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Unveiling the Threat: Sea Level Rise and Saltwater Intrusion's Menace to Building Stability

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Abstract

The evolution of construction laws, as witnessed in the Babylonian code of King Hammurabi dating back 4000 years, marked the inception of a symbiotic relationship between occupants and builders, emphasizing safety to prevent failures. This historical perspective set the stage for a foundational approach to architecture, relying on well-designed foundation systems, stable soils, and a vertical datum based on mean sea level for building elevations. However, the contemporary scenario presents a challenge as global mean sea levels experience a significant rise, disrupting the established equilibrium.

This paper explores the implications of sea level rise (SLR) on building foundations, addressing a critical gap in current knowledge. While the scientific community widely acknowledges the escalating global mean sea level, the specific impact on building foundations remains understudied. The shifting relationships between sea level and terrestrial surfaces demand a reevaluation of existing assumptions and practices in the realm of architectural safety.

A comprehensive review of existing literature reveals a consensus on the rise in global mean sea level. However, the lack of detailed investigations into the consequences of this phenomenon on building foundations prompts a call for urgent research. The potential risks associated with SLR include compromised structural integrity, increased vulnerability to natural disasters, and economic ramifications due to damages.

This paper employs a multi-disciplinary approach, combining insights from geology, architecture, and environmental science, to elucidate the intricate interplay between rising sea levels and building foundations. Utilizing advanced modeling techniques and case studies from vulnerable regions, we aim to quantify the extent of the threat posed by SLR. The findings from this research will contribute to informed decision-making in urban planning, construction practices, and policy development.

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Introduction

The earliest known construction laws, found in the Babylonian code of King Hammurabi written 4000 years ago, effectively aligned the interests of occupants and builders to minimize or eliminate the risk of failure and ensure safety. (FS 2021) Throughout the history of architecture, the safety of buildings against collapse has rested on welldesigned foundation systems, the assumed stability of the soils, and reliance on a vertical datum for building elevations that is based on a mean sea level. While studies agree on a significant rise in global mean sea level and that the assumed relationships between sea level and dry land are changing, little is known about the extent of the effect of sea level rise (SLR) on the foundations of buildings.

On June 23, 2021, half of a building (the "Subject Building"), situated on the Atlantic shoreline of the Town of Surfside, Florida collapsed on sleeping residents at 1:30 in the morning. Immediately following this catastrophic event, which resulted in in 98 fatalities, several weeks were spent on a frantic search and rescue effort for trapped residents that sadly transitioned into disaster recovery efforts and cleaning up the rubble. The National Institute of Standards and Technology (NIST) is the Federal Agency leading the forensic investigations into the building collapse, and while the investigation is underway, much more data and information will eventually surface about the causes and circumstances behind this failure. As these investigations continue, there is sure to be ongoing debate about the responsibility of each of the stakeholders in the design, construction, inspection, and maintenance and upkeep of buildings. Concerns have been raised about the potential for other coastal buildings be similarly at risk and the impact this event would have on property values and sales of condominiums in aging buildings. However, the negative impact on sales has not materialized according to local media reports (Randall 2021).

Two south Florida counties, Miami-Dade and Broward, have a statutory requirement that all buildings over 40 years old be inspected for structural integrity. However, a Tampa Bay Times and a Miami Herald investigation indicated that less than 30% of the buildings had complied with this requirement (Tampa Bay Times 2021; Robertson, et al 2021). No other governmental agency in Florida had such a requirement, with the exception of the City of Boca Raton, which recently passed an ordinance requiring such inspections after 30 years (Austin Erblat, 2021), until Florida passed legislation in May of 2022for "Milestone Inspections" (Florida SB) consisting of structural integrity assessments for all condominium or cooperative buildings three or more stories in height and 25 or 30 years of age.

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The failed condominium tower in Surfside (Figures 1 and 2), located in Miami-Dade County, had undertaken the required structural inspection. The engineer's report, filed in 2018, identified structural issues in the basement of the building. The estimated cost to repair the structure was over $15 million dollars, which amounted to an average assessment of $120,000 per dwelling unit in a building where the average value of a unit was $600,000 (Tolan 2021). In the three years following the last report on record, none of the repairs had been undertaken.

With respect to Champlain Towers South, the residents took action to replace the Board after the 2018 engineer's report and the building's failure occurred before any agreement to correct the issues noted three years earlier could be initiated. The Town of Surfside had a copy of the report on file but had no means to enforce any corrective action. The Associated Press (AP) News service reported that "some of the damage to the concrete in the parking garage was minor, while other columns had exposed and deteriorating rebar." It also noted that "many of the building's previous attempts to fix the columns and other damages with epoxy were marred by poor workmanship and were failing" (Anderson and Condon 2021).The 2018 engineering report suggests the presence of significant cracking and reports from residents about water in the garage.

In this paper, the authors focus on the potential for sea level rise (SLR) to increase exposure to saltwater, which can accelerate corrosion of the structural elements? The sea level rise/saltwater issues that are raised in this case are as follows:

- The building is on coastal land, specifically a beach, and therefore exposed to constant salt-laden breezes.
- The foundations are frequently exposed to salty groundwater.
- Tidal action potentially directs saltwater into the substructure (in the case of this building, the garage).
- The building is 40 years old, built to a previous building code standard that assumed a stationary sea-level datum.

Figure 1. Champlain Towers prior to the collapse of the south tower. The portion of building that collapsed is on the right.

Source: "Champlain Towers South (87th Terrace view, Surfside, Miami, FL)" by Mapillary user 'Microsoft' is licensed under CC BY-SA 4.0.

Figure 2. Search and rescue teams at the site of the collapse. Photo: National Institute of Standards and Technology (NIST, 2021).

Sea Level Rise (SLR)

Various organizations document the rates of sea level rise using a variety of measurement tools. Among these are the National Oceanographic and Atmospheric Administration (NOAA 2010) and Intergovernmental Panel on Climate Change (IPCC 2013) whose projections suggest that by 2100, global temperatures will be on the order of 2-3°C higher and, consequentially, sea levels will rise by 3 feet. The NOAA (2017) intermediate high projection, which is used by the National Flood Insurance Program of the Federal Emergency Management Agency (FEMA 2018), and the United States Army Corps of Engineers projection, is 5 feet in south Florida (see Figure3). A review of tide gage data during the past 140 years also indicates an increase in sea levels. The tidal gage at Key West, Florida has the longest record (Bloetscher 2012). Various studies (Domingues et al. 2008; Gregory 2008; Vermeer and Rahmstorf 2009; Jevrejeva, Moore and Grinsted 2010; Bloetscher, et al. 2010, 2011; IPCC 2007; Heimlich et al. 2009) indicate a wide variation in projected rates of rise due to uncertainty in the dynamics of sea level rise by 2100. The rate of rise is accelerating. During the last two decades, the global rate of sea level rise has been higher than the 20th-century timemean (Gregory et al. 2012).

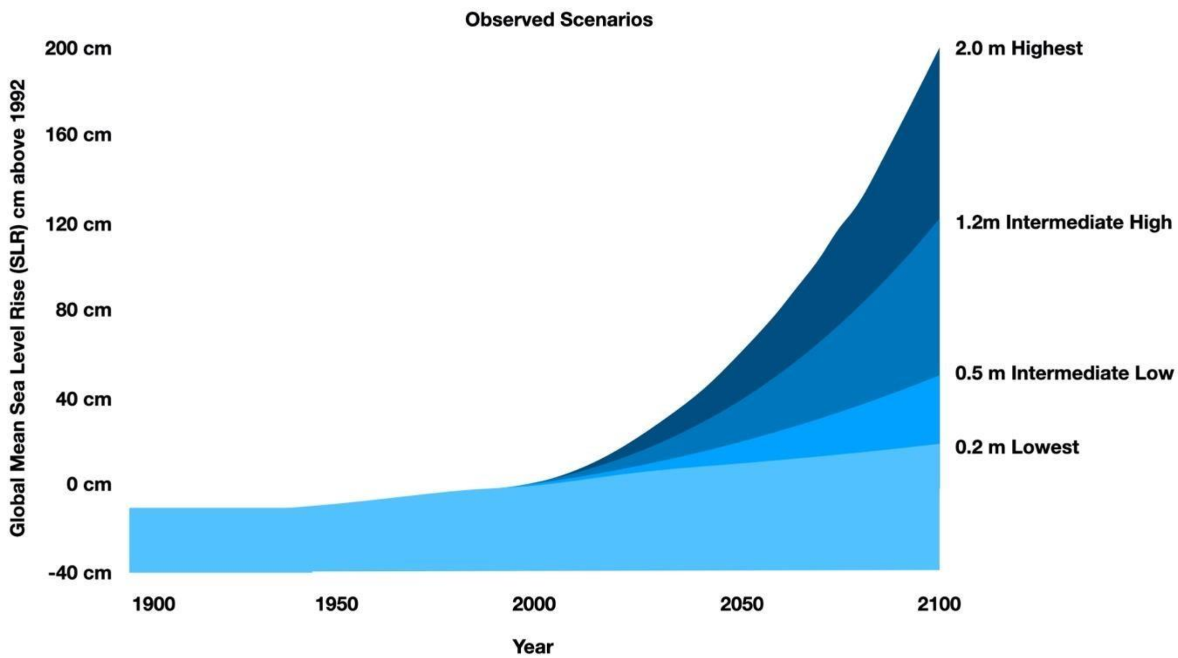

Figure 3. Graphic of sea level rise projections from NOAA

Source: Global mean sea level (GMSL) rise scenarios. Parris et al. (2012) in NOAA Technical Report NOS CO-OPS
083 (2017). Graphic edits by Abbate (2023).

Measurements of Florida's east coast (Maul 2008) present an average rate of sea level rise of 2.27 ± 0.04 mm per year from 1915 to 1992 based on tide gauge readings. From 1929 to 1992, over eight inches of sea level rise has been documented; see Figure 4 (Bloetscher 2012). There has been an additional rise of 5 inches since 1992, presenting significant impacts on coastal communities. In these areas, significant population growth and development have increased the need for improved flood management strategies (Bloetscher 2008; Parkinson 2009; Zhang et al. 2011, 2011a; NFIP 2011; Schmidt et al., 2011; Warner et al. 2012). For planning purposes, the participating counties of the Southeast Florida Regional Climate Compact (SFRCC 2012) have adopted the projection recommended by its scientific working group for years 2030 (3" to 7") and 2060 (9" to 24").

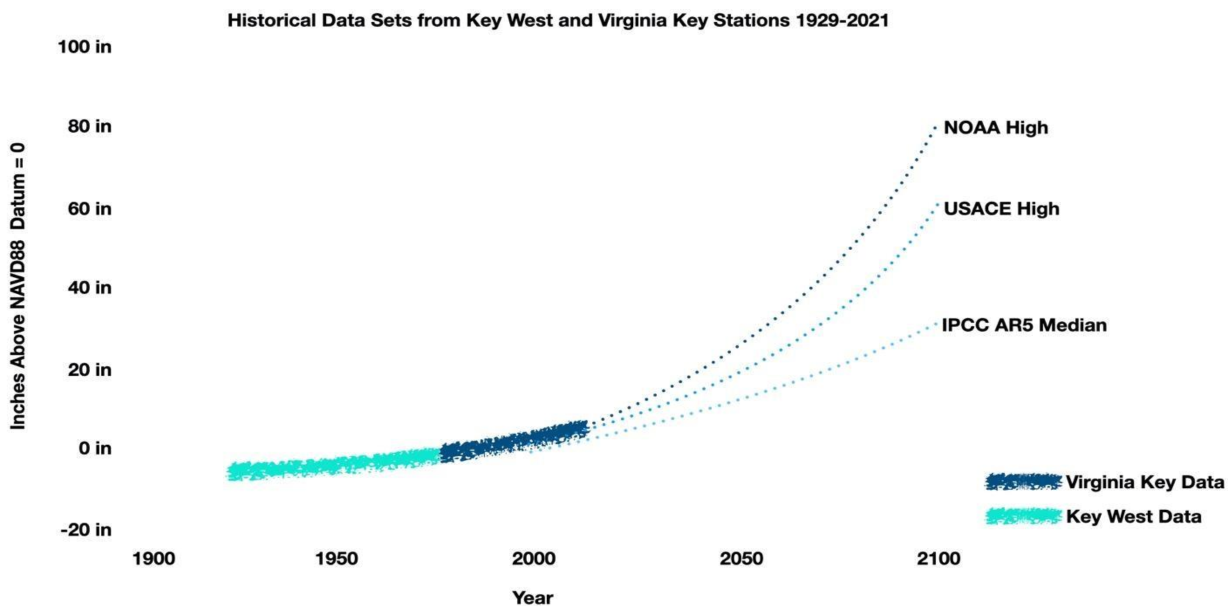

Figure 4. Historical and projected sea level rise from 1929 to 2100 – Miami Beach Station
Source: Bloetscher (2012), graphic by Abbate (2023)

Prior monitoring well studies (E Sciences 2014) also provide useful data. The City of Surfside borders the City of Miami Beach. The firm "E Sciences" was engaged by the City of Miami Beach in 2012 to evaluate vulnerable areas in anticipation of sea level rise (SLR) and assist the City in establishing baseline design elevations for stormwater facilities. The purpose of the study was to evaluate low lying areas vulnerable to SLR based on the assumption that the groundwater levels under the city are tidally influenced and therefore flooding may also be influenced or exacerbated by tidal fluctuations. To accomplish this, the E Sciences Team monitored groundwater elevations and other data over a twelve-month period from October 17, 2012, through November 4, 2013 (E Sciences 2014). The data included:

- Groundwater elevation data collected by dataloggers installed in selected monitoring wells.
- Tidal data from the Virginia Key, FL station (Station ID 8723214) in feet North American Vertical Datum of 1988 (NAVD 88) from the National Oceanic and Atmospheric Administration (NOAA) Tides & Current online database.
- Rainfall data provided by the city.

The elevation data collected was used in conjunction with Light Detection and Ranging (LiDAR) topography and tidal data to model flood vulnerability and provide guidance regarding potential stormwater priorities for the city. To account for the difference between the location of NOAA's tidal station (at Virginia Key) and the project study locations, the E Sciences Team used a one-hour correction factor as recommended by the NOAA National Ocean Service. Six stations were monitored, including a Marina site located on the southwest portion of the main island adjacent to tidal waters. E Sciences used a CT2X datalogger which measures pressure and salinity in addition to groundwater elevations. The CT2X returns a pressure measurement relative to the water above the sensor expressed in units of feet of water. During site visits, E Sciences recorded DTW measurements from the well risers using a water level indicator and compared these to the pressure measurements from the same time to determine the total distance between the top of the riser pipe to the bottom of the CT2X sensor. Based on these measurements, E Sciences converted pressure readings to DTW measurements.

The CT2X measures salinity in practical salinity units (PSU). According to information provided by the manufacturer, the CT2X calculates salinity from temperature, conductivity, and pressure measurements. Prior to installing the CT2X, the datalogger was calibrated by the manufacturer. Pressure was calibrated using 0.000, 7.500 and 15.000 pounds per square inch (psi) standards and conductivity was calibrated using a 12.88 milli-siemens per centimeter (ms/cm) standard. The dataloggers are factory calibrated by the manufacturer. Figure 5 depicts the groundwater elevation at the Miami Beach Marina (DL-6) which was within 50 feet of saltwater in the marina. During the study period an equipment failure occurred between May 24 and August 13, 2013, and thus groundwater data for this period was not collected. This gap is reflected in the assembled data presented in Figure 5. The results indicate that groundwater elevations remained generally just above the highest daily tidal elevations for the monitoring period. In addition, the water levels in the Marina generally float near high tide, and do not fluctuate like the tides do, which confirms that the groundwater is far slower to react than the tides.

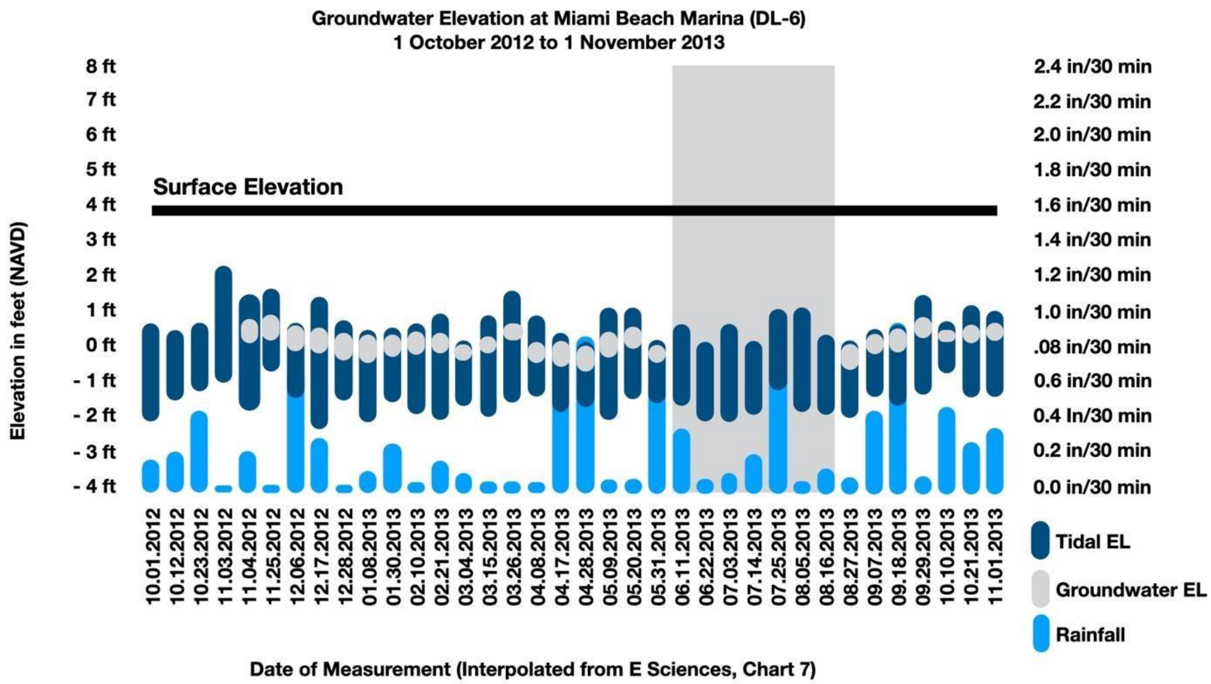

Figure 5 the groundwater elevation at the Miami Beach Marina compared to rainfall and tides. No groundwater elevation data was available from 24 May 2013 to 13 August 2013 due to equipment failure. Source: Bloetscher and Abbate (2023)

Corrosion Damage

Corrosion of reinforced concrete due to saltwater exposure is well known and the mechanisms for corrosion of steel in reinforced concrete have been well documented (Broomfield 1997; Allen 1998). Reinforcing steel is usually in a non-corroding (passive) state (Sobhan, et. al., 2021). However, because concrete is a porous material, it is pervious to water. The ingress of chloride in an aggressive saltwater environment disrupts the passive layer protecting the steel, resulting in rust or pitting corrosion (Sobhan, et. al., 2020, 2021).

Seawater contains 3.5 per cent of soluble salts by weight and the ionic concentration of Na^+ and Cl^- are maximum in seawater, generally normally 11,000 and 20,000 mg/L respectively (The Constructor ND). Chloride penetration is the greatest concern for the long-term durability of concrete structures (Angst, et. al., 2009; Gao and Wang, 2017). In the presence of saltwater, the chlorides accumulate on the concrete surface either through direct contact with the surrounding waterbody, by contaminated runoff flowing over the surface, or by exposure to saltladen airborne spray. In a tidal zone, concrete is also subject to periodic drying and wetting processes with the rising and falling tides. During wetting periods, chloride ions are brought into concrete along with seawater absorption (Liu, et. al., 2020). During drying periods, chloride diffuses from the exposed surface to the deeper areas of the structure. Cyclic wetting and drying conditions can significantly accelerate chloride penetration in concrete (Liu, et al 2020). As corrosion induced cracking increases, more saline water can penetrate the structural elements causing further corrosion and cracking. Hence, the exposure of reinforced concrete structures such as high-rise residential buildings, bridges, and piers to saline environments increases their susceptibility to the corrosion of the reinforcing steel, leading to chemical processes that accelerate physical damage of the concrete (Sobhan, et. al., 2021).

The chloride ingress process is further complicated by chloride binding, ionic interaction, aging factors, temperature, humidity, and submerged pressure effects (Johnson, and Grove 1931; Yonezawa, et. al., 1988; Borgard, et. al., 1990). After a long period of seawater exposure, (Wei, et. al., 2018) note that “a large amount of salt crystals, sand streaks, and slight exfoliation corrosion are observed on the surfaces.”

With the progress of the corrosion process, a solid corrosion product forms at the metal-concrete interface that absorbs water and expands in volume (Sobhan, et al 2021). This expansion exerts pressure on the concrete, resulting in cracking and spalling. At this stage of the process, the concrete no longer protects the reinforcing steel effectively (Liu, et al 2020), which accelerates the flow of chloride ions to the steel.

The corrosion-related expansion of the steel material reduces the mass of the steel member (Bossio, et. al., 2019; Xiong, et. al., 2019; Wei, et. al, 2018) note that corrosion of steel bars seriously compromises the long-term safety of reinforced concrete (RC) structures and reduces their functional lifespan (Djeddi, et. al., 2018). Corrosion degrades the reinforcement resulting in section loss and/or debonding with the surrounding concrete. The process accelerates as corrosion proceeds, resulting in additional and accelerated cracking and spalling of the concrete (Sobhan, et al 2021). With corroded members, durability modelling is complicated by the presence of cracks in the concrete, fatigue in the internal reinforcing, and changes to the reinforcing alloy and microstructure. The percent mass loss in concrete beams tested after accelerated corrosion can be as much as 50% to 72% (AASHTO 2009; Aligizaki, 2005; Dubois, et. al., 2008; Reddy, et. al., 2013).

Nolan et. al. (2021) noted that “traditional construction materials cannot reliably meet all these challenges for long-life coastal structures without periodic and often costly intervention.” The concern was also referenced the ASCE report card on the condition of bridge infrastructure (ASCE 2017, Reitsema, et. al., 2020). Clark (2020) notes that “the most serious threat to bridges in Florida is the corrosion of steel reinforced concrete substructures in coastal regions.”

Research Objective

The question to be evaluated was whether there is evidence for the increased likelihood of saltwater exposure due to sea level rise, compared to the assumed stationarity of sea level in 1979 when the Surfside building was designed. As a part of this effort, data will continue to be developed to determine the frequency of foundation exposure to saltwater conditions.

Methodology

To evaluate the potential for salt water to saturate or inundate the building data was gathered from the longterm trends for sea level rise, at the nearest NOAA tidal gage at Virginia Key and from two shallow groundwater monitoring wells located in proximity to the building site (see Figure 6). The tide values relate to the NAVD 88 datum, while the original construction of the Champlain Towers in 1979 assumed the 1929 datum. Freshwater will sit on top of saltwater due to density differences. The density differential is calculated using a derivation of the Ghyben-Herzberg principle. Note the Ghyben-Herzberg relation does not apply at a nonequilibrium condition which would appear to be the situation at the immediate coastline as the tides rise and fall. In simple form, the result is approximately equal to the following relationship: $z \approx 40h_f$

where, z = depth to saltwater from datum below the freshwater and h_f = height of groundwater above the datum. This implies that 1 ft of freshwater will depress saltwater 40 feet in conditions of equilibrium.

Figure 6. Location of the monitoring wells near the Town of Surfside

Abbate and Bloetscher, based on data from Miami Dade County GIS https://gisweb.miamidade.gov/NSPApp/NSPApp.htm

The architectural and engineering plans for Champlain Towers South were acquired and reviewed to determine the design elevations of the garage floor and foundation. Figure 7 shows the elevation of the Subject Building. The finished floor elevation of the Subject Building was 2 feet, 2 inches NGVD 1929 (or 2.17 ft). To convert between different datums or reference frames, the National Geodetic Survey Coordinate Conversion and Transformation Tool (NCAT) is used (https://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl). The difference between the two vertical datums at the subject building in Surfside is 1.555 feet. Therefore, the floor of the garage is at 2.1677-1.555 =0.61 feet. The garage floor is an 8-inch-thick concrete slab, meaning the bottom of the slab is at elevation -0.06 NAVD 88. The slab rested on the pile caps. Figures 8 to 10present the columns in the building, garage floor column plan and pile cap locations respectively. The reinforced concrete pilings appear to be 24” in diameter. Figure 11 shows that the pile caps are 3’-6” to 4’-0” thick, meaning they are all below -0.6 ft NAVD 88.

Based on the building details and the tide gages, comparisons will be made to identify the frequency of exposure of the floor and foundation to saltwater and how much freshwater might exist above the saltwater at this location.

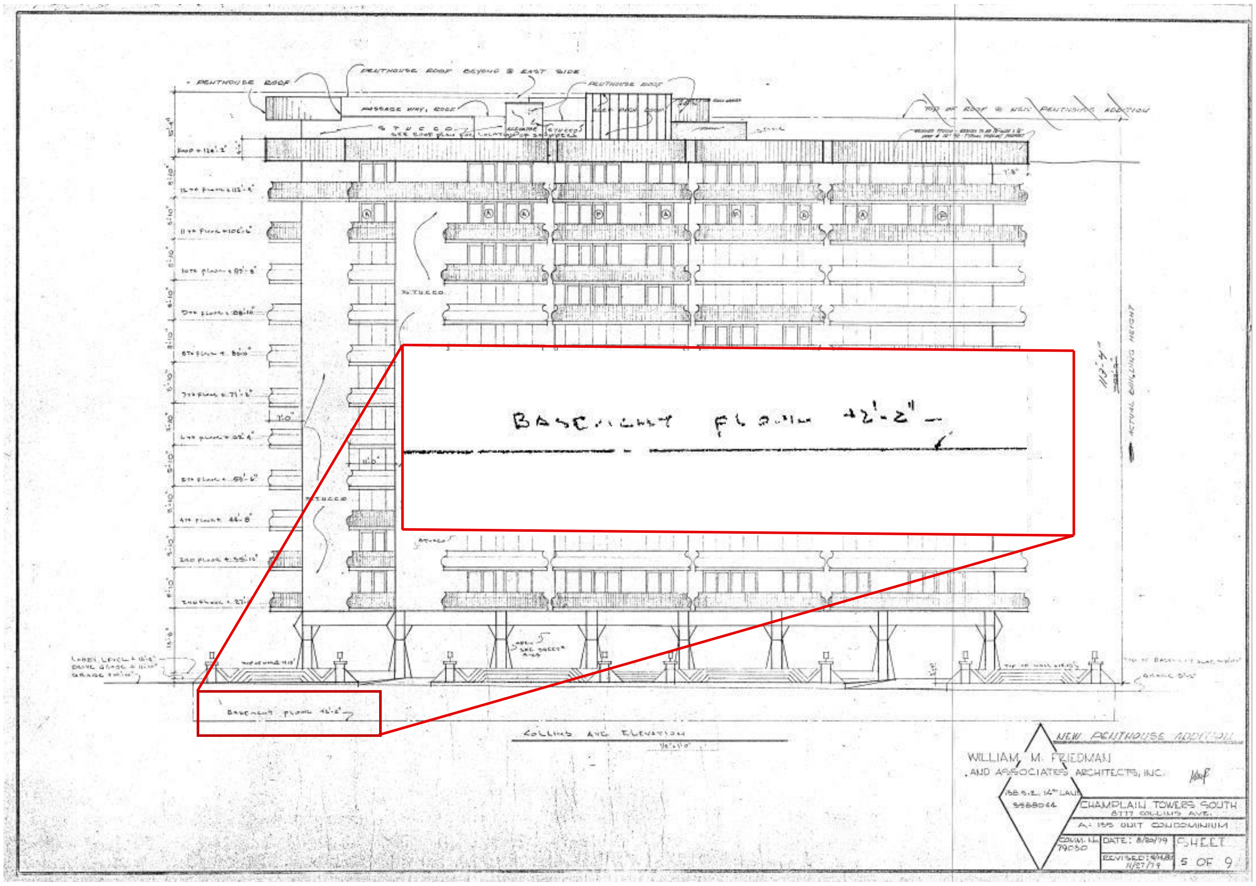

Figure 7. Elevation of the Champlain Towers South building indicating the garage floor at elevation 2' -2". Source: Freidman (Town of Surfside, Public Records. 1979.) Sheet 8 of 30.

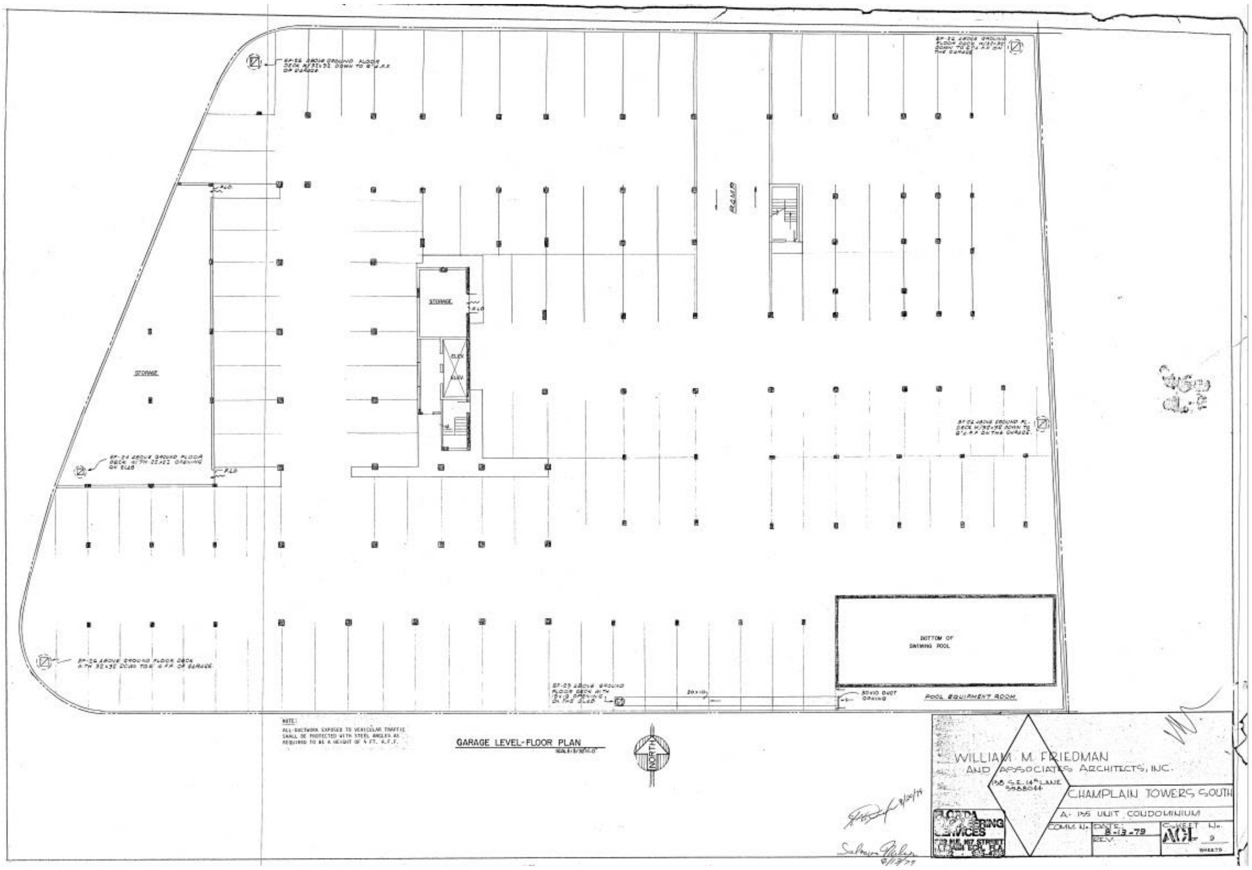

Figure 8. Location of the columns and walls at the garage level in the Champlain Towers South building.
Source: Freidman (Town of Surfside, Public Records. 1979.) Sheet AC1 of 9

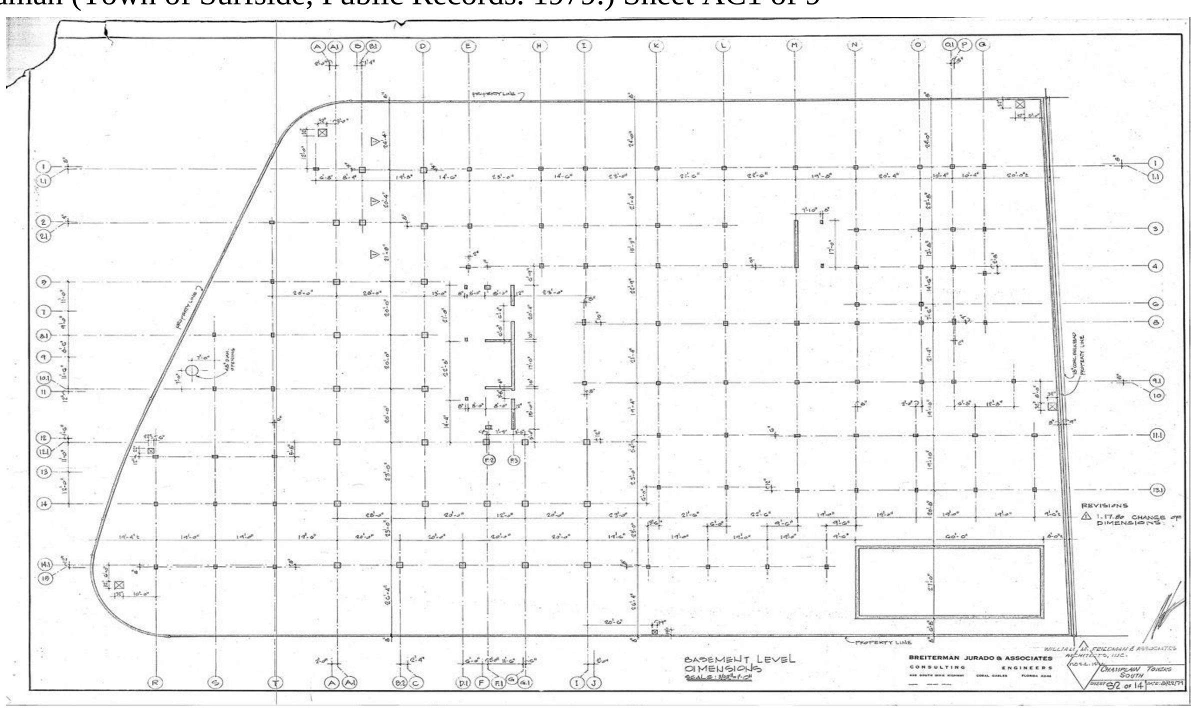

Figure 9. Location of the structural columns and walls at the garage level in the Champlain Towers South building. Source: Brieterman, Jurado & Friedman (Town of Surfside, Public Records. 1979.) Sheet S2 of 14.

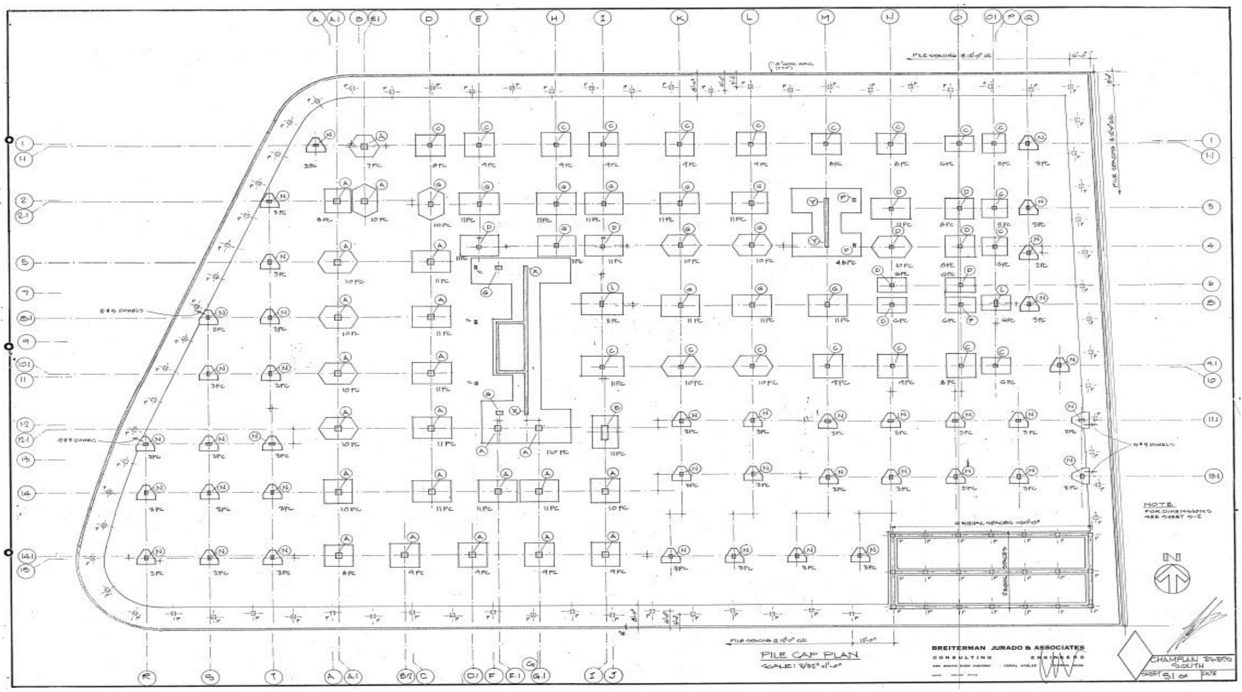

Figure 10. Location of pile caps in the Champlain Towers South building. Source: Brieterman, Jurado & Friedman (Town of Surfside, Public Records. 1979.) Sheet S1.

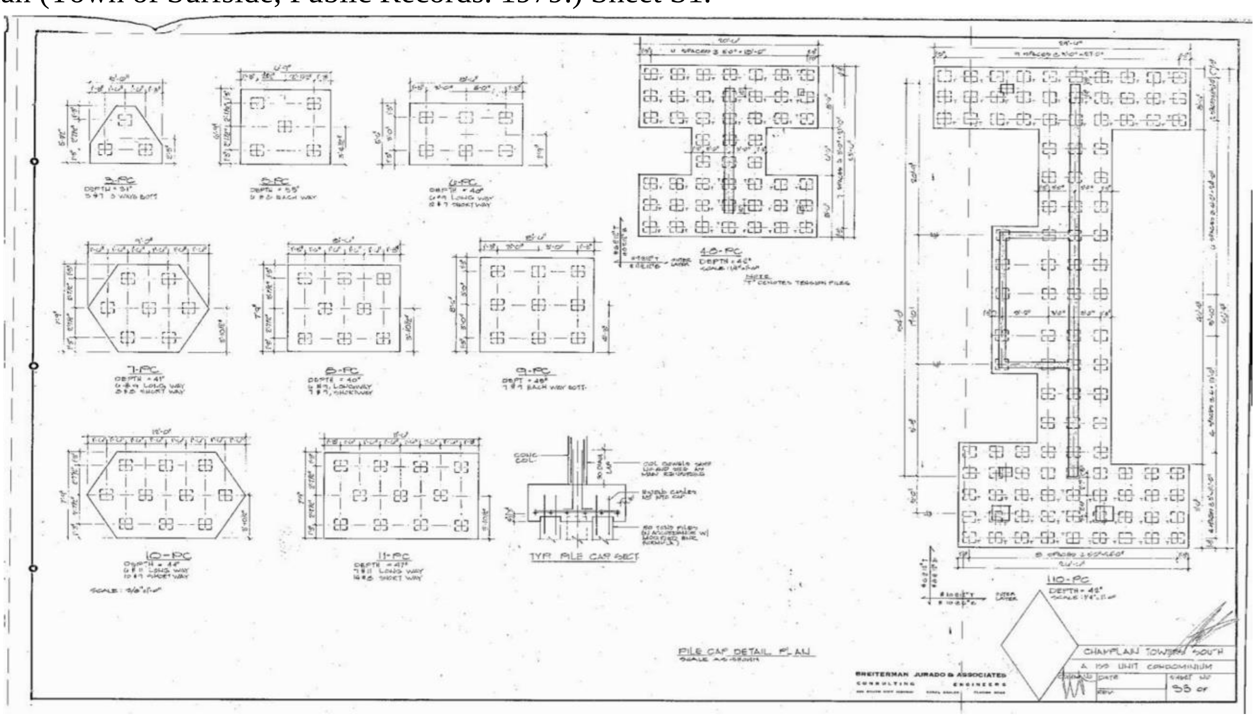

Figure 11. Pile cap details. Note that pile caps are located below the garage floor. Source: Brieterman, Jurado & Friedman (Town of Surfside, Public Records. 1979.) Sheet S3.

Results

The fluctuation of high and low tides is a twice daily occurrence in South Florida. The elevation of high tides is influenced by the combined gravitational forces of the earth, moon and sun. The highest tide levels occur twice annually when these bodies are aligned at perigean and perihelion. The annual and daily tidal cycles are shown in Figure 12 for the Virginia Key NOAA site, while Figure 13 shows the Virginia Key ("VK") site in addition to the two closest wells in Miami Beach at Stillwater Park ("SWP") and North Band Shell ("NSP"). Ten years of data is available for all three locations (there is 40 years of data at Virginia Key), which includes over 25,000 observations. The correlation between the three sites is indicated as follows:

VK SWP: 0.518452

Because historical data is not available for the Miami Beach wells, the correlation, especially with the NSP site, indicates that the Virginia Key site can be used as a surrogate to project the water levels at the SWP and NSP sites backwards and forward.

Based on an analysis of the groundwater at the two wells on the island, versus the tides (accounting fora 1hour delay for groundwater movement), the SWP site appears to be a few inches higher than the VK site for most of the time and presented less so for the NSP site. Figure 14indicates the difference between the two sites mapped chronologically. This data indicates that while freshwater may present above the saline water much of the time, there are many periods when the tides are higher than the measured groundwater levels, indicating the absence of appreciable freshwater at the sites. The presence or absence of a freshwater lens is justified by the Ghyben-Herzberg principle discussed earlier (see Figure 15).

Figure 16 shows the daily tidal trend at Virginia Key. Tides have been increasing over the past 10 years indicating the likelihood of more frequent saltwater saturation at the foundation. The estimated water levels under Champlin Towers present a condition where the wetting and drying, freshwater and saltwater cycles repeated with regularity. Correlating the tidal and garage floor elevations (see Figure 17: the red dashed line marks the garage floor elevation), suggests the foundations were likely to have been constantly exposed to saltwater (Figure 17).This would indicate that periodic and regular exposure to saltwater occurs to the foundation systems, precisely the condition that accelerates deterioration of the steel reinforcement.

Having determined that periodic exposure exists, and is increasing with time, Figure 18 shows a projection of the water levels back to 1979 when the project was designed. Note that the tide was 5 inches lower than the 2021 condition. A more infrequent salt-water exposure may have occurred during that time with the pile caps remaining above the groundwater levels. Also, given the assumption that the tidal levels were within a constant and predictable range and not subject to sea level rise at the time, there would have been little expectation that the pile caps were going to be exposed to saltwater. Going forward, projecting sea level with a linear increase indicates that by 2046 the top of the floor will be at the tide level for 50% of the time.

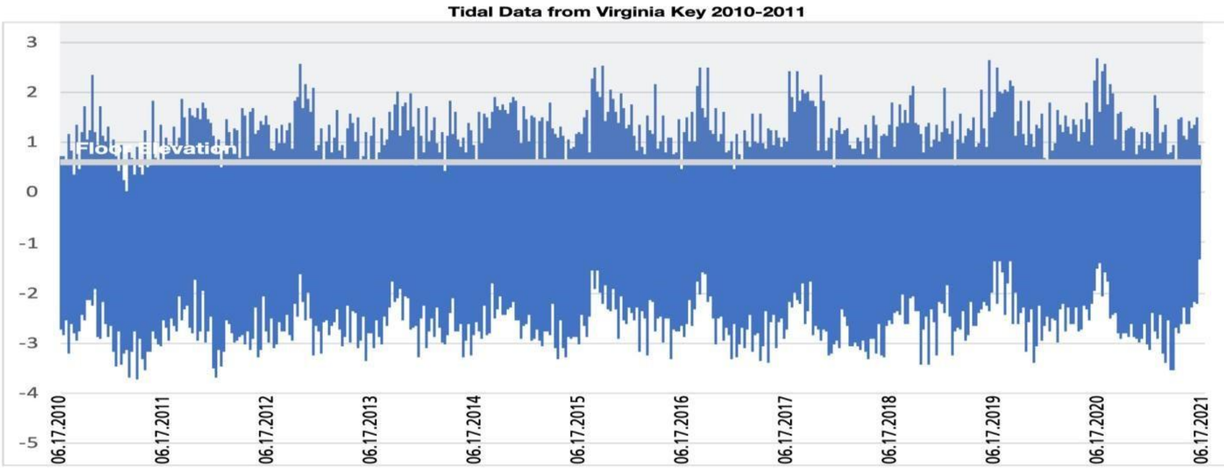

Figure 12. Tidal Data from Virginia Key 2010 to 2021. Note the level of the garage floor at Champlain Towers South. Graphic: Abbate and Bloetscher (2022)

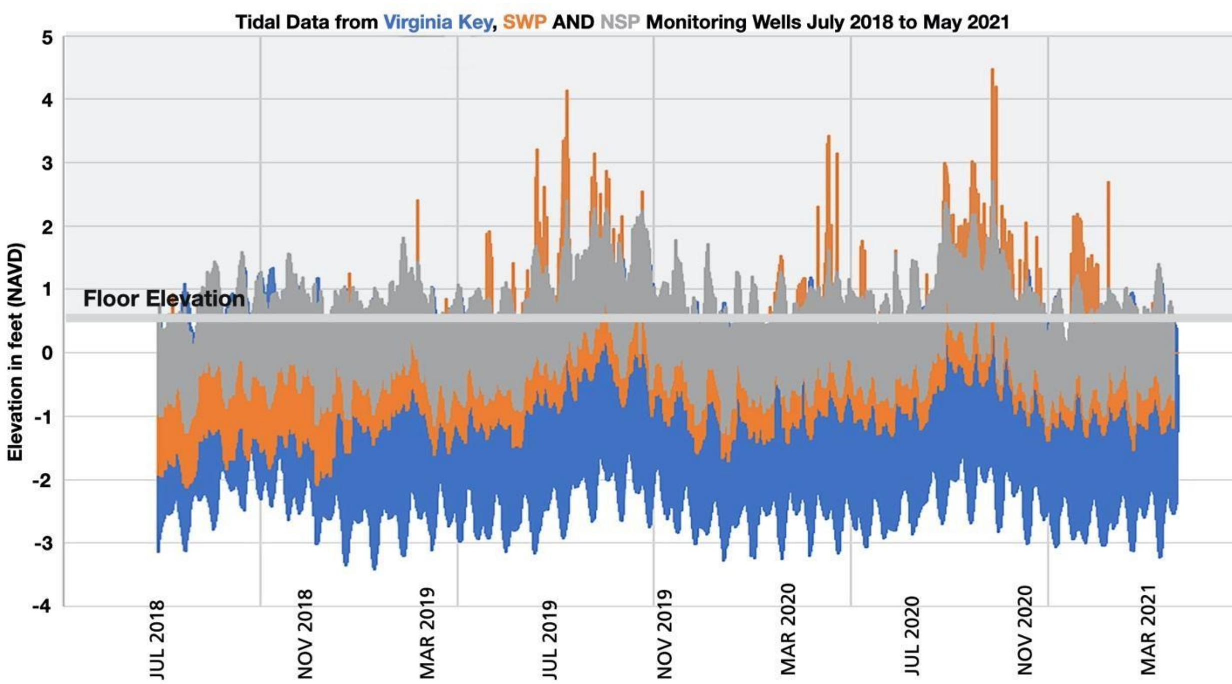

Figure 13. Virginia Key plus Monitoring Wells SWP and NSP. Notethe level of the garage floor at Champlain Towers South. Graphic: Abbate and Bloetscher (2022)

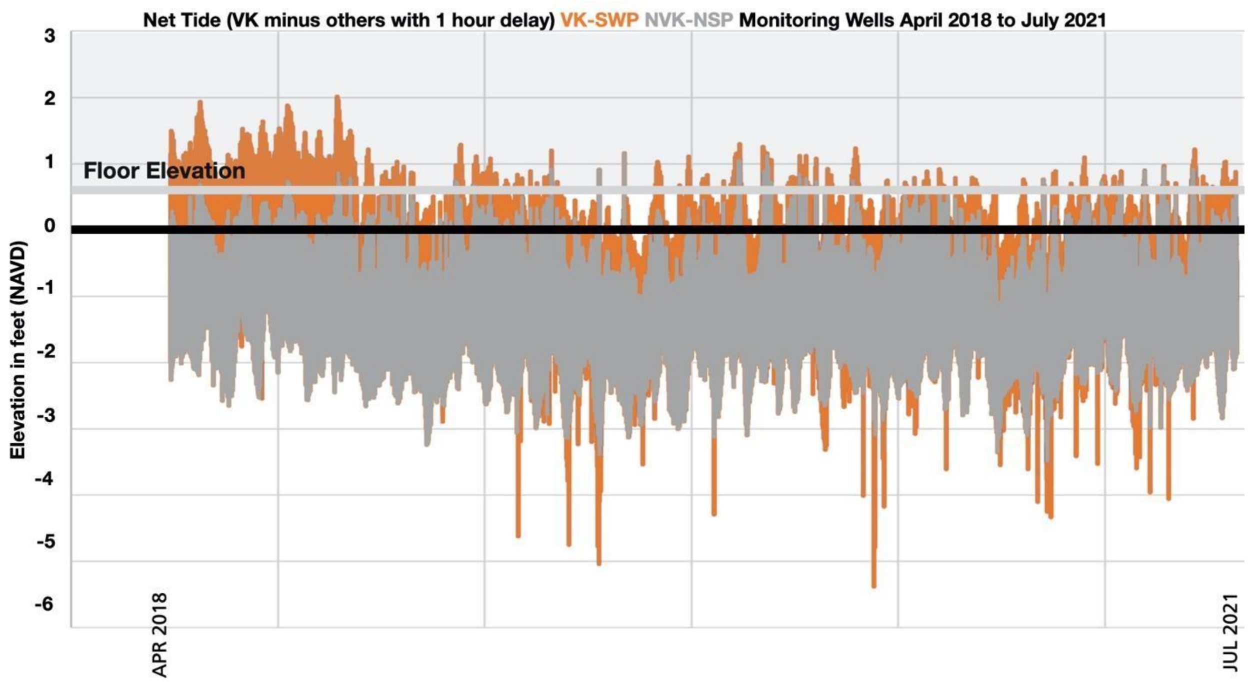

Figure 14. Difference between VK and the SWP and NSP sites. All recorded measurements presenting above the black line indicate where no freshwater lens likely exists. Graphic: Abbate and Bloetscher (2023)

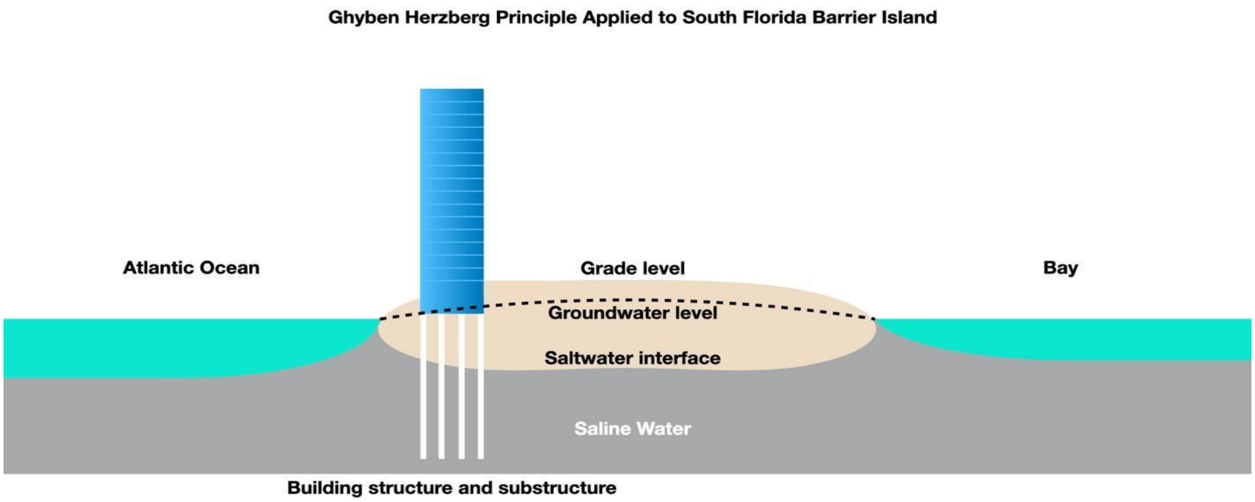

Figure 15. Illustration of the Ghyben Herzberg principle applied to a diagrammatic transect of the barrier island at Surfside, Florida. Graphic: Abbate and Bloetscher (2023)

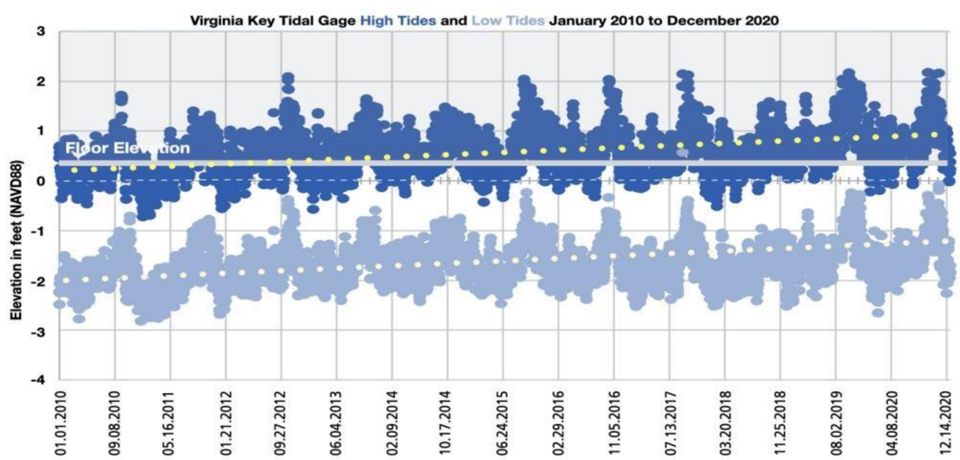

Figure 16. Trend of high and low tides recorded from the VK tidal gage. Floor elevation indicates the level of the garage floor at Champlain Towers South. Graphic: Abbate and Bloetscher (2023)

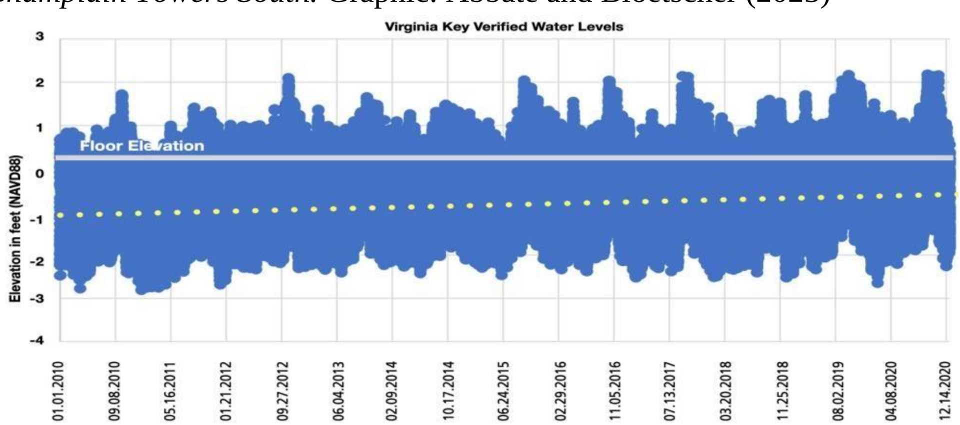

Figure 17. Estimated water levels under Champlin Towers over a 10 year period, indicating a condition where the wet/dry and fresh/salt cycle repeated with regularity (including "King Tide periods" where the foundations were continuously exposed to saltwater. Graphic: Abbate and Bloetscher (2023)

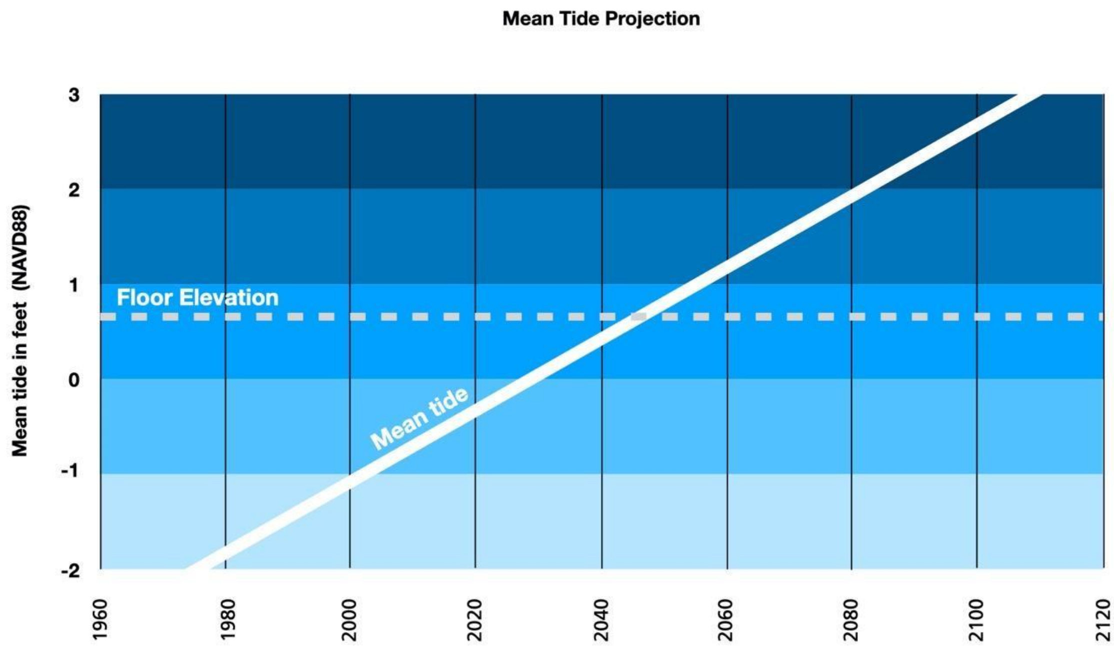

*Figure 18. Projection of mean tides from 1980 to 2100 showing that the mean tide will be above the garage floor by 2045. (Using a linear projection: Mean Tide – 0.038773*year-78.715)* Graphic: Abbate and Bloetscher (2023)

Discussion and Conclusions

The design and maintenance of building infrastructure is a necessary and long-term process. The failure to design for changing conditions, monitor conditions, and perform maintenance when needed can lead to catastrophic failures if the evidence of corrosion damage and degradation in building structures are left unattended.

Corrosion monitoring is a common practice for maintenance of built environment assets such as water systems, boilers, and cooling systems. However, the process for monitoring structural and substructure systems is more complex and costly. The most important data that a monitoring system collects include the source and location of corrosion, the extent of corrosion, the rate of spread, and the causes of corrosion. Visual inspection is the primary means architects use to identify corrosion. Ultrasonic testing is used to detect the loss of material due to corrosion. While it can be an effective tool for monitoring corrosion of steel, concrete, and other materials, it is not yet feasible for building substructures.

While this paper does not assert that sea level rise was the cause of the Champlin Towers South collapse, the exposure to saltwater that is coincident with sea level rise suggests that sea level rise maybe a contributing factor and should be examined further. The data suggests that water levels have increased concurrent with projected sea level rise and that the building substructure, including foundation piles, pile caps, columns, walls, retaining walls, and garage floor slab very likely may have been exposed to periodic saltwater, which is known to accelerate corrosion, in increasing amounts and with more frequency.

Solutions to this problem may be addressed with new construction. Two current methods, prophylactic protection, and non-metallic alternative materials can be employed. For example, auger cast type piles may be drilled as normal with a moisture barrier installed with the steel reinforcement cage. This concept is similar to the installation and grouting of well casings. A second method is the use of basalt or other non-metallic materials, such as glass fiber or carbon fiber reinforced polymeric composites (GFRP and CFRP) to replace the reinforcing steel. The use of basalt, a volcanic rock-based material, for structural concrete reinforcement has become commercially available and is recognized by the American Concrete Institute (ACI 440R-07). Given that it is a rock- based material, it is not subject to the corrosion processes that affect steel. The costs for reducing the risks to life and property damage from the effects of Sea Level Rise and accompanying saltwater intrusion may impact the real estate market and local property values.

Going forward, both public and private sector interests, including building officials, condominium associations, engineers and architects concerned with the lifespan and longevity of existing buildings may need to review the data for recurring flood and ground water levels, assess the potential for sea level rise impacts and saltwater exposure, and develop measures, best practices, and regulations to protect building infrastructure. Such a comprehensive system would be very different from the one that exists today. Additional data would contribute to the case for developing changes to existing building codes, new inspection techniques, and smart building system technologies for structural health monitoring that would include real-time detection of corrosion damage and risk, integrity and remaining lifespan assessments of building systems, structures, and substructures.

The longevity and viability of existing buildings at risk under these conditions could further be monitored and managed with a more rigorous statutory program that would include regular inspections and reporting every 5 years. Such a program could also empower local building officials to enforce action when deficiencies are found. With reliable data and timely inspections, condominium associations may be called upon to establish and maintain reserves and budget for assessments on unit owners for the repairs necessary to preserve building longevity and reduce risks to lives and property.

The issues with building maintenance are not different than that of other infrastructure systems such as bridges, road, water, sewer, and stormwater, as identified by Nolan (2021). Prior to 1980, the US spent 3.4 to 3.6 percent of GDP on infrastructure, that number was reduced to about 1.3 percent post-1980, and the ASCE's evaluation of our infrastructure went from a B to a D in 40 years, risking system failure. And while the recent bipartisan passage of an historic US$ 1.2 trillion infrastructure bill may redress the issues with public infrastructure, the looming problems associated with long-term maintenance of private sector built environment remains fraught with unknowns and controversy.

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