is the expected 100-year flood elevation of the community, which has a 1% chance of occurring in a given year. The higher a home is elevated, the greater insurance discount the home receives [7].

1.2.2.2 Resilience

Another benefit of elevated housing is its resilience against flood waters. Flood waters move beneath or around the structure leaving the livable space within the home untouched. Numerous strategies exist to achieve desired levels of elevation and are discussed in later sections. These strategies include elevating on piles, extending existing foundation walls or even abandoning the lower areas of the home to live at higher levels [7].

1.2.2.3 Familiarity

As mentioned previously, home elevation is well-known and has existed in construction for quite some time. Therefore, qualified contractors are readily available to complete elevation jobs [8]. This contrasts with other adaptive forms of living, which have traditionally been viewed as an alternative form of living entirely. Industries promoting the construction of these adaptive methods, such as floating home construction for example, have not expanded to levels comparable to those of elevated houses.

1.2.2.4 Maintenance

It is significantly easier to access certain aspects of an elevated home to install necessary additions. For example, cable, wiring and plumbing systems could run underneath the floor and these features could be installed without damaging existing features such as the walls of the home [9]. Building owners and contractors can easily move beneath the structure to install any necessary additions or make improvements.

1.2.3 Challenges of Elevated Structures

1.2.3.1 Accessibility

A common complaint with permanently elevated homes is their lack of accessibility for the elderly and disabled, who often find it challenging to climb the staircases required to access their front door [10]. Attempts are ongoing to solve this issue. For example, New York Rising, a reconstruction program developed after Hurricane Sandy, provided disabled homeowners in New York with up to $22,000 to install lifts and elevators to access the first floor of their home [10]. However, homeowners were still reluctant to install the lift system.

1.2.3.2 Aesthetics

There are also complaints that certain permanent elevation techniques are not aesthetically pleasing and are eyesores in certain communities [8]. If such opinions become popular, they could discourage future home elevations in these communities. To combat such opinions, strategies such as planting shrubbery around the home or extending the siding down the foundation walls are recommended to alleviate the issue [8].

1.2.3.3 Foundation Type before Elevating

Difficulties can arise in the elevation process because of the home's original foundation, as some structural foundations are easier to elevate than others. Homes with crawlspaces are easiest to elevate, as contractors can maneuver underneath buildings to place beams and jacks [8]. Homes with piers, columns, or shear walls however, are more difficult, as original piers or walls need to be removed, which can only be done with the home lifted and placed to the side [8]. New piers or walls are then installed. The most difficult foundation to work with is a slab-on-grade foundation as contractors must prevent the slab from cracking during the elevation process. The area under the slab also must be excavated to insert lifting equipment [8].

1.2.3.4 Vulnerability to Wind

Elevated homes face an additional challenge of withstanding wind forces, which get stronger with increasing height. This is a result of the derived wind pressure on a building being a function of the square of the wind speed [11]. Although raised housing avoids flood damage, it is exposed to stronger winds. This permanent exposure over time could lead to unexpected building damage and economic losses [11]. Therefore, studies are being conducted on alternative resilient building strategies that do not permanently elevate the home.

1.2.4 The Floating Home

The floating home is one alternative to elevated residential construction. This section explores the floating structure’s suitability as a design strategy for coastal residents through examined literature. It discusses its global history, with a specific focus on its development and use in the Netherlands, and examines the methods used to ensure its structural stability on water. It also addresses the building strategy’s benefits and the unique challenges it presents to residents.

1.2.4.1 History & Usage

Floating homes have been in existence for many years and are found throughout the globe. Reasons for their development vary from region to region. In China, between the tenth and thirteenth centuries, houseboats developed as “refined” methods of traveling [12]. The boats held suites for travelers, with decks that functioned as a roof for passengers as well as a living and work space for crew members [12]. High ranking officials made use of these boats for travel and brought their family with them [12]. Unlike houseboats however, the floating homes explored in this thesis remain in one location and have no propulsion power [13].

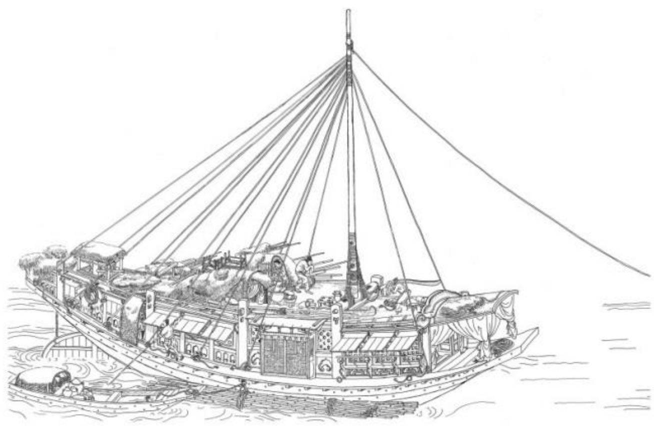

Figure 6. Line drawing of a portion of Guo Zhongshu's 'Travelling on the Yangzi through a Snow Night'. The painting presents an image of a Chinese houseboat, as windows are observed below the deck (Nanny Kim)

In the United States, floating residential structures were found in coastal towns on the West Coast [13]. Seattle in the 1930s for example, possessed a few thousand floating homes. Their existence during these time periods was primarily a result of unaffordable land rather than desires to live on water [13]. However, as cities such as Seattle cleaned their waterways, homes on the water became a more fashionable form of living [13]. Currently, some of these homes sell for as little as $200,000 while larger homes with multiple stories can cost up to $2.8 million [13]. Although the number of floating homes in Seattle have decreased over time, their prices have significantly risen.

Figure 7. Seattle Houseboats: Seattle Floating Homes for sale (Cooper Jacobs Real Estate Group)

New Orleans, Louisiana has also explored the capabilities of floating homes. Following the devastation of Hurricane Katrina in 2005, designers from Morphosis Architects developed a floating home to resist high storm surges. Named the FLOAT house, the sustainable floating home is designed to sustain its own water and power needs and is constructed on land, only rising during a flood. Created specifically for storm surge, it can rise to 12 feet while attached to guide posts. Despite their potential resilience, these homes are not designed for residents to remain inside during a storm [14].

Figure 8. FLOAT house on Tennessee St, New Orleans, LA in 2009 (Iwan Baan)

The floating structures mentioned thus far were built for several reasons. The houseboats in China were developed as a method of transportation, while past floating homes in Seattle sprung up because of climbing land prices. The FLOAT house in New Orleans was specifically designed to guard against storm surges. The Netherlands also has a history of adapting to rising waters. This is primarily a result of its land elevation, with many of its cities are already below sea level [15].

Cities like Amsterdam and others in the region are highly vulnerable to the effects of sea level rise and climate change given their growing population density [16]. If the modern Dutch coastal defenses were to fail during an emergency, it is estimated the nation could suffer damages above 400 billion euros [16]. As a result, numerous efforts have been made in throughout history to combat the threat of sea level rise and inundation.

As early as 500 B.C., settlers began building their homes on terps, which were mounds of clay and sand to elevate themselves above flood levels [15]. This concept was eventually expanded to ensure that entire groups of homes were above inundation levels. By 50 B.C. dikes were developed to provide a second level of protection for homes and agricultural land [15]. To further enhance the living scenario, windmills were introduced in 1200, and were used to pump excess water out of the settlement, increasing the amount of available land for residents in these areas [15].

These windmills had negative consequences however. The water removed by the windmills exposed the base of the mounds, causing the organic materials utilized during construction to oxidize and decompose [15]. Thus, the mounds began to sink, and flooding began to increase again due to the land's closer proximity to the groundwater table [15]. As a result, more windmills were built to pump out additional water, which only further intensified land subsidence. This period in Dutch history contributed to the region's present low land elevation relative to sea level. Today, Dutch engineers and designers are exploring the option of designing on the water itself.

A study conducted in 2006 by DeltaSync, a Dutch based floating urbanization consulting firm, explored the feasibility of designing a floating city for the Amsterdam-Almere region of the Netherlands [16]. Since the Amsterdam-Almere region is an important economic engine, designing an adaptable and sustainable floating city on the IJmeer Lake between the two cities seemed reasonable, as it had the potential to alleviate some of the stress the region could face due to climate change and sea level rise [16].

The floating city would be a source of housing, which is urgently needed as both population and urbanization rises alongside flood risks. Some of its other benefits include boosting the local economy by attracting tourists and aiding the local ecology as the constructed wetlands surrounding the city appeal to migratory birds. These wetlands also efficiently serve as breakwaters to reduce the wave action experienced on the floating structures within the city [16].

These examples of floating structures and their historical and modern-day applications illustrate their usefulness against rising waters. Communities throughout the globe have used them to their benefit. Even though their potential benefits have been realized within certain communities, buoyant structures possess unique setbacks as well. These benefits and setbacks are discussed in the following section.

Figure 9. Proposed floating city concept by DeltaSync for the Amsterdam-Almere region (DeltaSync)

1.2.5 Benefits of Floating Structures

1.2.5.1 Resilience & Sustainability

Like elevated structures, floating structures are resilient to sea level rise and flooding. As waters rise, floating structures rest on the water surface, avoiding inundation. If properly designed, this significantly reduces and potentially eliminates the structural damage experienced due to inundation.

Figure 10. Fraunhofer floating home concept (Fraunhofer)

Given the resilience and renewed interest in floating structures, opportunities arise to incorporate sustainable materials to their design. For example, Fraunhofer, a German research organization, began developing a sustainable floating home prototype in 2015 (Figure 10). The finished product sought to contain an adiabatic cooling system that cools itself in the summer [17]. For this process, a surface on the side of the house is moistened and over time evaporation cools the building [17]. The house also contains a zeolite thermal storage unit that stores heat in the summer and releases it in the winter to increase comfort. This process is purely physical and occurs without the use of electricity [17].

Floating homes elsewhere have also incorporated sustainable concepts in their design. The FLOAT house previously mentioned for example has a net-zero annual energy consumption [14]. Each house is designed with a ground source heat pump that naturally conditions the air depending on the season [14]. This geothermal heating and cooling system reduces the energy required to keep the indoor air temperature at desired levels. Additionally, these homes are equipped with solar panels and sloped roofs that collect rainwater which is filtered and stored for regular use [14].

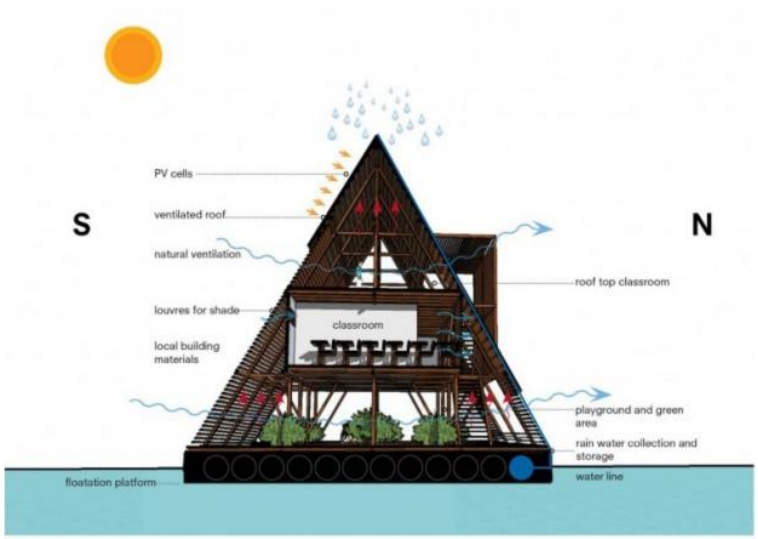

Figure 11. Makoko Floating School, Logos, Nigeria (NLÉ)

A third example of a floating structure designed with sustainable materials is the Makoko Floating School, formerly located on the Lagos Lagoon in Lagos, Nigeria (Figure 11). The school was constructed in 2013 to serve as a teaching facility for residents of Makoko, an informal settlement on the Lagos Lagoon. The design utilized locally sourced timber to create the triangular structure, which is buoyed on floating barrels [18]. The use of local materials that have relatively low production costs is a sustainable strategy of construction for the community, given its location. Unfortunately, the structure collapsed in 2016 due to heavy rainfall.

Figure 12. Aerial photograph of Makoko Floating School alongside the Makoko settlement (Iwan Baan)

1.2.5.2 Additional Land Space

Given their nature, floating homes provide homeowners the option of building directly on water or extremely close to it. Building on the water provides more space inland. This is particularly useful in densely populated regions with growing populations. The city of London, for example, has experienced a significant population increases between 2011 and 2015, growing twice as fast as the rest of the UK over the four-year period [19]. As a result, designers are developing solutions to utilize available water space for housing (Figure 13). Baca Architects for example, have proposed that prefabricated floating homes be developed along London's waterways [20].

Figure 13. Concept drawings of proposed floating homes along London's rivers and canals. (Baca Architects)

1.2.5.3 Sense of Community

Floating structures and their design can also create a sense of community among residents. Rather than retreating from the shoreline, buoyant design keeps communities together ultimately strengthening bonds between residents. This is evident in the Makoko Waterfront community in Nigeria, as they have adapted and created a lifestyle to survive on the open water. The construction of the floating school in Makoko gave residents a "…powerful sense of ownership…" and a feeling of importance, as the structure represented something that was resilient and able to withstand future sea level rise [18].

1.2.6 Challenges of Floating Structures

1.2.6.1 Waste Removal

Despite the evident benefits of floating construction, multiple challenges arise when constructing such structures. For example, if a structure is built to sit permanently on water, waste removal becomes an issue. In the United States, it is illegal and unsanitary to dispose of waste in the waterways on which these structures are built. For example, the state of Oregon's Department of Environmental Quality (DEQ) states that floating homes must have permanent plumbing systems that are connected to a DEQ approved sewage system [21]. These plumbing systems must be designed to account for the potential vertical movement of the home due to rising and falling water levels. Regular trash must also be walked back up to dry land for disposal and residents have grown wary of this routine in the past [22].

1.2.6.2 Safety

Additionally, since some floating structures are located permanently on bodies of water, there are safety concerns for young children and pets that utilize the docks around the homes. In 2015, a couple living on Lake Union in Washington described the regulations their young children, ages 8 and 3 must follow when on the docks around their home [23]. The children wear life jackets on the deck and are taught swimming lessons from an early age. There are also specific sections of the deck around the home that are off limits to the children [23].

1.2.6.3 Wind

Apart from large storm surges, hurricanes can bring significant amounts of wind. Wind gusts from Hurricane Michael, which struck the Florida in late 2018, were reported as high as 150 miles per hour [24]. Ideally, structures that can survive flood inundation should also be able to withstand other aspects of storm systems such as their winds. Depending on the elevation technique, permanently raised homes have the option of installing bracing between piles or columns to resist lateral wind loads the structure could face, preventing it from overturning. Although floating structures utilize posts to resist lateral loads, a robust lateral system is needed to insure minimal wind damage to the home during a high wind event.

Chapter 2: Concepts & Designs

2.1 Elevated Homes

Numerous methods of home elevation exist and historically this has been achieved by using two foundation types: closed foundations and open foundations. Closed foundations force water to move around the structure in the event of a flood. Residents utilize the space within some closed foundations for storage and other functions. Open foundations exist in the form of posts, piles, or piers, and allow water to flow freely under the structure in the event of a flood. This section describes several types of closed and open foundations.

2.1.1 Elevating on a Closed Foundation

2.1.1.1 Extending Existing Foundation Walls

Foundation walls are part of the foundation system for a building. They provide support for the home's superstructure. One elevation option involves increasing the height of these foundation walls. This is done by creating openings in the foundation walls and installing I-beams beneath the floor joists of the structure's first floor (Figure 14). Then, these beams are lifted with jacks, subsequently lifting the entire structure (Figure 15). Once at the desired height, the foundation wall is extended to reconnect with the first floor of the home (Figure 16). Gaps are then left in the foundation walls for floodwaters to flow through [7].

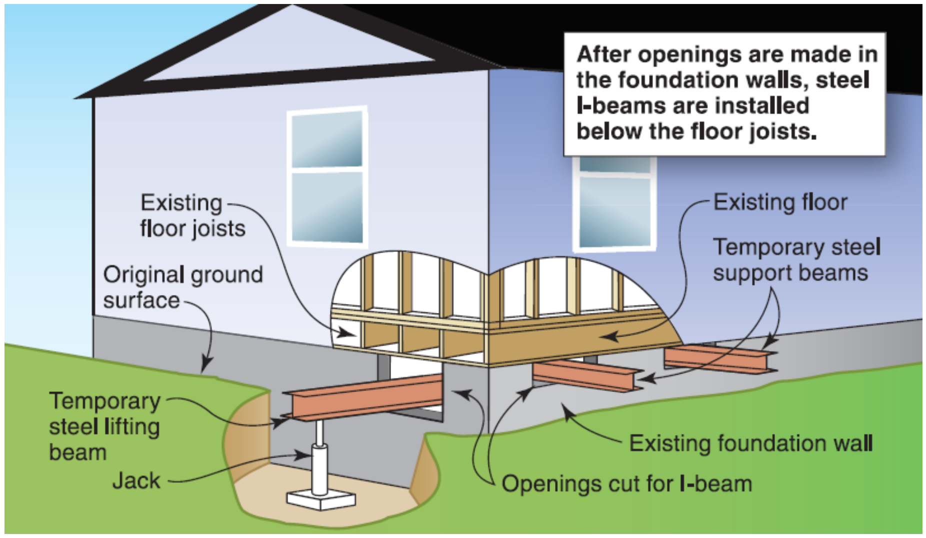

Figure 14. Temporary Jacks installed beneath the home to begin the elevation process (FEMA)

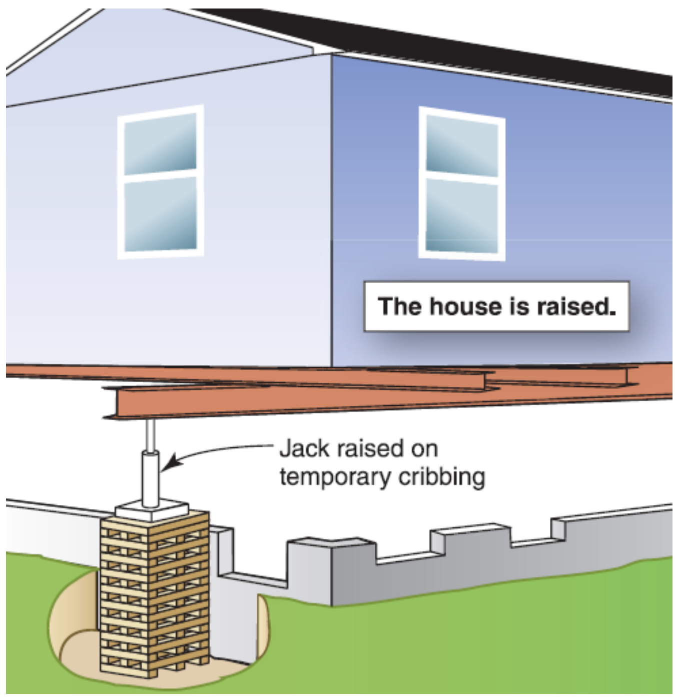

Figure 15. Raised home using jack system (FEMA)

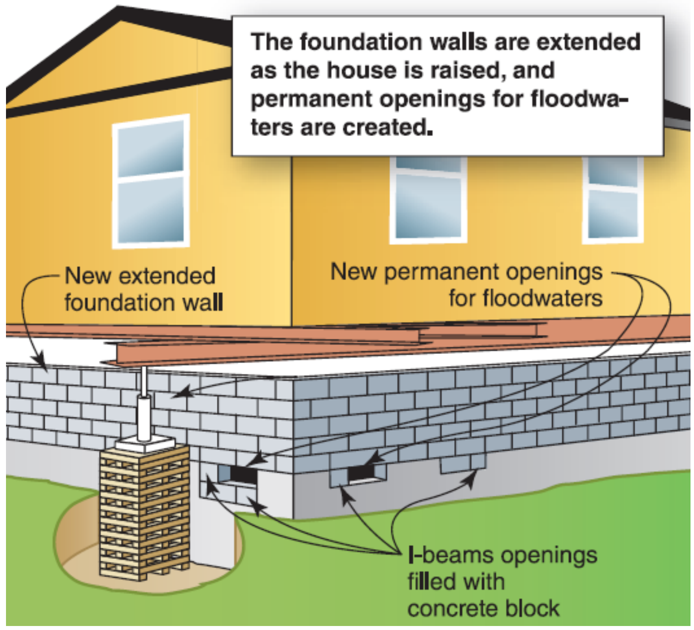

Figure 16. Foundation wall is extended to reconnection with the first floor of the home (FEMA).

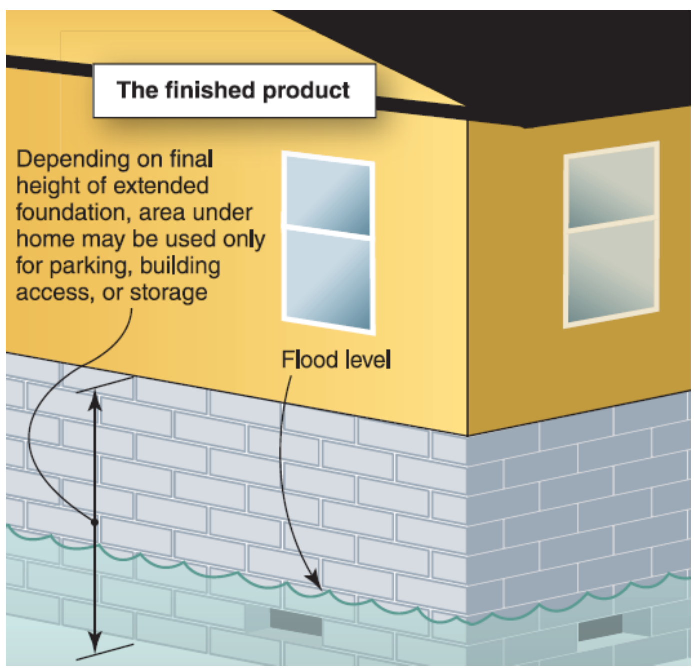

Figure 17. Openings are sometimes left in the foundation wall to all water to flow through the wall, lowering the lateral pressure experienced by the wall (FEMA)

2.1.1.2 Extending Home Walls

The walls of the home itself can also be extended. To do this, the roof of the home is first removed. Then, the walls are built to a desired height based on how much the first floor needs to be raised. Once the floor is raised, the area beneath becomes a crawlspace and openings must be placed in the walls for floodwater to ensure water pressures equalize in the event of a flood. After the floor and walls are raised to their desired height, the roof is reinstalled [7].

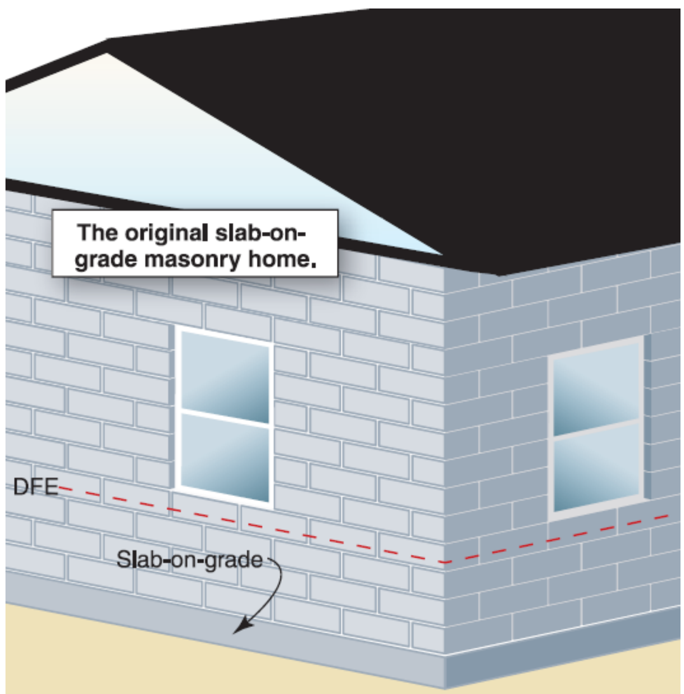

Figure 18. Original slab on grade masonry home (FEMA)

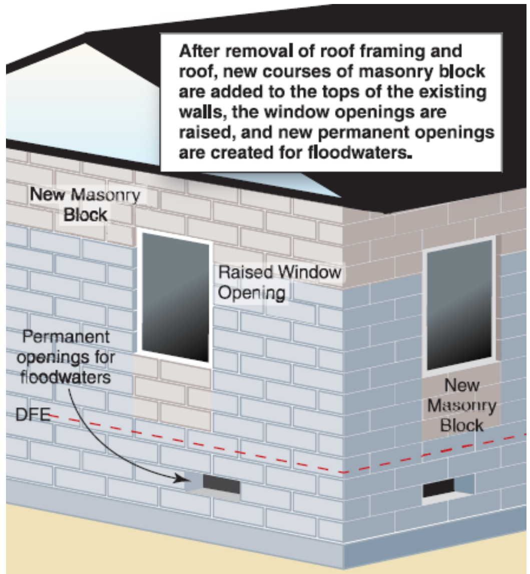

Figure 19. Once the roof is removed, additional masonry is added to raise walls and window openings are raised (FEMA)

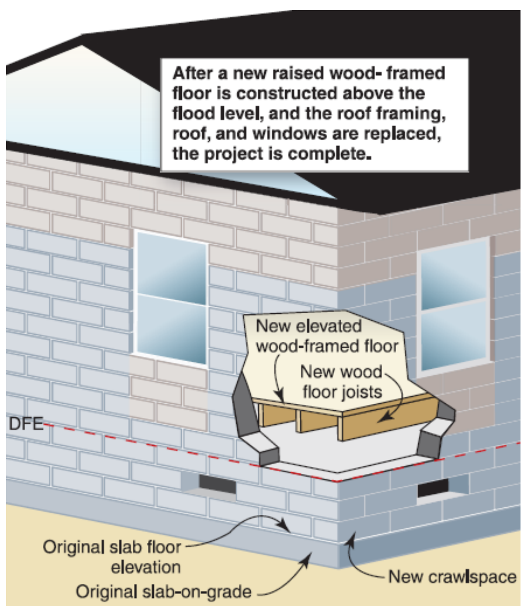

Figure 20. A new first floor is built above the design flood elevation (FEMA)

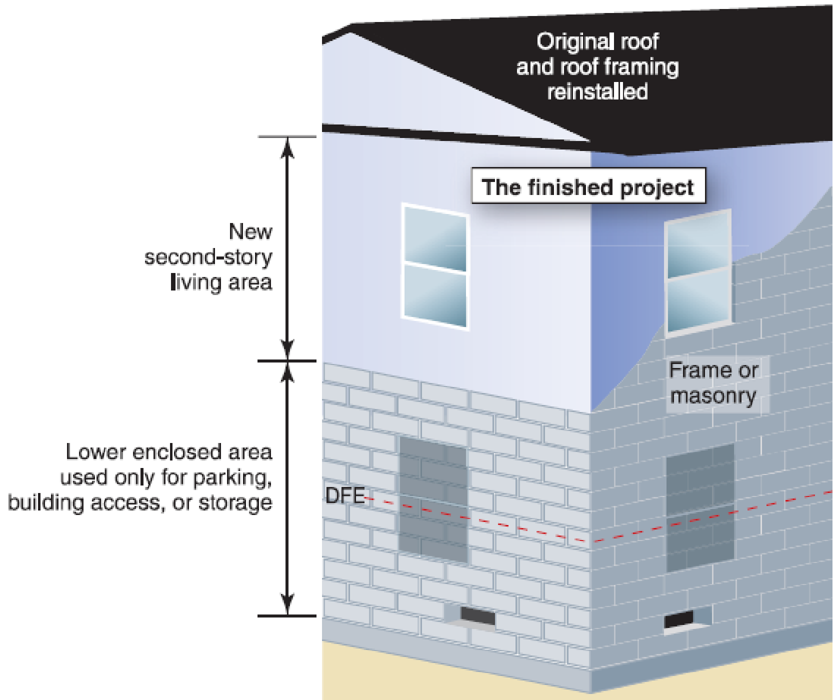

Figure 21. Original roof framing reinstalled (FEMA)

2.1.2 Abandoning Lower Enclosed Area

Another elevation technique involves abandoning the lower enclosed area of the home and moving all living space to the upper floors. This is best suited for masonry homes on slab-on-grade foundations, as floodwaters do not easily damage concrete or masonry floors and walls [7]. In this situation, the abandoned lower level is used for parking, building access, or storage [7].

2.1.3 Elevating on an Open Foundation

2.1.3.1 Piers

The technique of elevating a home to support it with masonry piers is similar to the technique used to extend foundation walls. Steel I-beams are placed beneath the floor joists with their ends resting on jacks. The home is then gradually lifted to the desired elevation using the jacks. Once this is done, the masonry piers are constructed under the home. Given the need to resist lateral loads such as floodwaters, these piers are reinforced with steel [7].

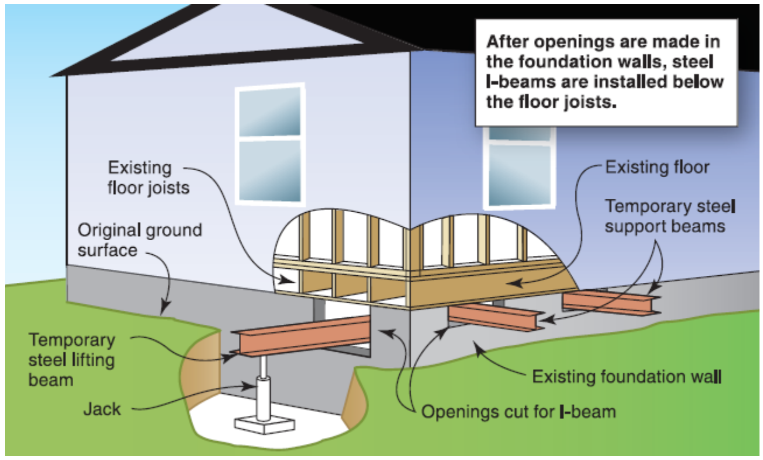

Figure 22. Jacks installed beneath the first floor of the home (FEMA)

If the home being lifted had a basement, the exposed basement space is filled with dirt and graded. If the home has a basement slab, it is permitted to remain there so long as the slab is broken into pieces first before filling the basement space. This allows infiltration in the case of a flood and decreases buoyancy forces underneath the home [7].

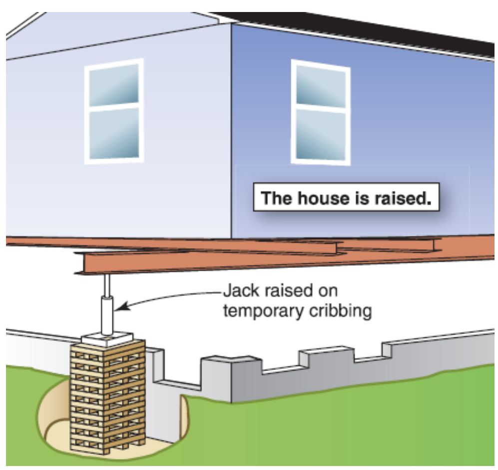

Figure 23. Using jacks, the home is raised to its desired height (FEMA)

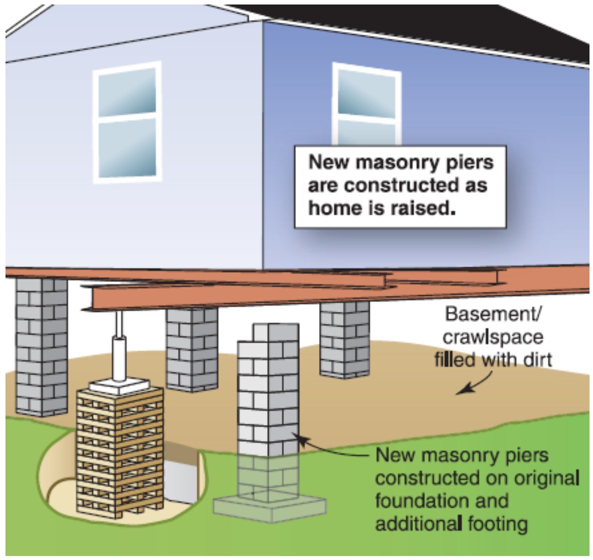

Figure 24. New masonry piers are then installed to support the raised home (FEMA)

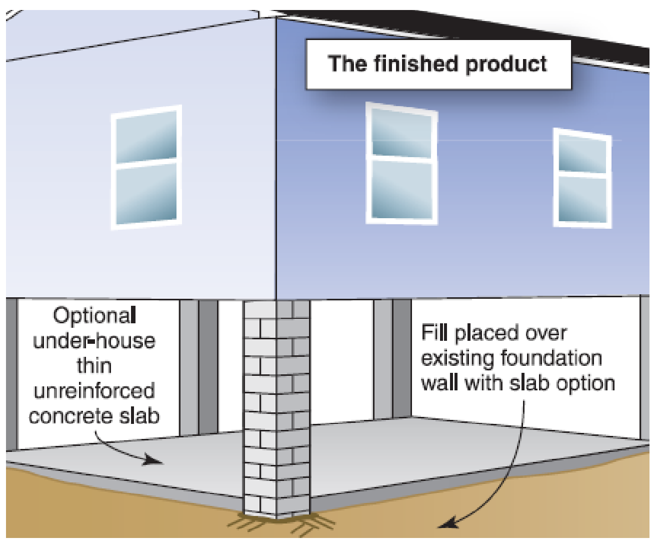

Figure 25. A slab is installed under the lifted home (FEMA)

2.1.3.2 Posts or Columns

Homes elevated using posts or columns do not utilize the existing house foundation. Instead, the previous foundation is removed for the posts to be installed in concrete encasements or pads. Holes are drilled into the ground and each post rests in a concrete footing [7].

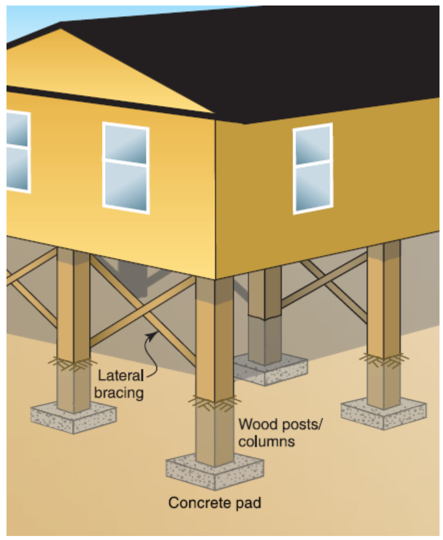

Figure 26. Wooden posts installed beneath an elevated structure. Each post sits in a concrete pad or footing (FEMA).

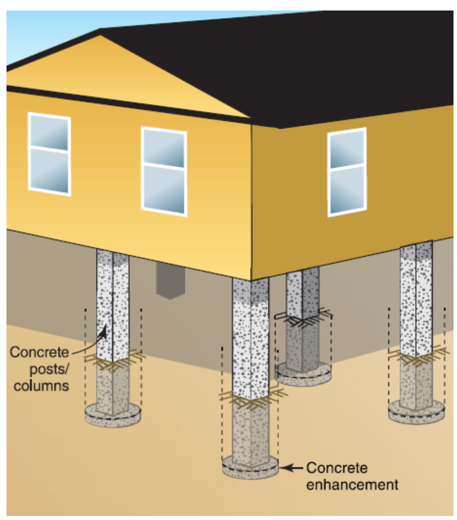

Figure 27. Concrete posts installed beneath an elevated structure (FEMA).

Lateral loads are a concern in this elevation scenario. These loads can be a result of earthquakes, flooding, or wind. It is possible to laterally brace these posts with cross-bracing systems, but only recommended to increase occupant comfort [7]. These braces should not be used as the primary lateral load resisting system to protect the foundation. Depending on the magnitude of the lateral loads expected, a metal framing system may also need to be installed [7].

2.1.3.3 Piles

Piles are a third form of open foundation. They go much deeper into the ground that the previously mentioned options, driven or jetted with high pressured water [7]. Pile driving requires heavy machinery and cannot be carried out with the assistance of jacks to lift the home. Therefore, the existing home foundation is removed, and the entire home is lifted and placed aside before the pile driving [7].

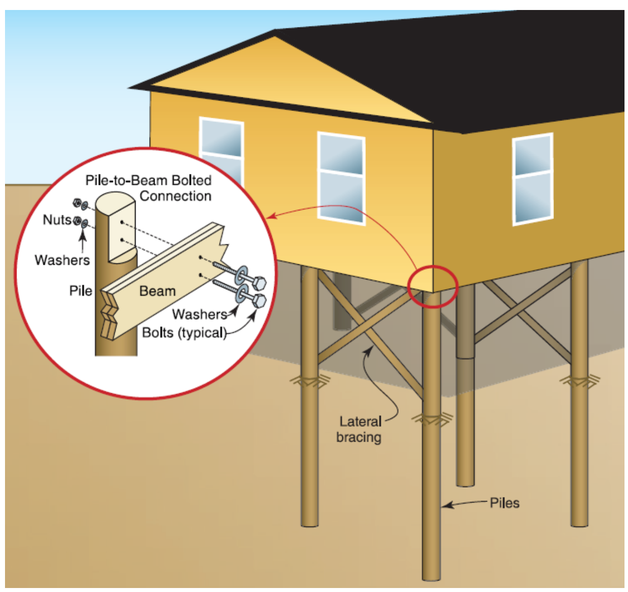

Figure 28. Elevated structure on piles (FEMA)

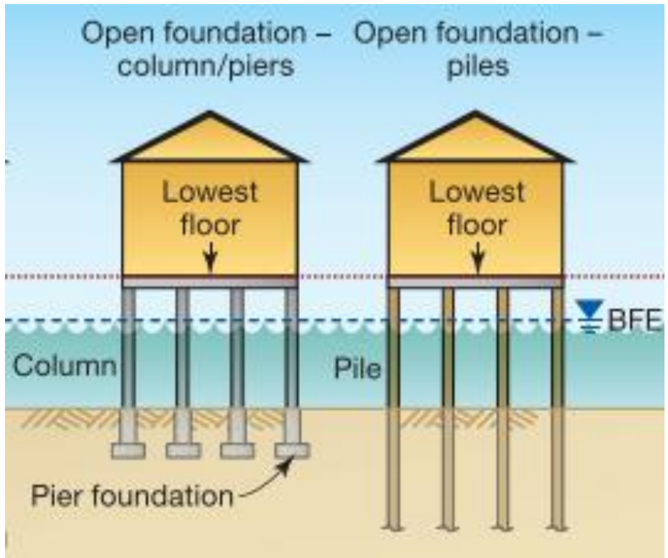

Figure 29. Two types of open foundations: Columns and piles (FEMA)

2.2 Floating Homes

Floating structures rely on two principal components to operate. These components are a floating base that keeps the structure afloat, and guide posts that prevent lateral movement. The materials that comprise these components vary based on numerous factors, such as availability, home location, home weight and size, along with a list of other factors. This section outlines a few design options for floating residential structures.

2.2.1 Buoyant Foundation Types

2.2.1.1 Expanded Polystyrene Base

One common material used to provide buoyancy is expanded polystyrene or EPS. EPS is lightweight and rigid, and is commonly used as insulation for walls, foundations and roofing [25]. As a result, EPS is placed beneath the first floor of homes to promote buoyancy. Homes in certain parts of southern Louisiana have utilized this material with smaller residences for over

30 years to escape flood waters [26]. Figure 30 for example, shows EPS blocks held within a steel framing under a home in Louisiana. In the presence of a flood, EPS allows the home to easily remain above flood levels due to its light weight.

Figure 30. A floating home with EPS base in rural Louisiana. EPS blocks are encased in a steel frame (E. English)

Figure 31. A similar house in Louisiana with an EPS base, floating during a flood event (E. English)

2.2.1.2 Concrete & Polystyrene (EPS) Base

Another design strategy encases EPS in concrete and utilizes both materials to create a floating platform. Floating homes in the Ijburg neighborhood in Amsterdam utilizes this type of base to support two to three floors of livable space [15]. To remain in place, the house is moored to a platform, with each mooring located diagonally across from one another to reduce sway and the effects of waves on the home [15]. This design concept has similarities to the EPS supported homes constructed in Louisiana. Unlike the Louisiana homes however, the Amsterdam units are built to permanently rest in water.

Figure 32. Floating homes in the Ijburg neighborhood of Amsterdam (George Steinmetz)

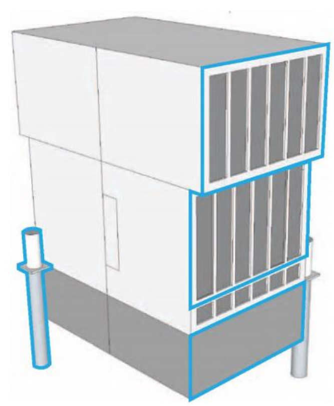

Figure 33. Conceptual illustration of the Ijburg floating homes. The EPS filled base sits beneath the superstructure and is moored to posts that prevent lateral movement (Chelsea Anderson)

2.2.1.3 Hollow Concrete or Steel Hull

Alternatively, strategies exist that exclude the use of EPS. For example, in New Orleans, a home completed in 2008 utilized a hollow steel box that acted as its buoyant base [26]. This base was then attached to wooden posts by a series of steel sleeves. Floating bases made of steel alone are less common but still functional.

Figure 34. New Orleans floating home which sits in a hollow steel box (E. English)

Figure 35. The buoyant steel base is attached to wooden guide posts on its exterior (E. English)

A reinforced concrete hollow box base has also been employed in various situations. Floating Homes Ltd, a UK based company utilizes this method to create their buoyant base. Alongside Baca Architects, they were one of ten winners of the New London Architecture's International Ideas Competition in 2015, proposing floating structures to provide more land space and solve London's housing crisis [27].

Figure 36. Hollow reinforce concrete hull (Floating Homes Ltd)

2.2.1.4 Floating Logs, Barrels, and Other Materials

Finally, additional methods utilize combinations of logs, barrels, and other materials to ensure the home's buoyancy. Logs are typically stacked in groups of inverted triangles beneath the water while additional timber sits on top of them to collect the weight of the above structure [28]. Over time, logs sink as they absorb more water however.

Figure 37. Makoko floating school in Lagos, Nigeria, sits on floating barrels encased in a wooden frame.

Barrels, however, do not absorb additional water, and are arranged in rows beneath the structure encased in frames made from varied materials to create a floating platform. One example of this method is the Makoko floating school, formerly in Lagos, Nigeria. The structure, which unfortunately is no longer standing, was designed to float on blue barrels encased within a wooden frame [18].

Another example of this type of platform is the floating docks created by Rolling Barge. The company creates floating docks out of barrels and an aluminum frame. Figure 38 shows a 40ft by 16ft floating platform created from these materials that can support 38 pounds per square foot while insuring the aluminum frame is kept 2 inches above the water [29].

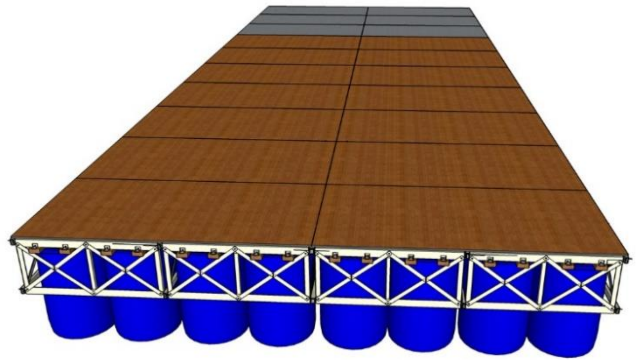

Figure 38. Floating platforms created by Rolling Barge made from barrels held within an aluminum frame (Rolling Barge)

A final example of a floating base built with alternative, affordable materials is the LIFT house in Bangladesh. LIFT is an acronym for Low Income Flood-proof Technology. The home is a low-cost, sustainable amphibious house and is designed for single family dwellings and low-income slum dwellers [26]. The base of the floating structure is comprised of several blocks made from recapped, recycled plastic bottles, encased in bamboo (Figure 39).

Figure 39. Recycled plastic bottles encased in bamboo use as a buoyant base for the LIFT house (E. English)

Chapter 3: Floating Home Design

The floating home concept for coastal homes allows these homes to remain occupiable, functional, stationary and afloat following a 100-year flood event with minor or no damage. A good structural design is a design that is safe, economical, constructible, and functional with minimum maintenance. The selected size of the structural components and the associated details of the structure are selected following the applicable codes and specifications. The floating home design considered in this research is a 900 square foot one-level single family home supported on a hollow reinforced concrete base. The floating base is 9 feet deep, made of lightweight concrete and reinforced steel. The selected depth was based on the anticipated flood level and buoyancy principles. The base is placed in a trench slightly wider than itself so that the home's first floor is at least half a foot above ground level. The wider trench also allows for flood water to get in during a flood event and for drainage following the flood event. The floating base is attached to six (6) external hollow steel guide posts that prevent the structure from moving laterally during a flood event.

The home is connected to the guide posts with connections that can slide up and down the guide posts during flooding, allowing the home to rise with flood levels. The critical components of this system are the floating base, the guide posts, the connections between the steel guide posts and the hollow lightweight concrete base, and the trench surrounding the base. This chapter outlines the design of both the floating base and guide posts to resist high velocity waves and winds, along with high flood levels, typically caused by hurricanes and storm surges. The factors that significantly influence the design of floating home components are noted and discussed in this chapter.

Figures 40 and 41 show the plan and elevation of the floating home respectively. Figure 42 and Figure 43 show the home during dry and flooded scenarios.

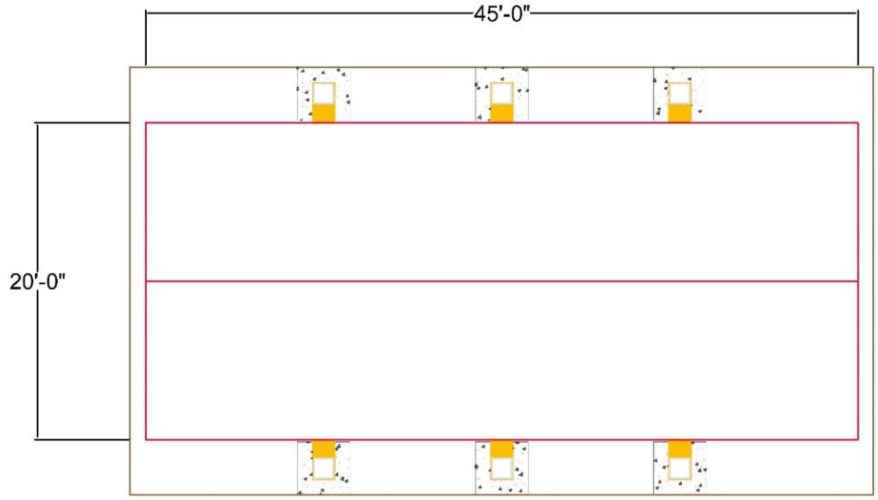

Figure 40. Plan view of the floating home

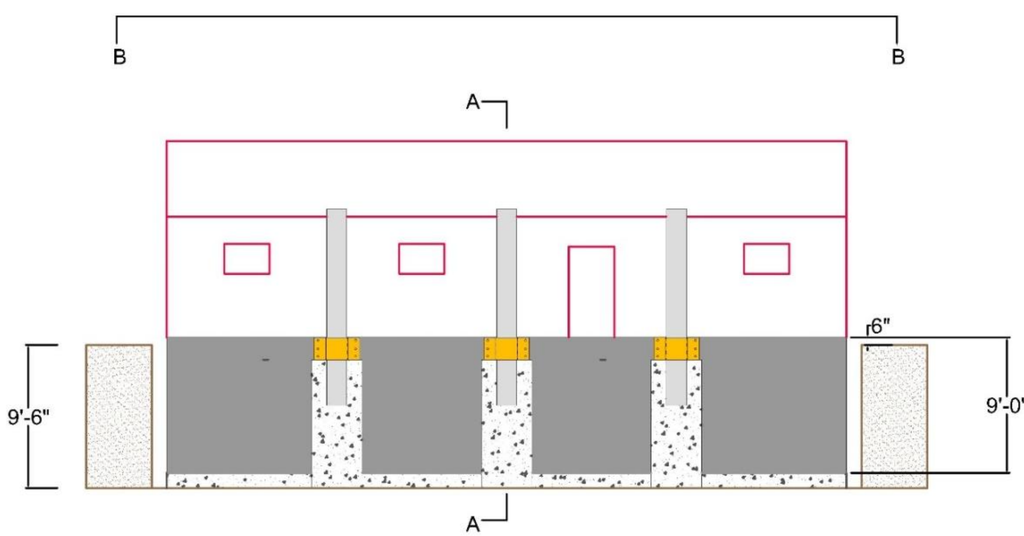

Figure 41. Elevation view of the floating home.

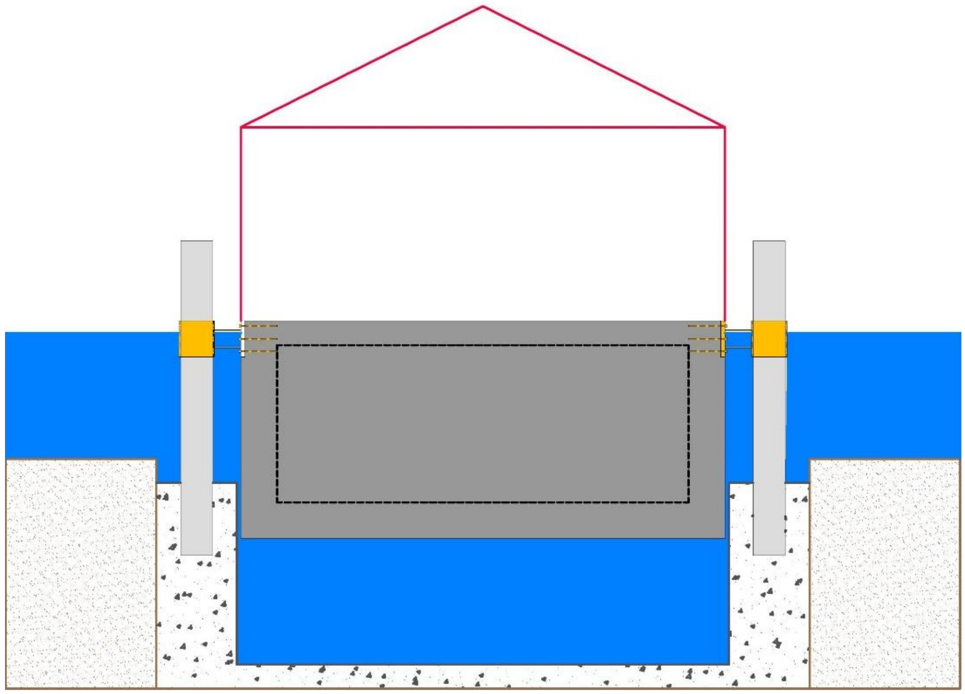

Figure 42. Floating home during flood

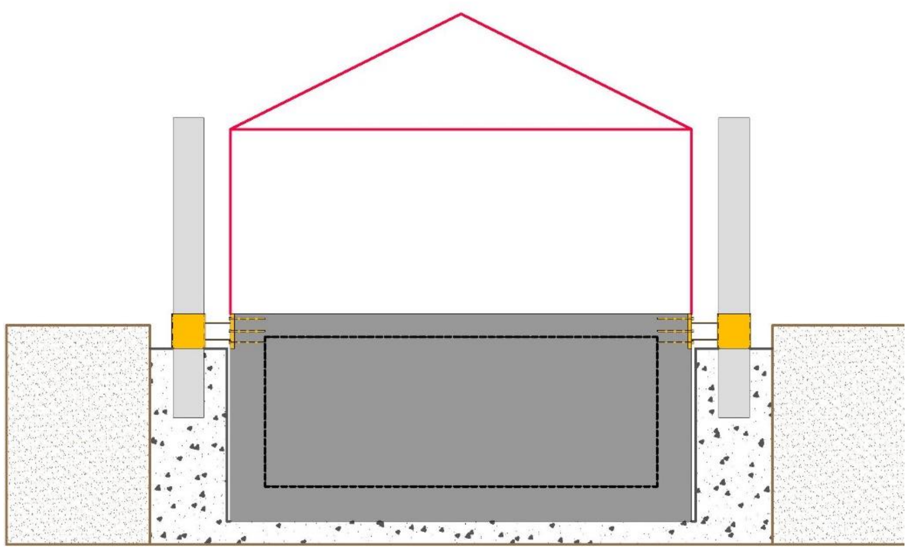

Figure 43. Floating home without flood.

3.1 Floating Base Design

As mentioned previously, floating structures utilize varied materials for their floating bases. These materials include logs, barrels, and concrete among others. This analysis focuses on the design of a hollow reinforced lightweight concrete hull, which acts as the floating base for the structure. The analysis outlines important aspects of how the loads acting on this type of floating base were determined. Then, the key factors found to influence the design process are discussed.

Figure 44. Hollow reinforced concrete floating base. (Floating Homes Ltd)

The floating base is subject to three types of forces during a flood event. These include: 1) the downward forces acting on the structure which include dead loads and live loads. 2) the upward buoyant forces created by the water pressure beneath the floating base, and 3) the lateral loads resulting from flood waters surrounding the home (Figure 45). The methodology for estimating these forces on a structure have been made publicly available by FEMA in their design guides, ‘Engineering Principles and Practices for Retrofitting Flood-Prone Residential Structures’, and ‘Recommended Residential Construction for Coastal Areas’. The methods outlined in these two documents, both of which reference ASCE 7-05’s design standard for flood loads, are used to determine the loads acting on the floating home. Loads obtained in this analysis for the floating base slabs and walls are then applied in the finite element analysis software, SAP2000 to determine internal forces in the slab walls and the top and bottom slab. These loads act per unit length of the floating base, since reinforcement is required to be specified per foot length of all slabs and walls.

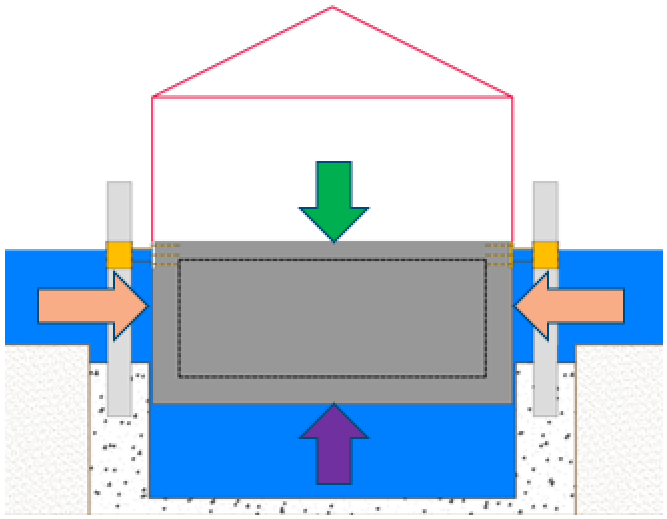

Figure 45. Loads acting on the floating base. Buoyant load (purple), dead and live loads (green), lateral flood loads (pink)

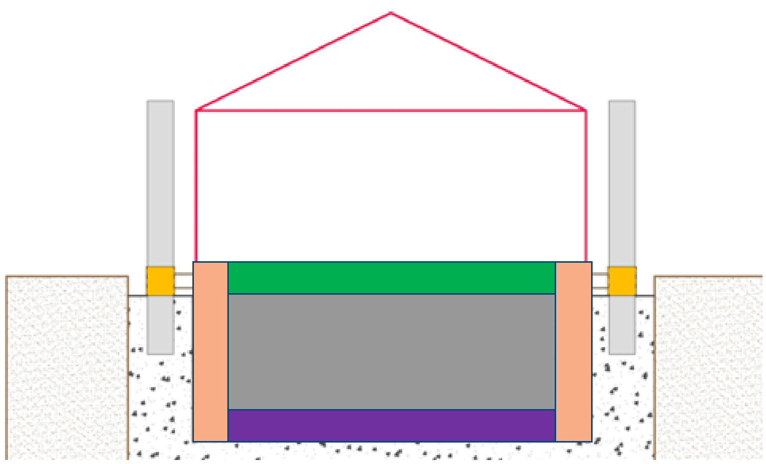

Figure 46. Sections of floating base. Upper Slab (green). Walls (pink). Lower Slab (purple)

3.1.1 Upper Slab Dead and Live Loads

To determine the required minimum longitudinal steel reinforcement per linear foot of the upper slab, the downward dead and live loads were calculated. Dead loads acting on the upper slab include its self-weight, the weight of floor materials, and the weight of the interior structural walls. Live loads include the weight of residents and furniture that will vary throughout the structural life-span. Once all factored loads were considered, the determined downward acting distributed load on the upper slab was 0.231 kip per foot.

Hand calculations were then used to approximate the amount of bending a linear foot length of the upper slab experiences. Initially assuming wall widths of 9 inches, the clear span of the upper slab is 18.5 feet. Therefore, for an 18.5-foot clear span with fixed ends, a 0.231 kip per foot load creates 3.29 kip-feet of bending at midspan and -6.59 kip-feet of bending at the end spans. Although the slab is supported on all sides by base walls, one-way slab behavior was assumed for all calculations as the ratio of slab length to width is greater than two. Since the upper slab moments are affected by other parts of the base, such as its walls due to their monolithic connection, an analysis was conducted in SAP2000 to achieve further accuracy.

3.1.2 Finite Element Analysis of the Upper Slab

The SAP2000 model is a 2-dimensional representation of the loads on a 1-foot length of the floating base. It is composed of a 6.5-foot-tall, 18.5-foot-wide, continuously connected hollow box, with pinned connections at its bottom corners for model stability (Figure 47). To simulate the effects on the upper slab in flooded and dry scenarios, the model was first run without flood loading, and then ran a second time with flood loads. The derivation of flood loading is discussed in later sections. The upper slab experienced a larger midspan moment in the non-flooded case, with 3.83 kip-feet at midspan (Figure 49). The moments at its ends however, were controlled by the flooded scenario, with -5.68 kip-feet (Figure 50). Midspan immediate live load deflections were also calculated by applying the service loads to upper slab modeled in this example. An immediate live load midspan deflection of 0.0026 inches is expected for the 1-foot thick upper slab.

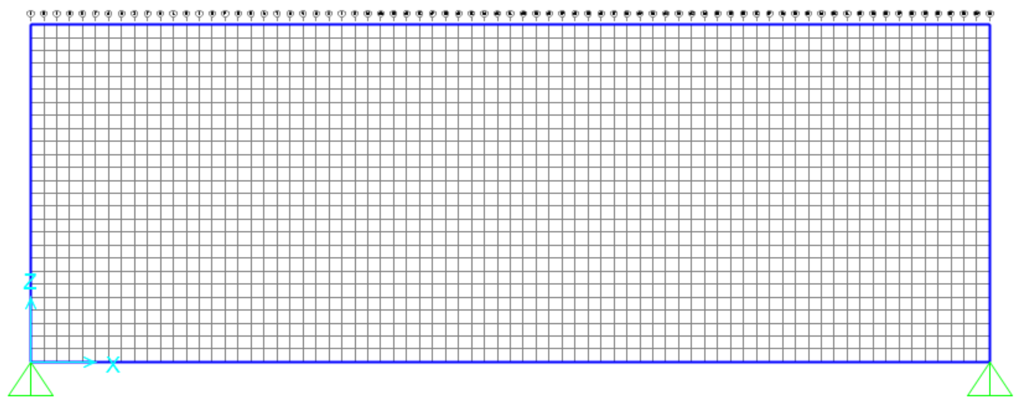

Figure 47. 2-dimensional SAP200 model of a linear foot of the buoyant base. Gridlines are 0.25 ft apart.

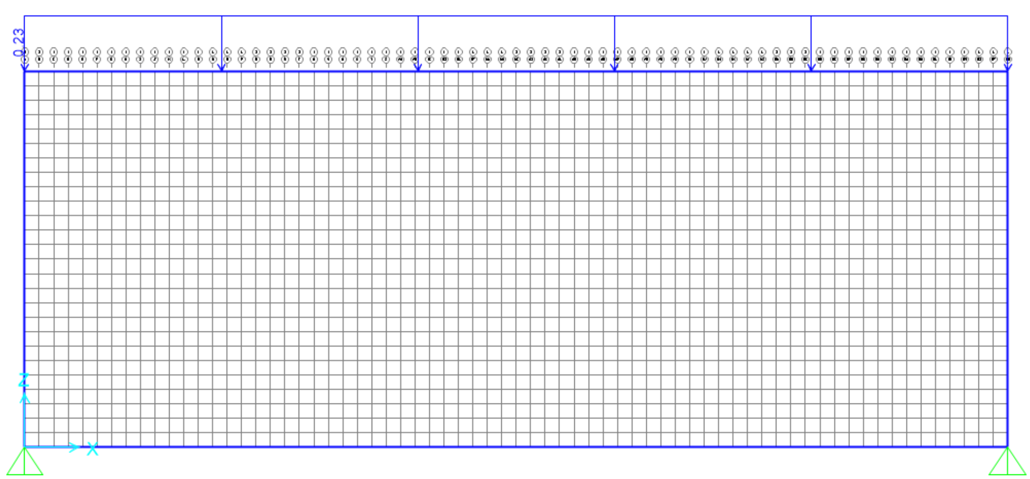

Figure 48. Factored dead and live loads acting on the upper slab

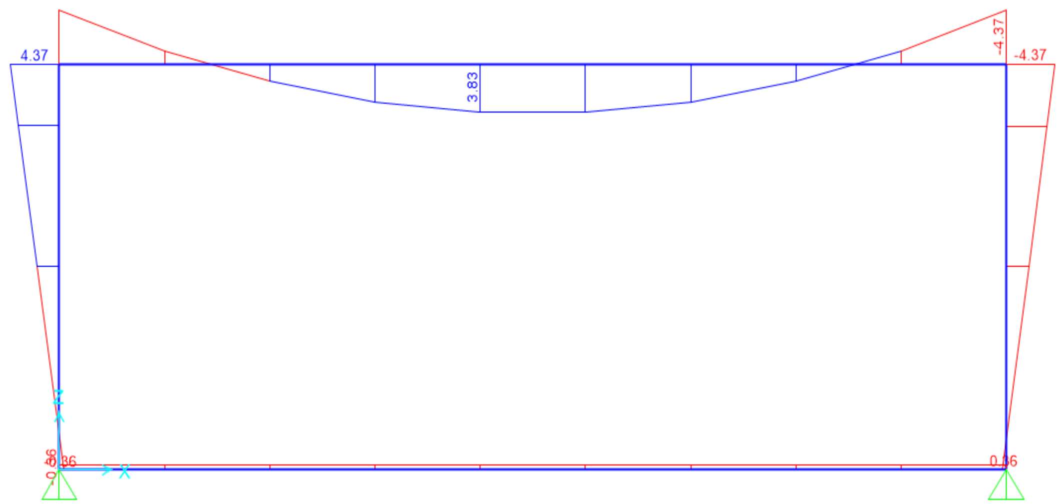

Figure 49. Floating base moment diagram without a flood

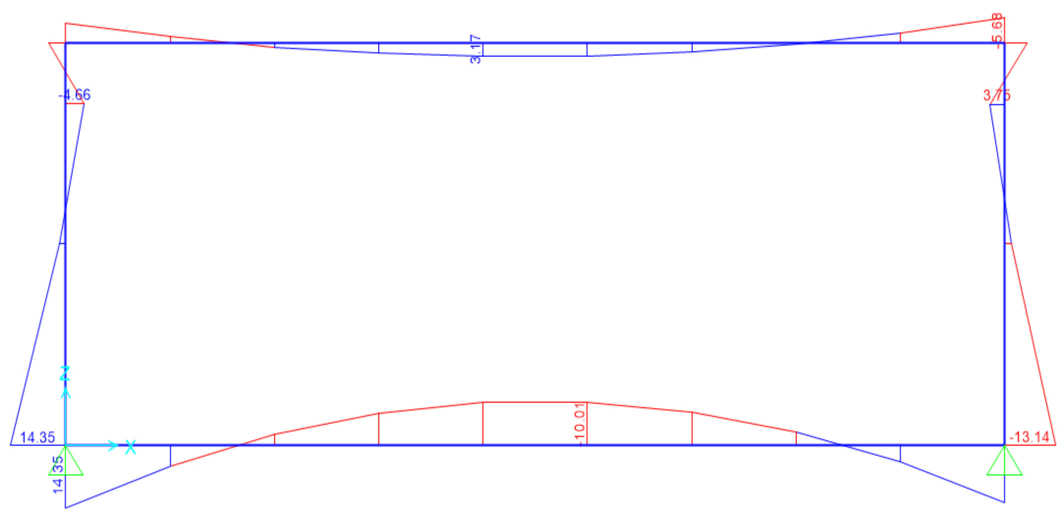

Figure 50. Floating base moment diagram with a flood.

3.1.3 Upper Slab Design

The upper slab design considers the slabs ability to resist expected bending, shear forces and deflections. To resist midspan bending, No. 3 bars are provided every 10 inches along the upper slab length. Negative moments at the end spans are also resist with No. 3 bars every 10 inches. Temperature and shrinkage reinforcement is also included in the form of No. 3 bars spaced every 6 inches in the transverse direction. A summary of the reinforcement in the upper slab is provided in Table 1.

The slab thickness was determined based on minimum thicknesses specified by ACI for one-way non-prestressed slabs, which was $\frac{L}{20}$ [30]. To remain conservative, L was chosen as 20 feet instead of the clear span. Therefore, the upper slab has a thickness of 1 foot. This 1-foot thickness was easily resistant to expected shear loads on the slab. It's expected live load deflection was also minimal, as it was 0.0026 inches, which is much less than ACI's specified $\frac{L}{360}$ immediate live load deflection limit. Figure 51is a detail of the reinforcement for a section of the upper slab.

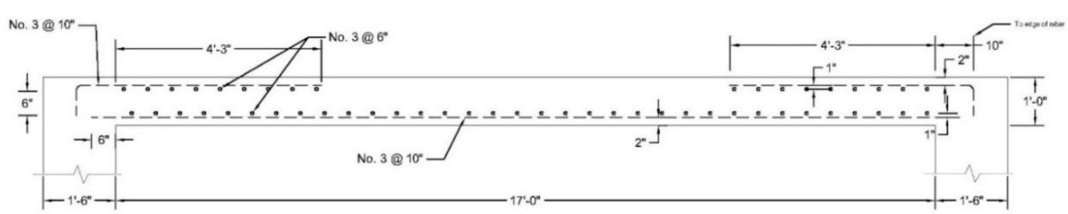

Figure 51. Upper Slab reinforcement detail

Table 1. Upper slab reinforcement

Upper Slab	
$Midspan\ Moment$	$3.30\ kft$
$Midspan\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.077\ in^2$ $Provided: No. 3\ @\ 10\ inches$
$End\ Moment$	$-5.83\ kft$
$End\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.114\ in^2$ $Provided: No. 3\ @\ 10\ inches$
$Temperature\ \&\ Shrinkage\ Reinforcement$	$Required = 0.22\ in^2$ $Provided: No. 3\ @\ 6\ inches$

3.1.4 Lower Slab Buoyancy Loads

Following the design of the upper slab, the buoyant load acting directly on the lower slab during a flood event was determined. The buoyant load exists due to Archimedes' principle, which states that the upward force acting on a body submerged in water is equal to the weight of water displaced by the body [31]. The buoyant force is the primary load considered in the design of the lower slab. The floating home rises when the buoyant force is greater than the sum of all downward acting loads during a flood event. Ultimately, the factored buoyant distributed load on the lower slab was 0.664 kip per foot, acting upward on the lower slab surface.

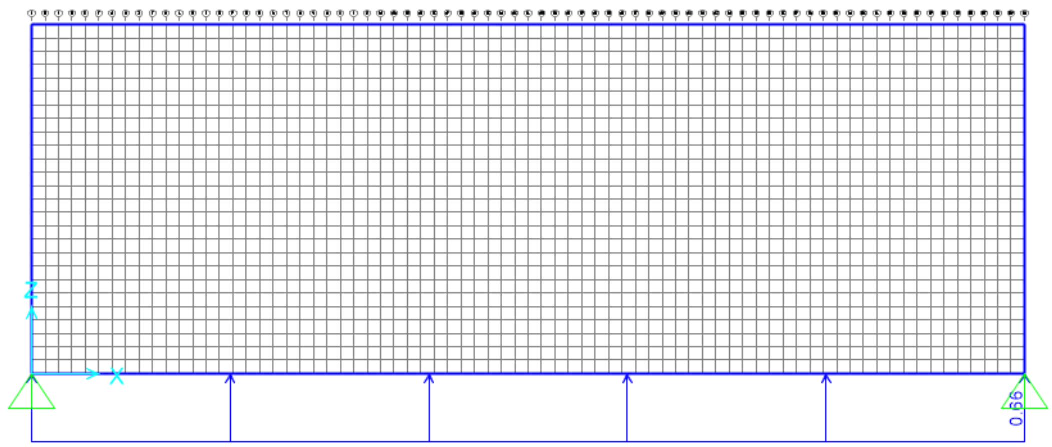

Figure 52. Factored buoyant load acting on the lower slab.

3.1.5 Finite Element Analysis of Lower Slab

The SAP model demonstrates that during a flood event, the lower slab will be subject to a maximum midspan bending moment of -10.01 kip-foot, while the maximum bending moment experienced at its end spans is 14.35 kip-foot (Figure 53). Like the upper slab, the shear loads on the lower slab were observed before determining appropriate base and slab dimensions and properties. The lower slab was subject to maximum shear force of 5.72 kips (Figure 54). Although the lower slab is not considered livable space, deflections of the lower slab were checked. It's the maximum expected midspan deflection due to the unfactored buoyant load was 0.01 inches.

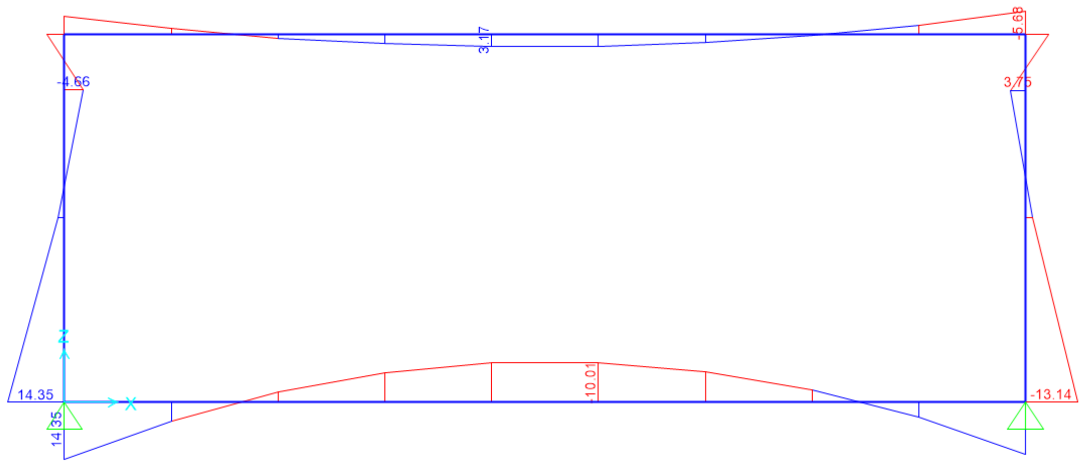

Figure 53. Moments on the floating base during a flood event. The moments on the lower slab indicates upward bending in the lower slab.

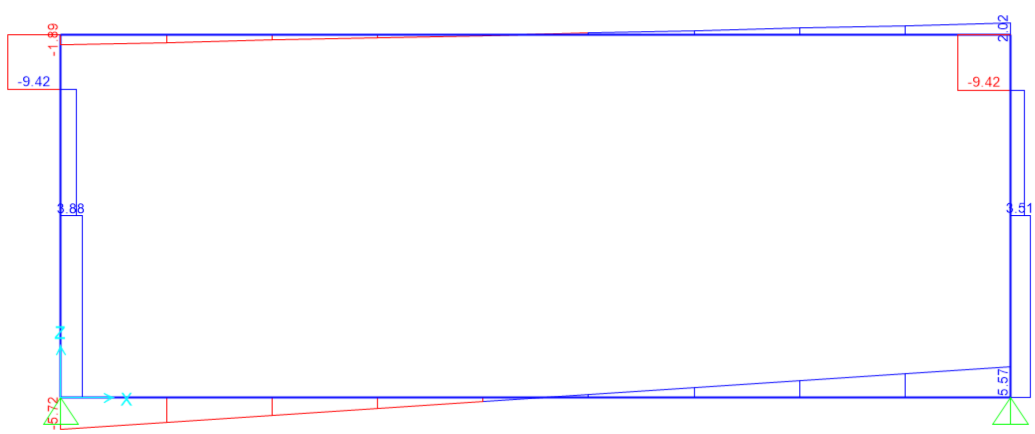

Figure 54. Shear forces on the floating base during a flood event. The lower slab is subject to a maximum shear force of 5.72 kips.

3.1.6 Lower Slab Design

To resist negative midspan bending moments, No. 3 bars every 6 inches are provided along the lower slab length. The maximum end span moment of 14.35 kip-foot is also resisted by No. 3 bars spaced 6 inches apart. Temperature and shrinkage reinforcement is provided by No. 3 bars spaced 4 inches apart in the transverse direction. The lower slab is 1.5 feet thick which can be observed in Figure 55.

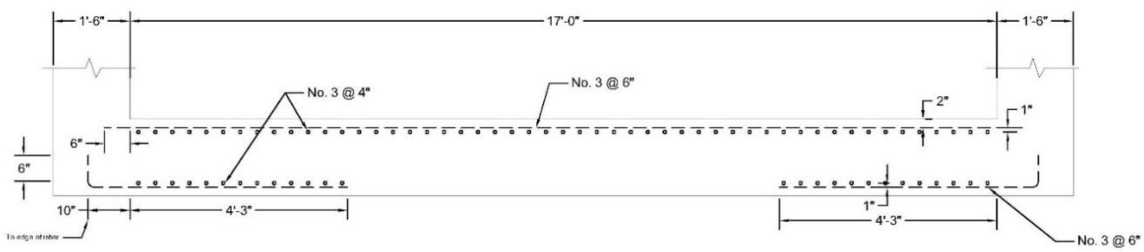

Figure 55. Detail of lower slab reinforcement in the floating base

Table 2. Lower slab reinforcement

Lower Slab	
$Midspan\ Moment$	$-10.01\ kft$
$Midspan\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.13\ in^2$ $Provided: No.3\ @\ 6\ inches$
$End\ Moment$	$14.35\ kft$
$End\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.31\ in^2$ $Provided: No.3\ @\ 6\ inches$
$Temperature\ \&\ Shrinkage\ Reinforcemet$	$Required = 0.33\ in^2$ $Provided: No.3\ @\ 4\ inches$

3.1.7 Lateral Loads on Base Walls

Following the design of the upper and lower slabs, the floating base walls were designed. Using FEMA specifications for the design of foundation walls, three types of flood loads were simultaneously applied. These loads included the hydrodynamic load, the debris impact load, and the breaking wave load. Before these loads were computed, certain assumptions were made and are listed below.

- An impact load will not act on more than one base wall at once. Therefore, in the SAP model, the debris impact force is applied the left wall, with the knowledge that all other walls will be designed for the maximum experienced wall load.

- The shorter walls, not pictured in the SAP 2-dimensional model, will be sufficiently reinforced by the same size and length of reinforcement provided for the longer walls, as they are subject to lesser loads due to their size.

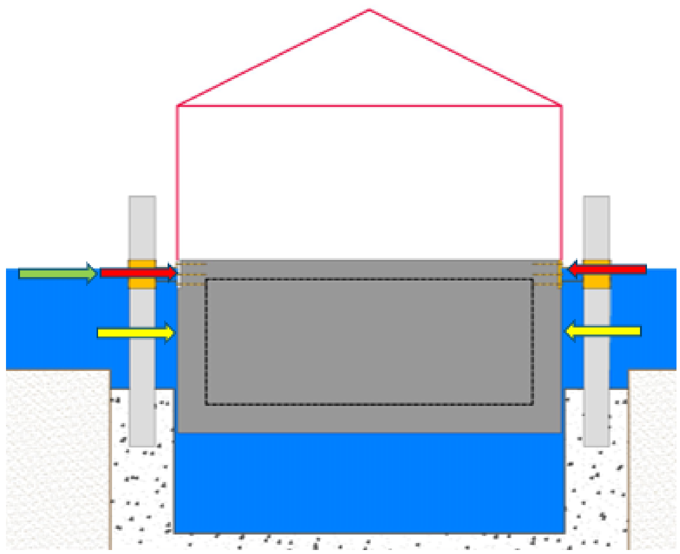

Figure 56. Point of application of the lateral flood loads. Breaking wave load (red), debris impact (green), hydrodynamic load (yellow)

3.1.8 Finite Element Analysis of Base Walls

The final finite element analysis examined the effects of the flood loads on the floating base walls. A hydrodynamic load of 0.54 kips was applied as a point load in the SAP2000 model, acting at the base mid-height on both base walls. Then the tabulated breaking wave load of 5.9 kips was applied 1-foot below the elevation of the upper slab on both walls. Finally, a debris impact load of 0.19 kips for a hypothetical 1000-pound floating object was applied at the same elevation as the breaking wave load, but only on the left wall of the SAP model. The derivations of each of these loads can be found in Appendix A.

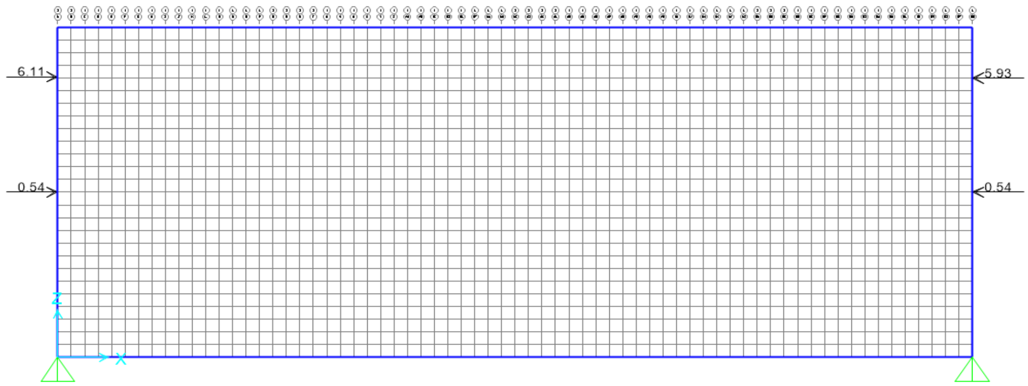

Figure 57. Flood load resultants acting on the buoyant base walls

Moments and shears in both walls were noted after the application of these flood loads. The left wall experienced the largest bending moment of 14.35 kips per foot length of the wall (Figure 58). The lateral flood loads also introduced large shear forces on the sides of the buoyant base. The maximum shear force experienced due to the factored flood loading was 9.42 kips (Figure 59).

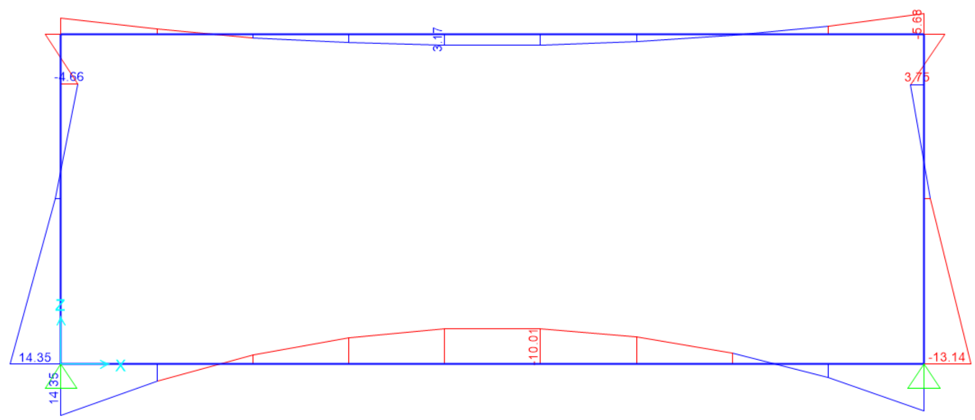

Figure 58. Bending moments in the floating base. The maximum bending moment in the floating base is 14.35 kft

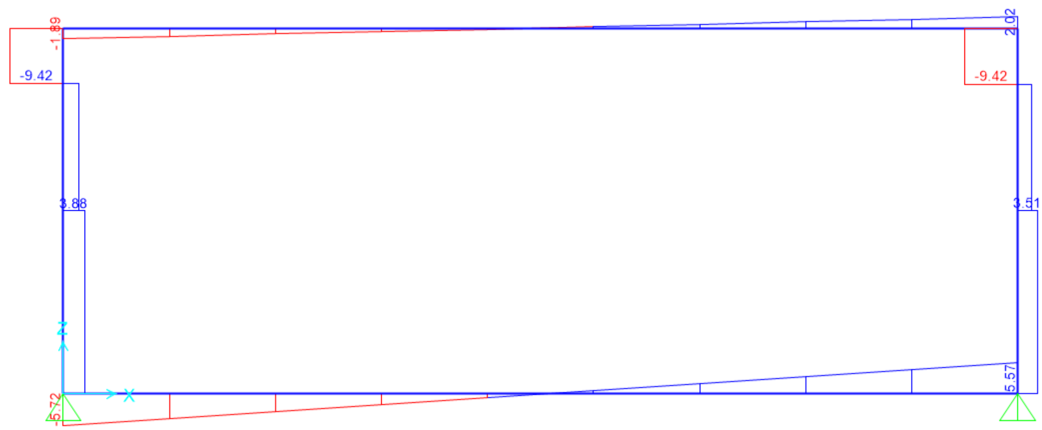

Figure 59. Shear diagram of floating base. The maximum shear in the base walls is 9.42 kips

3.1.9 Design of Base Walls

As mentioned above, the reinforcement and thickness of all walls will match the design of the wall with the largest experienced shear and moment forces in the SAP model. The left wall was subject to the largest bending moment, due to the debris impact load being applied. Therefore, all walls in the floating base will be designed to resist the moments and shears experienced by the left base wall. To resist the 14.35 kip-foot moment experienced on the wall, No. 3 bars every 6 inches will be provided to resist positive and negative bending of the base walls. Although the largest shear force in the base wall is 9.72 kips, the base walls will be 1.5 feet thick to allow for sufficient embedment length for the anchor rods that attach the floating base to the guide posts.

Table 3. Reinforcement for floating base walls

$\boldsymbol{Walls}$	
$Maximum\ Moment$	$14.35\ kft$
$Positive\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.193\ in^2$ $Provided: No. 3\ @\ 6\ inches$
$Negative\ Reinforcement$	$Required\ Bending\ Reinforcement = 0.193\ in^2$ $Provided: No. 3\ @\ 6\ inches$
$Temperature\ a\&\ Shrinkage\ Reinforcement$	$Required = 0.33\ in^2$ $Provided: No. 3\ @\ 4\ inches$

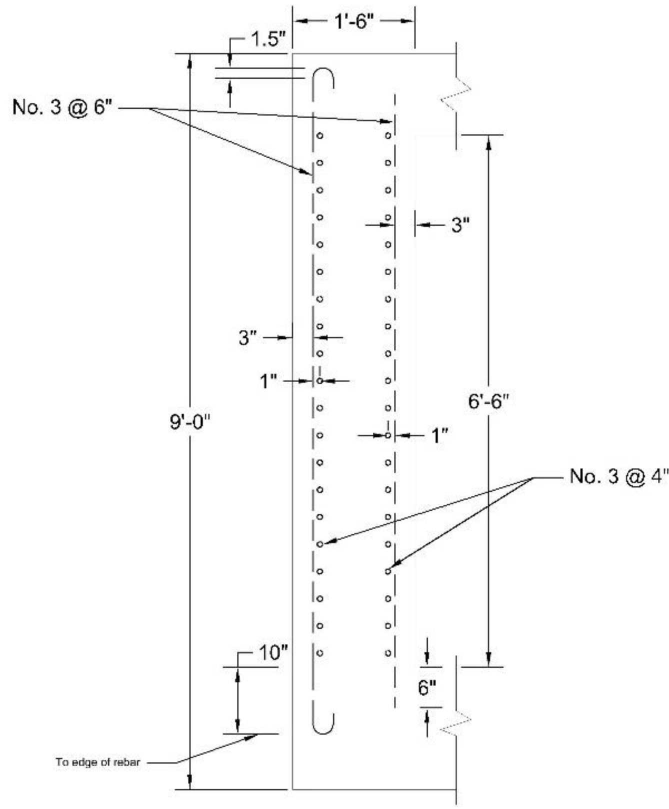

Figure 60. Floating base wall reinforcement detail

3.2 Governing Factors for Floating Base Design

After determining the necessary reinforcement for all sections of the floating base, it was evident that specific factors influence the design more than others. Knowledge of these issues before undergoing a design can ultimately save time and money when considering the practicality of implementing a floating structure. The factors discussed below are noted as items for designers to keep specifically when designing the floating base.

3.2.1 Weight of Home

The weight of the home is one of the most important items to consider when designing the floating base. It directly affects the required dimensions and reinforcement of the upper and lower slabs. Loads on the upper slab, such as the interior walls and floor materials, affect the slab thickness and reinforcement necessary to support the livable space within the structure, while all the loads affect the ultimate buoyant load acting on the lower slab.

Apart from its influence on these two parts of the base, the structural weight also affects the required base depth to achieve buoyancy. As previously mentioned, the floating home functions based on the Archimedes principle. Therefore, the floating home will only float when the weight of the displaced water is greater than the total weight of the house. As a result, the depth of the base, and the trench it sits in, should be deep enough to account for this.

The trench only needs to be slightly larger in size than the floating base because buoyancy is easily achieved once waters rise above the trench depth. At this point, flood waters will be dispersed far enough to where a minimal change in flood height will be equivalent to a substantial change in surrounding water volume. In other words, once waters rise above the trench, the weight of displaced water necessary to achieve buoyancy will be easily reached.

Due to these direct effects of the overall home weight on the floating base, special attention should be paid to its building materials, number of stories, and the overall square footage of the home. Family size, location and other factors play a role in determining these variables. In the example studied in this thesis, 8.5-foot flood level was sufficient to create buoyancy, but this minimum required flood level could quickly change given a heavier structure.

3.2.2 Expected Flood Level

In addition to structural weight, the expected flood levels in a region affects the ultimate depth of a floating base. Figure 61 shows the flood level required to lift homes of different structural weight. The chart demonstrates how the required flood level changes if additional stories are added to the home discussed in this thesis. For example, a home of identical building footprint and material composition with an additional story would require at least 8.75 feet of water to surround the floating base to achieve buoyancy.

From a design perspective, it would be more practical to build a deep base in a region that expects a greater amount of water. Regions with a lower likelihood of exposure to high floods, have less water available to create the buoyancy necessary to support a heavy structure (i.e. structures with deep floating bases). A heavy home with too deep of a base will not float during a minor flood event. However, if the home is much lighter, it will be able to achieve the necessary buoyancy in the water levels it is subject to. Therefore, in the United States for example, designers should pay close attention to a region's base flood elevation which could be used to guide expectations on flood levels.

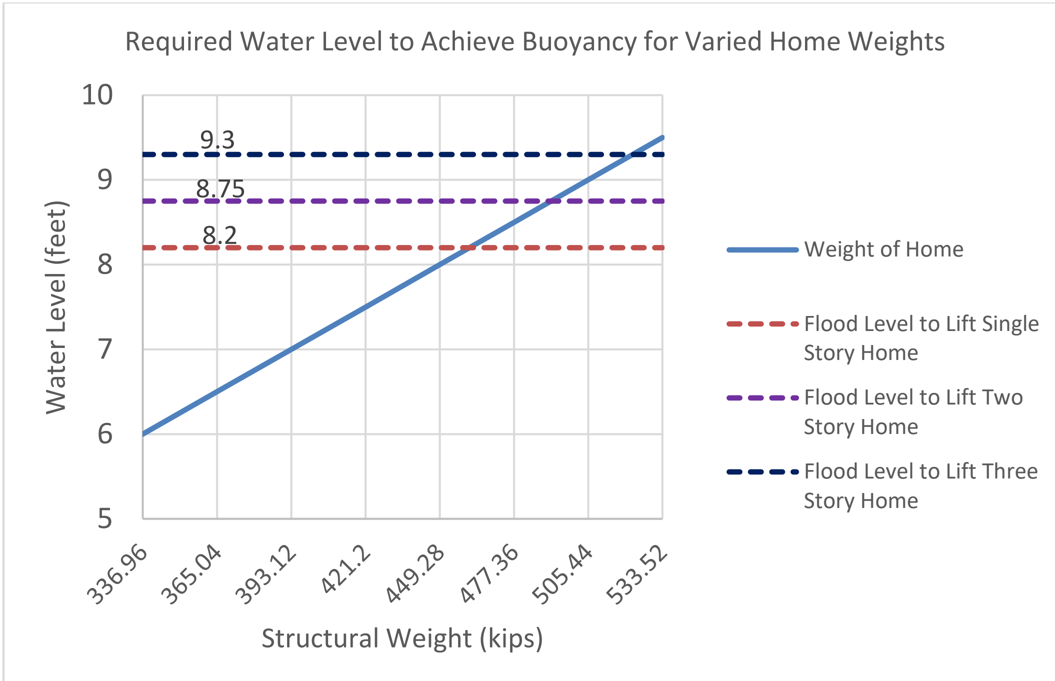

Figure 61. Required Water Level to Achieve Buoyancy for Homes of Varied Weights

3.2.3 Floating Base Shell Thickness

A third factor that had a major effect on the design process was the floating base wall and slab thicknesses. Multiple iterations of the design had to be performed due to necessary changes in the thickness of the floating base walls. These changes had to be made for numerous reasons. For example, initially, the walls were assumed to be 9 inches thick, but when the shear due to the lateral flood loads were calculated, it was determined that the base walls needed to be thicker. Therefore, they increased to a thickness of 18 inches. This increase in wall thickness increased the self-weight of the base, thereby increasing the buoyant force necessary to lift the structure. Subsequently, the greater buoyant force required additional reinforcement to resist lower slab bending. Therefore, designers and engineers should consider that any changes in size of components of the base will increase the structural load, thereby increasing the level of water necessary to achieve buoyancy. From this perspective, the design of the base is very much a cyclical or iterative process.

3.3 Guide Post Design

The guide posts connected to the floating base are another critical component of the floating home system. These posts restrict the structure's lateral movement during a storm surge, protecting other structures in its vicinity from collision damage. These posts are similar to piles seen under elevated homes in coastal communities and can be made from varied materials, such as wood, reinforced concrete, masonry, or steel. However, unlike piles, the posts of the floating home are not subject to axial compression, and only resist lateral loads. Sleeve connections connected to the floating base allow this to be possible.

The example explored in this thesis utilizes 6 guide posts placed around the structure's edge to resist lateral wind and flood loads that act upon the structure. Flood loads acting both on the floating base walls and on the posts directly were determined using formulation specified in FEMA's 'Recommended Residential Construction for Coastal Areas' and resulting moments from the worst-case load scenario were calculated. Once the moments due to flooding and wind were combined, an appropriate square hollow steel section was selected to resist the maximum factored moments.

3.3.1 Wind Loads on Guide Posts

Wind loads on the house in the example are calculated using formulation provided in ASCE 7-10. The house is located on the New Jersey coast, which has a design wind speed of 130 mph. Its risk category and other important parameters were determined by taking into consideration its expected occupancy and the potential landscape surrounding the structure. Then the velocity pressures on the house due to wind was determined for two heights; at the mid-height of the of the exterior walls, and at the mid-height of the roof. Three wind cases were examined, each pictured below.

1. 100% of the wind load in the x-direction
2. 100% of the wind load in the y-direction
3. 75% of the loads applied in case 1 and 2, applied simultaneously.

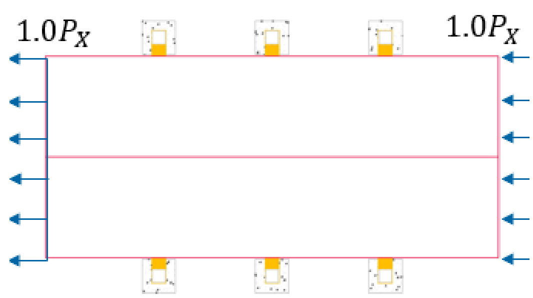

Figure 62. 100% wind load in X-direction

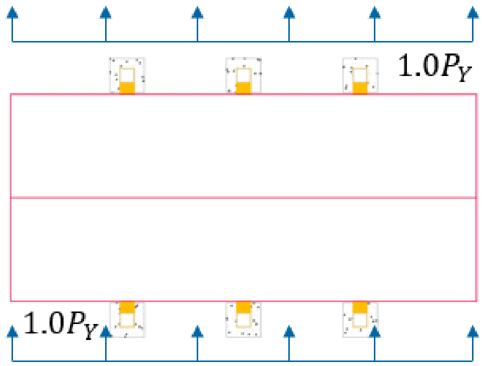

Figure 63. 100% wind load in Y-direction

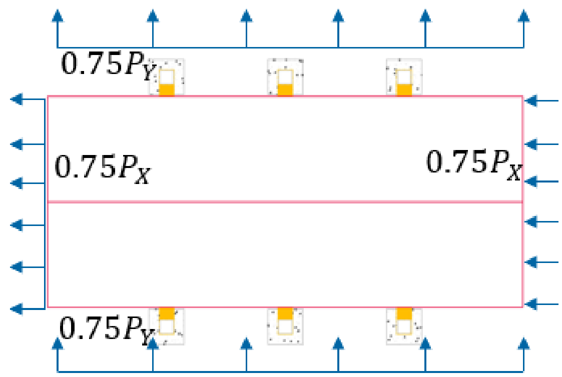

Figure 64. 75% wind load in X & Y direction

Load case two produced the largest wind load per guide post of 3.1 kips, acting in the y-direction across the home's plan. This resultant lateral force of the wind load acts on each guide post at the design still water elevation of 5.2 feet above ground level. Thus, the moment on an individual guide post due to wind is 27.9 kip-foot, for a home floating at the base flood elevation.

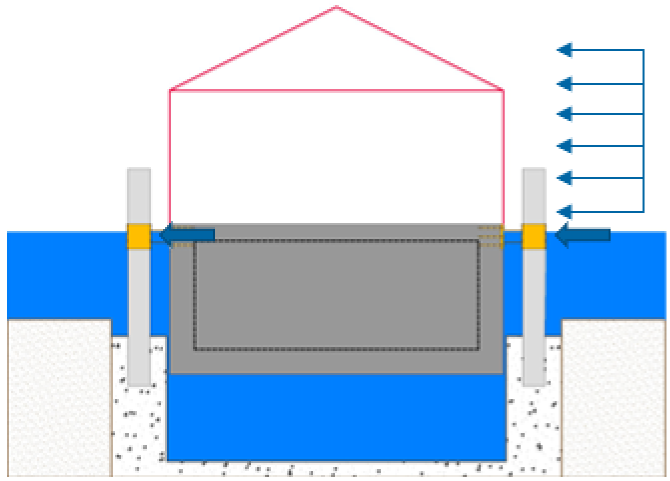

Figure 65. Resultant point of application of the wind loads

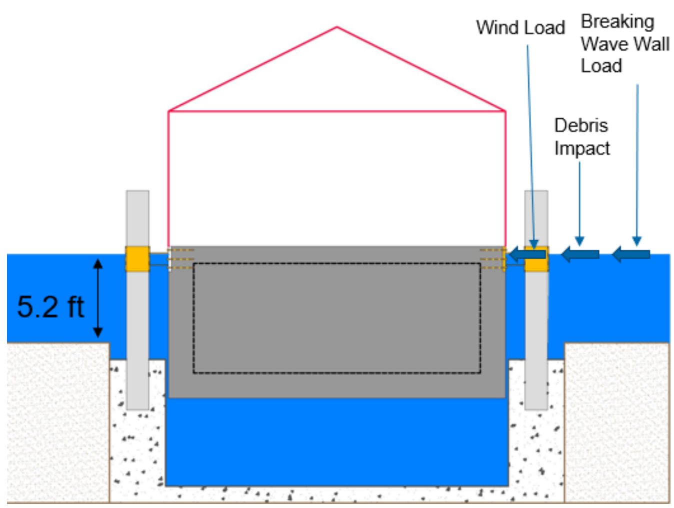

Figure 66. Lateral loads act at the design still water flood depth of 5.2 feet

3.3.2 Flood Loads on Guide Posts

Flood loads are developed using methodology outlined by FEMA in their 2009 publication, 'Recommended Residential Construction for Coastal Areas'. Its third chapter focuses on coastal foundation design and outlines how to calculate various flood loads for pile and wall foundations [32]. Since the floating base walls and guide posts are subject to lateral flood loads simultaneously, both components are examined. One case studies the effect of flood loads that hit the posts directly. The other case examines flood loads transferred from water hitting the floating base walls to the posts. Ultimately, the worst-case resulting loads from each scenario are used for the final design of the guide posts.

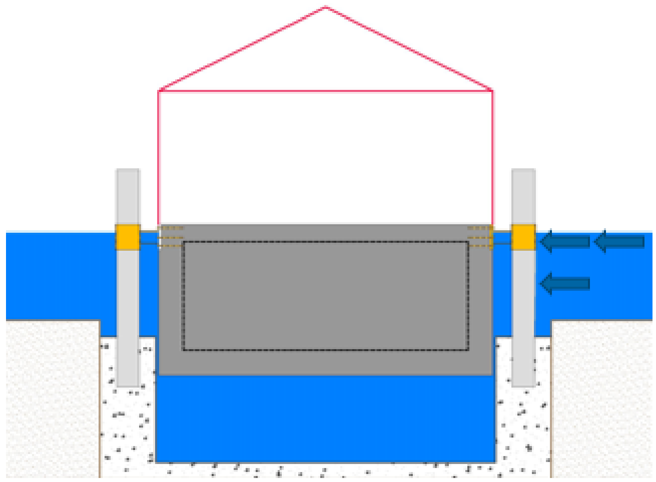

Figure 67. Flood loads directly striking the guide posts.

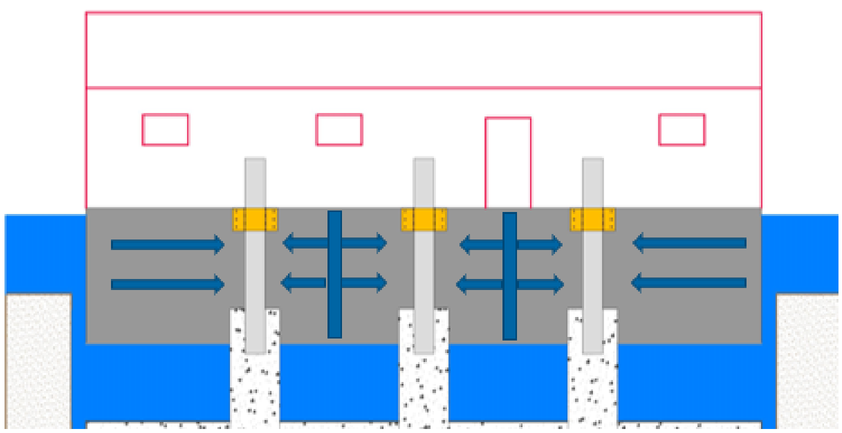

Figure 68. Flood loads striking the floating base being transferred to the guide posts.

3.3.2.1 Direct Post Loads

In the first case, flood waters hit the guide posts directly. Before magnitudes are determined however, it is important to estimate reasonable values for various parameters that would be unique to each house in practice, based on their location. These parameters include:

- The design still-water depth (d_s), given by $d_s = 0.65(BFE - G)$, where BFE is the base flood Elevation of the area and G is the ground elevation [33].
- The design wave height (H_b), given by $H_b = 0.78(d_s)$ [32].
- The design flood velocity (V), which is calculated as an upper-bound to remain conservative, with $= (gd_s)^{0.5}$, where g is acceleration due to gravity [32].

Assuming a 5-foot ground elevation, and a 13-foot base flood elevation, each parameter is calculated as follows:

$$d_s = 0.65(BFE - G) = 0.65(13\,ft - 5\,ft) = 5.2\,ft$$

$$H_b = 0.78(d_s) = 0.78(5.2\,ft) = 4.1\,ft$$

$$V = (gd_s)^{0.5} = \left[\left(32.2\frac{ft}{s^2}\right)(5.2\,ft)\right]^{0.5} = 12.9\frac{ft}{s}$$

Once these values are determined, it is possible to estimate the magnitude of all relevant flood loads, as each depends on the parameters previously mentioned. These loads and their determined magnitudes are listed below in Table 4. Direct flood loads on an individual guide post, along with the formulas they are derived from.

Table 4. Direct flood loads on an individual guide post

Load	Formula	Magnitude per Post
Hydrodynamic Load	$F_{dyn} = \frac{\frac{1}{2} C_d \rho V^2 A}{(R)(6)}$	$0.23\ kips$
Breaking Wave Load on Pile	$F_{brkp} = \frac{\frac{1}{2} \gamma_w C_d D H_b^2}{(R)(6)}$	$0.1\ kips$
Debris Impact Load	$F_i = \frac{\pi W V}{2 g t_i (R)(6)}$	$1.4\ kips$

<u>**Notes**</u>

R - Reduction Factor

Hydrodynamic Load

- Acts at the still water mid-depth
- C_d - drag coefficient
- A - area the load will act upon
- ρ - Mass density of fluid ($1.99 \frac{slugs}{ft^3}$ for saltwater)

Breaking Wave Load

- Acts at the still water flood level
- D - width of the pile or column

Debris Impact Load

- Acts at still water flood level
- W - weight of the debris
- t_i - duration of impact

3.3.2.2 Post Loads Transferred from Floating Base Walls

In the second case, flood loads hit the floating base walls before being transferred to the guide posts. Flood loads that act directly on the floating base walls were discussed during the floating base design. These include the hydrodynamic load, the debris impact load, and the breaking wave wall load. Assuming the home is buoyant and floating at the design still water flood level, the resultant lateral loads on the base wall from all flood loads are determined. Like the previous scenario, the hydrodynamic load acts at the still water mid-depth, while the debris impact and resultant breaking wave load acts at the still water flood level. Once the magnitude of each load is determined for the exposed base wall surface, the lateral force is distributed equally among all guide posts, with each load still acting at their designated heights.

Table 5. Transferred flood loads from floating base walls

Load	Formula	Magnitude per Post
Hydrodynamic Load	$F_{dyn} = \dfrac{\frac{1}{2} C_d \rho V^2 A}{(R)(6)}$	$4.1\ kips$
Breaking Wave Load on Wall	$F_{brkw} = \dfrac{1.1 Cp \gamma_w d_s^2 + 2.4 \gamma_w d_s^2}{(R)(6)}$	$44.5\ kips$
Debris Impact Load	$F_i = \dfrac{\pi W V}{2 g t_i (R)(6)}$	$1.4\ kips$

Notes

R - Reduction Factor

Hydrodynamic Load

- Acts at the still water mid-depth
- C_d - drag coefficient
- A - area the load will act upon
- ρ - Mass density of fluid (1.99 $\frac{slugs}{ft^3}$ for saltwater)

Breaking Wave Load on Wall

- Acts at the still water flood level
- γ_w- density of salt water
- Cp = Dynamic pressure coefficient

Debris Impact Load

- Acts at still water flood level
- W - weight of the debris
- t_i - duration of impact

3.3.2.3 Lateral Load Reduction

The initial design of the floating home utilized an elastic design process, which required 12 guide posts to resist expected lateral loads. The elastic design concept presumes the guide posts will undergo no permanent deformation during the flood event. This option however, was not aesthetically pleasing, as it left the home surrounded by too many posts and was more expensive. Therefore, an inelastic design approach was used for the guide posts.

Figure 69. Elevation view of initial design concept (elastic design).

Figure 70. Plan view of initial design concept (elastic design)

The 6 smaller guide posts are expected to undergo some permanent deformation during the 100-year flood event, but not enough to cause collapse. These deformations can be repaired following the flood event if need be. This reduction in lateral load is specified by the R factor in the equations in Table 4 and Table 5. R is selected based on reduction factors used in seismic design. Steel special cantilever column systems like the ones used in the floating home design have an R factor (Response Modification Coefficient) of 2.5 according to Table 12.4 in ASCE 7-10 [33]. This reduction factor was also applied in the previous wind design to reduce lateral wind loads.

Table 6. Response modification factors for lateral seismic loads in ASCE 7-10

ASCE 7-10

Table 12.2-1 *(Continued)*

Seismic Force-Resisting System	ASCE 7 Section Where Detailing Requirements Are Specified	Response Modification Coefficient, R^a	Overstrength Factor, Ω_0^g	Deflection Amplification Factor, C_d^b	Structural System Limitations Including Structural Height, h_n (ft) Limits[c] — Seismic Design Category: B	C	D^d	E^d	F^e
G. CANTILEVERED COLUMN SYSTEMS DETAILED TO CONFORM TO THE REQUIREMENTS FOR:	12.2.5.2								
1. Steel special cantilever column systems	14.1	2½	1¼	2½	35	35	35	35	35
2. Steel ordinary cantilever column systems	14.1	1¼	1¼	1¼	35	35	NP[i]	NP[i]	NP[i]
3. Special reinforced concrete moment frames[n]	12.2.5.5 and 14.2	2½	1¼	2½	35	35	35	35	35
4. Intermediate reinforced concrete moment frames	14.2	1½	1¼	1½	35	35	NP	NP	NP
5. Ordinary reinforced concrete moment frames	14.2	1	1¼	1	35	NP	NP	NP	NP

3.3.2.4 Resultant Moments

After reducing the expected lateral loads, resultant moments due to each case are determined for the lateral flood loads that affect the floating base. These flood loads include the hydrodynamic load, the debris impact load, and the breaking wave load. These moments are then used to design the guide posts guided by FEMA specificities. The moments used to design guide posts are the breaking wave wall load and a debris impact load. The moment a post experiences due to a breaking wave acting on the floating base's longest wall is 400.5 kip-foot, while a debris impact load striking a post directly produces a moment of 12.6 kip-foot.

Table 7. Moments acting on individual guide posts due to various flood loads.

	$M_{F_{dyn}}$	M_{F_i}	$M_{F_{brkw}}$ or $M_{F_{bkrp}}$
Transferred Flood Load from Base Wall	19.2 kft	12.6 kft	400.5 kft
Direct Flood Load on Guide Posts	1.1 kft	12.6 kft	0.9 kft

3.3.3 Guide Posts: Design

3.3.3.1 Load Combinations

After determining the expected wind and flood loading, appropriate factored load combinations are selected to design all guide posts. Structures in coastal A or V zones are required to follow specific load combinations for strength design [32]. These are taken as the greater of the two combinations presented below.

1. $1.2D + 1.0W + 2.0F_a + L + 0.5(L_r \text{ or } S \text{ or } R)$
2. $0.9D + 1.0W + 2.0F_r + 1.6H$

$$D = dead\ load$$

$$W = wind\ load$$

$$E = earthquake\ load$$

$$F_a = flood\ load$$

$$F = load\ due\ to\ fluids\ with\ well - defined\ pressures\ and\ maximum\ heights$$

$$L = live\ load$$

$$L_r = roof\ live\ load$$

$$S = snow\ load$$

$$R = rain\ load$$

$$H = lateral\ earth\ pressure$$

Since the only loads considered in the design of the guide posts are the lateral wind and flood loads, these combinations are reduced to two loads.

$$1.0W + 2.0F_a$$

Furthermore, additional specifications exist regarding which flood loads are most practical to apply for foundation design, since all flood loads do not occur simultaneously. For example, it is unlikely a breaking wave load will affect all guide posts the same time as an impact load. As a result, FEMA, in the Coastal Construction Manual recommends certain piles or posts be checked for specific groups of flood loads. These groups for these checks are specified below in Table 8. The first option of Case 1 is selected for the lateral flood load combination because it suggests applying the breaking wave load to all piles. Therefore, the transferred breaking wave load from the wall as well as the debris impact load was applied to each guide post

Table 8. FEMA guidelines for flood load combinations of select piles

Case 1	**Pile or Open Foundation in V Zone (Required)**
1. Fbrkp (on all piles) + Fi (on one corner or critical pile only) or 2. Fbrkp (on front row of piles only) + Fdyn (on all piles but front row) +Fi (on one corner or critical pile only)	
Case 2	**Pile or Open Foundation in Coastal A Zone (Recommended)**
1. Fbrkp (on all piles) + Fi (on one corner or critical pile only) or 2. Fbrkp (on front row of piles only) + Fdyn (on all piles but front row) +Fi (on one corner or critical pile only)	
Case 3	**Solid (Wall) Foundation in Coastal A Zone (NOT Recommended)**
Fbrkp (on walls facing shoreline, including hydrostatic component) + Fdyn; assume one corner is destroyed by debris, and design in redundancy	
Case 4	**Solid (Wall) Foundation in Non-Coastal A Zone (Shown for Comparison)**
Fsta + Fdyn	

FEMA recommends that piles coastal A zones are checked for a combination of either breaking wave and impact loads, or a combination of the breaking wave, hydrodynamic and impact loads. These flood combinations are mandatory in V zones. Additionally, load checks are suggested at specific locations, such as the impact loads at corner piles for example. FEMA recommends the breaking wave pile load be checked together with the impact load as a first option in Case 1 and Case 2 of Table 8. However, due to the discovered larger magnitude of the breaking wave wall load in the example, it replaces the breaking wave pile load in this analysis.

Given that all guide posts are identical in the floating home design, the same combination of flood loads are checked at each post. Due to the magnitude of the breaking wave wall load and the direct debris impact load on the guide posts, both are chosen as the ultimate flood loads used during the design phase. Therefore, the factored applied moment each guide post must resist is 854.1 kip-foot.

$$M_u = 1.0W \ + \ 2F_a$$

$$M_u = (27.9 \ \ kft) + 2(12.6 \ kft + 400.5 \ kft)$$

$$M_u = 854.1 \ kft$$

3.3.3.2 Member Selection

Six HSS 16 x 16 x 0.75 ASTM A1085 steel sections were selected to resist the given applied moment. During nominal strength considerations, the thickness of the section is decreased by one-sixteenth of an inch to account for potential corrosion due to water exposure. The nominal moment of the corroded section is thus calculated using the section modulus and minimum steel strength. Each guide post has a nominal moment resistance of 892.5 kip-foot, which is greater than the applied factored moment of 854.1 kip-foot.

$$M_n = F_y Z$$

$$\varphi M_n = (0.9)\frac{(50 \ ksi)(238 \ in^3)}{12 \ in}$$

$$\varphi M_n = 892.5 \ kft$$

Due to the use of inelastic design, lateral deflections were computed to ensure the guide posts remain within tolerable limits. A maximum lateral deflection of 2.13 inches was tabulated from the applied forces which are within the second structural performance level (SP2) of acceptable lateral displacement in a structural system.

$$\Delta_y + 0.3\Delta_p = 2.34\ in$$

$$\Delta_{max} = 2.13\ in$$

$$\Delta_{max} < \Delta_y + 0.3\Delta_p$$

Table 9. System displacement lateral displacement limits arranged by structural performance levels

Structural Performance Level	Qualitative Description	System Displacement Limit	Inelastic Displacement Demand Ratio (IDDR))	Nonstructural Performance Level	Nonstructural Damage Ratio
SP1	Operational	Δ_y	0%	NP1	0%-10%
SP2	Occupiable	Δ_y+.3Δ_p	30%	NP2	5%-30%
SP3	Life safe	Δ_y+.6Δ_p	60%	NP3	20%-50%
SP4	Near collapse	Δ_y+.8Δ_p	80%	NP4	40%-80%
SP5	Collapsed	Δ_y+Δ_p	100%	NP5	>70%

3.4 Guide Posts: Governing Factors

In a similar fashion as the floating base design, specific factors have significant effects on the final design of the lateral load resisting guide posts. Some of these factors include the base flood elevation of the region, the number of guide posts used to resist lateral loading, the guide post material, and more. This section discusses these factors and how they influence each other.

3.4.1 Base Flood Elevation

The base flood elevation of a region controls the required height of the guide posts. Currently, FEMA recommends elevated structures have at least one foot of freeboard, which is a home's first floor height above BFE. The posts designed in this thesis extend an extra foot above BFE to tolerate these water heights in an extreme flood scenario. Since the base flood elevation varies from region to region, the required guide post height of a home will vary. In general, as one moves further inland, base flood elevations tend to decrease. As a result, floating homes built further inland will require shorter guide posts than floating homes closer to the coast.

3.4.2 Number of Guide Posts

During the structural analysis, it was evident that the number of guide posts used in the design will influence their required size. In this example, six 16 x 16 HSS sections were used to resist the given loads. However, if the floating base was smaller in size, the wall area impacted by flood loads would decrease, thus decreasing the transferred loading to the guide posts. A smaller lateral load would decrease the required number of posts needed. Fewer guide posts also could also be more aesthetically pleasing.

3.4.3 Post Material & Shape

The shape and materials used to design the guide posts are additional factors important to consider. Round sections have less hydrodynamic drag than rectangular or square sections. This reduces the effect of lateral flood loads that hit the column directly. This is accounted for during the design process by including drag coefficients in the calculation of the hydrodynamic pile load for example; 1.75 for round piles, and 2.25 for square piles. Rectangular and square piles are subject to greater flood loads when struck directly by water. Therefore, round piles are more common in the elevated structures seen on the coast today.

Square posts were selected to resist the forces experienced in this example however because the flood loads that strike the posts directly did not control the design. Instead, the transferred loads from water striking the floating base walls took precedence. A square section of identical diameter provides greater bending capacity than a round section. For example, a 16-inch diameter square HSS section with 0.75-inch-thick walls has a moment capacity of 656 kip-foot, while a round HSS section of equivalent diameter and wall thickness has a moment capacity of 450 kip-foot. Designers should note this when selecting the suitable shape for the guide posts.

The material composition of the guide posts could also affect numerous factors. Apart from the bending strength, the material choice affects the overall construction costs. Before utilizing hollow steel sections, a reinforced concrete section was evaluated. However, due to the amount of longitudinal rebar required to resist the lateral flood loads, the reinforced concrete section was deemed impractical for this implementation.

3.5 Guide Post and Foundation Connections

Another key component of the floating home system is the connection between the guide posts and the rest of the structure. These connections insure the home's lateral stability while allowing for vertical movement in rising and falling flood waters. The connection explored in this thesis utilizes a welded steel sleeve made of four 0.5-inch-thick steel plates. These plates are each 18 inches long and the connection fits around each square guide post leaving a quarter inch space between their surface and the exterior of the post.

This part of the connection is joined to the floating base by 2 additional steel plates. Ultimately, the entire connection is fixed to the floating base wall by 6 anchor rods, designed to resist the potential pullout forces the connection could experience. Each anchor rod had a required embedment length of 16 inches, which influenced the required thickness of the base walls. This connection was custom made to fit this specific steel section, but it is possible to use different connection configurations to suite the type of guide posts the design contains. A few alternative connections are available in Appendix A.

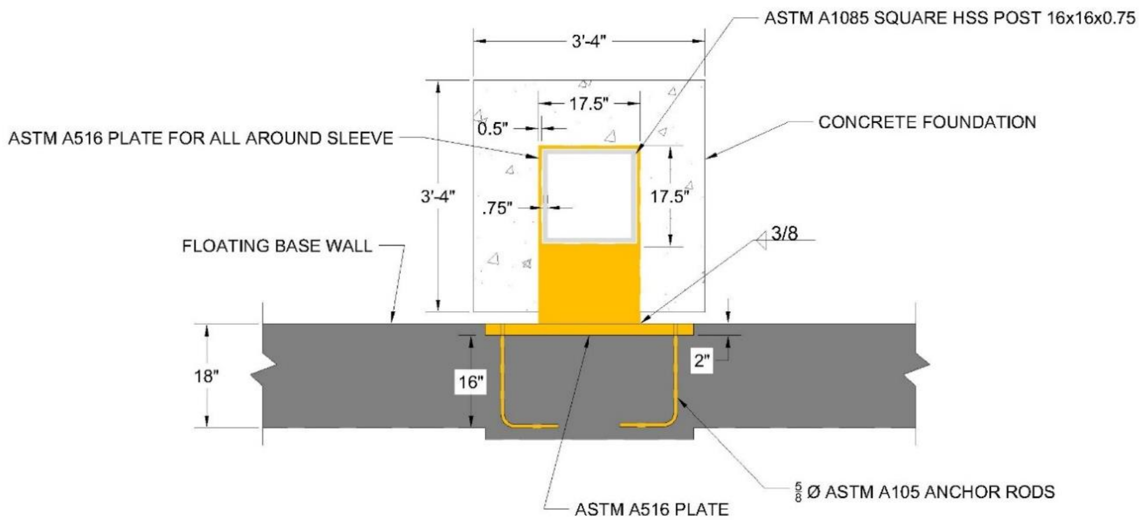

Figure 71. Plan view of typical guide post to base connection

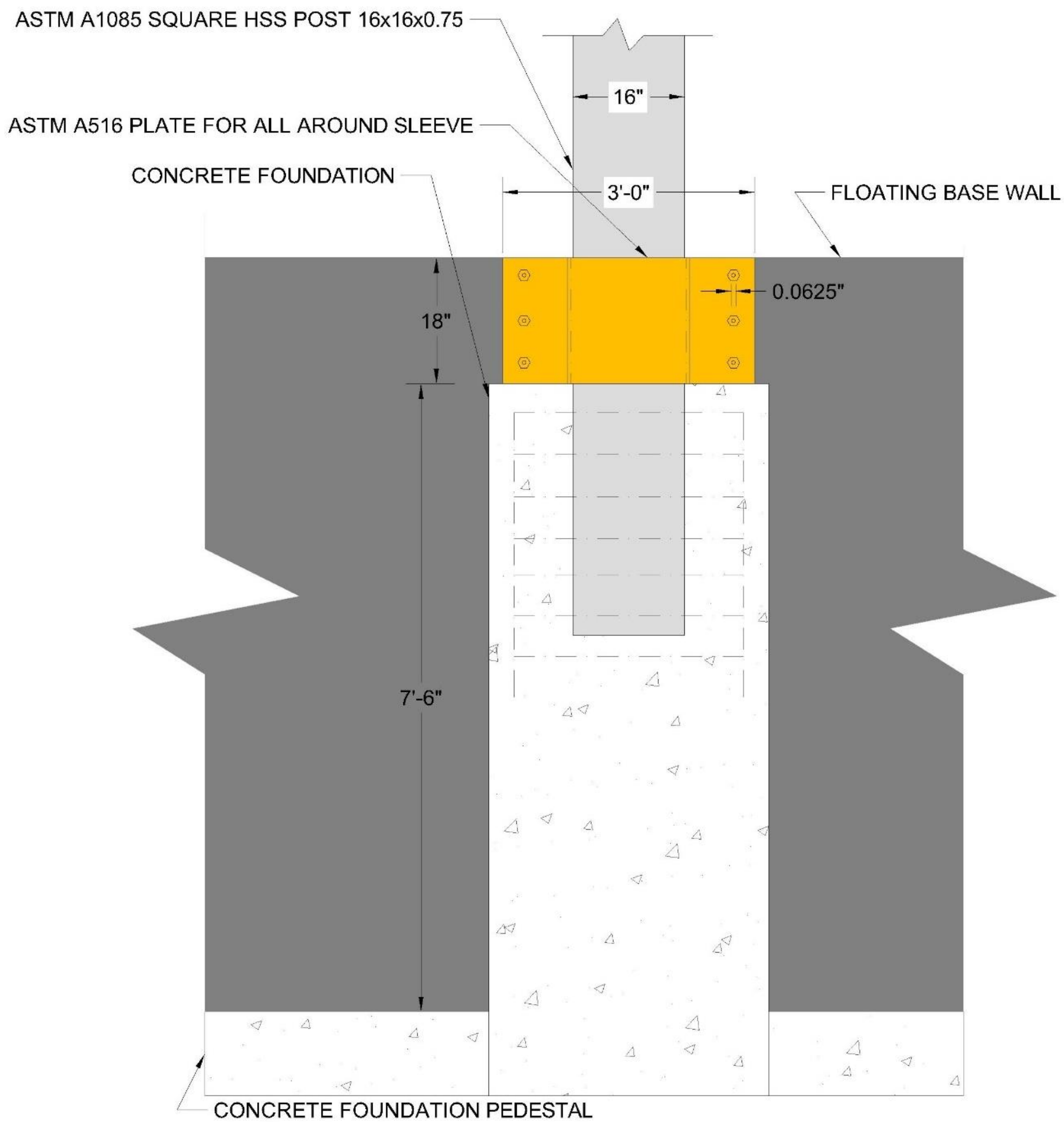

Figure 72. Front view of the base-post connection as well as the post-foundation connection

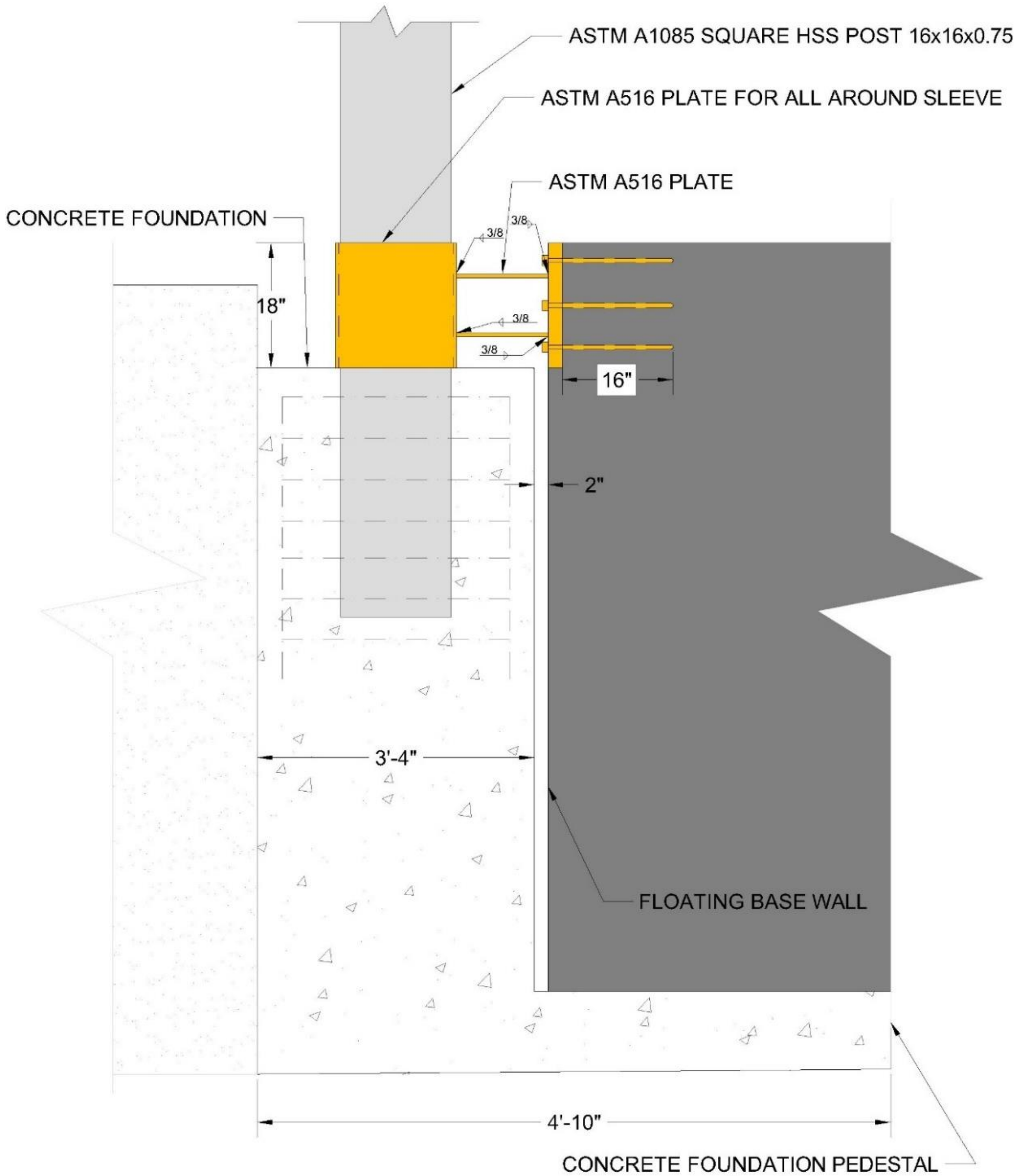

Figure 73. Side view of the base-post connection as well as the post-foundation connection

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After determining the connection design, it was important to design a foundation that allowed for sufficient embedment of the guide posts. Therefore, each guide post is embedded 3 feet deep into the center of square concrete foundations, leaving 1 foot between the edge of the guide post and the edge of the concrete footings. This 1-foot distance provides enough shear resistance to the expected lateral loads from flood and wind.

Chapter 4: Life Cycle Cost Analysis

The cost of a structure plays a significant role in determining its feasibility. Engineers and residents should conduct a life cycle cost analysis to determine how much money would be spent over the life of the home to be constructed and maintain such a structure. Literature states that life cycle cost studies can be broken into multiple categories, including energy systems, mechanical systems, electrical systems, building envelope, siting and massing, as well as structural systems [34].

This analysis examines the cost of constructing and maintaining the structural system of the floating home designed in this thesis and its maintenance costs over a 50-year period. The 50-year period is selected since it is typical for the life span of buildings. Then it compares these estimates with the same predicted costs for an elevated home of equivalent size and material make composition. Sources for material and labor costs for each home the building components were obtained from the National Ready Mix Concrete Association, Cost Owl and the Craftsman National Building Cost Manual. Additional sources include Homeadvisor, which obtain cost reports through customer surveys, and Homewyse, a price resource supported by various trade associations such as the American Institute of Architects and others.

After these estimates are made, a loss assessment is conducted for the town of Seaside Park; New Jersey using the GIS based risk assessment software, HAZUS. For different flood scenarios, HAZUS outputs estimates of monetary losses for specified study regions. A 100-year flood scenario was applied to the town of Seaside Park, and the monetary value of structural damage was output by the HAZUS software. This initial structural loss was then combined with the 50-year cost of replacing and maintaining the damaged homes, with either floating or elevated housing. A comparison is then made between the final costs of both options. It is important to note that values tabulated in this analysis are estimates, since prices vary over time and by region.

4.1 Floating Home Initial Costs

4.1.1 Floating Base

The first major component of the floating home is the floating base composed of reinforced concrete walls and two reinforced concrete slabs. The approximate cost of constructing this component is derived from the material costs of concrete and steel, as well as the cost of labor. In 2016, the National Ready Mix Concrete Association (NRMCA) reported the cost of concrete as $108.22 per cubic yard [35]. Labor for pouring concrete ranged between $2.5 to $8 per square foot, averaging to $5.25 per square foot of for the upper and lower slabs [36]. Cost Owl advises between $5 to $7 per square foot be used to estimate the labor cost for concrete walls [37]. An averaged $6 per square foot is used for the labor of floating base walls. Using these values, a total cost of $28,690 is estimated for the concrete used in the floating base.

The cost steel rebar is approximated based on the weight of steel. The production cost of steel is approximately $400 per ton, while it costs approximately $1350 per ton to fabricate [38]. This equates to about 90 cents per pound considering production and fabrication. Accounting for the total length and weight of all rebar used in the floating base, the approximate cost of the reinforcement provided to resist all bending and the effects of temperature and shrinkage is approximately $5595. The labor fee for installing rebar is approximately $1.00 per square foot [39]. Considering all surfaces of the floating base, the approximate installation and labor fee for this amount of rebar is $2970. A summary of the labor and material costs for the floating base is in Table 10. A detailed calculation for these costs are available in the Appendix A.

Table 10. Summary of material and labor costs for the floating base

	Material Cost	Labor	Total
Buoyant Base Concrete	$13,864	$14,826	$28,690
Buoyant Base Reinforcement	$5595	$2970	$8565
Total Cost	$19,459	$17,796	$37,255

4.1.1 Cost of Guide Posts

The lateral load resisting guide posts are the second major component in the floating home system. Assuming the cost of steel remains at $0.90 per pound to produce and fabricate and the material cost of all six square HSS posts is $15,269. The cost of labor and installation must be accounted for as well. FEMA, in Recommended Residential Construction for Coastal Areas, recommends using a minimal lump sum fee of $5500 for foundations with steel pipes, concrete columns and grade beams, which is similar to the foundation discussed in this thesis [40]. Therefore, the total cost of the guide posts is $15,269.

$$Guide\ Post\ Material\ Cost = (total\ combined\ post\ length)(weight)(cost\ per\ pound)$$

$$= (6\ x\ 12\ ft)\left(150.75\frac{lb}{ft}\right)\left(\frac{\$0.90}{lb}\right) = \$9769$$

$$Guide\ Post\ Labor\ and\ Installation\ Cost = \$5500$$

$$Total\ Guide\ Post\ Cost = Material\ Cost + Labor\ and\ Installation\ Cost = \$9769 + \$5500$$
$$= \$15269$$

4.1.2 Post to Base Connections & Foundation

Guide posts are connected to the floating base using welded ASTM A516 Grade 70 steel plates that create a sleeve connection which attaches to the floating base using A105 steel anchor rods. Considering production and fabrication of steel costs at $0.90 per pound, each sleeve connection is estimated to cost $561 in materials composition. An additional $300 is added per connection to account for the welding required [41]. As a result, the 6 connections used to attach the floating base to the steel guide posts are estimated to cost $5166.

Additionally, the size of the foundation for the floating structure contributed to its initial cost. Constructing the foundation involves excavating existing ground and pouring the concrete foundation in which the guide posts are embedded. Using average foundation costs reported home Wyse, the cost of excavating the foundation necessary to place the floating base is $41,525, based on an average rate of $93 per cubic yard [42]. This fee is combined with the cost of installing the foundation's concrete of $10,605 [35].

4.1.3 Additional Home Materials

The cost of the rest of the home was approximated using guidelines from the Craftsman National Building Cost Manual, which uses information such as building quality, shape, floor area, wall height and building location to estimate the cost of construction of a home. In this thesis, the example floating home is a single-family residence at the New Jersey coast. Additional materials that make up the house include an oak wood floor finish above the floor slab, wooden stud walls with insulation and roof materials such as shingles, felt and plywood.

Craftsman's National Building Cost Manual has six quality classifications for buildings: Luxury (Class 1), Semi-Luxury (Class 2), Best Standard (Class 3), Good Standard (Class 4), Average Standard (Class 5), and Minimum Standard (Class 6). The materials used in the floating home example best fits Craftsman's 'Best Standard' quality classification or Class 3 out of their six quality classification types.

After the location and quality class is determined, the final cost is derived by utilizing the square footage of the home and building shape. A 900 square foot residence with four corners is estimated to cost $155,070 to construct, at $172.30 per square foot [43]. Location modification factors created based on empirical housing data suggests that on average, homes built in New Jersey cost 9% more than their initially determined labor and material costs [43]. Therefore, the final cost of the structure, excluding the floating base and guide posts is approximately $169,027. Therefore, after combining this with the floating base, guide posts and additional component costs, the final cost of constructing the proposed 900 square foot floating home on the New Jersey coast is approximately $318,760.

Table 11. Initial cost of floating home

Floating Home Components	Cost (Materials and Labor)
Floating Base (Concrete & Rebar)	$37,255
Foundation Excavation	$41,525
Concrete Foundation	$10,605
Guide Posts	$15,269
Connections	$5166
Superstructure	$169,027
Total Cost	$278,847

4.2 Initial Cost of Elevated Homes

Similarly, an initial cost estimate for an elevated home of equivalent size and material composition can be made. The elevated structure is presumed to be a single story, 900 square foot home, composed of 8 ft tall wood stud walls, a shingled roof, elevated on six hollow steel sections. This assessment also considers materials, building shape, floor area, labor and other factors to classify and estimate the home's value using the National Building Cost Manual.

As previously stated, according the Craftsman's National Building Cost Manual, a 900 square foot residence with four corners in 'Best Standard' condition located in New Jersey, will cost $169,027 to construct [43]. If steel piers identical in size and number to those used with the floating home are used to elevate this structure, their material and implementation cost will be equivalent to that of the floating home.

The piers of a raised home are exposed to less lateral flood load than those of the floating home, as proven in the guide post analysis. Also, due to their steel material makeup, their compressive strength will be sufficient to resist vertical forces of the elevated structure, which is now unattached to the floating base. In practice, it likely that these steel sections would be decreased in size and change in material and number to be more cost efficient. However, for comparative reasons, it is assumed the amount and type of steel pier remains the same to support the now elevated coastal home. Observing Table 12, the initial cost of a new elevated structure is $194,901, combining the cost of the superstructure, foundation and total material and installation cost of each pier, which is lower than the proposed floating structure.

Table 12. Initial cost of elevated home

Elevated Home Components	**Cost (Materials and Labor)**
Concrete Foundation	$10,605
Guide Posts	$15,269
Superstructure	$169,027
Total Cost	$194,901

4.3 50-Year Cost of Floating Home

4.3.1 Maintenance and Inspection Costs

Long-term maintenance costs are not readily available for floating structures as they have not been constructed extensively. However, in general it is suggested that homeowners use 1% the construction price to estimate annual maintenance fees [44]. The cost covers any unexpected repairs needed throughout the home over the course of a year. Therefore, the estimated annual maintenance cost of the proposed floating home is $2789. Extended over a period of the life-cycle analysis, the total 50-year maintenance cost of the floating home is $139,424.

4.3.2 Flood Insurance Premiums

Unlike elevated structures, it is unclear how the concept of flood insurance will be applied to a floating structure. Currently, insurance premiums are based on a resident's elevation above the base flood elevation. Although the floating structure does not sit above the BFE initially, it can remain level with flood waters, keeping the interior safe from water damage. Currently, an annual flood insurance premium of $2476 is charged to homeowners that reside in a V-zone [45]. Given that information is not readily available on how floating homes will be insured for flooding, this analysis assumes the floating homeowner pays the same amount of flood insurance as the elevated homeowner. Therefore, over a 50-year period, the floating homeowner will pay $123,800 in flood insurance premiums.

4.4 50-Year Cost of Elevated Homes

4.4.1 Maintenance and Flood Insurance Costs

The maintenance fee of the proposed elevated home is derived using the same method as the floating home. One-percent of the total initial home cost is used, making the elevated home annual maintenance fee $1949. Extended over 50 years, a homeowner should budget $97,451 to maintain the elevated home.

Unlike floating homes, flood insurance premiums for elevated structures are well documented. Premium rates are based the structure's flood zone, and its elevation above the

BFE. The piers, given their 9 ft height above ground level allow the elevated structure to be sufficiently above the required BFE in many coastal New Jersey towns. These premiums help financially protect coastal homeowners from expenses due to flood damage. The NFIP has developed a formula for estimating flood insurance premiums. Residents in homes in an A-zone elevated 2 feet above BFE with only one floor would pay $446 annually, while residents in V-zone with the same freeboard would pay $2476 annually [45]. If the $2476 annual fee is applied to the elevated structure, the 50-year flood insurance cost is also $123,800.

4.5 Expected Damages from 100-year Flood: HAZUS

Economic loss estimations from FEMA's HAZUS software was combined with the calculated construction, maintenance and insurance costs to determine whether floating home implementation would result in long-term monetary benefits. HAZUS is publicly available software that uses Geographic Information Systems (GIS) to estimate physical, economic, and social impact of disasters [46]. It can be used to identify risk due to earthquakes, hurricanes, floods and tsunamis in a selected region by outputting the monetary value of expected damages to several types of infrastructure within the region. In this thesis, the HAZUS software is used to derive the expected damage due to a 100-year flood to residential property within the town of Seaside Park, New Jersey.

Seaside Park is a beach town in Ocean County, New Jersey which was negatively affected by Hurricane Sandy in 2012. Residential homes make up 95% of Seaside Park and it has an estimated population of 1,600 people, with 673 total households [47]. The base flood elevation for Seaside Park ranges between 8 and 9 feet for most of the town. During Hurricane Sandy, the region saw as much as 7 feet of water above NAVD88 [5].

Given that 7-foot Hurricane Sandy flood level is lower than the heights of the guide posts and piers discussed for the homes in this thesis, and the small average number of people per household, Seaside Park was chosen as a feasible location to examine whether the implementation of floating homes of identical size to those studied in this thesis had potential to lessen the long-term economic impact of a 100-year flood. As a result, a 100-year flood elevation of 7 feet was selected for the simulation. Outputs were compared with the actual losses the borough experienced due to Hurricane Sandy. It is estimated that Seaside Park lost approximately $31,312,342 in taxable property value because of Super Storm Sandy [48]. It is important to note the key assumptions before examining the results of the HAZUS analysis.

- All residential buildings in Seaside Park are single-family residences
- All homes are approximately the same size and material make up as the home discussed in the example
- The Seaside Park region is only affected by one 100-year storm during a 50-year period
- All rebuilt elevated homes are elevated to the same height
- All buildings that sustained damage will be rebuilt

Although in practice the homes in a community will have numerous differences, this assessment provides an example of a general estimate of the economic benefits and setbacks of implementing floating homes on a broad scale. Observing Table 13, it is evident that all buildings exposed to flood inundation and damaged were residential. Therefore, the structural damage loss amounts are presumed to only include damage the residential structures. Potential losses and savings were calculated for two scenarios: elevating all damaged structures after the 100-

year flood event or replacing each damaged structure with a floating structure before the 100-year flood event occurs.

Table 13. Count of number of buildings damaged in HAZUS by the 100-year flood event by arranged by building type.

	Count of Buildings (#) by Range of Damage (%)							
	None	1-10	11-20	21-30	31-40	41-50	Substantial	Total
New Jersey								
Ocean								
Religion	0	0	0	0	0	0	0	0
Commercial	0	0	0	0	0	0	0	0
Industrial	0	0	0	0	0	0	0	0
Education	0	0	0	0	0	0	0	0
Government	0	0	0	0	0	0	0	0
Agriculture	0	0	0	0	0	0	0	0
Residential	654	54	128	17	2	0	0	855
Total	**654**	**54**	**128**	**17**	**2**	**0**	**0**	**855**
Total	**654**	**54**	**128**	**17**	**2**	**0**	**0**	**855**
Scenario Total	**654**	**54**	**128**	**17**	**2**	**0**	**0**	**855**

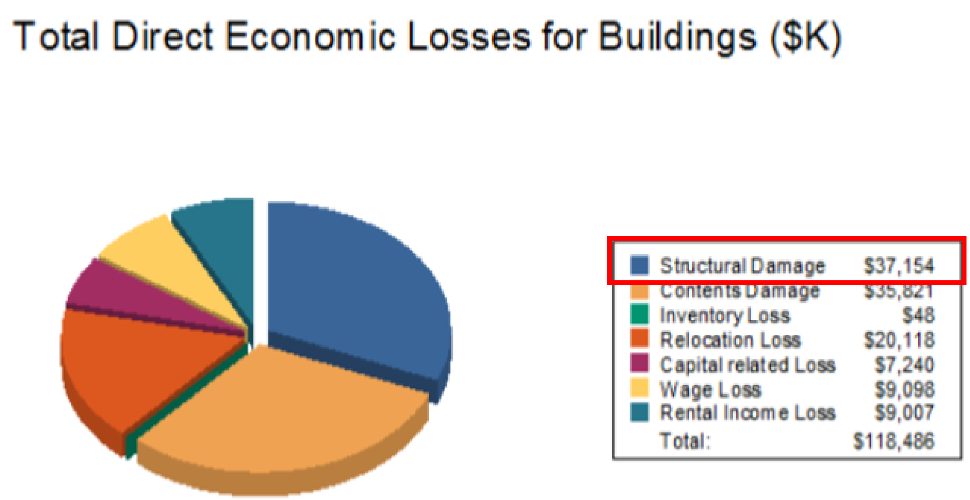

Figure 74. Total Direct Economic Losses for buildings in Seaside Park, NJ after a 100-year storm

4.6 Cost of Replacement of Damaged Homes with Elevated Ones

Out of the 855 homes in Seaside Park affected by the 7-foot inundation simulated in HAZUS, 201 residential structures in Seaside Park experienced some type of damage due to the flooding scenario. This means that 23% of affected residential structures in Seaside Park would receive minor to major damage from a 100-year flood that brought 7 feet of inundation. HAZUS estimates that this amount of building damage would lead to a direct structural loss of $37,154,000 for residential structures.

Presuming these damaged buildings were not already elevated, and owners of the damaged homes chose to rebuild each house entirely using the type of elevated home discussed previously in this thesis, it would cost $39,175,101 in materials and construction fees to rebuild and elevate the 201 damaged structures.

$$\boldsymbol{Rebuild\ Elevated\ Homes} = (\mathbf{201})(\$\mathbf{194,901}) = \$\mathbf{39,175,101}$$

Excluding the other 654 unaffected homes, these rebuilt structures will need to be maintained and insured over the next 50 years. As a result, using the estimates from above, the 201 damaged homes will cost $19,587,651 in total to maintain, and another $24,883,800 to insure over the next 50 years.

$$\boldsymbol{Elevated\ Home\ Maintenance} = (\mathbf{201})(\$\mathbf{97,451}) = \$\mathbf{19,587,651}$$

$$\boldsymbol{Elevated\ Home\ Flood\ Insurance} = (\mathbf{201})(\$\mathbf{123,800}) = \$\mathbf{24,883,800}$$

At the end of the 50-year life-cycle, if a major storm event were to occur, the town would have spent an additional $83,646,552 in rebuilding and maintaining the damaged property, apart from the already lost $37,154,000. This is a total loss of $120,800,552 over a 50-year period.

$$\textbf{\textit{Total Cost}} = \textbf{\textit{Structural Loss}} + \textbf{\textit{Construction}} + \textbf{\textit{Maintenance}} + \textbf{\textit{Insurance}}$$

$$\textbf{\textit{Total Cost}} = \$\mathbf{37,154,000} + \$\mathbf{39,175,101} + \$\mathbf{19,587,651} + \$\mathbf{24,883,800}$$

$$\textbf{\textit{Total Cost}} = \$\mathbf{120,800,552}$$

4.7 Cost of Building Floating Homes

Another scenario studies the effect on cost of having floating homes installed prior to the 100-year flood event. Here it is assumed that the 201 damaged homes at risk of flood damage were built to be buoyant. The initial cost of constructing these 201 buoyant homes would be $56,048,247. Since these homes are theoretically immune to the effects of this amount of inundation, it is assumed they suffer no structural flood damage, and thus no monetary loss due to the initial flood.

$$\textbf{\textit{Prior Built Floaitng Homes}} = (\mathbf{201})(\$\mathbf{278,847}) = \$\mathbf{56,048,247}$$

Following their construction however, these structures would need to be maintained and insured throughout their lifetime like their elevated counterparts. The cost of maintaining the 201 buoyant homes of would be approximately $32,039,400, and the cost of insuring these structures would be another $24,883,800.

$$\textbf{\textit{Floating Home Maintenance}} = (\mathbf{201})(\$\mathbf{139,424}) = \$\mathbf{28,024,124}$$

$$\textbf{\textit{Floating Home Flood Insurance}} = (\mathbf{201})(\$\mathbf{123,800}) = \$\mathbf{24,883,800}$$

Adding the initial estimated losses and construction fees, along with the long-term maintenance costs, the floating home solution results in a total loss of $108,956,171 for the town of Seaside Park within a 50-year time frame. This estimate is approximately $11.8 million less than if elevated homes were installed following the flood event.

$$\boldsymbol{Total\ Cost = Structural\ Loss + Construction + Maintenance + Insurance}$$

$$\boldsymbol{Total\ Cost = \$0 + \$56,048,247 + \$28,024,124 + \$24,883,800}$$

$$\boldsymbol{Total\ Cost = \$108,956,171}$$

Chapter 5: Conclusions and Recommendations

A floating home system is proposed to resist hurricane forces and storm surges. The innovative system and its components have the potential to remedy some of the issues brought to coastal communities by hurricanes, intense winds and high storm surges. Multiple strategies and material options exist within the structural design process to ensure buoyancy and lateral stability. Wood, concrete, and steel are a few examples of building materials that can be combined or used exclusively to build the structure's critical components, which include a floating base, guide posts, and sliding connection between the floating base and the guideposts. A detailed example presented in Appendix A uses a reinforced concrete floating base and hollow steel guide posts to ensure structural stability during a flood. The design process of the various components revealed several key factors that practicing engineers and home owners should be aware of when utilizing this type of floating home system.

5.1 Floating Base

The weight of the home and the floating base self-weight is a major factor that influenced the required depth of the floating base. For the water level to remain below the ground level of the home during a major flood event, the floating base depth should allow flood waters to rise to a level such that a buoyant force on the base equivalent to the total structural weight of the house and the base is created. Once this buoyant force is achieved, the home will float and rise with the water to the desired design level. The results also showed that it may not be practical to design for floating heavy structures that require deep floating base in low flood level zones.

Other factors that impacted the floating base design were the shear forces on the base walls and the anchor details. For example, shear loads and the required anchor rod embedment length of the steel connections required thicker base walls. Consequently, the overall structural weight was increased, which required a greater volume of water, or higher water level to lift the home. The shear loads were a result large lateral flood loading on the base. Using design guidelines specified by the American Society of Civil Engineers and FEMA recommendations, the breaking wave load, due to its magnitude, had the greatest influence on the design of the floating base walls.

5.2 Guide Posts

The guide posts of the structural system are designed to resist lateral flood loads transferred from the floating base as well as flood loads that strike the post directly. The guideposts are also designed to resist wind loads affecting the superstructure. Therefore, like the floating base, numerous factors influence their design.

Flood risk was a key factor in the ultimate design of the all guide posts because of its effect on base flood elevation. Higher base flood elevations, or regions at risk of greater inundation in a 100-year flood event, will require taller guide posts. These regions therefore, if subject to an extreme flood event, will cause flood loads to be transferred higher along the length of each guide post. Therefore, the posts were designed to sit at a height 1-foot above the BFE, which allows the floating home to rise to the BFE if necessary. This is similar to FEMA floodplain regulations that mandate homes be elevated with at least 1-foot of freeboard.

Despite the impact of BFE and flood risk, the component which had the greatest influence on the loads experienced on each guide post was the flood forces on the floating base.

Its exposed area, specifically its length and depth, significantly impacted the loads applied to guide posts. The breaking wave wall load was the largest flood load as it was responsible for 93% of the applied moment at the base of the post.

Additional factors found to impact the guide post design include the post shape and number of posts provided. An entirely elastic design would require more posts compared to an inelastic design. In addition, more posts will affect the overall aesthetics of the home. Using an inelastic design approach similar to the inelastic approach followed in seismic design, the number of posts was reduced, provided there are enough posts to provide redundancy and sufficient detailing to provide inelasticity and energy dissipation. The inelastic displacement was slightly higher than the elastic displacements, thus only minor damage may occur in the case of major flood event.

Although rectangular HSS guide posts were selected for the design example, round HSS sections provide less resistance to drag resistance to water. However, depending on the design requirements, the needed size of the post should be provided.

5.3 Guide Post & Foundation Connections

A critical part of the sleeve connections to the exterior guide posts were the anchor rods, embedded in the floating base walls as well as the sliding sleeve connection. The steel anchor rods needed to be long enough to engage the lightweight concrete and prevent pullout, should the connection be subject to any tensile loads. Additionally, the welds between the plates of this connection should be designed to resist the expected loads.

The depth of embedment into the concrete foundation for each guide post is also critical. Given the calculated lateral loads, a 3-foot embedment depth was necessary to resist expected lateral loads for the selected design example. The embedment length will vary depending on the expected force levels.

5.4 Life Cycle Cost Analysis

The life cycle analysis sought to further assess the floating structure's feasibility for implementation on a broad scale to insure coastal safety and resilience in the event of hurricane force winds and high flood levels. Using the cost data from various resources such as the National Ready Mix Concrete Association, Cost Owl, the Craftsman National Building Cost Manual, Homeadvisor and Homewyse, cost estimates for construction and long-term maintenance were created for the floating home and an elevated home of equivalent size and material composition over a 50-year life cycle. Then, estimates for the potential damage experienced from a 100-year flood in the town of Seaside Park, NJ were derived using HAZUS. Long term damage losses from two scenarios were compared. One scenario assessed the total monetary losses over a 50-year period if elevated structures were installed to replace all damaged homes after the flood event. The other scenario determined the total cost over a 50-year period if floating homes were installed prior to the flood event. The cost analysis over the 50-year life showed that elevated structures installed to replace all damaged homes after the flood event would cost approximately $11.8 million dollars more than building floating homes

Although the floating structure is initially more expensive to install, there is a potential long-term benefit of installing these structures. However, it must be noted that varied materials and structural systems can be used to design the elevated homes in a more cost-efficient manner, since structural system and composition are selected on a case by case basis. However, the cost assessment conducted in this thesis provides a good starting point for future research.

5.5 Future Research

There are numerous avenues available for future research to be performed on floating structures subjected to hurricane forces and wave surge. The work conducted in this thesis provided an investigation of the design issues that need to be addressed in the design process. However, additional work can be conducted to investigate the effects of home sizes and geometry. This type of parametric study would be useful for future designers, owners, and local and state agencies. Additionally, further investigation should be done into the use and performance of other design materials, such as installing EPS in the floating base, as materials influence cost and weight significantly. Assessments of the best environments and regions suitable for floating homes and for different floating home materials is needed.

Finally, in the United States in particular, investigations need to be done on ways to integrate floating construction into the flood insurance initiatives. Currently this is not being done and owners of floating homes are being forced to obtain flood insurance from agencies other than FEMA. If broader floating home implementation is to be achieved, strategies must exist to integrate these structures into the discussions of planners and coastal residents.

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Appendix A

A.1 Detailed Example

The following section provides a step-by-step detailed example of all calculations conducted during the design of the buoyant base and lateral load resisting piers for the floating structure discussed in this thesis. It also includes all relevant cost calculations, including the material and labor costs for structural components. Listed below are important assumptions that were made before embarking on the design of the various components.

- Structure is a single-story, wood-frame residence located on the New Jersey coastline
- Property is in a FEMA floodplain (Zone V), with a BFE of 13 ft.
- 20 feet x 45 feet building footprint
- Gable roof with 1:5 slope

Per American Society of Civil Engineers (ASCE 7-10)

- 130 mph Basic Wind Speed
- Flat open terrain surrounding the house
- Exposure Category II

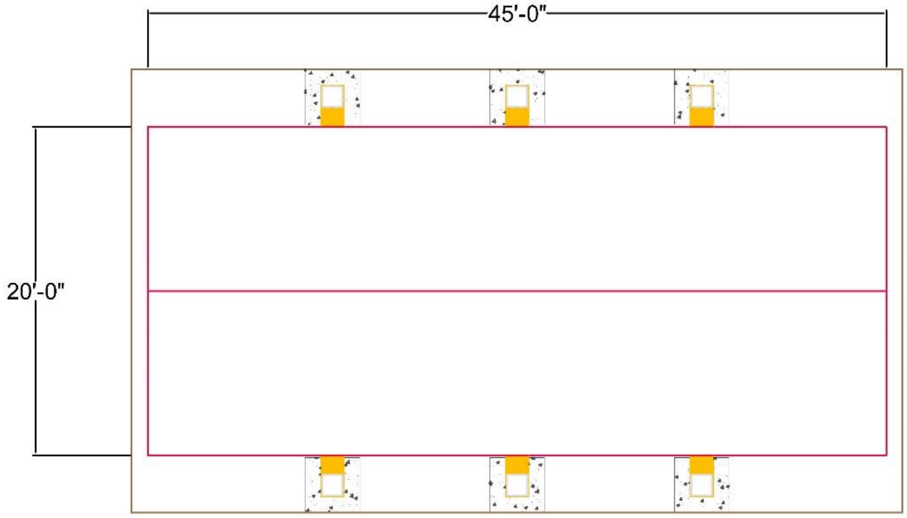


Figure 75. Plan view of floating home

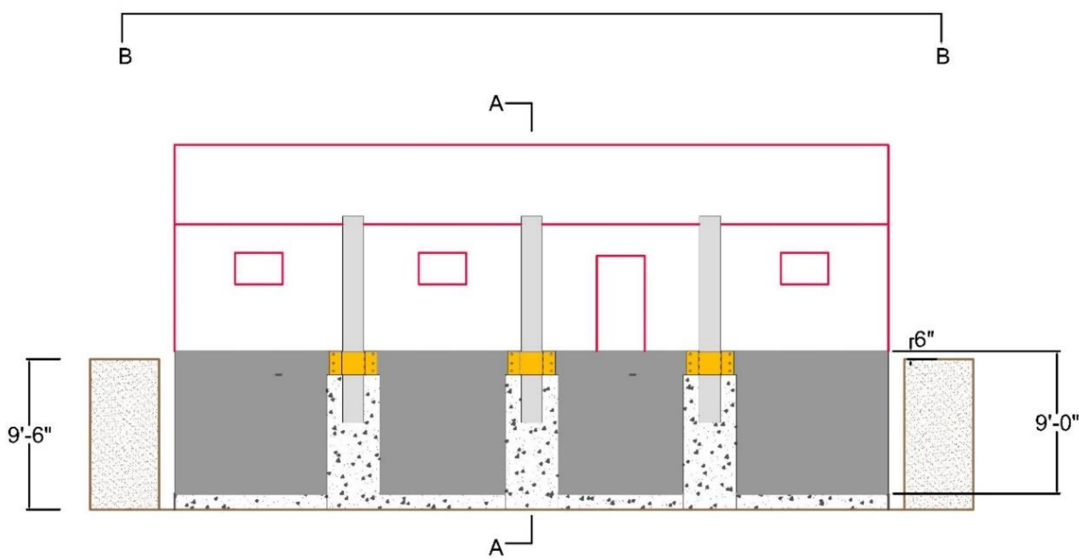


Figure 76. Elevation view of floating home

A.1.1 Floating Base Design

The floating base is subject to two primary types of loads. These include the downward vertical loads, which load the upper slab and give rise to the buoyant load on the lower slab, and the lateral flood loads. These loads, when combined, give rise to stresses within the concrete base that are ultimately resisted using its own bulk and steel reinforcement. This section details all calculations that involved in the floating base design.

A.1.1.1 Downward Vertical Dead Loads

First, the downward vertical dead loads were tabulated. This was done by estimating the material make-up and size of the home that sits of the 900 square foot slab floor slab.

$\boldsymbol{Floor}: (\mathbf{4}\frac{\boldsymbol{lb}}{\boldsymbol{ft^2}} + \mathbf{3}\frac{\boldsymbol{lb}}{\boldsymbol{ft^2}} + \mathbf{5}\frac{\boldsymbol{lb}}{\boldsymbol{ft^2}} + \mathbf{3}\frac{\boldsymbol{lb}}{\boldsymbol{ft^2}})\boldsymbol{x}\ \mathbf{45}\boldsymbol{ft}\ \boldsymbol{x}\ \mathbf{20}\boldsymbol{ft} = \mathbf{13500}\ \boldsymbol{lbs}$

$Oak\ Floor: 4\frac{lb}{ft^2}$

$Subfloor\ \left(\frac{3}{4} in\ plywood\right): 3\frac{lb}{ft^2}$

$Insulation: 5\frac{lb}{ft^2}$

$Electrical\ Mechanical: 3\frac{lb}{ft^2}$

$\boldsymbol{Interior\ Walls}: \mathbf{130}\ \boldsymbol{ft}\ \boldsymbol{x}\ \mathbf{0.77}\ \boldsymbol{x}\ \mathbf{4}\boldsymbol{ft}\ \boldsymbol{x}\ \mathbf{20}\frac{\boldsymbol{lb}}{\boldsymbol{ft^2}} = \mathbf{8008}\ \boldsymbol{lbs}$

- $Total\ length\ of\ exterior\ walls\ =\ 130\ ft$
- $Total\ interior\ wall\ length\ taken\ as\ 77\%\ of\ exterior\ wall\ length$
- $As\ is\ typical, half\ the\ wall\ height\ loads\ the\ floor\ below, hence\ 4\ ft$
- $Interior\ wall\ weight\ 20\frac{lb}{ft^2}$

$\boldsymbol{Exterior\ Walls}$: $\mathbf{130\ ft\ x\ \ 4ft\ x\ 18\frac{lb}{ft^2} = 9360\ lbs}$

- $Total\ length\ of\ exterior\ walls\ =\ 130\ ft$
- $Total\ interior\ wall\ length\ taken\ as\ 77\%\ of\ exterior\ wall\ length$
- $As\ is\ typical, half\ the\ wall\ height\ loads\ the\ floor\ below, hence\ 4\ ft$
- $Exterior\ wall\ weight\ 18\frac{lb}{ft^2}$

$\boldsymbol{Roof}$: $\mathbf{2478\ lbs + 867.3\ lbs + \ 1858.5\ lbs + 5540.8\ lbs + 1800\ lbs = 12544.4\ lbs}$

$Gable\ Height$: $5ft$

$Gable\ Hypotenuse$: $\sqrt{\left(\frac{20ft}{2}\right)^2 + (5ft)^2} = 11.18\ ft^2$

$Surface\ Area$: $(45ft + 2ft)(11.18ft + 2ft)(2) = 1239ft^2$

$Projected\ Area$: $\left[\left(\frac{20ft}{2}\right) + (2ft)\left(\frac{10ft}{11.18ft}\right)\right](45ft + 2ft)(2) = \ 1108.2\ ft^2$

$Shingles$: $(2\frac{lbs}{ft^2})(1239ft^2)\ =\ 2478\ lbs$

$Felt$: $\left(0.7\frac{lbs}{ft^2}\right)(1239ft^2\ ) = 867.3\ lbs$

$Plywood$: $(1.5\frac{lbs}{ft^2})(1239ft^2) = 1858.5\ lbs$

$Truss$: $(5\frac{lbs}{ft^2})(1108.2\ ft^2) = 5540.8\ lbs$

$Gable\ End\ Walls$: $(10ft)(5ft)(18\frac{lbs}{ft^2})(2)\ =\ 1800\ lbs$

$$\boldsymbol{Ceiling}: \left(8\frac{lbs}{ft^2} + 1.5\frac{lbs}{ft^2} + 10\frac{lbs}{ft^2} + 2\frac{lbs}{ft^2}\right)(45ft)(20ft) = 900\ lbs$$

$$Insulation: 8\frac{lbs}{ft^2}$$

$$Plywood: 1.5\frac{lbs}{ft^2}$$

$$Plaster: 10\frac{lbs}{ft^2}$$

$$Miscellaneous: 2\frac{lbs}{ft^2}$$

$$\boldsymbol{Upper\ Slab\ Self\ Weight}: \left(115\frac{lb}{ft^3}\right)(1ft)(45ft)(20ft)\ =\ 103500\ lbs$$

$$\boldsymbol{Lower\ Slab\ Self\ Weight}: \left(115\frac{lb}{ft^3}\right)(1.5ft)(45ft)(20ft)\ =\ 155250\ lbs$$

$$\boldsymbol{Base\ Walls}: (2)\left[\left(115\frac{lb}{ft^3}\right)(1.5ft)(9ft - 1.5ft - 1ft)(45ft)\right]$$

$$+ (2)\left[\left(115\frac{lb}{ft^3}\right)(1.5ft)(9ft - 1.5ft - 1ft)\big(20ft - (2)(1.5ft)\big)\right]$$

$$= 139035\ lbs$$

A.1.1.2 Downward Vertical Live Loads

Standard live loads for the roof of first floor slab were used in the design. These were obtained for ASCE 7-10.

$$\boldsymbol{Roof\ Live\ Load}: \left(20\frac{lb}{ft^2}\right)(45ft)(20ft) = 18000\ lbs$$

$$\boldsymbol{Floor\ Live\ Load}: \left(40\frac{lb}{ft^2}\right)(45ft)(20ft) =\ 36000lbs$$

A.1.1.3 Design Slab Loads

$\boldsymbol{Distributed\ Load\ on\ Upper\ Slab}$: $\mathbf{230.7\frac{lb}{ft}}$ $\boldsymbol{per\ foot\ length\ the\ upper\ slab}$

Only loads placed directly on the upper slab were considered in the final determination of its loading. These loads were the interior walls, the floor load, the upper slab self-weight and the floor live load.

$$\frac{factored\ load\ on\ upper\ slab}{building\ footprint}$$

$$= \frac{[(1.2)(Int.Walls\ +\ Upper\ Slab\ Weight +\ Floor\ Dead) +\ (1.6)(Floor\ Live)]}{(20ft)(45ft)}$$

$$= \frac{[(1.2)(8008\ lbs + 103500\ lbs +\ 13500\ lbs) +\ (1.6)(36000\ lbs)]}{(20ft)(45ft)}$$

$$= 230.7\frac{lb}{ft^2}$$

$$\left(230.7\frac{lb}{ft^2}\right)(1ft) =\ 230.7\frac{lb}{ft}$$

$\boldsymbol{Distributed\ Load\ on\ Lower\ Slab}$: $\mathbf{664\frac{lb}{ft}}$ $\boldsymbol{per\ foot\ length\ of\ the\ lower\ slab}$

The lower slab on the other hand, was affected by all downward acting loads, due to the development of the buoyant force. The buoyant force is directly related to volume of water displaced by the floating base. If the weight of the displaced volume of water is greater than the total weight of the home, the home to rise in a flood event.

$\boldsymbol{Weight\ of\ Entire\ Structure}$:

$$= Roof + Roof\ Live\ Load + Exteror\ Walls + \ Interior\ Walls\ + Ceiling$$

$$+ Floor + \ Upper\ Slab\ Self\ Weight + Base\ Walls$$

$$+ Lower\ Slab\ Self\ Weight$$

$$= 12544.4\ lbs + 18000\ lbs + 9360\ lbs + 8008\ lbs + 900\ lbs + 13500\ lbs$$

$$+ 103500\ lbs + 139035\ lbs + 155250\ lbs = 460097.4\ lbs$$

$\boldsymbol{Buoyant\ Force}$:

$$(water\ density)(building\ footprint)(required\ flood\ level)$$

$$= \left(62.4\frac{lb}{ft^3}\right)(20ft)(45ft)(8.5ft) = 477360\ lbs$$

$$\frac{factored\ buoyant\ force}{building\ footprint}$$

$$= \frac{(1.25)(477360\ lbs)}{(20ft)(45ft)} = \frac{596700\ lbs}{(20ft)(45ft)} = 664\frac{lb}{ft^2}$$

$$\left(664\frac{lb}{ft^2}\right)(1ft) = 664\frac{lb}{ft}$$

A.1.1.4 Design Wall Loads

After the expected loads were determined for the upper and lower slab, lateral flood loading was then formulated for the buoyant base walls. Using specifications from FEMA’s Recommended Residential Construction for Coastal Areas: Building on Strong and Safe Foundations, expected worst-case scenario loads were developed.

At the maximum assumed flood level, the base walls are subject to three primary loads according to FEMA. These loads include the debris impact load, the hydrodynamic load, and the breaking wave load. Formulas for each load is given below.

- Debris Impact Load: $F_i = \frac{\pi W V}{2 g t_i}$, typically acts at the stillwater flood level, where W is the weight of the debris and t_i is the duration of impact and V is the water velocity. However, to simulate a more critical loading scenario, the F_i was applied 1-foot below the upper slab bottom surface.
- Hydrodynamic Load:$F_{dyn} = \frac{1}{2} C_d \gamma_w V^2 A$, acting at the still water mid-depth, where C_d is the drag coefficient and A is the area the load will act upon. C_d 1.25 for a surface with a width to depth ratio between 1 and 12 [40].
- Breaking Wave Load: $F_{brkw} = 1.1 C_p \gamma_w d_s^2 + 2.4 \gamma_w d_s^2$, where C_p is the dynamic pressure coefficient and d_s is taken as the height of the buoyant base walls between the upper and lower slabs. The breaking wave load typically acts at the still water flood level; however, to simulate a more critical loading scenario, the breaking wave load was applied 1 foot below the upper slab bottom surface.

- FEMA's flood load determination process for foundation walls was designed for walls that remained at ground level. However, these walls are designed to resist flood loads that will occur while the structure is floating at the maximum flood level. Therefore, d_s is taken to be the height of the buoyant base, rather than the true design still water elevation in all load calculations for the buoyant base walls. This variable substituted for d_s shall be designated as $b_h = 6.5\ ft$ for all subsequent wall load calculations.

$\boldsymbol{Debris\ Impact\ Load}$: $\mathbf{499\frac{lb}{ft}}$

$$F_i = \frac{\pi WV}{2gt_i} = \frac{\pi(1000lbs)\left(12.9\frac{ft}{s}\right)}{(2)\left(32.2\frac{ft}{s^2}\right)(0.03s)} = 20977\ lbs$$

$$Load\ acting\ per\ linear\ foot\ of\ wall\ length\ = \frac{20977\ lbs}{42ft} = 499\frac{lb}{ft}$$

$\boldsymbol{Hydrodynamic\ Load}$: $\mathbf{1441.4\frac{lb}{ft}}$

$$F_{dyn} = \frac{1}{2}C_d\gamma_w V^2 A = \frac{1}{2}(1.25)\left(1.99\frac{slugs}{ft^3}\right)\left(12.9\frac{ft}{s}\right)^2(6.5ft)(45ft) = 60539.4\ lbs$$

$$Load\ acting\ per\ linear\ foot\ of\ wall\ length\ = \frac{60539.4\ lbs}{42ft} = 1441.4\frac{lb}{ft}$$

$\boldsymbol{Breaking\ Wave\ Load}$: $\mathbf{10947\frac{lb}{ft}}$

$$F_{brkw} = 1.1C_p\gamma_w d_s^2 + 2.4\gamma_w d_s^2 = 1.1(2.8)\left(62.4\frac{lb}{ft^3}\right)(6.5ft)^2 + 2.4\left(62.4\frac{lb}{ft^3}\right)(6.5ft)^2$$
$$= 10967\frac{lb}{ft}$$

A.1.1.5 SAP2000 Structural Analysis

Moment, shear and axial forces per unit length of the buoyant base were calculated using SAP2000 structural analysis software. The SAP model consisted of a 6.5-foot-tall, 18.5-foot-wide continuous, 2-dimensional hollow box, supported on pin supports at the lower left and right corners for stability. The top member represents the bottom surface of the upper slab, and the bottom member represents the top surface of the lower slab. The figures below display the model set up and the loads applied to the base.

A.1.1.5.1 Upper Slab Bending Moment

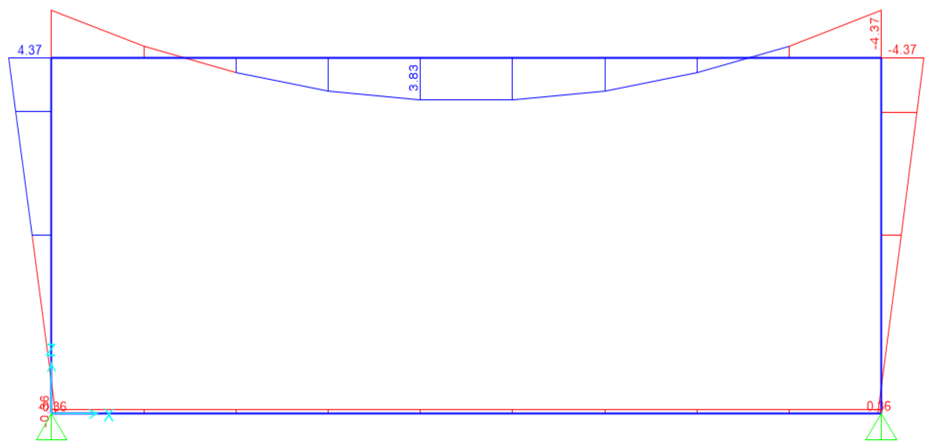


Figure 77. Moment in floating base without flood

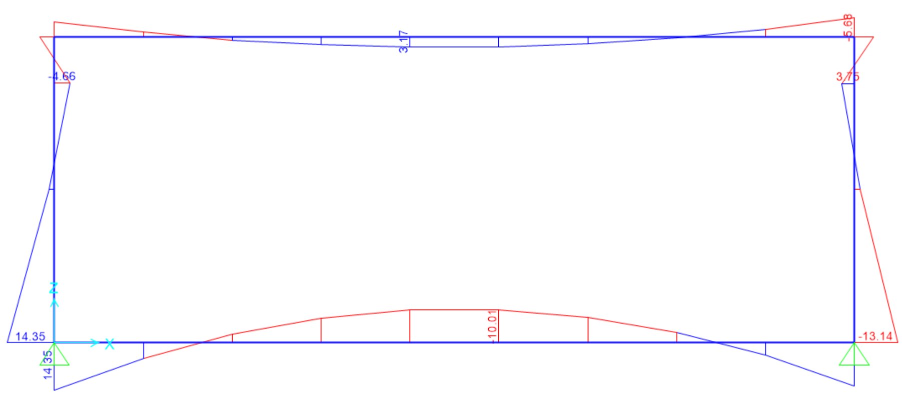


Figure 78. Moments in floating base with flood

$$Minimum\ d = \sqrt{\frac{M_u}{\varphi \rho f_y b \left(1 - 0.59\rho\left(\frac{f_y}{f_c'}\right)\right)}}$$

$$Minimum\ d = \sqrt{\frac{(3.83\ kft)(12in)}{(0.9)(0.0181)(60\ ksi)(12\ in)\left(1 - 0.59(0.0181)\left(\frac{60\ ksi}{4\ ksi}\right)\right)}} = 2.16\ in$$

A.1.1.5.2 Lower Slab Bending Moment

$$Minimum\ d = \sqrt{\frac{M_u}{\varphi \rho f_y b \left(1 - 0.59\rho \left(\frac{f_y}{f_c'}\right)\right)}}$$

$$Minimum\ d = \sqrt{\sqrt{\frac{(14.35\ kft)(12in)}{(0.9)(0.0181)(60\ ksi)(12\ in)\left(1 - 0.59(0.0181)\left(\frac{60\ ksi}{4\ ksi}\right)\right)}} = 4.18\ in}$$

A.1.1.5.3 Wall Bending Moment

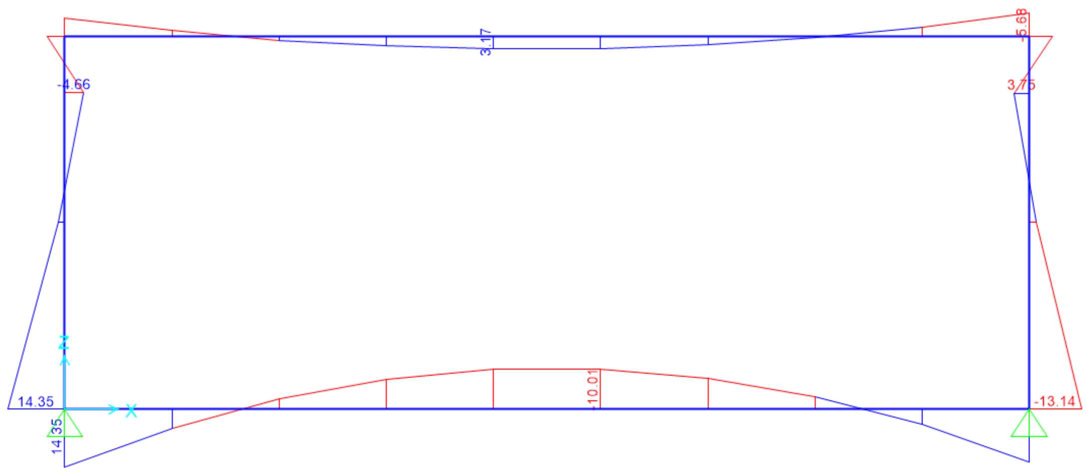


Figure 79. Moments in floating base walls

$$Minimum\ d = \sqrt{\frac{M_u}{\varphi \rho f_y b \left(1 - 0.59\rho \left(\frac{f_y}{f_c'}\right)\right)}}$$

$$Minimum\ d = \sqrt{\frac{(14.35\ kft)(12in)}{(0.9)(0.0181)(60\ ksi)(12\ in)\left(1 - 0.59(0.0181)\left(\frac{60\ ksi}{4\ ksi}\right)\right)}} = 4.18\ in$$

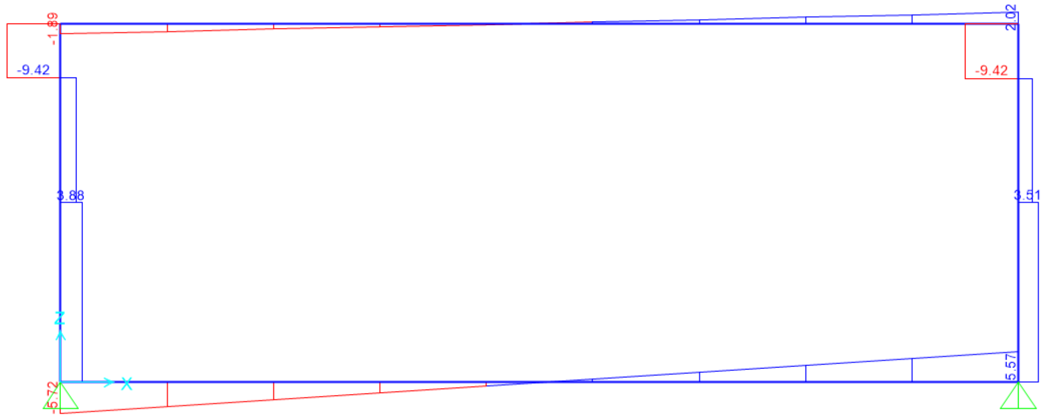


Figure 80. Shear in floating base with flood

Finite Element Analysis shows the wall will be subject to a maximum shear force of 9.42 kips.

$$V_c = 2\sqrt{f'c}bd$$

ACI recommends that $\sqrt{f'c}$ be replaced with $\frac{f_{ct}}{6.7}$ for lightweight concrete. The minimum strength of lightweight concrete is 290 psi.

A.1.1.5.4 Upper Slab Shear Capacity

$$V_c = 2\left(\frac{f_{ct}}{6.7}\right)bd = 2\left(\frac{290\ psi}{6.7}\right)(12\ in)\ (12\ in) = 12{,}465.6\ lbs = 12.46\ kips$$

A.1.1.5.5 Lower Sab Shear Capacity

$$V_c = 2\left(\frac{f_{ct}}{6.7}\right)bd = 2\left(\frac{290\ psi}{6.7}\right)(12\ in)\ (18\ in) = 18{,}698.5\ lbs = 18.7\ kips$$

A.1.1.5.6 Wall Shear Capacity

$$V_c = 2\left(\frac{f_{ct}}{6.7}\right)bd = 2\left(\frac{290\ psi}{6.7}\right)(12\ in)\ (18\ in) = 18{,}698.5\ lbs = 18.7\ kips$$

A.1.1.6 Reinforcement

A.1.1.6.1 Upper Slab Top Reinforcement

$$A_s = \frac{M_u}{f_y\left(d - \frac{a}{2}\right)}$$

$$A_s = \frac{(5.68kft)(12in)}{(60\ ksi)\left(10\ in - \frac{2\ in}{2}\right)} = 0.126\ in^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{(0.126\ in^2)(60\ ksi)}{0.85(4\ ksi)(12\ in)} = 0.19\ in$$

$$A_s = \frac{(5.68kft)(12in)}{(60\ ksi)\left(10\ in - \frac{0.19\ in}{2}\right)} = 0.114\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.114\ in^2}{0.11\ in^2} = 1.03\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{1.03} = 11.6\ inches$$

A.1.1.6.2 Upper Slab Bottom Reinforcement

$$A_s = \frac{M_u}{f_y\left(d - \frac{a}{2}\right)}$$

$$A_s = \frac{(3.83kft)(12in)}{(60\ ksi)\left(10\ in - \frac{2\ in}{2}\right)} = 0.085\ in^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{(0.085\ in^2)(60\ ksi)}{0.85(4\ ksi)(12\ in)} = 0.125\ in$$

$$A_s = \frac{(3.83\ kft)(12in)}{(60\ ksi)\left(10\ in - \frac{0.125\ in}{2}\right)} = 0.077\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.077\ in^2}{0.11\ in^2} = 0.7\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{0.7} = 17.1\ inches$$

The spacing between tension reinforcement in slabs shall not be greater than 3 times the effective depth or 300 mm (11.8 inches). Therefore, the top and bottom reinforcement in the upper slab will be spaced at 10 inches. (No. 3 bars @ 10 in)

A.1.1.6.3 Upper Slab Temperature and Shrinkage Reinforcement

$$A_s = \rho bd = (0.0018)(12\ in)(10\ in) = 0.22\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.22\ in^2}{0.11\ in^2} = 2\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{2} = 6\ inches$$

The temperature and shrinkage reinforcement for the upper slab will be No. 3 bars @ 6 inches.

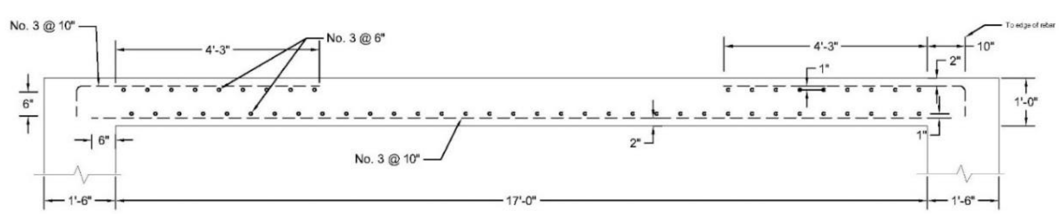


Figure 81. Reinforcement layout for upper slab

A.1.1.6.4 Lower Slab Top Reinforcement

$$A_s = \frac{M_u}{f_y\left(d - \frac{a}{2}\right)}$$

$$A_s = \frac{(10.01kft)(12in)}{(60\ ksi)\left(15\ in - \frac{2\ in}{2}\right)} = 0.143\ in^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{(0.143\ in^2)(60\ ksi)}{0.85(4\ ksi)(12\ in)} = 0.21\ in$$

$$A_s = \frac{(10.01kft)(12in)}{(60\ ksi)\left(15\ in - \frac{0.21\ in}{2}\right)} = 0.13\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.13\ in^2}{0.11\ in^2} = 1.1\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{1.1} = 10.1\ inches$$

A.1.1.6.5 Lower Slab Bottom Reinforcement

$$A_s = \frac{M_u}{f_y\left(d - \frac{a}{2}\right)}$$

$$A_s = \frac{(14.35\ kft)(12in)}{(60\ ksi)\left(15\ in - \frac{2\ in}{2}\right)} = 0.205\ in^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{(0.205\ in^2)(60\ ksi)}{0.85(4\ ksi)(12\ in)} = 0.3\ in$$

$$A_s = \frac{(14.35\ kft)(12in)}{(60\ ksi)\left(15\ in - \frac{0.3\ in}{2}\right)} = 0.19\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.19\ in^2}{0.11\ in^2} = 1.75\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{1.75} = 6.8\ inches$$

The spacing between tension reinforcement in slabs shall not be greater than 3 times the effective depth or 300 mm (11.8 inches), whichever is smaller. Therefore, the top and bottom reinforcement in the lower slab will be spaced at 6 inches. (No. 3 bars @ 6 in)

A.1.1.6.6 Lower Slab Temperature and Shrinkage Reinforcement

$$A_s = \rho bd = (0.0018)(12\ in)(15\ in) = 0.33\ in^2$$

$$No.3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.33\ in^2}{0.11\ in^2} = 3\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{3} = 4\ inches$$

The temperature and shrinkage reinforcement for the floating base lower slab will be No. 3 bars @ 4 inches.

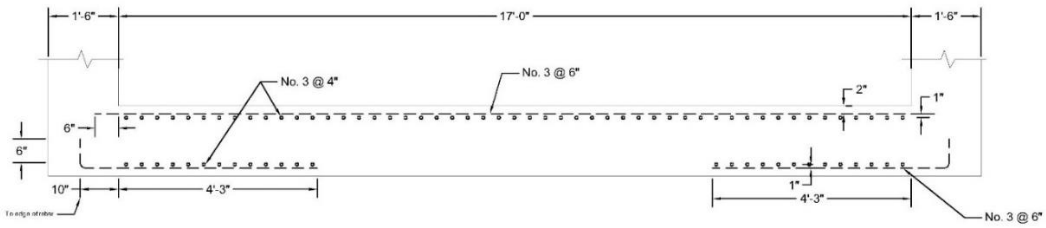


Figure 82. Reinforcement layout for lower slab

A.1.1.6.7 Wall Reinforcement

$$A_s = \frac{M_u}{f_y\left(d - \frac{a}{2}\right)}$$

$$A_s = \frac{(14.35\ kft)(12in)}{(60\ ksi)\left(15\ in - \frac{2\ in}{2}\right)} = 0.205\ in^2$$

$$a = \frac{A_s f_y}{0.85 f_c' b} = \frac{(0.205\ in^2)(60\ ksi)}{0.85(4\ ksi)(12\ in)} = 0.30\ in$$

$$A_s = \frac{(14.35\ kft)(12in)}{(60\ ksi)\left(15\ in - \frac{0.30\ in}{2}\right)} = 0.193\ in^2$$

$$No. 3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.193\ in^2}{0.11\ in^2} = 1.75\ bars\ per\ foot\ necessary$$

$$maximum\ bar\ spacing = \frac{12\ in}{1.75} = 6.8\ inches$$

Bars cannot be spaced more than 6.8 inches apart. Therefore, use No. 3 bars @ 6 inches for floating base walls.

$$A_s = \rho bd = (0.0018)(12\ in)(15\ in) = 0.33\ in^2$$

$$No. 3\ bar\ diameter = 0.11\ in^2$$

$$\frac{0.33\ in^2}{0.11\ in^2} = 3\ bars\ per\ foot\ necessary$$

$$\frac{12\ in}{3} = 4\ inches$$

Temperature and shrinkage reinforcement shall not be spaced more than 5 times the effective depth or 450 mm (17.7 inches), whichever is smaller. Therefore, No. 3 bars at 4 inches will be used as the temperature and shrinkage reinforcement for the floating base walls.

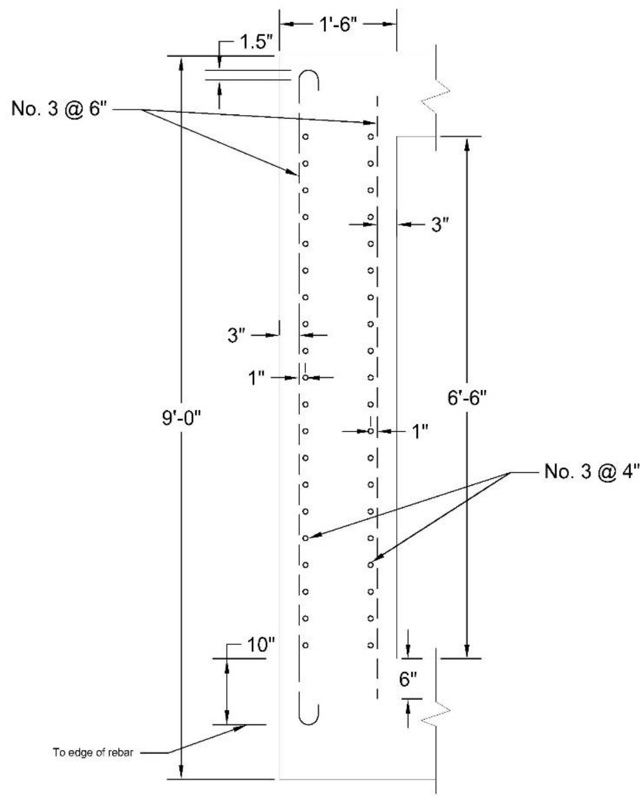


Figure 83. Reinforcement layout for floating base wall

A.1.2 Guide Post Design

Lateral loads such as wind and flood loads controlled the design of the guide posts. It was determined that the posts would experience their largest lateral load during a 100-year storm. In such a load scenario, it is assumed that flood levels would be at the design still water elevation, and winds would act at the design wind speed for the region, given by ASCE 7-10. Therefore, the piers are designed to resist both the transferred wind load from the structure and lateral flood loads during a large storm event.

A.1.2.1 Wind Loads

The expected wind loads affecting the individual piers were calculated using standard formulation provided by ASCE 7-10. The single-family home used in this study was classified as a Risk Category II structure along the New Jersey coastline, which has a design wind speed of 130 mph [33]. Three wind load cases were considered in the wind load analysis.

Figure 84. 100% of wind load applied in X-direction

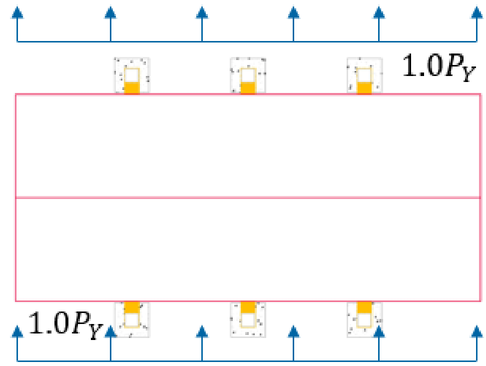


Figure 85. 100% of wind load applied in Y-direction

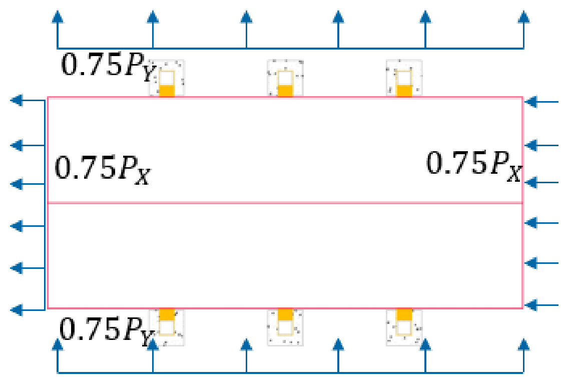


Figure 86. 75% of wind load applied in X & Y direction

For each load case, the resultant point load from q_z was calculated for two heights; the mid-wall height, and the mid-roof height. The combined total lateral load due to wind for an individual pier was then calculated

Case 1

$$q_{wall} = 0.00256 K_z K_{zt} K_d V^2 \frac{lb}{ft^2} = 0.00256(1.05)(0.85)(1.0)(130\ mph)^2 = 38.6 \frac{lb}{ft^2}$$

$$W_{wall} = \left(38.6 \frac{lb}{ft^2}\right)(360\ ft^2) = 13896\ lbs = 13.9\ k$$

$$q_{roof} = 0.00256 K_Z K_{zt} K_d V^2 \frac{lb}{ft^2} = 0.00256(1.104)(0.85)(1.0)(130\ mph)^2 = 40.6 \frac{lb}{ft^2}$$

$$W_{roof} = \left(40.6 \frac{lb}{ft^2}\right)(225\ ft^2) = 9135\ lbs = 9.14\ k$$

$$Guide\ Post\ Lateral\ Load = 2\left(\frac{W_{wall}}{6}\right) + 2\left(\frac{W_{roof}}{6}\right) = 2\left(\frac{13.9\ k}{6}\right) + 2\left(\frac{9.14\ k}{6}\right) = 7.67\ k$$

$$Reduced\ Lateral\ Load = \frac{7.67}{R} = \frac{7.67}{2.5} = 3.1\ k$$

Case 2

$$q_{wall} = 0.00256 K_Z K_{zt} K_d V^2 \frac{lb}{ft^2} = 0.00256(1.05)(0.85)(1.0)(130\ mph)^2 = 38.6 \frac{lb}{ft^2}$$

$$W_{wall} = \left(38.6 \frac{lb}{ft^2}\right)(160\ ft^2) = 6176\ lbs = 6.2\ k$$

$$q_{roof} = 0.00256 K_Z K_{zt} K_d V^2 \frac{lb}{ft^2} = 0.00256(1.104)(0.85)(1.0)(130\ mph)^2 = 40.6 \frac{lb}{ft^2}$$

$$W_{roof} = \left(40.6 \frac{lb}{ft^2}\right)(50\ ft^2) = 2030\ lbs = 2.03\ k$$

$$Case\ 2\ Pier\ Lateral\ Load = 2\left(\frac{W_{wall}}{6}\right) + 2\left(\frac{W_{roof}}{6}\right) = 2\left(\frac{6.2\ k}{6}\right) + 2\left(\frac{2.03\ k}{6}\right) = 2.74\ k$$

$$Reduced\ Lateral\ Load = \frac{2.74}{R} = \frac{2.74}{2.5} = 1.1\ k$$

Case 3

$$(Case\ 1\ Guide\ Post\ Lateral\ Load)(0.75) = (7.67\ k)(0.75) = 5.75\ k$$

$$(Case\ 2\ Guide\ Lateral\ Load)(0.75) = (2.74\ k)(0.75) = 2.1\ k$$

$$Guide\ Post\ Lateral\ Load = \sqrt{(5.75\ k)^2 + (2.1)^2} = \sqrt{21.05\ k^2} = 6.12\ k$$

$$Reduced\ Lateral\ Load = \frac{6.12}{R} = \frac{6.12}{2.5} = 2.5\ k$$

Case 1 has the largest magnitude resultant load therefore, 3.1 k will be used as the applied wind load for design.

A.1.2.2 Flood Loads

The magnitude of the flood loads acting on the guide posts were determined using formulation specified by FEMA in 'Recommended Residential Construction for Coastal Areas', which cites design standards from ASCE 7-05. The flood loads acting on each guide post include the breaking wave load, hydrodynamic load and a potential debris impact load. The home is assumed to be floating at the 100-year design still water elevation to simulate the worst case bending a guide post could be subject to. Formulas for each flood load type are provided below, along with the height at which each would act in a flood scenario.

- Hydrodynamic Load: $f_{dyn} = \frac{1}{2} C_d \gamma_w V^2 A$, acting at the still water mid depth, where C_d is the drag coefficient and A is the area the load will act upon. C_d is taken as 2.25 for square piles and 1.75 for round piles.
- Breaking Wave Load for piles or columns: $F_{brkp} = \frac{1}{2} \gamma_w C_d D H_b^2$, acting at the still water flood level, where D is the width of the pile or column.
- Debris Impact Load: $F_i = \frac{\pi W V}{2 g t_i}$, acting at the still water flood level, where W is the weight of the debris and t_i is the duration of impact.

Three parameters were critical to calculate before determining each flood load. These include the design still water depth (d_s), design wave height (H_b), and design flood velocity (V), which were predetermined based on reasonable assumptions before calculating expected flood loads. Each flood load was reduced by the selected reduction factor (R) and divided among 6 guide posts to determine the individual post load.

$$d_s = 0.65(BFE - G) = 0.65(13\ ft - 5\ ft) = 5.2\ ft$$

$$H_b = 0.78(d_s) = 0.78(5.2\ ft) = 4.1\ ft$$

$$V_{upperbound} = (gd_s)^{0.5} = \left[\left(32.2\frac{ft}{s^2}\right)(5.2\ ft)\right]^{0.5} = 12.9\frac{ft}{s}$$

$$V_{lowerbound} = \frac{d_s}{t} = \frac{5.2\ ft}{1\ s} = 5.2\frac{ft}{s}$$

$$F_{dyn} = \frac{1}{2}C_d\rho V^2 A = \frac{1}{2}(1.2)\left(1.99\frac{slugs}{ft^3}\right)\left(12.9\frac{ft}{s}\right)^2 (6.2ft)(1.66ft) = 3408.3\ lbs$$

$$\frac{F_{dyn}}{(R)(6)} = \frac{3408.3\ lbs}{(2.5)(6)} = 227.3\ lbs = 0.23\ kips$$

$$F_{brkp} = \frac{1}{2}\gamma_w C_d D H_b^2 = \frac{1}{2}\left(64\frac{lb}{ft^3}\right)(1.75)(1.66\ ft)(4.1ft)^2 = 1562.7\ lbs$$

$$\frac{F_{brkp}}{(R)(6)} = \frac{1562.7\ lbs}{(2.5)(6)} = 104.2\ lbs = 0.1\ kips$$

$$F_i = \frac{\pi WV}{2gt_i} = \frac{\pi(1000\ lbs)\left(12.9\frac{ft}{s}\right)}{2\left(32.2\frac{ft}{s}\right)(0.03\ s)} = 20977\ lbs$$

$$\frac{F_i}{(R)(6)} = \frac{20977\ lbs}{(2.5)(6)} = 1399\ lbs = 1.4\ kips$$

In addition to flood loads acting directly on each post, flood loads acting on the buoyant base walls are transferred and resisted by the guide posts. Therefore, the loads on each post due to the flood are calculated below. Although FEMA recommends these loads be calculated for a total depth equal to the design still water flood level, this analysis uses the base wall clear span (CS_{wall}) of 6.5 feet as the height along which these flood loads act, since it is larger than d_s. These loads are also reduced by the reduction factor (R) and distributed among 6 guide posts.

$$F_{brkw} = \frac{\left[(45\ ft)\left[1.1C_p \gamma_w (CS_{wall})^2 + 2.4\gamma_w (CS_{wall})^2\right]\right]}{(R)(6)}$$

$$= \frac{\left[(45ft)\left[1.1(2.8)\left(64\frac{lb}{ft^3}\right)(6.5\ ft)^2 + 2.4\left(64\frac{lb}{ft^3}\right)(6.5\ ft)^2\right]\right]}{(2.5)(6)}$$

$$= \frac{(45ft)\left(5927.2\frac{lb}{ft}\right)}{(6)} = 44{,}454\ lbs = 44.5\ kips$$

$$F_i = \frac{20977\ lbs}{(R)(6)} = \frac{20977\ lbs}{(2.5)(6)} = 1399\ lbs = 1.4\ kips$$

$$F_{dyn} = \frac{\left[\frac{1}{2}C_d \gamma_w V^2 A\right]}{(R)(6)} = \frac{\left[\frac{1}{2}(1.25)\left(1.99\frac{slugs}{ft^3}\right)\left(12.9\frac{ft}{s}\right)^2(6.2ft)(45ft)\right]}{(2.5)(6)} = \frac{60539.5\ lbs}{(2.5)(6)}$$

$$= 4035\ lbs = 4.04\ kips$$

Table 14. FEMA suggested flood load combinations

Case 1	**Pile or Open Foundation in V Zone (Required)**
	F_{brkp} (on all piles) + F_i (on one corner or critical pile only) or F_{brkp} (on front row of piles only) + F_{dyn} (on all piles but front row) +F_i (on one corner or critical pile only)
Case 2	**Pile or Open Foundation in Coastal A Zone (Recommended)**
	F_{brkp} (on all piles) + F_i (on one corner or critical pile only) or F_{brkp} (on front row of piles only) + F_{dyn} (on all piles but front row) +F_i (on one corner or critical pile only)
Case 3	**Solid (Wall) Foundation in Coastal A Zone (NOT Recommended)**
	F_{brkp} (on walls facing shoreline, including hydrostatic component) + F_{dyn}; assume one corner is destroyed by debris, and design in redundancy
Case 4	**Solid (Wall) Foundation in Non-Coastal A Zone (Shown for Comparison)**
	F_{sta} + F_{dyn}

` FEMA recommends piers in certain locations be evaluated for certain loads and separates these combinations of lateral flood loads by foundation type and flood zone. The case study analyzed in this thesis studies a home in a coastal V zone. During a flood event, water moves beneath the home, and the foundation functions as an open foundation. However, flood loads still strike the base walls during these events.

Flood Load Transferred from Base Wall

$$M_{F_{dyn}} = (4.04\ k)(4.75\ ft) = 19.2\ kft$$

$$M_{F_i} = (1.4\ k)(9ft) = 12.6\ kft$$

$$M_{F_{brkw}} = (44.5\ k)(9\ ft) = 400.5\ kft$$

Direct Flood Load on Guide Post

$$M_{F_{dyn}} = (0.23\ k)(4.75\ ft) = 1.1\ kft$$

$$M_{F_i} = (1.4\ k)(9ft) = 12.6\ kft$$

$$M_{F_{brkp}} = (0.1\ k)(9\ ft) = 0.9\ kft$$

A summary of these moments on an individual guide post is provided in Table _. The first option of Case 1 is selected for the lateral flood load combination because it suggests applying the breaking wave load to all piles. Therefore, the transferred breaking wave load from the wall as well as the debris impact load is applied to each guide post.

Table 15. Applied moments on individual guide posts

	$M_{F_{dyn}}$	M_{F_i}	$M_{F_{brkw}}$ or $M_{F_{bkrp}}$
Transferred Flood Load from Base	19.2 kft	12.6 kft	400.5 kft
Direct Flood Load on Guide Posts	1.1 kft	12.6 kft	0.9 kft

Load Combinations

Load combinations were selected using ASCE 7-10, which specifies combinations 4 and 6 be utilized for strength design, with the flood load doubled. Both combinations are listed below.

$$1.2D + 1.0W + 2.0F_a + L + 0.5(L_r \; or \; S \; or \; R)$$

$$0.9D + 1.0W + 2.0F_a + 1.6H$$

$Where$

$D = dead\ load$

$W = wind\ load$

$E = earthquake\ load$

$F_a = flood\ load$

$F = load\ due\ to\ fluids\ with\ well - defined\ pressures\ and\ maximum\ heights$

$L = live\ load$

$L_r = roof\ live\ load$

$S = snow\ load$

$R = rain\ load$

$H = lateral\ earth\ pressure$

Given that the guide post analysis only considered lateral loading, loads other than the wind and flood were excluded from the analysis. Therefore, the final combination utilized to assess the effect of the applied loads is given below.

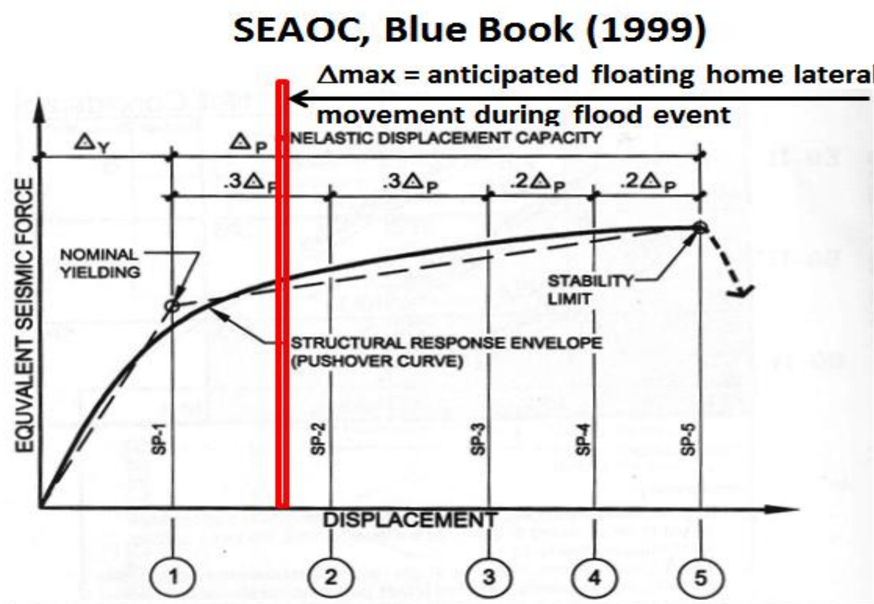
$1.0W + 2.0F_a$.

Therefore, the applied moment for design is given as: $M_{F_{bkrw}}$ M_{F_i}

$$M_u = 1.0(M_W) + 2.0(M_{F_i} + M_{F_{bkrw}}) = 1.0(27.9\ kft) + 2.0(12.6\ kft + 400.5\ kft)$$

$$M_u = 854.1\ kft$$

The minimum required plastic section modulus of a steel section to resist this bending moment is $Z = 227.8\ in^3$, assuming a 50 ksi steel strength. Therefore, an ASTM 1085 HSS 16 x 16 x ¾ is selected, with $Z = 250\ in^3$ [49]. However, given their exposure to salt water, 1/16th of an inch is removed from all sides of the square guide posts, resulting in $Z_{corroded} = 238\ in^3$, which is still larger than the minimum required plastic section modulus.



Structural Performance Level	Qualitative Description	System Displacement Limit	Inelastic Displacement Demand Ratio (IDDR))	Nonstructural Performance Level	Nonstructural Damage Ratio
SP1	Operational	Δ_y	0%	NP1	0%-10%
SP2	Occupiable	Δ_y+.3Δ_P	30%	NP2	5%-30%
SP3	Life safe	Δ_y+.6Δ_P	60%	NP3	20%-50%
SP4	Near collapse	Δ_y+.8Δ_P	80%	NP4	40%-80%
SP5	Collapsed	Δ_y+Δ_P	100%	NP5	>70%

=

Figure 87. Graphic illustrates the acceptable range of plastic displacement. Guide posts were designed to remain in the SP2 displacement range (SEAOC Blue Book, 1999)

A.1.2.3 Pushover Analysis

A pushover analysis was conducted to insure the deflections on the guide posts remain within the SP2 range.

Elastic Deflection (Δ_y)

$$\Delta_y = \frac{P_y L^3}{3EI_{corroded}} \; where \; P_y = \frac{M_y}{L}$$

$$M_y = F_y S_{corroded} = (50\ ksi)(202.7\ in^3) = 844.6\ kft$$

$$P_y = \frac{M_y}{L} = \frac{844.6\ kft}{9\ ft} = 93.8\ k$$

$$\Delta_y = \frac{P_y L^3}{3EI_{corroded}} = \frac{(93.8\ k)[(9\ ft)(12\ in)]^3}{3(29000\ ksi)(1608.9\ in^4)}$$

$$\Delta_y = 0.84\ in$$

Plastic Deflection (Δ_p)

$$\Delta_p = \theta_p(L - \frac{L_p}{2})$$

$$\frac{L_p}{2} = \frac{\left(\frac{M_p - M_y}{M_y}\right)L}{2} = \frac{\left(\frac{991.7\ kft - 844.6\ kft}{844.6\ kft}\right)(9\ ft)}{2} = 0.784\ ft = 9.4\ in$$

$$\theta_p = (\varphi_u - \varphi_y)L_p\ where\ \varphi_y = \frac{(\varepsilon_y)}{\frac{d}{2}} = \frac{\frac{F_y}{E}}{\frac{d}{2}} = \frac{\frac{50\ ksi}{29000\ ksi}}{8} = 0.0002155,\ and\ \varphi_u - \varphi_y = 25\varphi_y$$

Therefore

$$\theta_p = (\varphi_u - \varphi_y)L_p = 25(0.0002155)(9.4\ in) = 0.05065$$

$$\Delta_p = \theta_p\left(L - \frac{L_p}{2}\right) = 0.05065(108\ in - 9.4\ in)$$

$$\Delta_p = 5\ in$$

$$0.3\Delta_p = 0.3(5\ in) = 1.5\ in$$

$$\Delta_y + 0.3\Delta_p = 0.84\ in + 1.5\ in = 2.34\ in$$

Deflection due to the Applied Load

$$\Delta_u = \frac{P_u L^3}{3EI_{corroded}} = \frac{(95\ k)[(9\ ft)(12\ in)]^3}{3(29000\ ksi)(1608.9\ in^3)}$$

$$\Delta_u = 0.85\ in$$

Amplification Factor

$$\Delta_{max} = \frac{C_d(\Delta_u)}{I} = \frac{(2.5)(0.85\ in)}{1}$$

$$\Delta_{max} = 2.13\ in$$

Δ_{max} is acceptable because it is less than $\Delta_y + 0.3\Delta_p$ leaving the lateral deflection in SP2.

A.1.3 Guide Post to Floating Base Connection

ASTM A516 Grade 70 Plate Design

$$Maximum\ Lateral\ Load = P_u = 1.0W + 2.0F_a = 3.1\ kips + 2(1.4\ kips + 44.5\ kips)$$

$$P_u = 95\ kips$$

$$M_u = \frac{wL^2}{24} = \frac{\frac{(95\ kips)}{16.5\ in}(16.5\ in)^2}{24}$$

$$M_u = 65.3\ kip\ inch = 5.4\ kft$$

$$Z_x = \frac{bd^2}{4} = \frac{(17.5\ in)(0.5\ in)^2}{4} = 1.1\ in^3$$

$$Plate\ Capacity = \varphi M_n = 0.9(F_y)(Z_x) = 0.9(70\ ksi)(1.1\ in^3)$$

$$Plate\ Capacity = \varphi M_n = 69.3\ kip\ inch = 5.7\ kft$$

Anchor Rod Embedment Length

$$l_{dh} = d_b\frac{(0.02)(f_y)(\varphi_e)}{\lambda\sqrt{f_c'}} = (0.625)\frac{(0.02)(60{,}000\ psi)(1.0)}{0.75\sqrt{4000\ psi}} = 16\ in$$

Number of Anchor Rods

The number of anchor rods used in the connection design is based on the concrete pullout strength of an individual Grade 105 5/8 inch diameter anchor rod (Table 16)

$$Available\ Capacity = (19.3\ k)(6) = 115.8\ k$$

$115.6\ k > 95\ k$ therefore 6 anchor rods are sufficient to resist the expected lateral force.

Table 16. Anchor rod available pullout strength (AISC)

Rod Diameter, in.	Rod Area, A_n, in²	Bearing Area, in²	Concrete Pullout Strength, ϕN_p		
			Grade 36, kips	Grade 55, kips	Grade 105, kips
⅝	0.307	0.689	11.6	15.4	19.3
¾	0.442	0.906	15.2	20.3	25.4
⅞	0.601	1.22	20.5	27.3	34.1
1	0.785	1.50	25.2	33.6	42.0

Individual Weld Strength along Connection Plate

$$\varphi R_n = 0.6F_{exx}(0.707)(w)(L) = 0.9(0.6)(70\ ksi)(0.707)\left(\frac{3}{8}in\right)(17.5in)$$

$$\varphi R_n = 175.4\ kips$$

A.1.4 Guide Post to Foundation

$$V_c = (2)\left(2\sqrt{f'cbd}\right) = (2)(2)\sqrt{4000\ psi}(3\ ft)(12\ in)(1\ ft)(12\ in)$$

$$V_c = (2)(2\sqrt{}(f^{\wedge\prime}\ c)\ bd) = 109288\ lbs = 109.3\ kips$$

$109.3\ kips > 95\ kips$, therefore, the guide post embedment and concrete foundation thickness is sufficient to resist the expected lateral forces.

A.2 Life Cycle Cost Analysis

A.2.1 Floating Base Concrete Cost

$$Upper\ Slab\ = \frac{\$108.22}{yd^3}(33.3\ yd^3) = \$3604$$

$$Lower\ Slab\ = \frac{\$108.22}{yd^3}(50\ yd^3) = \$5411$$

$$Long\ Walls\ = \frac{\$108.22}{yd^3}(15.2\ yd^3)(2) = \$3290$$

$$Short\ Walls\ = \frac{\$108.22}{yd^3}(7.2\ yd^3)(2) = \$1559$$

$$Total\ Cost\ = \$3604 + \$5411 + \$3290 + \$1559 = \$13864$$

A.2.2 Floating Base Concrete Labor Cost

$$Upper\ and\ Lower\ Slab = \left(\frac{\$5.25}{ft^2}\right)(900\ ft^2)(2) = \$9450$$

$$Base\ Walls = \left(\frac{\$6}{ft^2}\right)(130\ ft^2)(2) + \left(\frac{\$6}{ft^2}\right)(273\ ft^2)(2) = \$1560 + \$3276 = \$4836$$

$$Total\ Cost\ = \$9450 + \$4836 = \$14286$$

A.2.3 Floating Base Rebar Cost

Upper Slab

Longitudinal Reinforcement Cost

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ longitudinal\ rebar\ every\ 10")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(42\ ft)(12\ in)}{10\ in})(25.5\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$435$$

Bottom Transverse Reinforcement Cost

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ transverse\ rebar\ every\ 6")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(17ft)(12\ in)}{6\ in})(42\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$484$$

Top Transverse Reinforcement Cost

$$= (number\ of\ bars)(length\ of\ transverse\ rebar)(bar\ weight)(cost\ per\ pound)$$

$$= (18)(42\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$256$$

$$Total\ Upper\ Slab\ Reinforcement\ Cost = \$1175$$

Lower Slab

Longitudinal Reinforcement Cost

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ longitudinal\ rebar\ every\ 6")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(42\ ft)(12\ in)}{6\ in})(25.5\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$725$$

Top Transverse Reinforcement Cost

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ transverse\ rebar\ every\ 6")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(17ft)(12\ in)}{4\ in})(42\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$725$$

$$Bottom\ Transverse\ Reinforcement\ Cost$$

$$= (number\ of\ bars)(length\ of\ transverse\ rebar)(bar\ weight)(cost\ per\ pound)$$

$$= (26)(42\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$370$$

$$Total\ Lower\ Slab\ Reinforcement\ Cost = \$1820$$

Long Wall

$$Longitudinal\ Reinforcement\ Cost$$

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ longitudinal\ rebar\ every\ 6")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(42\ ft)(12\ in)}{6\ in})(13\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$370$$

$$Transverse\ Reinforcement\ Cost$$

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ transverse\ rebar\ every\ 4")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(6.5\ ft)(12\ in)}{4\ in})(84ft)(0.376\ lb/ft)(\$0.90/lb) = \$555$$

Short Wall

$$Longitudinal\ Reinforcement\ Cost$$

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ longitudinal\ rebar\ every\ 6")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(17\ ft)(12\ in)}{6\ in})(13\ ft)(0.376\ lb/ft)(\$0.90/lb) = \$150$$

$$Transverse\ Reinforcement\ Cost$$

$$= (\frac{clear\ span}{bar\ spacing})(length\ of\ transverse\ rebar\ every\ 4")(bar\ weight)(cost\ per\ pound)$$

$$= (\frac{(6.5ft)(12\ in)}{4\ in})(34ft)(0.376\ lb/ft)(\$0.90/lb) = \$225$$

$$Total\ Wall\ Reinforcement\ Cost = (2)(\$370 + \$555) + (2)(\$150 + \$225) = \$2600$$

A.2.4 Floating Base Rebar Labor Cost

$$Upper\ and\ Lower\ Slabs = \left(\frac{\$1}{ft^2}\right)(900\ ft^2)(2) = \$1800$$

$$Walls = \left(\frac{\$1}{ft^2}\right)(1170\ ft^2) = \$1170$$

$$Total\ Floating\ Base\ Rebar\ Labor\ Cost = \$1800 + \$1170 = \$2970$$

A.2.5 Foundation Excavation

$$Excavation\ Cost = \left(\frac{\$93}{yd^3}\right)(446.5\ yd^3) = \$41{,}525$$

A.2.6 Concrete Foundation

$$Material\ Cost = \left(\frac{\$108.22}{yd^3}\right)(3.5\ yd^3)(6) + \left(\frac{\$108.22}{yd^3}\right)(33.33\ yd^3) = \$2273 + \$3607$$

$$= \$5880$$

$$Labor = \left(\frac{\$5.25}{ft^2}\right)(900\ ft^2) = \$4725$$

$$Total\ Concrete\ Foundation\ Cost = \$5880 + \$4725 = \$10605$$

A.2.7 Guide Posts

$$Guide\ Post\ Material\ Cost = (total\ combined\ post\ length)(weight)(cost\ per\ pound)$$

$$= (6\ x\ 12\ ft)\left(150.75\frac{lb}{ft}\right)\left(\frac{\$0.90}{lb}\right) = \$9769$$

$Guide\ Post\ Labor\ and\ Installation\ Cost = \$5500$

$Total\ Guide\ Post\ Cost = Material\ Cost + Labor\ and\ Installation\ Cost = \$9769 + \$5500$

$= \$15269$

A.2.8 Connections

$Plates\ around\ post$

$= (volumes\ of\ steel\ plate)(number\ of\ steel\ plates)(density\ of\ steel)(cost\ of\ steel)$

$= (157.5\ in^3)(4)\left(0.284 \frac{lb}{in^3}\right)\left(\frac{\$0.90}{lb}\right) = \$161$

$Attaching\ Plates$

$= (volumes\ of\ steel\ plate)(number\ of\ steel\ plates)(density\ of\ steel)(cost\ of\ steel)$

$= (116\ in^3)(2)\left(0.284 \frac{lb}{in^3}\right)\left(\frac{\$0.90}{lb}\right) = \$60$

$Plate\ in\ Base\ Wall$

$= (volumes\ of\ steel\ plate)(number\ of\ steel\ plates)(density\ of\ steel)(cost\ of\ steel)$

$= (1296\ in^3)(1)\left(0.284 \frac{lb}{in^3}\right)\left(\frac{\$0.90}{lb}\right) = \$332$

$Anchor\ Rods$

$= (embedment\ length)(rods\ per\ connection)(rod\ weight)(cost\ per\ pound)$

$= (16\ in)\left(\frac{1\ ft}{12\ in}\right)(6)\left(1.043 \frac{lbs}{ft}\right)\left(\frac{\$0.90}{lb}\right) = \$8$

$Material\ Cost = \$161 + \$60 + \$332 + \$8 = \$561\ per\ connection$

$Cost\ of\ Welding = \$300\ per\ connection$

$$Total\ Connection\ Cost = (\$561 + \$300)(6) = (\$861)(6) = \$5166$$

Table 17. Cost of floating home components

Floating Home Components	Cost (Materials and Labor)
Floating Base (Concrete & Rebar)	$37,255
Foundation Excavation	$41,525
Concrete Foundation	$10,605
Guide Posts	$15,269
Connections	$5166
Superstructure	$169,027
Total Cost	$278,847

Table 18. Cost of elevated home components

Elevated Home Components	Cost (Materials and Labor)
Concrete Foundation	$10,605
Guide Posts	$15,269
Superstructure	$169,027
Total Cost	$194,901

A.2.9 Elevated Homes 50-Year Total Cost

$$\boldsymbol{Direct\ Structural\ Loss} = \$\mathbf{37,154,000}$$

$$\boldsymbol{Rebuild\ Elevated\ Homes} = (\mathbf{201})(\$\mathbf{194,901}) = \$\mathbf{39,175,101}$$

$$\boldsymbol{Elevated\ Home\ Maintenance} = (\mathbf{201})(\mathbf{0.01})(\$\mathbf{194,901})(\mathbf{50}) = \$\mathbf{19,587,651}$$

$$\boldsymbol{Elevated\ Home\ Flood\ Insurance} = (\mathbf{201})(\$\mathbf{123,800}) = \$\mathbf{24,883,800}$$

$$\boldsymbol{Total\ Cost} = \boldsymbol{Structural\ Loss} + \boldsymbol{Construction} + \boldsymbol{Maintenance} + \boldsymbol{Insurance}$$

$$\boldsymbol{Total\ Cost} = \$\mathbf{37,154,000} + \$\mathbf{39,175,101} + \$\mathbf{19,587,651} + \$\mathbf{24,883,800}$$

$$\boldsymbol{Total\ Cost} = \$\mathbf{120,800,552}$$

A.2.10 Floating Homes 50-Year Total Cost

$$\boldsymbol{Prior\ Built\ Floaitng\ Homes} = (\mathbf{201})(\$\mathbf{278,847}) = \$\mathbf{56,048,247}$$

$$\boldsymbol{Residential\ Property\ Losses} = \$\mathbf{0}$$

$$\boldsymbol{Floating\ Home\ Maintenance} = (\mathbf{201})(\mathbf{0.01})(\$\mathbf{278,847})(\mathbf{50}) = \$\mathbf{28,024,124}$$

$$\boldsymbol{Floating\ Home\ Flood\ Insurance} = (\mathbf{201})(\$\mathbf{123,800}) = \$\mathbf{24,883,800}$$

$$\boldsymbol{Total\ Cost} = \boldsymbol{Loss} + \boldsymbol{Construction} + \boldsymbol{Maintenance} + \boldsymbol{Insurance}$$

$$\boldsymbol{Total\ Cost} = \boldsymbol{Loss} + \boldsymbol{Construction} + \boldsymbol{Maintenance} + \boldsymbol{Insurance}$$

$$\boldsymbol{Total\ Cost} = \$\mathbf{0} + \$\mathbf{56,048,247} + \$\mathbf{28,024,124} + \$\mathbf{24,883,800}$$

$$\boldsymbol{Total\ Cost} = \mathbf{108,956,171}$$

A.3 Post to Floating Base Alternative Connections

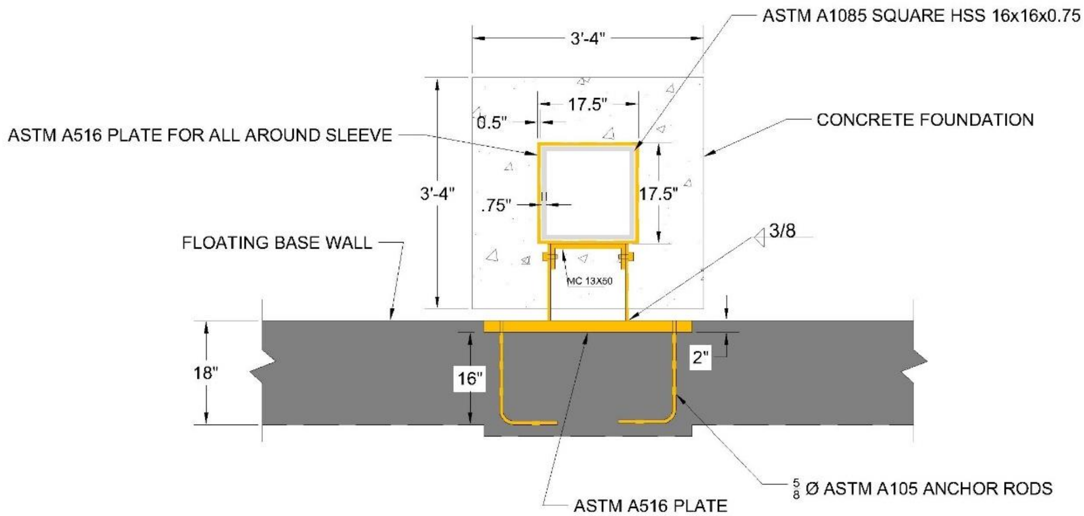


Figure 88. Plan view of Alternative Connection 1

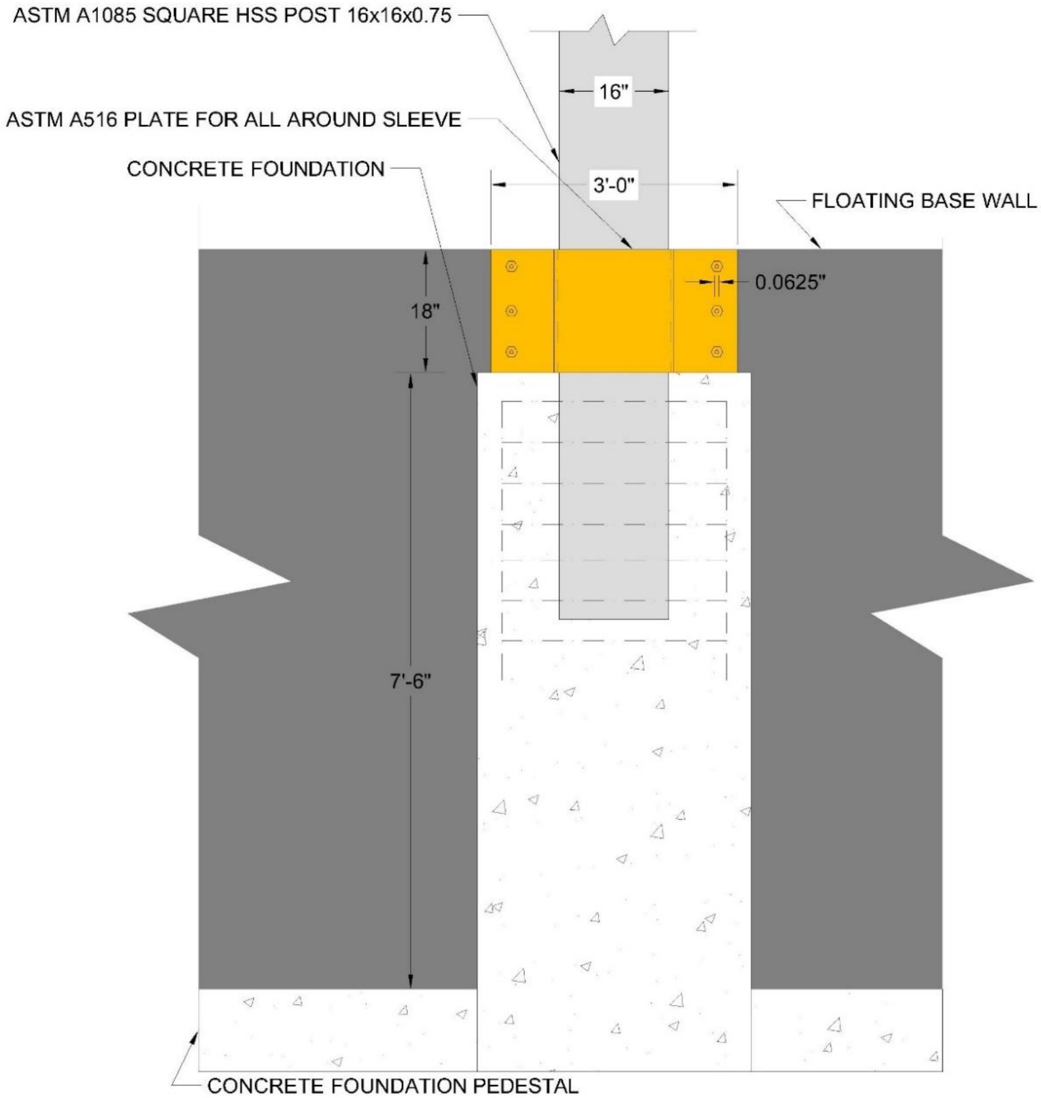


Figure 89. Front view of Alternative Connection 1

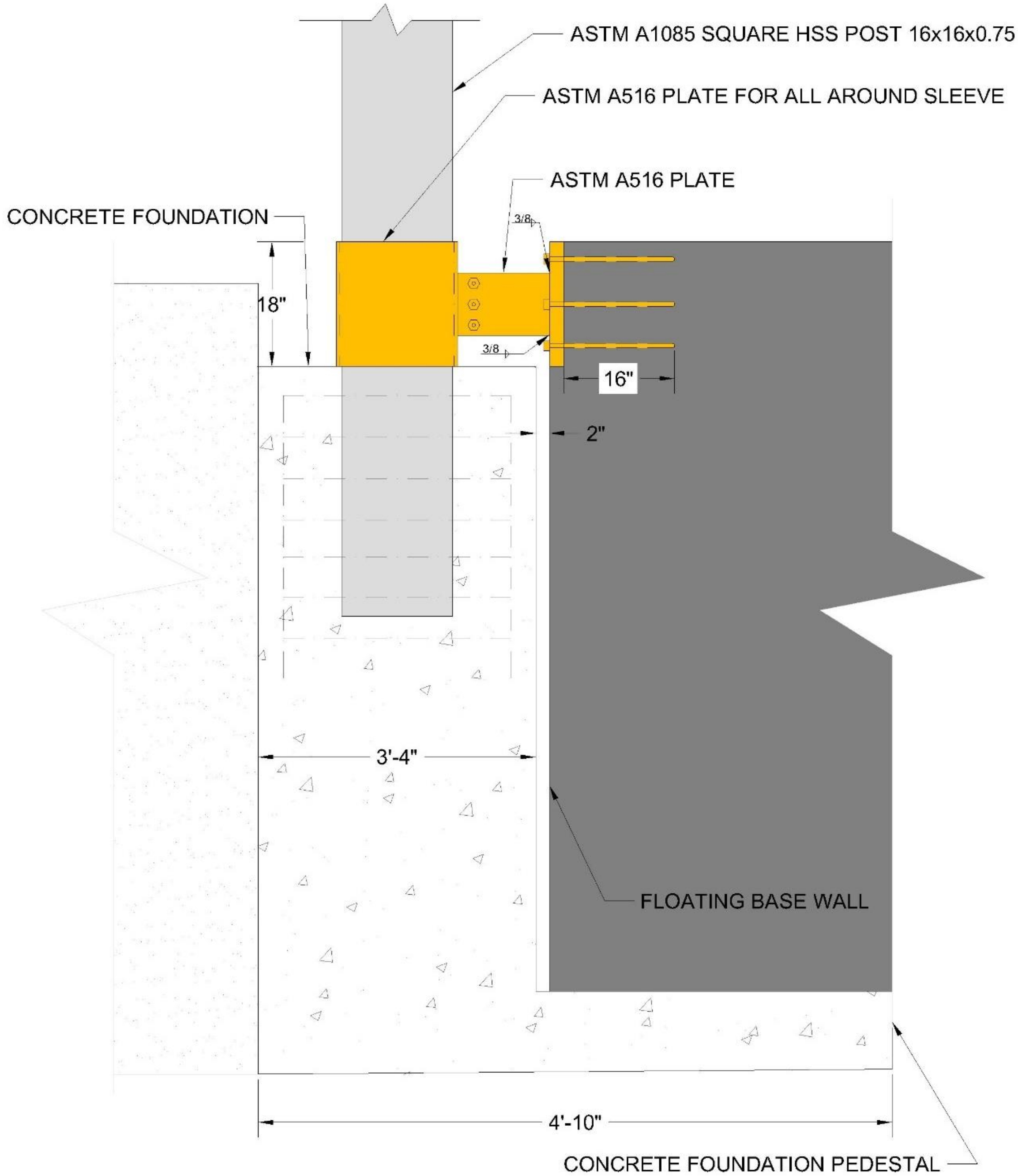


Figure 90. Side view of Alternative Connection 1

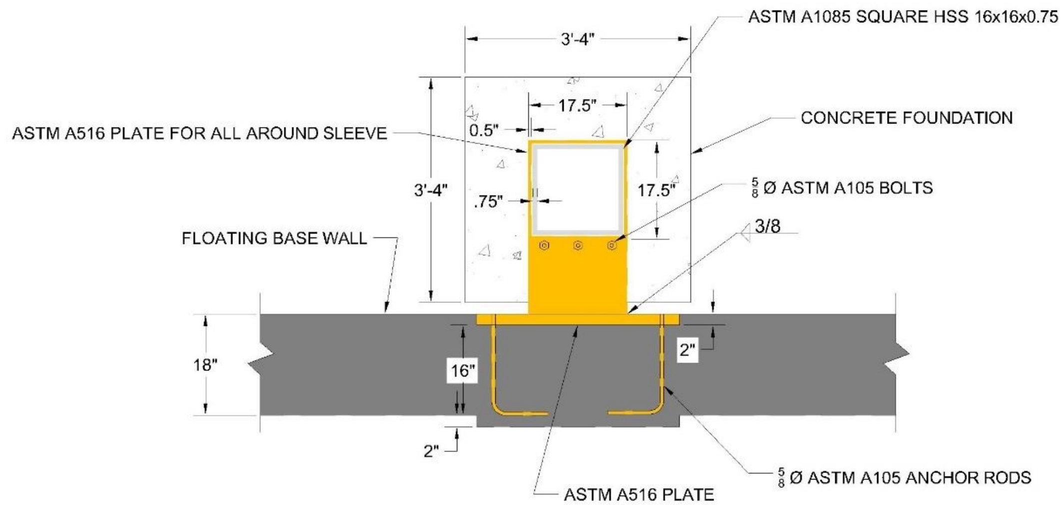


Figure 91. Plan view of Alternative Connection 2

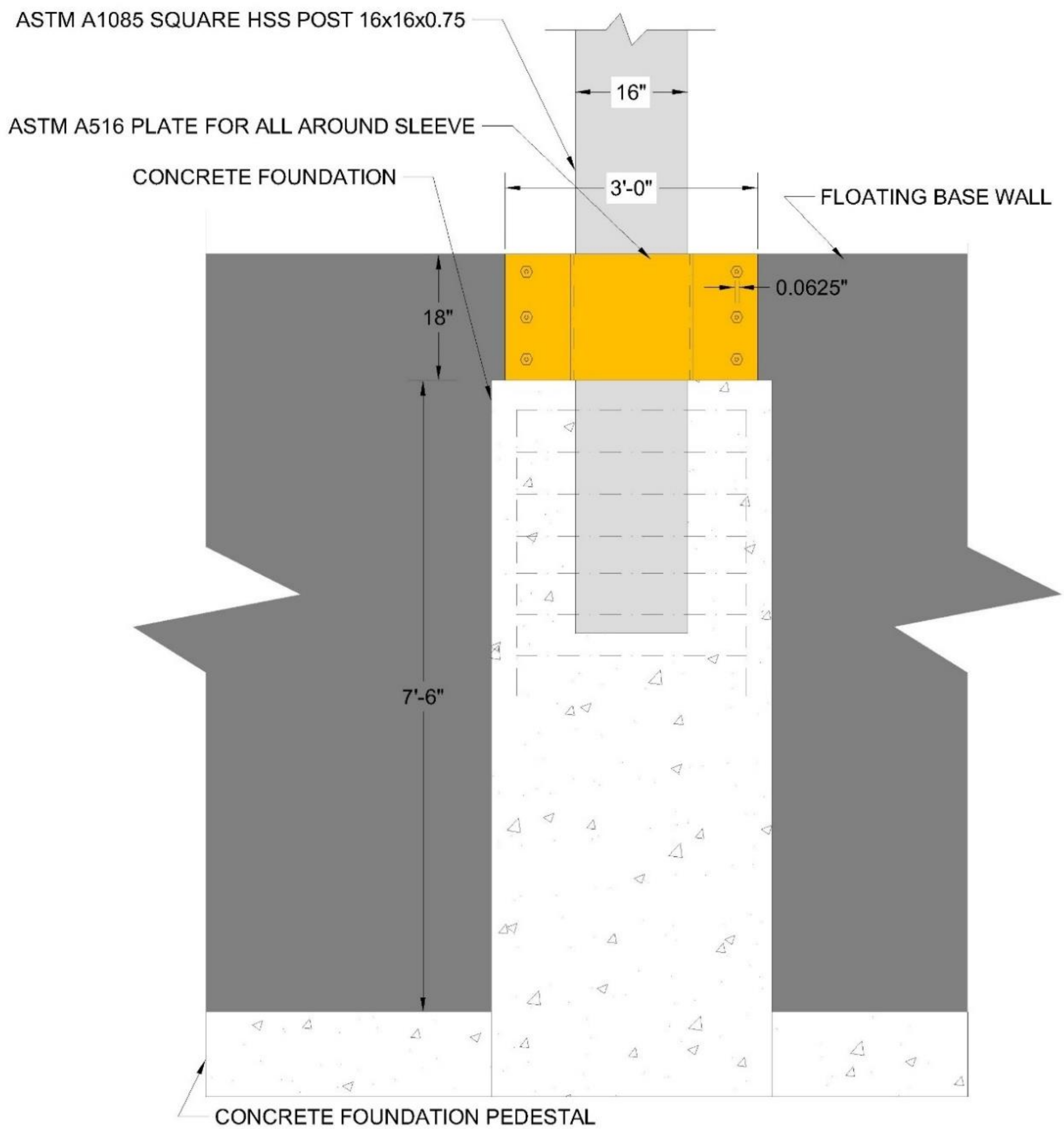


Figure 92. Front view of Alternative Connection 2

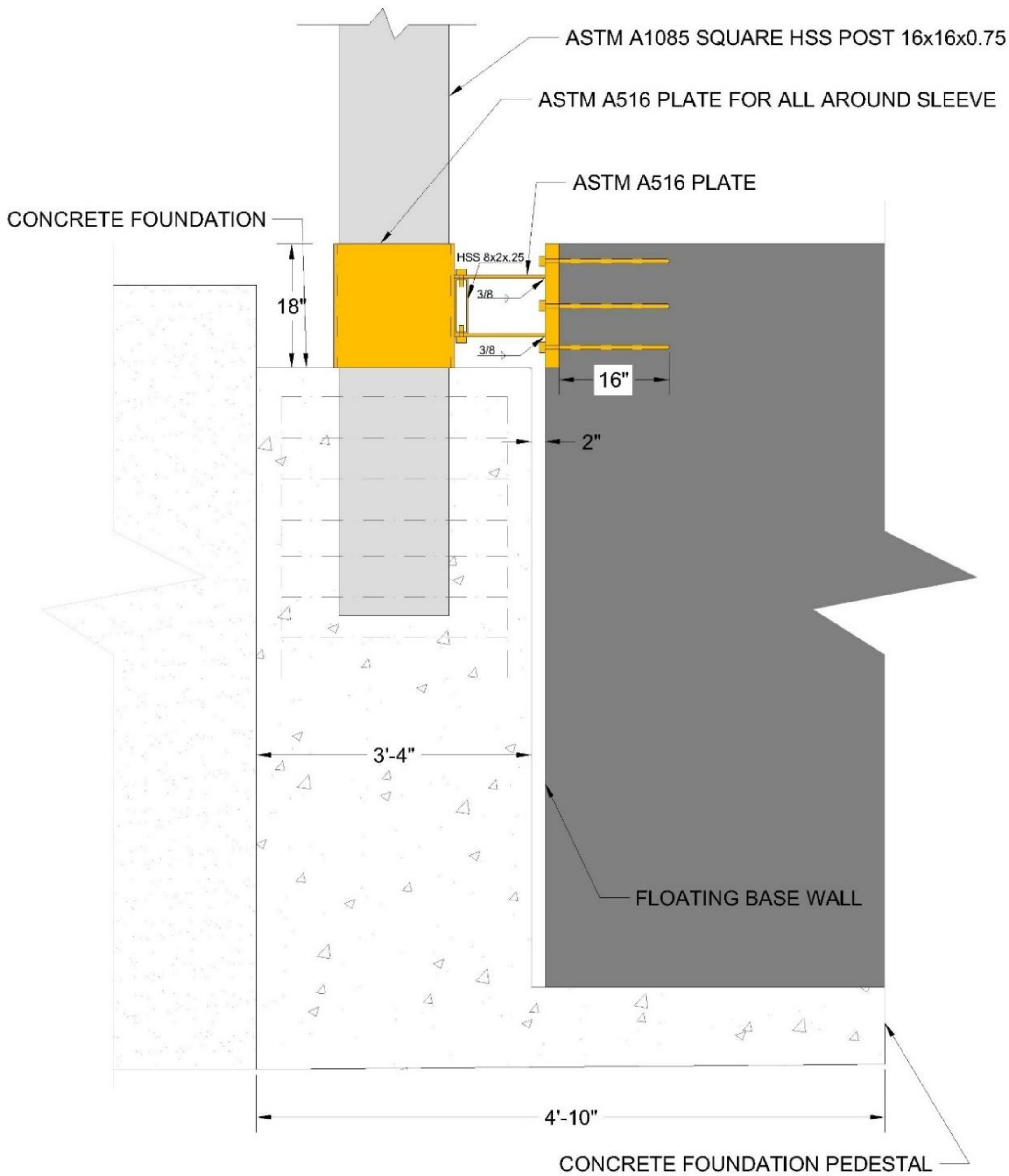


Figure 93. Side view of Alternative Connection 2

Appendix B

B.1 Floating Home Prototype

A model floating home was constructed at Rutgers University to illustrate the floating home concept. The model is composed of the materials listed below.

- Metal base frame on wheels: 24” x 30” x 30”
- Control System
- Lower reservoir tank
- Display Tank – ½” Plexiglass, 12”x12”x24”
- ½” copper tube water supply inlet
- 1 ½” PVC drainage pipe
- Submersible pump
- 2 light status indicators
  - Red light indicates rising flood
  - White light indicates receding flood

The floating home model home sits within a Plexiglas display case on a movable steel frame. There is a lower reservoir tank which sits beneath the Plexiglas encasement that is filled with water. PVC pipes connect the tank and the Plexiglas case above, acting as pathways for water travel.

The control system is a box that sits behind the model, and is operated by three primary switches, the left switch, a central orange switch, and a right switch. The configuration of these switches control whether the floating home operates manually or automatically. With the central orange switch down, the right switch down and the left switch up, the system pumps water from the lower reservoir into the display case. This simulates a quickly rising flood. However, with the left and middle switches remaining the same and the right switch up, water enters the display case slowly. This is because turning the right switch up opens an additional valve that allows water to go back into the lower reservoir. Turning the pump off by flipping down the left switch and leaving the additional valve open allows water to recede back into the tank. If the middle orange switch is turned up however, the system operates on a cycle, pumping water into the case until it reaches a desired height. Then, the water automatically recedes. This process is then repeated and allows the floating home model to be left on and the rising and falling of the house can be observed for extended periods of time. A summary of the combinations of switch statuses and their effects are in Table 19.

Table 19. Switch combinations to operate the floating home model system

Left Switch	**Middle Switch**	**Right Switch**	**Effect**
Up	Down	Down	Fast Rising Flood
Up	Down	Up	Slow Rising Flood
Down	Down	Up	Fast Receding Flood
Down	Down	Down	No Effect (Empty display case) Slow Receding Flood (Full display case)
Up	Up	Down	Automatic Cycle (Fast Rising Flood)
Up	Up	Up	Automatic Cycle (Slow Rising Flood)

Two status light indicators signal the operating status of the system. If flood waters are rising, a red light shines, and when flood waters are receding, a white light shines. The buoyancy principle discussed in the thesis causes the home to float. The pump system carries water from the tank below into the Plexiglas case above. As waters rise around the home, it becomes more buoyant. Eventually, once the appropriate volume of water is around the home, the house lifts from its resting point, maintaining a steady level in rising waters. The system is designed so that waters do not rise above the floating base height, like the concept discussed throughout this thesis.

Eight guide posts within the display case serve the same purpose as the guide posts discussed in the case study. These, in theory, prevent the floating home from moving significantly in the lateral direction as waters rise, although the model is not subject to significant lateral flood loads. Once a desired flood height is achieved, another switch is used to pump the water from the above encasement back into the tank below. This illustrates the performance of a floating structure as flood waters recede.

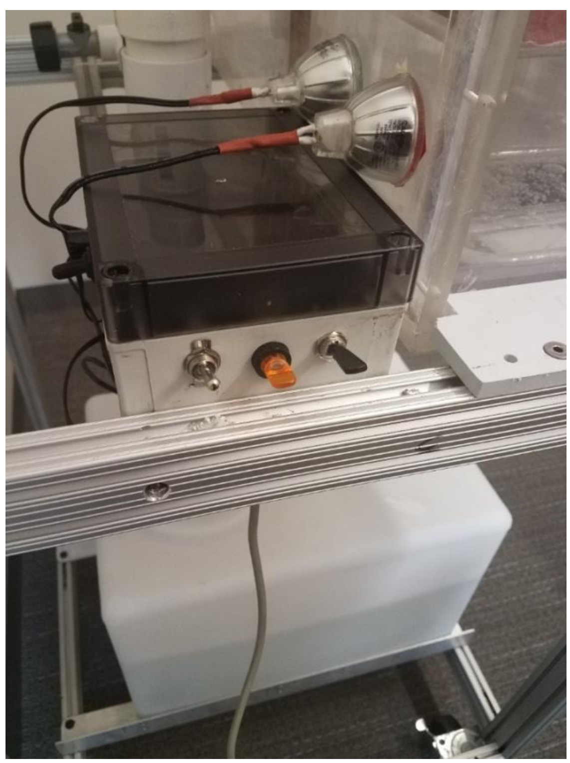


Figure 94. Control box for floating home model. Three operational switches are located on the front of the box

Figure 95. Plexiglas floating home

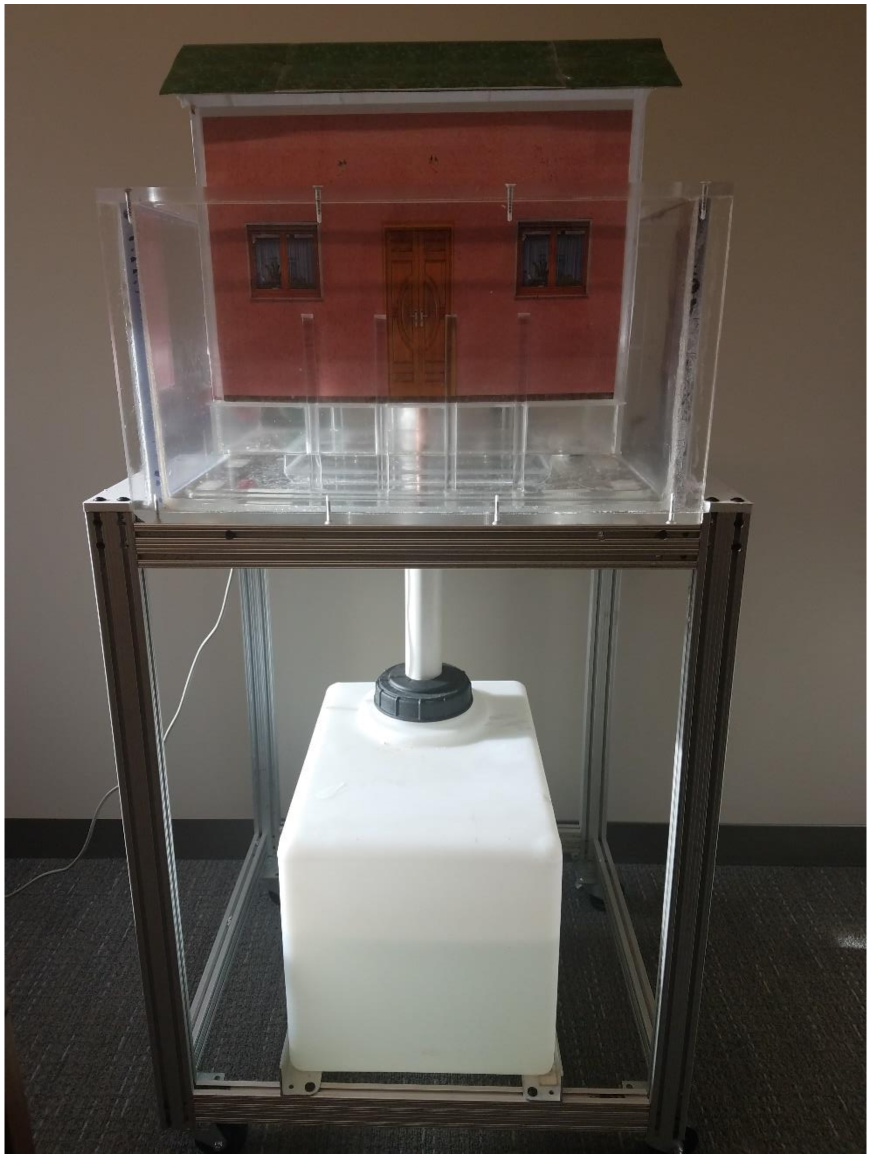


Figure 96. Plexiglas floating home model supported on a Plexiglas base and housed in a Plexiglas tank. Eight round Plexiglas guide posts (four on each side) prevent the floating model from being swept away as it floats.

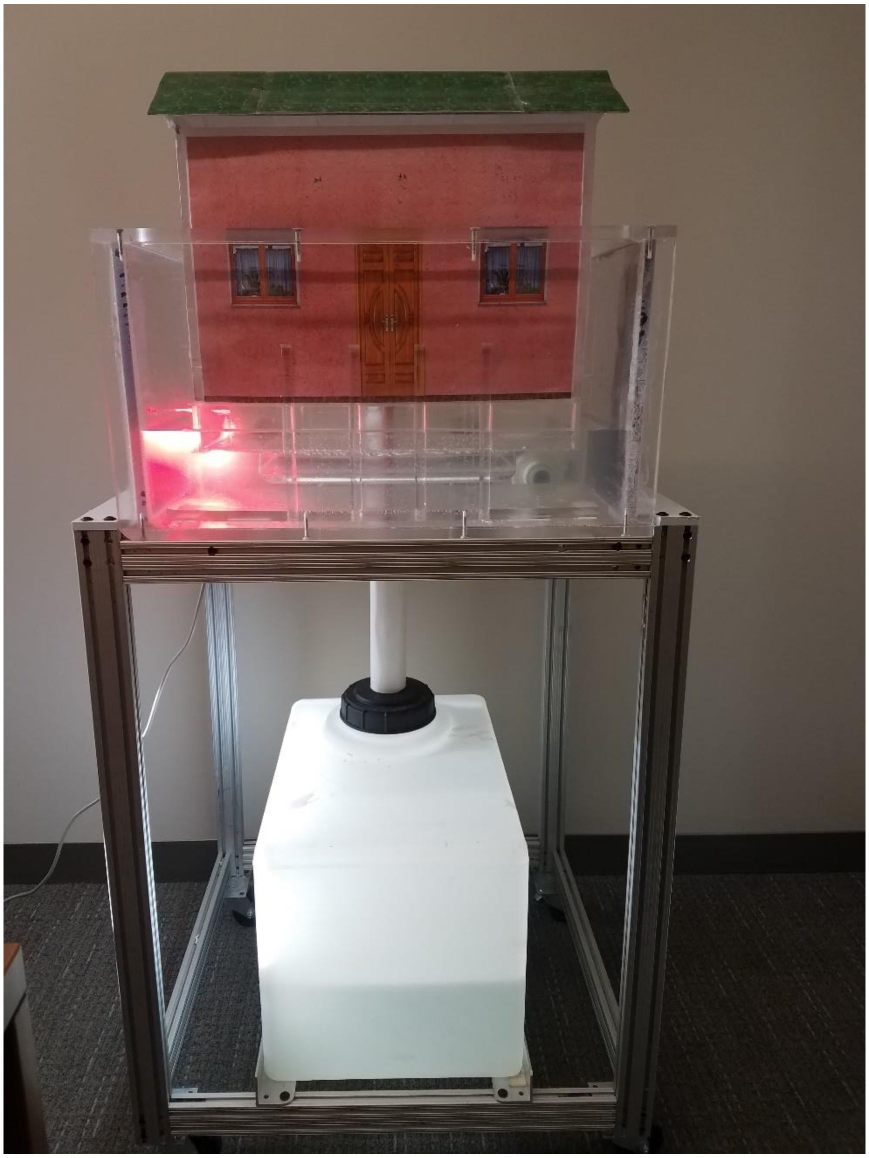


Figure 97. Water from the reservoir below is pumped into the display case once the switch is turned on. Water surrounds the floating base and the home rises gradually as the water level increases

Figure 98. The water continues to rise to the simulated flood level but stays less than the top of the base slab.