GEOTECHNICAL RECONNAISSANCE AND INVESTIGATION OF IMPACTS FROM HURRICANE IAN

Geotechnical Extreme Events Reconnaissance
GEER Report - 080

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CHAPTER 1
INTRODUCTION

Hurricane Ian was a category 4 hurricane when it first made landfall in the contiguous United States near the city of Fort Myers, Florida on September, 28 2022. It had sustained winds of 150 mph, rainfall totals ranging from 10 to 20 inches across Florida, and storm surge heights up to 12 feet in coastal communities near Fort Myers. After traversing the Florida Peninsula, Hurricane Ian later made landfall as a category 1 hurricane on September 30 near Georgetown, South Carolina, with sustained winds of 85 mph and storm surge heights of 5 feet in Myrtle Beach, the third highest level on record for this area (NOAA, 2022). Hurricane Ian was a catastrophic event and is reportedly the deadliest hurricane to impact Florida since 1935, with 149 deaths reported in the state (of Law Enforcement, 2023) and at least 152 deaths attributed to the event overall in the United States (NOAA, 2023). Estimated damages are expected to exceed $50 billion in Florida, which surpasses previous records set by Hurricanes Andrew and Irma (NOAA, 2023). Total insured and uninsured damages in the United States are estimated to be approximately $113 billion (NOAA, 2023), making Hurricane Ian the third costliest hurricane to ever impact the United States.

A reconnaissance team, consisting of five members from the National Science Foundation (NSF)-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association, first deployed to the Fort Myers area from October 18, 2022, to October 22, 2022, to document the geotechnical impacts imposed by flooding, storm surge, and winds. The GEER team surveyed the city of Fort Myers, including areas downtown, communities near the Peace and Caloosahatchee Rivers, and Cape Coral. A substantial amount of time was also spent documenting the impacts on nearby barrier islands, including Fort Myers Beach, Pine Island, and Sanibel Island, which were particularly hard hit. Two team members returned from November 29, 2022, to November 30, 2022, to perform follow-up surveys. The GEER team documented the field observations in the form of photos taken at the surveyed locations and collected data in order to gain an insight into the sequence of events and mechanisms that lead to the geotechnical failures caused by Hurricane Ian. The report provides no detailed interpretations or conclusions but aims to observe this event. The opinions presented in this report are based on professional expertise gained by studying geological and geotechnical engineering in an academic setting, in addition to field observations.

CHAPTER 2
BACKGROUND

2.1 Geology

Florida is perched atop the Florida Platform, a wide, flat platform that reaches out around 100 meters and is mostly submerged. The Florida Platform has experienced complete submergence and elevation above sea level during the interglacial and glacial periods, respectively. The Florida Peninsula is supported by a remarkably solid, tectonically quiet base as evidenced by its lengthy geological history (Bostick *et al.*, 2018). The principal geological formations in South Florida are distributed on the surface in a pseudo-atoll lagoon with fossil reefs surrounding it. The Anastasia Formation, Miami Formation, Tamiami Formation, Caloosahatchee Formation, and Fort Thompson Formation are the principal geological formations (Figure 2.1). The surveying was done on the west coast of Florida as a part of the Anastasia Formation.

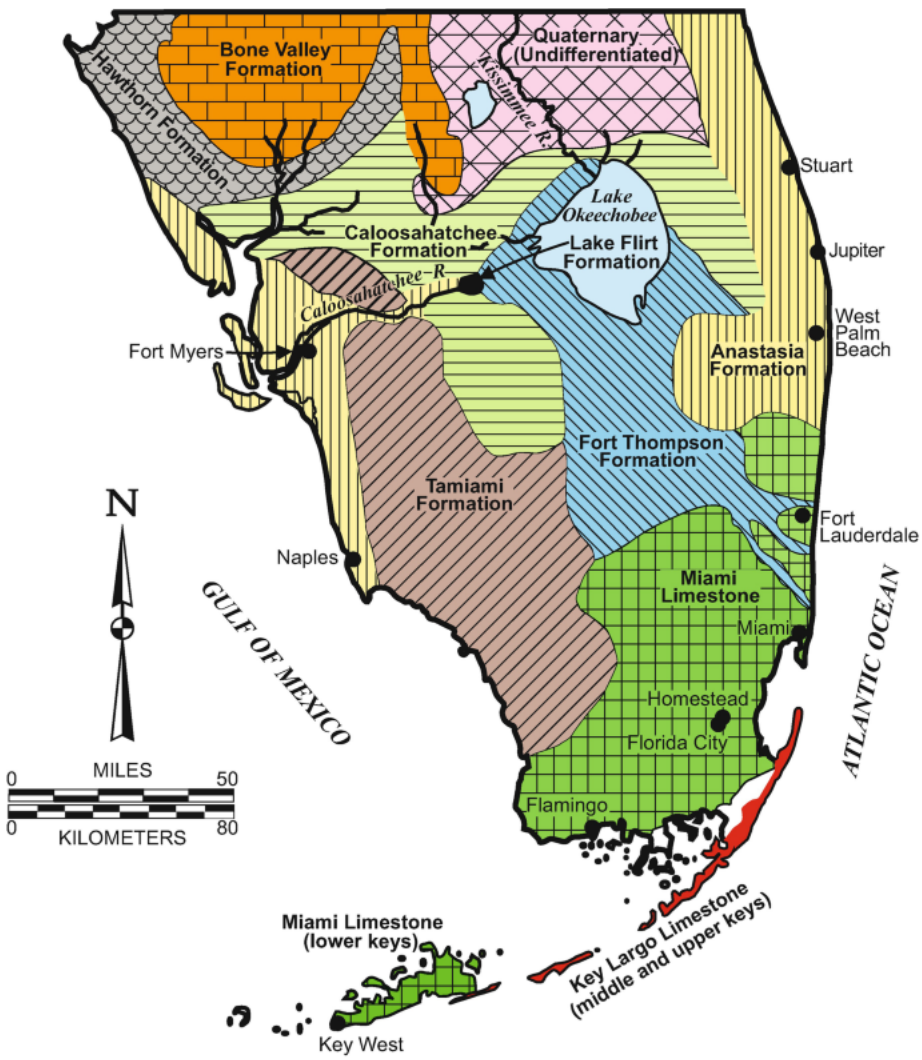


Figure 2.1: Geologic formation in South Florida (Lodge, 2019)

Sellards gave the Anastasia Formation its name in 1912. "The enormous deposit of coquina rock found along the east coast," he referred to it as (Sellards, 1912). Quartz sands and calcite coquina make up the Anastasia Formation, along with rare fossilized remains (Portell *et al.*, 2003). Anastasia Island in St. John's County serves as the type locality. South of the island, the Anastasia Formation stretches for at least 150 miles (320 km), where it transitions into Miami Limestone. To the north of Boca Raton, it makes up the Atlantic Ridge. Rarely does the formation reach three miles inland from the Intracoastal Waterway (Cooke, 1945). In regard to how far inland the Anastasia Formation extends, various scholars are at odds (Scott, 1991). The Anastasia Formation combines with the Fort Thompson Formation near the depression between Lake Okeechobee and the Everglades (Puri & Vernon, 1964). Along the West Coast, close to Sarasota, a small fraction is also exposed. It is unknown how far out to sea the structure extends(Randazzo & Jones, 1997). Although Anastasia's bottom has not been seen, it is believed to lay unevenly on Caloosahatchee marl. Pamlico Sand is typically the underlying formation (Cooke, 1945).

Several ages have now been attributed to the Anastasia and each of them places its origin in the Pleistocene which ranges from 130,000 to 100,000 years (McNeill, 1985) and more specifically, The Anastasia grades in the Miami Limestone are 130,000 years old (Halley & Evans, 1983). It is referred to as a "multicyclic deposit" and was produced over the course of numerous sea transgressions (Randazzo & Jones, 1997).

Understanding the lithologic constituents of the Anastasia Formation is crucial for interpreting its depositional history, sediment sources, and hydrocarbon reservoir potential. The formation is primarily composed of limestone beds made up of calcium carbonate in the form of calcite and unconsolidated coarse-detrital sands mainly consisting of silicate minerals such as quartz, feldspar, and mica. The limestone beds are characterized by abundant shell fragments, primarily mollusk shells, in a sandy matrix, while the sands can be light gray to tan and orangish brown and may or may not contain fossils. (Cooke, 1945)

The lithology of the Anastasia Formation reflects its depositional environment during the Pleistocene epoch, a time when sea level fluctuations were frequent due to glacial-interglacial cycles (Scott, 1991). As the sea level rose, the formation accumulated as barrier islands, spits, and beaches. New layers of sediment raised the land as transgressing seas deposited sand and shells on the beaches. However, during periods of high sea level, the formation was exposed to weathering and erosion, resulting in the development of extensive karst topography (Crespo, 2005).

This process dissolved the calcium carbonate and cemented the sediments into distinct horizons, which today can be observed as calcite crystals up to three-eighths of an inch in shells and in the exoskeletons of invertebrates. As regressing seas exposed the sediments, freshwater dissolved calcite and cemented the sediments into distinct horizons. This mineralogy shows how the cementing process has taken place within the various layers of the Anastasia Formation (Halley & Evans, 1983).

The composition of the Anastasia Formation is a critical economic resource for the state of Florida. The formation is the source of much of the sand that comprises Florida's beaches, which are a critical economic resource for the state. However, the formation is also highly vulnerable to erosion from storm surges and sea level rise, as well as human activities such as coastal development and dredging (Davis Jr & Fitzgerald, 2004).

Today, the unconsolidated sands and sediments that makeup Florida's east coast beaches are Holocene Age and are subject to the wiles of wind and wave. In recent years, tens of millions of dollars have been spent renourishing the beaches with sand due to erosion caused by coastal development and natural disasters. One good nor'easter let alone three hurricanes, (Charley, Frances, and Jeanne) that directly impacted Florida's east coast in 2004 have removed vast quantities of sand, leaving coastal communities to deal with the loss (Dean, 2011).

2.2 Winds and Storm Surge

Hurricane Ian's origins can be traced back to a tropical wave that emerged on September 19, to the east of the Windward Islands in the Caribbean. The wave gradually intensified and developed into a tropical depression four days later. Located in the central Caribbean, the depression grew in strength as convection increased and wind shear decreased. By the end of the day, it had become Tropical Storm Ian. The warm ocean sea surface temperatures and mild wind shear conditions contributed to Ian's rapid organization and its progression to a Category 1 hurricane on September 26. As it moved towards western Cuba, Ian made landfall as a Category 3 hurricane with winds of 125 mph, and after a brief weakening phase, it reached Category 4 intensity on September 28. As Ian approached the central Florida coast, it continued to intensify, peaking with sustained winds of 155 mph.

Ian's track (figure 2.2) was one of the worst-case scenarios for Southwest Florida, as storm surge is the most severe on the right-front quadrant of a storm, which is the quadrant that crossed over the area during Ian's landfall. This quadrant allows strong winds to pile up water, resulting in a large storm surge that often overflows onto land. Southwest Florida is particularly susceptible to surge because of the shallow Gulf of Mexico off its coast, which cannot absorb the storm surge as it approaches land, causing the surge to plow into inland areas. Figure 2.3 exemplifies how the interplay between geography and wind can significantly influence the intensity of storm surges.

As previously stated, the geography of the area is also a major reason for the extreme surge. Southwest Florida is remarkably flat, with a minimal increase in elevation, allowing the surge to penetrate inland areas. Additionally, the area has a significant river, the Caloosahatchee, which allowed the surge to push up the river and flood out much of Downtown Fort Myers. In contrast, Northeast Florida and Southeast Georgia have some advantages to mitigate storm surges, including deeper water off their coasts and minor elevation increases that protect the higher ground from surges.

From September 24th to October 8th, 2022, the water level rose to significant heights in certain locations, measured in feet, which could be considered as key areas in figure 2.4. Ian's surge of at least 13.2 feet along Fort Myers Beach is the highest surge ever recorded in Southwest Florida over the past 150 years. It was double the surge produced by Hurricane Charley in 2004, a smaller storm that took nearly the same track at the same intensity. The combination of every possible dynamic working against the area in this worst-case scenario resulted in Ian's surge being so devastating. Not only was Ian's wind field much larger than Charley's, but it also moved significantly slower. Additionally, it hit just after a new moon elevating tides, the storm's angle of approach, and the inward shape of Southwest Florida's coastline.

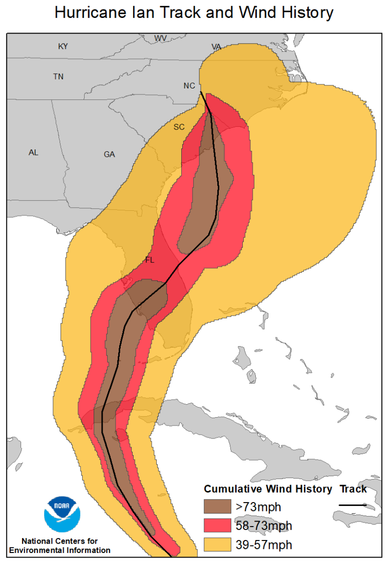


Figure 2.2: The wind fields and trajectory of Tropical Storm and Hurricane Ian (NOAA, 2022)

On the west coast of Florida, specifically Southwest Florida, the vulnerability is much higher than on the east coast of Florida due to the overall shallow depth of the water, according to a storm surge specialist from the National Hurricane Center. All of these factors caused water to travel as far as 25 miles inland. With landfall on Cayo Costa, the counterclockwise motion around Ian brought a big difference in the surge, with 13 feet on Sanibel but just 3 feet on Boca Grande. Both areas saw the destructive eyewall 20 miles apart, but Sanibel's wind came from the Gulf, forcing water up, while Boca Grande's wind came from the land in the opposite direction.

The surge is the deadliest and most significant part of most hurricanes, and Hurricane Ian was no exception. It is the deadliest hurricane in Florida in 87 years due to its storm surge. High water marks on residential homes in the Fort Myers area indicates surge heights of up to 10 feet, and values were almost certainly higher in parts of the Florida coast. A surge of around 5 feet was also reported near Myrtle Beach, S.C., its third-highest on record, as Ian made its second U.S. landfall nearby. Tide gauges in Naples and Fort Myers posted their highest water levels on record, with forecast values of 12 to 18 feet suspected to have occurred in some spots.

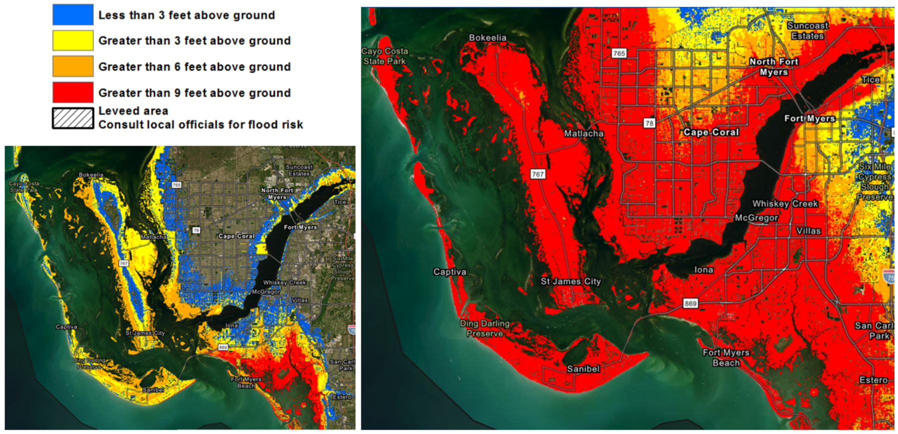


Figure 2.3: Storm surge inundation predicted by the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model utilized by the National Oceanic and Atmospheric Administration, left: Category 1 Hurricane and right: Category 4 Hurricane

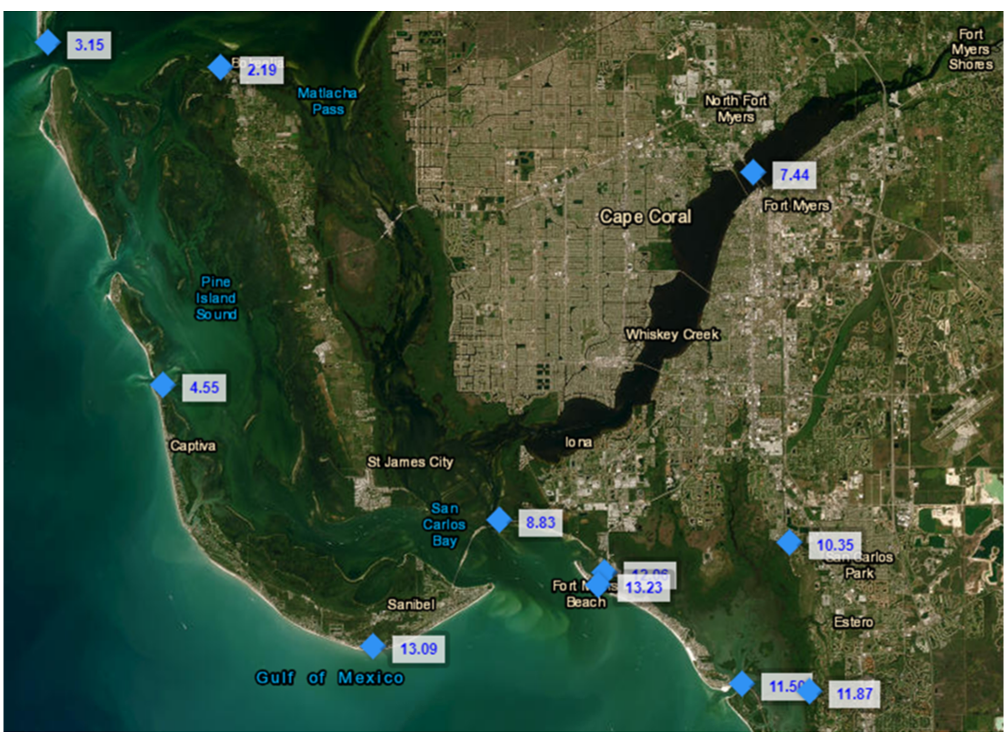


Figure 2.4: High water mark heights, in feet, in key locations 24 Sep 2022 thru 8 Oct 2022

2.3 Precipitation

Elevated water levels were observed in the recordings of water level gages operated by the USGS. Figure 2.5 shows the time series of water surface elevation above NAVD 1988 from the monitoring location 02293202 situated at Caloosahatchee River at Fort Myers. It can be observed that the water level recorded before and after the storm varied between 0 and 2 ft. However, negative values of water level were recorded as -0.75 ft below the NAVD 1988 at 6 am on September 28th. This water level evolved to be as high as 7.44 ft at 6:30 pm on the same day. The water level was back to normal after September 30th.

Figure 2.6 plots the elevation of tides as recorded at the NOAA station 8725520 Fort Myers, Florida. The green plot shows the recorded values, and the blue plot shows the predicted values of tide elevations. The recorded tidal elevations show a similar trend where the tide elevation dropped to negative values of -0.82 ft at 8 am on September 28th. This value drastically increased to 7.43 ft at 6 pm on the same day.

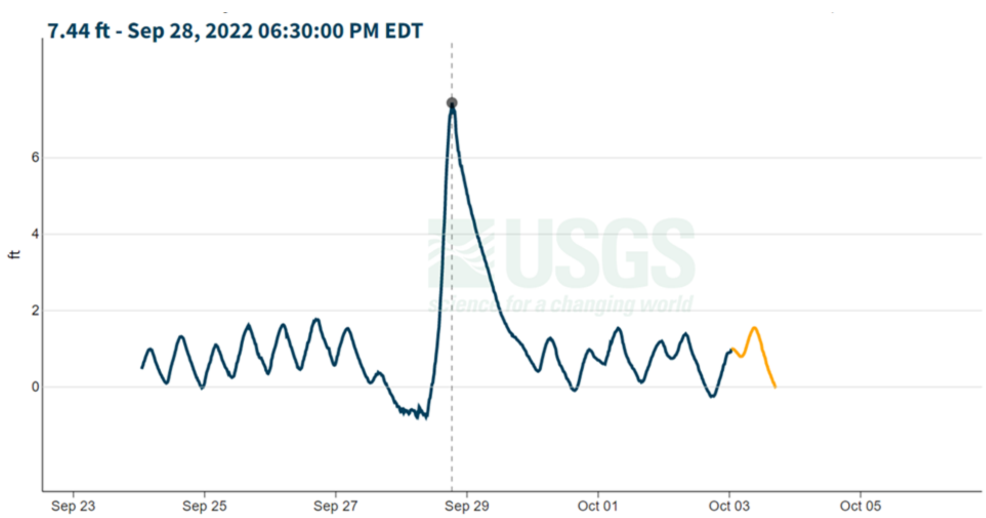


Figure 2.5: The time series of water surface elevation from monitoring location 02293202 situated at Caloosahatchee River at Fort Myers.

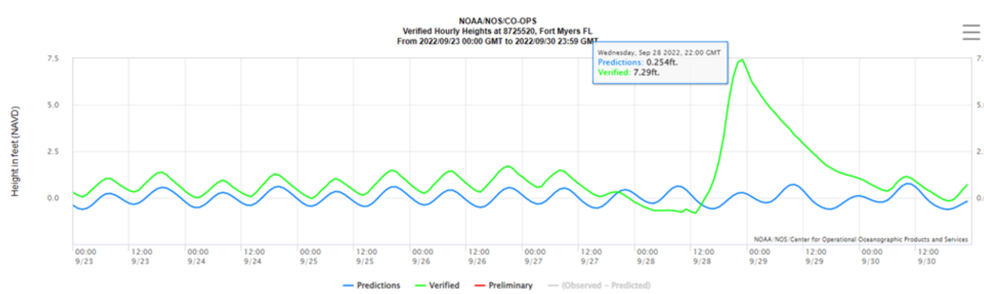


Figure 2.6: The time series of tides from the NOAA monitoring station 8725520 Fort Myers, Florida.

2.4 Previous Event Consequences

2.4.1 Hurricane Charley (2004)

Hurricane Charley formed as a tropical depression in the Caribbean Sea on August 9, 2004. It quickly strengthened into a tropical storm and moved towards the west-northwest. On August 11, Charley passed over the Cayman Islands and then turned towards the northwest. It continued to strengthen and became a Category 2 hurricane on August 12. Charley then turned towards the north-northeast and made landfall in Cuba as a Category 3 hurricane on August 13. It then crossed over the island and emerged into the Florida Straits, where it rapidly intensified into a Category 4 hurricane with maximum sustained winds of 150 mph. Charley then made landfall on the southwest coast of Florida near Punta Gorda on August 13, 2004, causing widespread damage.

Hurricane Charley caused extensive damage in Florida, particularly in the areas of Punta Gorda, Port Charlotte, and Arcadia. The storm caused 10 deaths and over $15 billion in damages. The winds from the storm destroyed homes and buildings, uprooted trees, and knocked out power to millions of people. The storm surge also caused flooding in coastal areas, and many people had to be rescued from their homes by boat. In addition to Florida, Hurricane Charley also caused damage in Georgia, South Carolina, and North Carolina.

A tide gauge located in Estero Bay, in close proximity to Horseshoe Key and Fort Myers Beach, recorded a storm surge measuring 4.2 feet. Similarly, tide gauges located on the Caloosahatchee River, in the vicinity of Fort Myers, recorded storm surges of 3.4 and 3.6 feet. Additionally, based on visual assessments, storm surges of 6 to 7 feet were estimated on both Sanibel and Estero Islands (Pasch *et al.*, 2005).

Charley and Ian have followed a strikingly similar path (figure 2.11), making landfall as category 4 hurricanes with maximum sustained winds of 150 mph (figure 2.12). However, despite these similarities, the impact of Ian is considerably more severe. The primary reason for this is Ian's slower pace, which resulted in prolonged exposure of areas along its path to the storm's high winds and rainfall, causing greater devastation and damage to infrastructure and communities.

Another crucial factor is the larger area experiencing hurricane-force winds in Ian, almost three times the size of Charley's landfall area. This expansion will result in a broader swath of communities and infrastructure being exposed to destructive winds and rainfall.

Moreover, Ian's larger size and slower speed indicate its potential to generate a significant storm surge than Charley, with a maximum of 12 to 18 feet compared to Charley's seven feet. This, combined with prolonged exposure to the hurricane's high winds and rainfall, increases the potential for catastrophic damage to coastal communities and infrastructure.

It can be shown that the Fort Myers Beach area suffered only minor geotechnical damage during both hurricanes Charley and Ian when comparing the same surveyed regions. Homes that were initially impacted by the hurricanes' course fell away at the connection of piers, however the pier footings were unharmed. Additionally, it was noted that houses elevated higher on piles were not impacted by the storm surge and only experienced mild scouring around their piles. (figure 2.7). This shows that major instances of storm damage were observed as structural damage rather than geotechnical damage in both hurricanes.

One significant impact of Hurricane Charley in Pine Island was foundation damage, which included shifting of the units on the foundations leading to out-of-plumb foundations (piers) or full collapse of the foundation. The unit was renovated in the late 1990s as part of a park-wide mitigation project that inserted additional tie-downs so that spacing wouldn't exceed 4 feet. Despite the fact that this incident was significant, the failures were probably caused by improper extra tie-down installation and moist soil. The fact that this was an isolated incidence and was not prevalent throughout the Pile Island region serves as more evidence for fewer geotechnical damages being done by Hurricane Charley (figure 2.8).

Due to the storm's powerful winds, some of the shingles at the Cape Coral fire station were torn off (figure 2.9). Following an inquiry, it was discovered that the facility's roof had been harmed by a faulty prong-type splice connector with prongs approved for roof heights up to 75 feet. More structural damage was recorded in Cape Coral, Sanibel Island, and Fort Myers Beach. Generally rooftop equipment was moved, substantial amount of glazing damage, and aluminum and sheet metal debris from adjacent structures collapsed (figure 2.10) (Ingargiola *et al.*, 2005).

Figure 2.7: No storm surge damage was done to a newly built house perched on piles in Fort Myers Beach. Coordinates: 26.97066, -82.08998. (Ingargiola *et al.*, 2005)

Figure 2.8: An older manufactured home that was uprooted off its base and damaged the building itself in Pine Island. Coordinates: 26.49995, -82.08538 (Ingargiola *et al.*, 2005)

2.4.2 Hurricane Irma (2014)

Hurricane Irma was a category 5 hurricane, which made landfall on Southwest coast of Florida in September 2017 (figure 2.17). The affected areas of Hurricane Irma are spatially close to the ones from Hurricane Ian. Therefore, they potentially could cause similar geotechnical failures and damages. Two GEER teams, supported by NSF, were deployed after Hurricane Irma to investigate the geotechnical impacts of the hurricane. Beach and shoreline erosion, overwash deposits, undermining of infrastructure, scour, failure of seawalls and piers, and damage to road embankment and pavement were observed during the investigation (Stark & Hudyma, 2017).

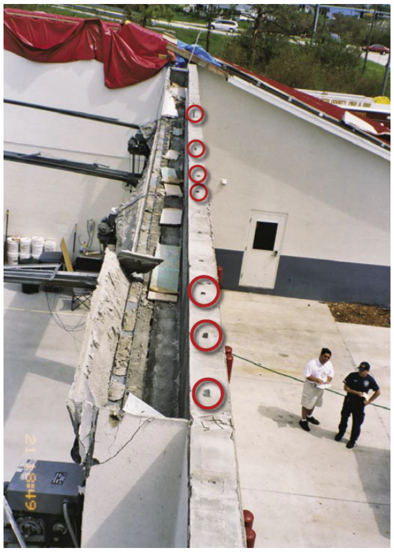


Figure 2.9: At Fire Station No. 12, the tie-beam storm anchor straps for the roof truss failed in Port Charlotte. Coordinates: 27.00927, -82.035509. (Ingargiola *et al.*, 2005)

Figure 2.10: Scouring of the road and damage to the infrastructure in Fort Myers Beach. Coordinates: 26.45060, -81.95103

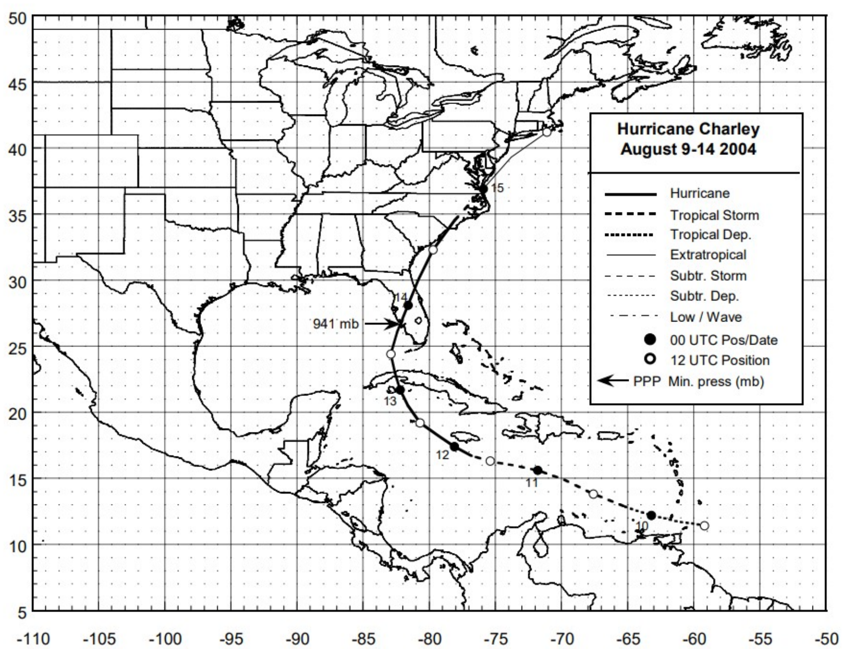


Figure 1. Best track positions for Hurricane Charley, 9-14 August 2004.

Figure 2.11: Best track positions for Hurricane Charley, 9-14 August 2004. (Pasch *et al.*, 2005)

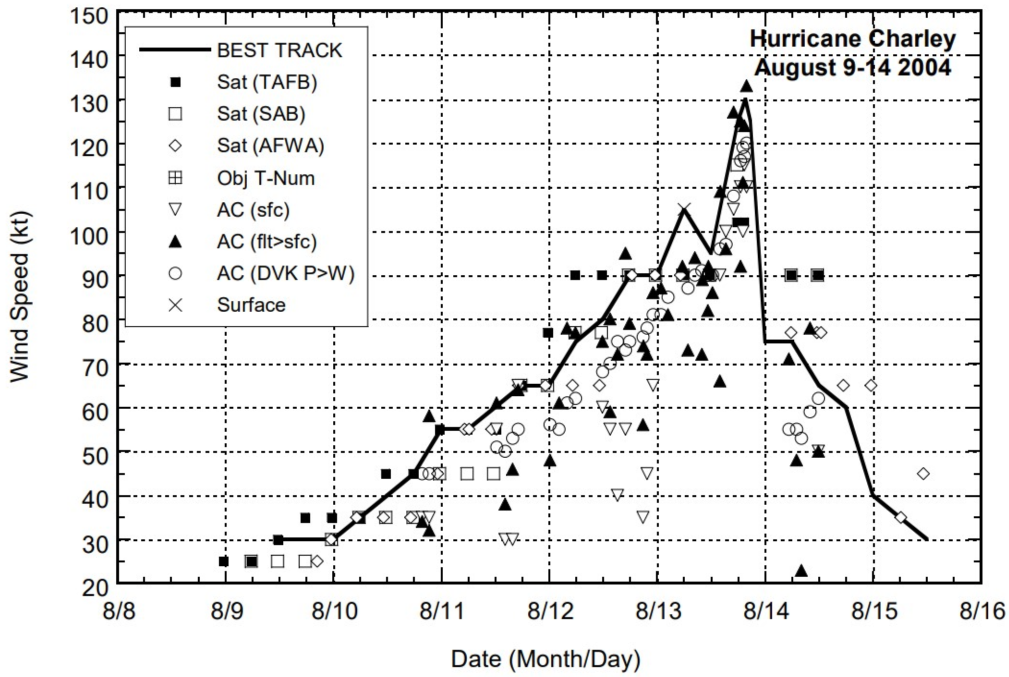


Figure 2.12: The wind data and maximum sustained surface wind speed curve for Hurricane Charley during August 9-14, 2004 have been compiled. The aircraft observations have been corrected for elevation by applying 90% and 80% reduction factors for observations made at 700 mb and 850 mb, respectively. (Pasch *et al.*, 2005)

The combination of storm surge and tide caused flooding between Cape Sable and Cape Romano, affecting the unpopulated coastline of southwestern Florida, Everglades National Park, and the Ten Thousand Islands National Wildlife Refuge. The maximum inundation level was 6 to 10 feet above ground level, with the highest water level recorded in Everglades City at 8.31 feet NAVD88 (7.5 ft MHHW). The area hit by Irma's eastern eyewall between Everglades City and Goodland could have experienced a peak inundation of up to 10 feet above ground level, but no observations were available to confirm this. The remaining southwestern coast of Florida from Marco Island to Ft. Myers experienced a maximum inundation level of 3 to 5 feet above ground level due to weakened onshore winds within Irma's deteriorating western eyewall. Prior to inundation, strong offshore winds initially caused water levels to recede below normal levels. Once the center moved north of Naples and the winds shifted to onshore, the water level at the site increased by 9 feet in just 3 hours, with 6 feet within the first hour (Cangialosi *et al.*, 2021).

These are some highlights of storm Irma-related failures that occurred quite nearby to the regions that the crew assessed for hurricane Ian. The GEER team (figure 2.13) discovered that one property's seawall was in poor condition. The failures are defined in detail. The barrier rotated with areas that were noticeably out of line in the longitudinal direction because the seawall's foundation appeared to be eroding. The wall was partially immersed in the canal in some places. Cape Coral Beach, which is located in the southern part of the city, was also surveyed by the GEER team (figure 2.14). The beach's surface and the areas

Figure 2.13: Seawall collapse at Cornwallis Parkway in Cape Coral. Coordinates: 26.595572, -81.930611 (Stark & Hudyma, 2017)

Figure 2.14: Surface erosion in Cape Coral. Coordinates: 26.596114, -81.926528 (Stark & Hudyma, 2017)

Figure 2.15: Scour at the base of the Ft. Myers beach finishing pier. Coordinates: 26.449636, - 81.944446 (Stark & Hudyma, 2017)

Figure 2.16: Bridge scour at the base of the piers, Big Carlos Pass Bridge. Coordinates: 26.404081, -81.878197(Stark & Hudyma, 2017)

near the ocean were undermined by the storm surge. The storm surge eroded the beach's surface and the places around the water. The side of state road 865 in Fort Myers, which runs parallel to the shoreline, shows signs of beach erosion and deposition as well (figure 2.15). The team also inspected the Big Carlos Pass drawbridge (figure 2.16) and found that the southernmost bridge pile had around 9 inches (23 cm) of scour. Riprap stopped the abutment from being destroyed. GEER did not find any significant structural damage to the bridge while they were there (Stark & Hudyma, 2017).

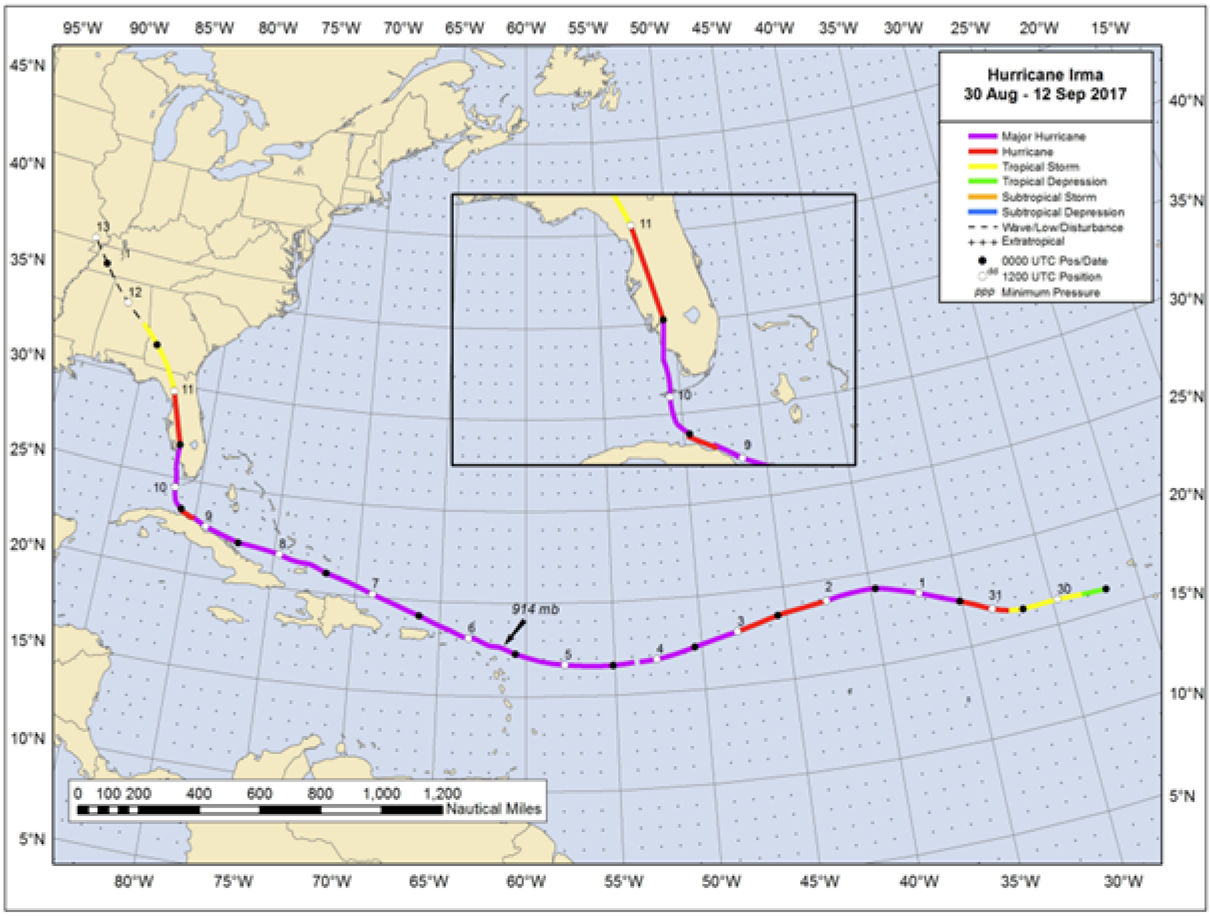


Figure 2.17: Best track position for Hurricane Irma (Cangialosi *et al.*, 2021)

CHAPTER 3
METHODS AND INSTRUMENTATION

3.1 Study Area

In October 2022, the GEER team conducted investigations at various selected sites along the Peace River and Caloosahatchee River on the west coast of Florida. The team utilized two vehicles to efficiently cover all areas. Specific sites of interest were identified based on the information gathered from the media and other reconnaissance teams encountered during the survey. Figure 3.1 shows a damage proxy map, which was developed on October 2, 2022 by the Advanced Rapid Imaging and Analysis (ARIA) team at NASA's Jet Propulsion Laboratory and Caltech, illustrates which areas of the Fort Myers region most likely sustained storm damage. The synthetic aperture radar (SAR) photos obtained by the Copernicus Sentinel-1 satellites, which are run by the European Space Agency, were used to create the map (ESA) (Credit: NASA/JPL-Caltech/ESA). The team conducted detailed investigations at Cape Coral, Pine Island, Fort Myers, and Fort Myers Beach. Figure 3.2 provides an overview of the locations surveyed by the GEER team.

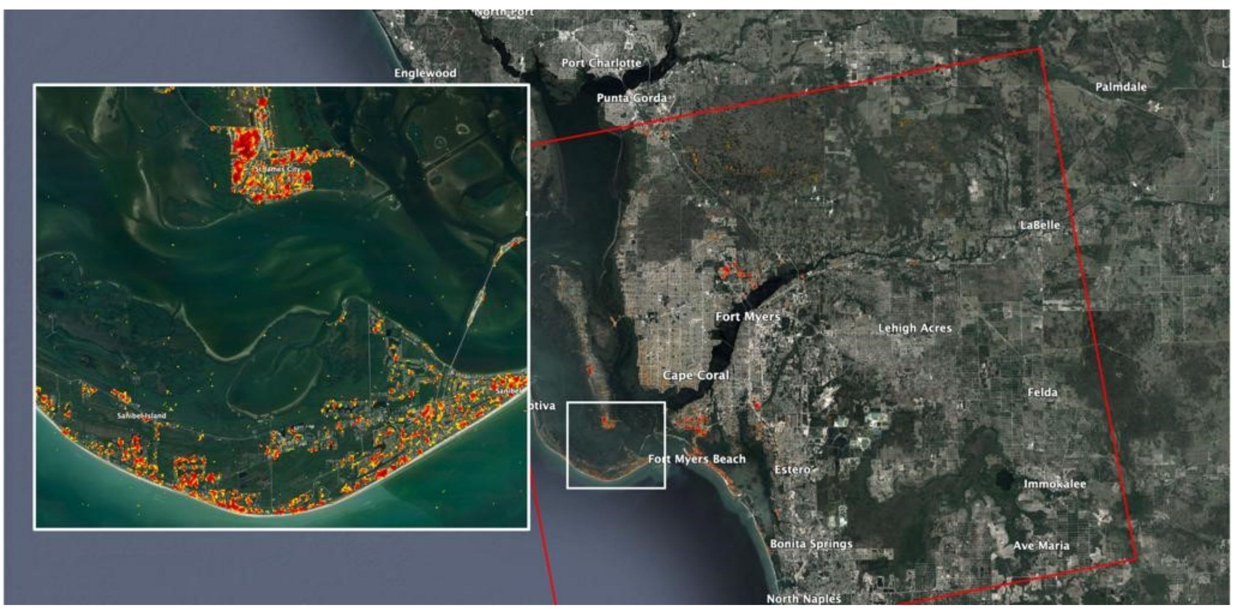


Figure 3.1: ARIA Map showing damage in Fort Myers from Hurricane Ian (NASA)

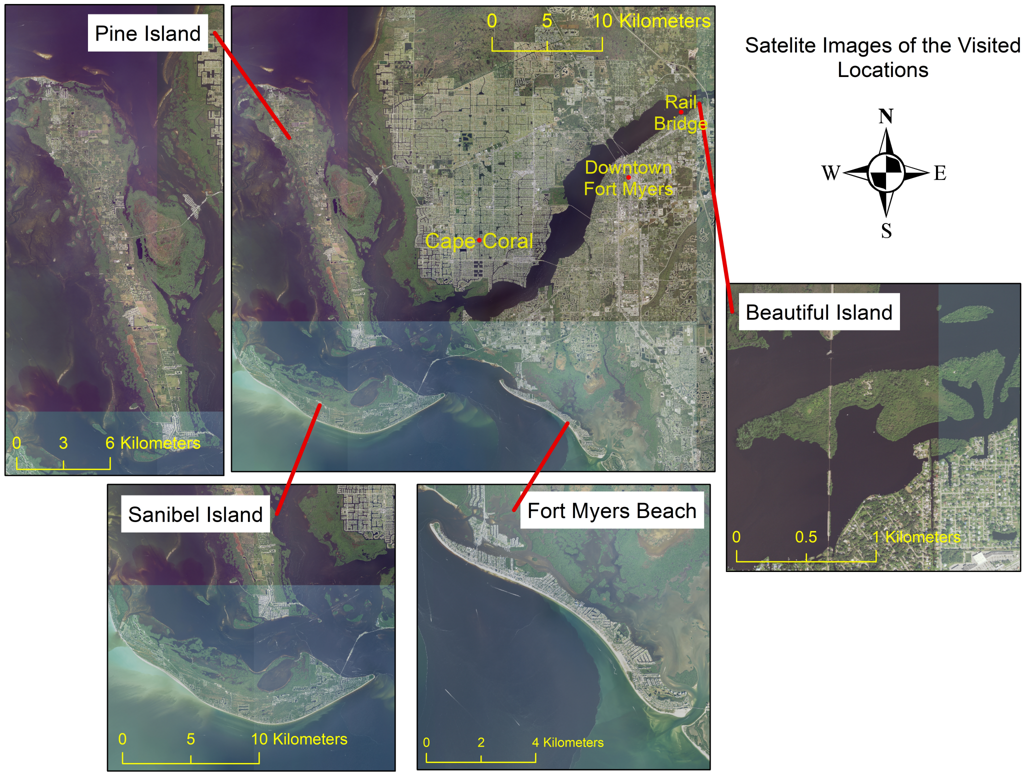


Figure 3.2: Overview of locations surveyed by the GEER team: Downtown Fort Myers, Rail Bridge near Beautiful Island, Cape Coral, Pine Island, Sanibel Island, Fort Myers Beach.

3.2 Instrumentation

The reconnaissance data for this study were collected using four primary technologies, which were Terrestrial Light Detection and Ranging (LiDAR), Uncrewed Aerial Systems (UAS), a Multispectral Camera, and Mobile optical imagery. Terrestrial LiDAR was utilized to map the earth's surface using an active light source with a Maptek LR3 system, which was processed in Maptek's PointStudio software and open source software CloudCompare. LiDAR scans were taken at three locations, including a retaining wall failure in Cape Coral and two possible sinkhole locations on Fort Myers Beach.

The team used a DJI Phantom 4 Pro to obtain imagery of difficult-to-reach areas and perform more efficient scouting, while also using Structure from Motion (SfM) photogrammetry with Pix4D to create a 3D point cloud of an extensive rail bridge failure along the Caloosahatchee River. The primary location for UAS flights was Pine Island and the associated entrance road.

In addition, a MicaSense Altum multispectral camera was used in a brief secondary deployment to determine its capability to detect water damage and other damage features only visible in the near infrared electromagnetic spectrum. The camera has six sensors, and imagery was processed using MicaSense image processing libraries in Python. The handheld multispectral camera was primarily used in Pine Island, Downtown Fort Myers, Fort Myers Beach, and along the Caloosahatchee River.

Finally, the field team documented the impacts of Hurricane Ian by scouting areas and taking mobile photos with their cell phones. This provided a quick, easy, and non-invasive method to document impacts while maintaining geo-location accuracy. The mobile phone application usage for documenting geo-location and route-tracking is discussed in the following section.

3.3 Software Applications

3.3.1 Filio

The Filio application was utilized during the GEER trip to save and document site photos and inspections. Figure 3.3 presents the interface of the Hurricane Ian disaster reconnaissance project in Filio. This application enables team members to work collaboratively on the same project and store all the images on the cloud, making them easily accessible to everyone on the project. Filio offers an interface that maps the photos onto Google maps based on their geo-location, allowing users to select images directly from the map. It also includes a feature for users to add a description to each photo, making it an ideal app for disaster reconnaissance teams.

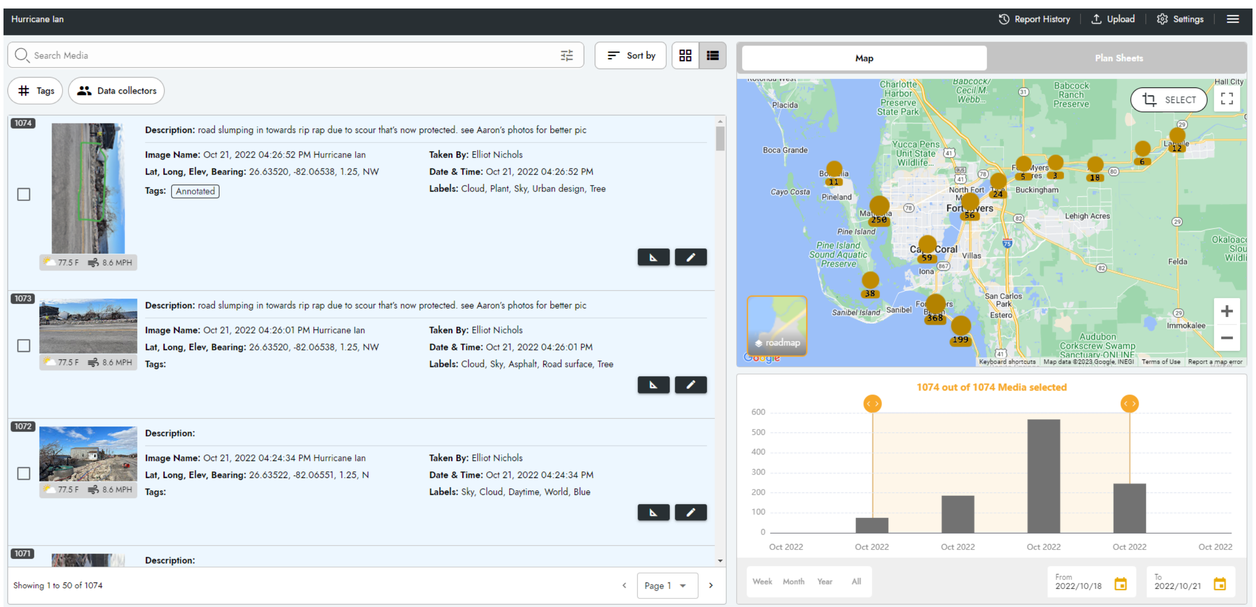


Figure 3.3: The interface of Hurricane Ian disaster reconnaissance project in Filio. The numbers at each location indicate the number of photos taken and are a proxy for the amount of time spent surveying each location

3.3.2 Theodolite

The GEER team utilized Theodolite to capture data-overlay photos during their trip. This technology enabled the team to produce images that include relevant geographic data, angle markings, date/time, author/company information, and project notes. By including this information within the images themselves, they can serve as a valuable reference when creating the final report.

3.3.3 GPX Tracker

During the GEER mission, a GPX tracker was utilized to track the disaster reconnaissance route. This allowed the team to easily reference their previous routes when planning for the next day of the field trip, as well as providing a useful tool for generating the final report. The GPX tracker recorded the route taken by the team and stored the data in a file format that can be easily accessed and analyzed, providing valuable information about the team's movements and locations visited during the trip.

CHAPTER 4
FIELD OBSERVATIONS

4.1 Visit Itinerary

The study team conducted a reconnaissance mission to regions severely affected by Hurricane Ian in two separate periods: from October 18 to October 22, 2022, and from November 29 to November 30, 2022. The research sites were selected based on information obtained from various sources, including residents' observations, news reports, and feedback from colleagues. A comprehensive list of the studied locations can be found in Table 4.1. To enhance data collection, measurements, and communication with local authorities and survivors, the team was divided into two to three smaller groups.

Table 4.1: Reconnaissance visit itinerary

Date	*Location*
Oct 18th	Arrival, Team meeting
Oct 19th	Downtown Fort Myers, Beautiful Island, Centinental Park, St. James City
Oct 20th	Fort Myers Beach, Matlacha, Shoreview Dr.
Oct 21st	Cape Coral, Matlacha, Shoreview Dr.
Oct 22nd	Attempted to go to Sanibel Island, Group meeting, Departure
Nov 29th	Downtown Fort Myers, Caloosahatchee River
Nov 30th	Fort Myers Beach, Pine Island

4.2 Pine Island

Figure 4.1 shows the locations surveyed on Pine Island, the barrier island immediately west of Cape Coral. The most geotechnical impacts were observed on the island's east entrance near Shoreview Dr., the Matlacha Isles, and the Matlacha Shores (near Shoreview Drive) and Matlacha communities. The GEER team also surveyed St. James City and Bokeelia on the south and north ends of the island, respectively. The majority of the damage in these areas was flood- and structural-related with fewer to no geotechnical impacts than the island's east entrance.

Figure 4.1: Overview of locations surveyed on Pine Island, which include Shoreview Drive (in Matlacha Isles-Matlacha Shores), Matlacha, St. James City, and Bokeelia.Location: 26.610, -82.115

4.2.1 Shoreview Dr

Shoreview Drive, technically in Matlacha Isles-Matlacha Shores, is a road that forks off Pine Island Road (the main road leading to Pine Island) with a small residential community. As illustrated in pre-and post-event satellite imagery in figure 4.2, a section of the sea wall and Shoreview Drive were destroyed, making the road impassable immediately following the event. Notably, there was no damage observed to Pine Island Road near Shoreview Drive or nearby drainage infrastructure (e.g. culvert), though the damaged section of road does intersect with a small contained body of water (swamp) within this land bridge and eroded regions behind the failed sea wall. This suggests that the failure of the sea wall likely initiated erosion that retrogressed from the failed seawall towards Shoreview Drive, though it remains unclear how the presence of the swamp, configuration of homes, or potentially localized storm surge effects in this relatively unprotected section of Matlacha Isles-Matlacha Shores (e.g. fewer mangroves and open bodies of water on both sides) contributed to the failure of the sea wall and damage to the road on Shoreview Drive.

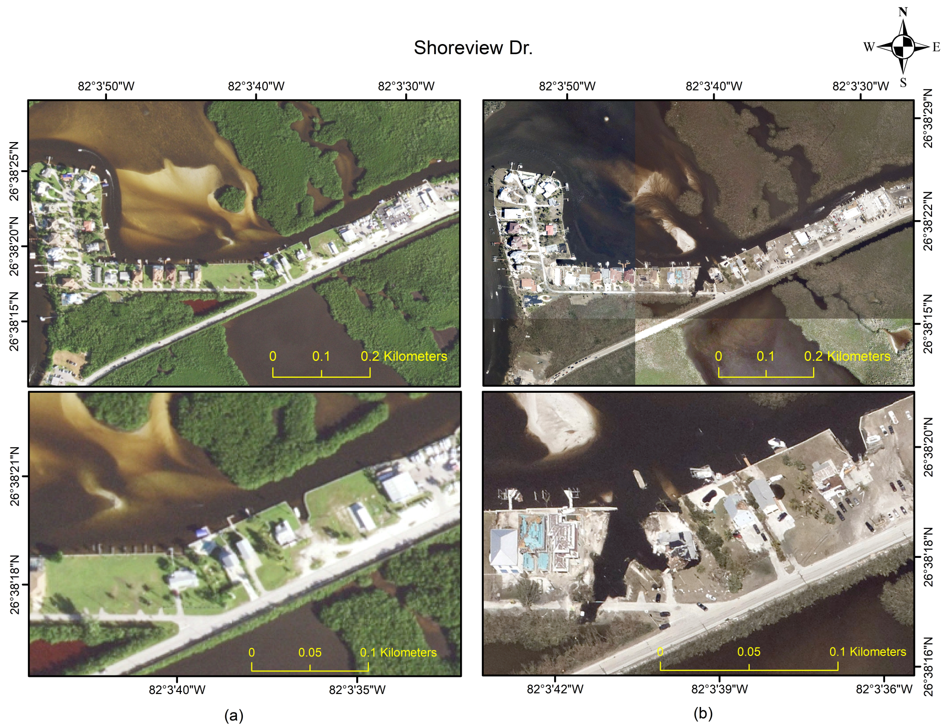


Figure 4.2: Satellite photos of Shoreview Drive in Matlacha Isles-Matlacha Shores at different scales (top vs. bottom) a.)before and b.)after Hurricane Ian, where it can be seen that a section of the sea wall and Shoreview Drive were eroded away and made impassable immediately after the storm. Note that the home shown immediately west of the eroded region was under construction and is not shown pre-event satellite imagery.

Figure 4.3 shows aerial and ground photographs of where Shoreview Drive was damaged. By the time the GEER team arrived in the Fort Myers area, Shoreview Drive had been repaired (figure 4.3a). However, no apparent repairs or filling had been performed in regions eroded behind the failed sea wall. A substantial amount of sediment had accumulated just beyond the seawall (more than observed in any historical satellite imagery), believed to be retained fill prior to the failure of the wall. Substantial erosion was observed in an undeveloped area that extended from a new home under construction (western side of the eroded area in figure 4.2b) to an older home that was completely destroyed (figure 4.3b,c). Erosion advanced up through the driveway (figure 4.3d) and beneath the foundation of the older home, which appeared to be largely responsible for the collapse of the structure (figure 4.3b,d,e). Observations consistently suggest environmental forcing conditions transported debris and sediment towards the retaining wall, such as the accumulated sediment beyond the wall (figure 4.3a), overturning direction of posts and trees near the driveway of the destroyed home (figure 4.3d), and the substantial accumulation of sediment on the front lawn, which was believed to have been piped from beneath the collapsed home (figure 4.3f).

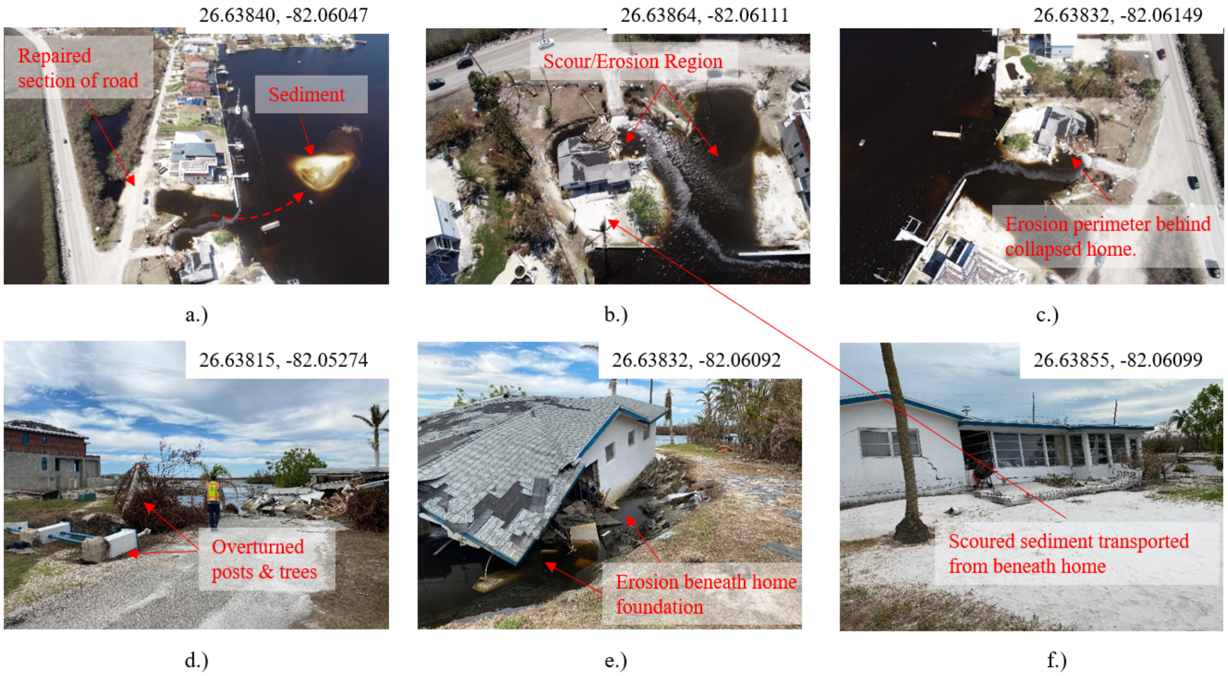
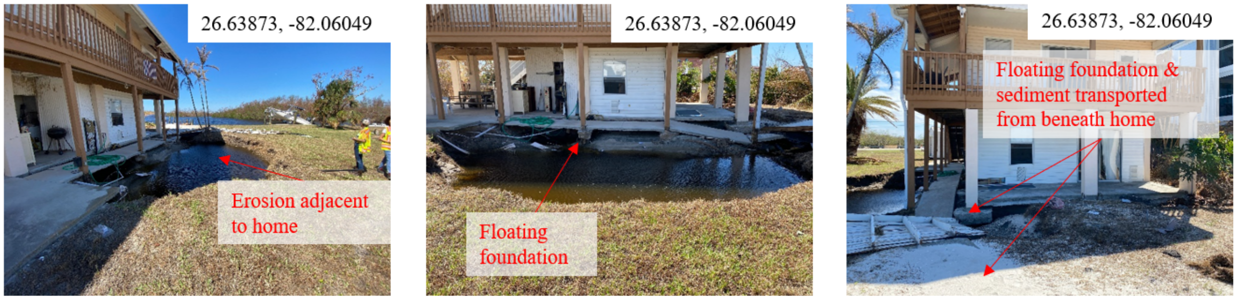


Figure 4.3: Damage and erosion near the intersection of Shoreview Drive and Pine Island Road in Matlacha: a.) drone image of repaired section of roadway and accumulation of sediment on shoal beyond failed retaining wall indicating likely direction of high water flow; b.) scour and erosion of lawn between new home under construction (right) and collapsed home (left); c.) erosion behind collapsed home; d.) overturned posts and trees potentially indicative of direction water flowed; e.) scour and erosion beneath foundation of collapsed home; f.) front of collapsed home and eroded sand sediment piped from beneath home to front lawn potentially indicating direction of water flow.

Ground photographs of the failed section of the seawall near the destroyed home are shown in figure 4.4a-c. The failed seawall appears to have occurred at or near the interface of older and newer sections of the seawall. Older and newer wall sections were distinguished primarily based on visual inspection of the coping and wall face. It remains unclear what specific differences there may have been between these two wall sections (e.g. anchorage, embedment, etc.) that contributed to the failure of the wall; though it was noted that anchorage was not observed behind exposed regions of the older wall figure 4.4b, but was observed behind damaged and exposed sections of the newer wall figure 4.4c. However, this does not necessarily imply there was no anchorage at all behind the old wall—where substantial portions remained intact and continued to retain soil comprising the front yard of the destroyed home figure 4.4b. No visible distress was observed (on the ground or via drone flights) in the seawall supporting the residential homes west of this location on Shoreview Drive. figure 4.4d-f shows failed retaining walls supporting a nearby boat ramp just east of where Shoreview Drive begins (also visible in figure 4.2). The eastern wall of the boat ramp was back-rated and partially collapsed in the middle figure 4.4e. There was some erosion behind the western wall and a distinct location where the wall had sheared off and was downdropped in the water figure 4.4f. The mechanisms and/or design flaws responsible for the failure of the wall were not readily apparent. Seawalls surrounding the failed sections near the boat ramp were intact with no visible signs of distress.

Figure 4.4: Damage to retaining walls near the intersection of Shoreview Drive and Pine Island Road in Matlacha Isles-Matlacha Shores: a.) drone image showing failed section of retaining wall believed to have occurred at the interface of older and newer section of the seawall; b.) older portion of sea wall; c.) newer section of sea wall; d.) drone image of failed retaining walls at a boat ramp; e.) back-rotated sea wall on one side of boat ramp; f.) sheared portion of a seawall underwater on other side of the boat ramp.

A substantial amount of erosion was also observed beneath a home nestled between the boat ramp and collapsed home at the start of Shoreview Drive (i.e. two homes west of the boat ramp and two homes east of the collapsed home in figure 4.2. The erosion and scoured regions adjacent to and beneath the foundation of this home are shown in figure 4.5.



a.) b.) c.)

Figure 4.5: Erosion near home on Pine Island Road in Matlacha near intersection with Shoreview Drive: a.) erosion adjacent to residential home; b.) scour beneath concrete slab and unsupported deck column; c.) unsupported foundation and sediment transported to front lawn from beneath the home. Coordinates: 26.63818, -82.06133

4.2.2 Matlacha

Figure 4.6 depicts an overview of the Matlacha region in the province of Pine Island. 4.6a. refers to the substantial damage the Island's east-facing entrance has sustained as a result of the storm surge's intensification. When the GEER team was investigating the area, the Matlacha entrance bridge on the east side had already been built. The construction of a temporary bridge began on October 3rd, 2022. The FDOT sent out more than 130 vehicles and laborers to work around-the-clock to help Lee County with the repairs. A temporary road linking Matlacha and Pine Island was built on October 4th, 2022, and was primarily used by the electrical and infrastructure trucks. Access to the Matlacha-Pine Island area was restricted and checkpoints were being manned by law enforcement. The bridge's construction was finished on October 8th, 2022, and the island was then accessible to all locals, business owners, emergency responders, and surveying teams.

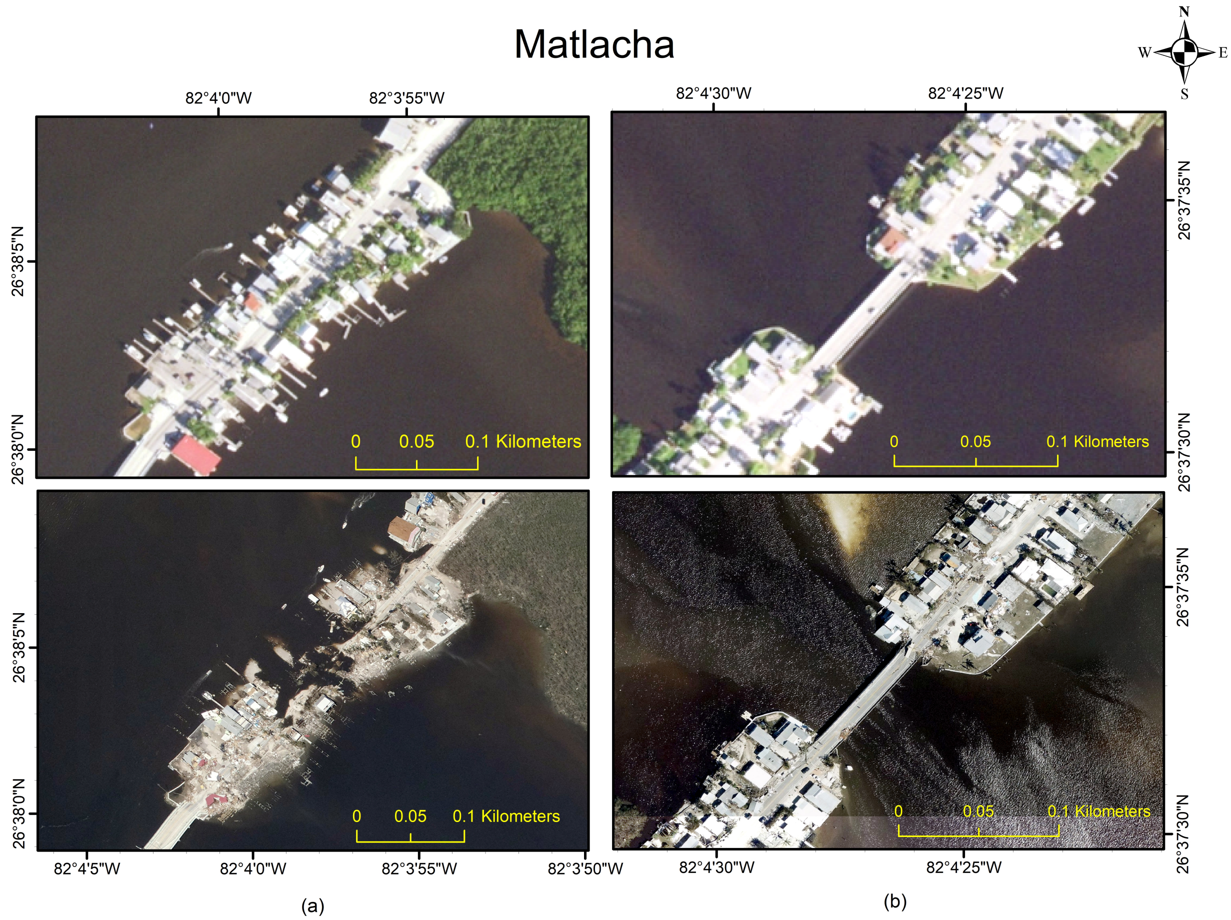


Figure 4.6: Pre- and post-event (top vs. bottom) satellite images of a.) the east entrance onto Matlacha and b.) west entrance onto Matlacha.

The newly constructed road on the eastern side is depicted in a ground photo in figure 4.7a. On the lower bound of the eastern side (4.6a.), to the right of the road, a considerable number of failures were observed in the pile-to-structure connections (figure 4.7c.), which were primarily due to the corrosion of the connections, and the excessive lateral or uplift forces acting on them. These forces were generated during high wind, waves, and storm surge events that occurred in the region. Moreover, there were instances of scour and erosion beneath houses (figure 4.7a-b.), which were situated adjacent to the repaired road on the left side of the road. The collapse of these houses was primarily attributed to the effects of the impact of debris coming from the other side of the road, and scour caused by flooding and wave power.

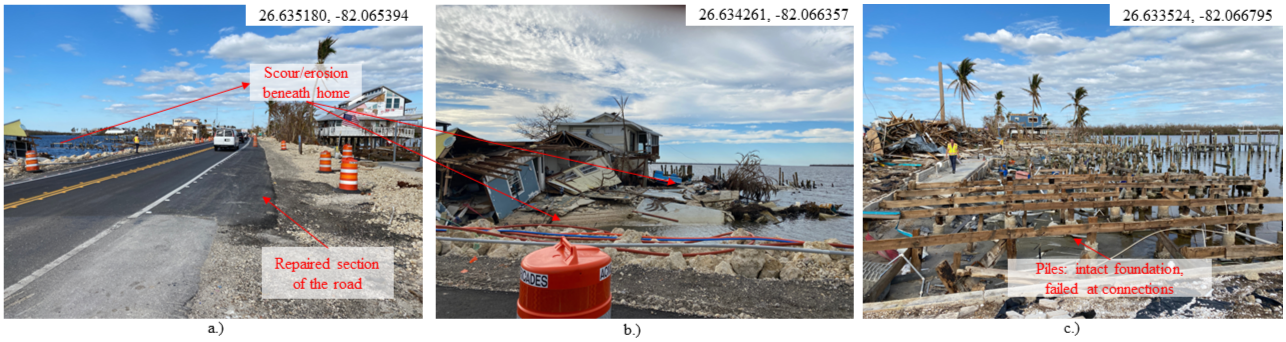


Figure 4.7: East entrance to Matlacha: a.) newly paved road connecting Matlacha and Pine Island; b.) erosion and scour underneath a house adjacent to the road on the upper east side of Matlacha; c.) lower left side of the east entrance of Matlacha where a significant number of houses slipped away due to failure at the piers connections.

Moving down Pine Island Road through the east entrance of Matlacha, scour and erosion was prevalent beneath houses as shown in figure 4.8a, 4.8b, and 4.8d. The degree of scour was observed to be different in each case depending on the elevation of the house in case by case basis. One incident of differential settlement was observed due to various levels of scour when comparing the right corner of a house and the back side (figure 4.8c.). The differential erosion observed on the property can be attributed to a combination of factors, including the absence of any obstacles on one side and the protection provided by the neighboring property on the other side. The eastern side of the property, which was left exposed due to the collapse of the neighboring house and the washing away of debris, suffered more erosion and damage from the powerful waves. In contrast, the protected side of the house, which was shielded by the neighbor's property, did not experience as much erosion or damage. The back of the house, being further away from the direct hit of the waves, was relatively unscathed. Despite the significant erosion and scour that occurred beneath the foundation of the house, no damages to the column footings or the foundation itself were observed (figure 4.8b, and 4.8d. This is a remarkable finding, given that these load-bearing columns are responsible for supporting the weight of the house and ensuring its stability. The lack of damage to the footings can be attributed to several factors, including the use of sturdy materials and a robust foundation design. Additionally, the house may have been constructed to withstand the effects of natural disasters, such as flooding and erosion. This underscores the importance of implementing appropriate design standards and building codes in regions that are prone to such natural disasters. Indeed, the absence of ongoing maintenance and monitoring can lead to serious consequences for structures located in coastal areas. Neglecting to monitor the effects of natural disasters such as flooding and erosion can result in unseen damage that could compromise the structural integrity of a building. Additionally, regular maintenance can help identify potential issues and allow for prompt repairs or remediation, preventing more significant damage in the future. In some cases observed so far, the lack of attention to this fact seemed to be the prominent reason for structural failure. Therefore, it is crucial for property owners and local authorities to prioritize ongoing maintenance and monitoring of structures in regions to ensure their long-term stability and safety.

Figure 4.8: East entrance to Matlacha: a.) accumulation of sediment and debris and erosion and scour underneath the house; b.) load-bearing column without any damage to the footing during the scour and erosion process underneath the foundation at the back of the house; c.) different levels of erosion underneath the house's foundation resulting in a differential settlement; d.) the load-bearing columns remaining intact without any damage, despite a significant amount of scouring and erosion

The effects of prompt repairs and remediation to prevent significant damage were apparent in the aftermath of the destruction observed on the east side of the Matlacha Isles-Matlacha Avenue. As seen in Figure 4.9a, depicts a drone image of the seawalls on an old property that had failed, causing the front of the seawall to collapse and resulting in the complete destruction of the house as shown in 4.9b. However, behind the newer seawalls on either side, while scour was observed due to the sunken seawall, neither the anchors nor the wall itself had failed (4.9c). The scope of the scour was only limited to the area where the two walls met. This highlights the importance of regular inspections and timely repairs to ensure the stability of seawalls and protect the structures they support. Had the old property's seawalls been properly maintained and promptly repaired, the destruction of the house could have been avoided.

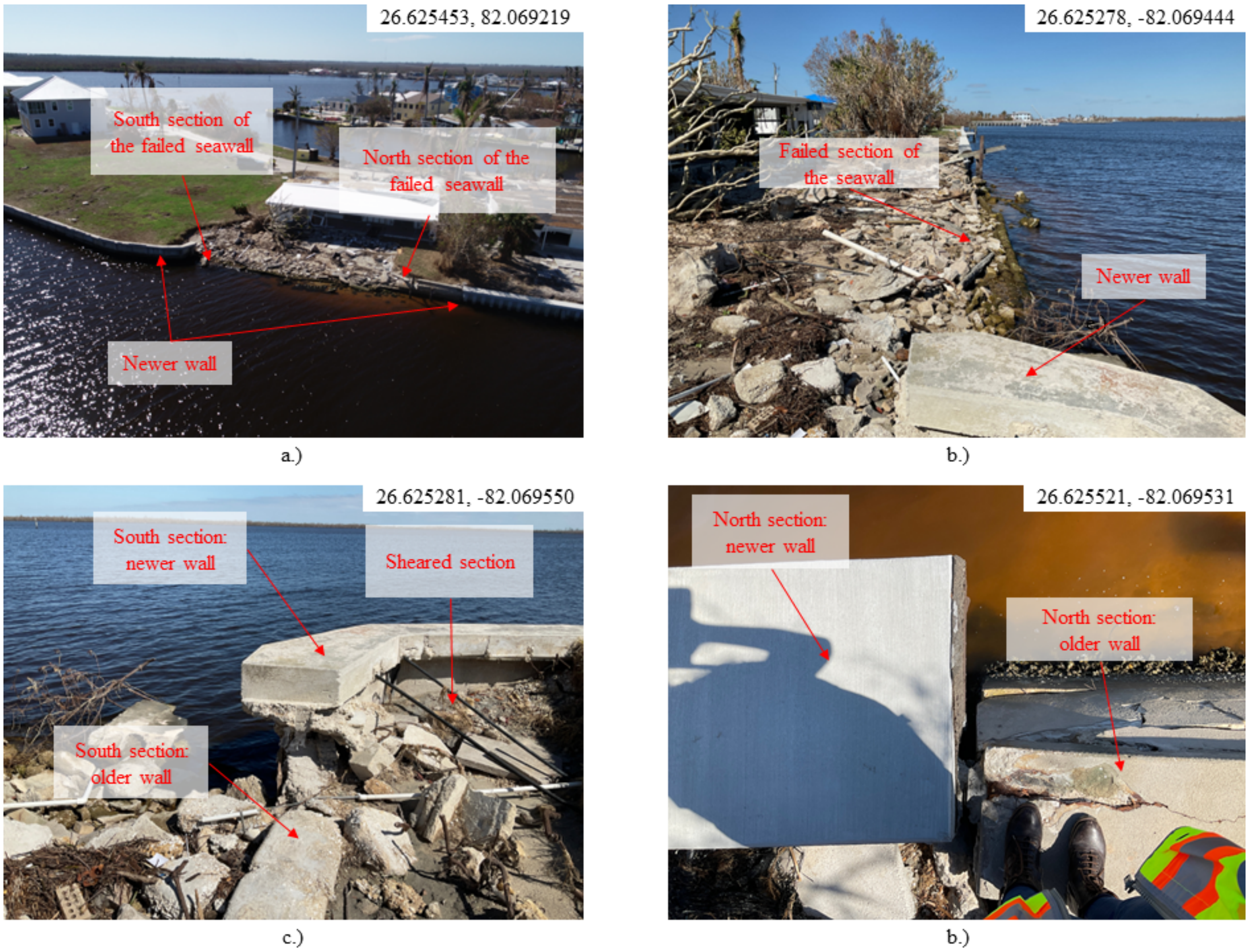


Figure 4.9: Damage to the seawall on the east of Matlacha Isles-Matlacha Avenue: a.) drone image depicting the newer installed seawall and the failed section of the old seawall believed to have failed at the intersection of the new and old one; b.) ground image showing the failed section of the seawall situated at the south of the river; c.) erosion behind the sheared section of the south seawall and breakage at the intersection of the old and new seawall; d.) plan view of the north section of the failed sea wall, depicting a stark contrast between the old failed seawall and the new one.

On the way to exit the Matlacha Isle, north of the west entrance, many houses were seen to have failed structurally caused by extreme erosion and the impact of waves directly coming towards the front of the house which coincidentally is facing the road. Sediments transported by the waves shown in the drone image in figure 4.10a and ground photo 4.10e suggest that the direction of water flow was from the road to the body of water behind the houses. This is further solidated by resident reports where they witnessed high storm surges coming from the opposite way that it was reported by news broadcasts. The rip rap seawalls behind the houses that were protecting them from the anticipated surge, remained intact

(4.10c), however significant damage was done to a few houses that were in direct impact range of the storm. Figure 4.10a-c show scour and erosion beneath houses and figure 4.10d shows the debris of a completely destructed house due to water impact which through more investigation it was concluded that the property was old and damaged before the storm hit causing it to be more vulnerable to fail structurally in comparison with the neighboring properties. When On the way to exit the Matlacha Isle, north of the west entrance, many houses were seen to have failed structurally caused by extreme erosion and the impact of waves directly coming towards the front of the house which coincidentally is facing the road. Sediments transported by the waves shown in the drone image in figure 4.10a and ground photo 4.10e suggest that the direction of water flow was from the road to the body of water behind the houses. This is further solidated by resident reports where they witnessed high storm surges coming from the opposite way that it was reported by news broadcasts. The rip rap seawalls behind the houses that were protecting them from the anticipated surge, remained intact (4.10c), however significant damage was done to a few houses that were in direct impact range of the storm. Figure 4.10a-c show scour and erosion beneath houses and figure 4.10d shows the debris of a completely destructed house due to water impact which through more investigation it was concluded that the property was old and damaged before the storm hit causing it to be more vulnerable to fail structurally in comparison with the neighboring properties.

On the way out of Matlacha Isle, it was observed that many houses had failed structurally due to extreme erosion and the direct impact of waves coming towards the front of the houses, coincidentally facing the road. Sediments transported by the waves, as seen in the drone image in Figure 4.10a and ground photo in Figure 4.10e, suggest that the direction of water flow was from the road to the body of water behind the houses. This was further confirmed by resident reports of high storm surges coming from the opposite direction than what was reported by news broadcasts. While rip rap seawalls behind the houses remained intact, significant damage was done to a few houses that were within direct impact range of the storm, as shown in Figures 4.10a-c. The erosion and scour observed beneath the houses highlight the destructive power of waves.

Figure 4.10d shows the debris of a completely destroyed house due to water impact. Further investigation revealed that the property was old and damaged before the storm hit, making it more vulnerable to structural failure compared to neighboring properties. The two neighboring properties, shown in figures 4.10b and 4.10c, were elevated higher than the collapsed house. Based on the owner's report, they renovated and repaired the foundation of the house and elevated it higher to account for flooding days before the storm. This proactive measure likely saved their homes from the same fate as the collapsed house.

Figure 4.10: Severe damage and erosion to houses on Matlacha Isle, located on the left side of Pine Island Road: a.) drone image showing sediment accumulation, indicating the direction of high water flow with evidence of scouring and erosion beneath the foundation of two homes; b.) ground image depicting evidence of scouring and erosion beneath the foundation of the yellow house; c.) ground image of the back of the blue house reveals transportation of sediment, indicating the direction of water flow from behind the intact rip rap seawalls. The settlement of the house is also visible due to erosion and scouring beneath its foundation; d.) One house has been completely destroyed, with debris and water accumulation observed at the site; e.) accumulation of sediment suggesting water flow direction from Pine Island Road to the back of the houses, which is opposite to the predicted path.

The west entrance of Matlacha has sustained less damage than the east entrance, although there has been significant damage to the north side of the bridge due to the collapse of the retaining walls next to the entrance. Figure 4.11 best illustrates this. The location of the recently constructed abutments (figures 4.11a, 4.11c, and 4.12c) and the areas where the sea walls were damaged and had failed to lead to the collapse of a house can be seen in the drone image displayed in 4.11a. Figures 4.11b and 4.11c show how half of the aforementioned house sank as a result of the failure of the sea wall on the right side of the bridge which was supporting the house. Figure 4.11d depicts the sea wall's broken remains.

Figure 4.11: West entrance to Matlacha: a.) drone image of a severe retaining wall failure on both sides of the bridge along with the newly built abutment; b.) ground photo of the back of the house showing the remaining section of the retaining wall and the magnitude of collapse caused by the failure leading to half of the house sinking; c.) ground photo showing the road front of the house with the abutment built after the collapse; d.) Plan ground photo of where the retaining wall failed behind the house.

On the left side of the bridge, shown in figure 4.12 a portion of the retaining wall also failed causing erosion and scour behind the wall however this incident was not as major as the right side of the bridge. On the south side of the bridge no discernable damage was seen as depicted in figure 4.12d.

Figure 4.12: Ground photo of the upper side of the bridge: (a) remaining piece of the broken seawall showing breakage in the sheet pile's connection; (b) scour and erosion as a result of the failed seawall behind the failed section causing more damage to the wall and accelerating the deterioration; (c) ground photo of the newly built abutment for the bridge; (d) ground photo of the lower side of the bridge showing the intact seawalls that had no damage.

4.2.3 Bokeelia and St. James City

Bokeelia in Pine Island, Florida, is a community that is vulnerable to the impacts of hurricanes due to its location along the coast. The area's geological context is crucial for effective planning and management in the face of ongoing changes caused by natural processes such as sediment transport and beach erosion.

GEER team visited Bokeelia to capture the aftermath of Hurricane Ian which has shown the extent of damage caused by the storm surge. A broken dock in Bokeelia as shown in figure 4.13a-b, highlights the vulnerability of coastal infrastructure to the power of the waves, with broken sections of the walkway shown to be a cause of pillars breaking in half or being picked up at the base by the wave power. A closer look at the broken sections of the dock's walkway shows the complete submergence of the supporting pillars.

The impact of elevation on storm surge damage is an important factor to consider in coastal communities. As seen in figure 4.13c-d, St. James City, houses that were elevated higher experienced less damage during the hurricane's storm surge. This is because as the water level rises, houses that are elevated higher have a lower chance of being submerged by the floodwaters. The water level would have to rise significantly higher to cause significant damage to these houses.

The effects of elevation on storm surge damage have been observed in previous hurricanes as well. For example, in Hurricane Katrina, houses that were elevated higher experienced significantly less damage compared to houses that were at lower elevations. This highlights the importance of considering elevation when planning and building coastal communities. By building houses at higher elevations, the risk of storm surge damage can be significantly reduced.

Additionally, understanding the geological context of the area can also be crucial in planning for and managing storm surge impacts. For example, in areas with sandy or unstable soils, building foundations may need to be strengthened to prevent damage during storm surges. Bokeelia, like other coastal areas, is subject to the constant evolution of its coastal environment due to natural processes such as sediment transport and beach erosion. This can result in the loss of natural protection against storms, making the community even more vulnerable to the impacts of hurricanes.

Hurricane Ian has brought to light the importance of mangroves in protecting against scouring. Reports indicate that in areas where mangroves are absent, there has been scouring observed behind the seawall. For instance, in figure 4.14a, it was noted that there was scouring behind the seawall, with no presence of mangroves, even though the seawall and anchors were intact. The same observation was made in location 4.14b, where the seawall and anchors were still intact, but scouring was observed behind them due to the lack of mangroves.

On the other hand, the presence of mangroves has been found to offer protection against scouring. In location 4.14c, where mangroves were present, no scouring was observed behind the seawall, indicating that the mangroves provided sufficient protection. Similarly, in location 4.14d, mangroves were observed to protect against scouring even in the absence of a seawall, demonstrating the effectiveness of these natural barriers. These findings emphasize the importance of preserving and protecting mangroves as a means of mitigating the impacts of future storms.

Mangroves play a crucial role in protecting the coastline from erosion by reducing wave energy and stabilizing sediment with their root systems. However, many areas in St. James City and Pine Island each have experienced mangrove loss due to human development and other factors, leaving the coastline more vulnerable to storm damage.

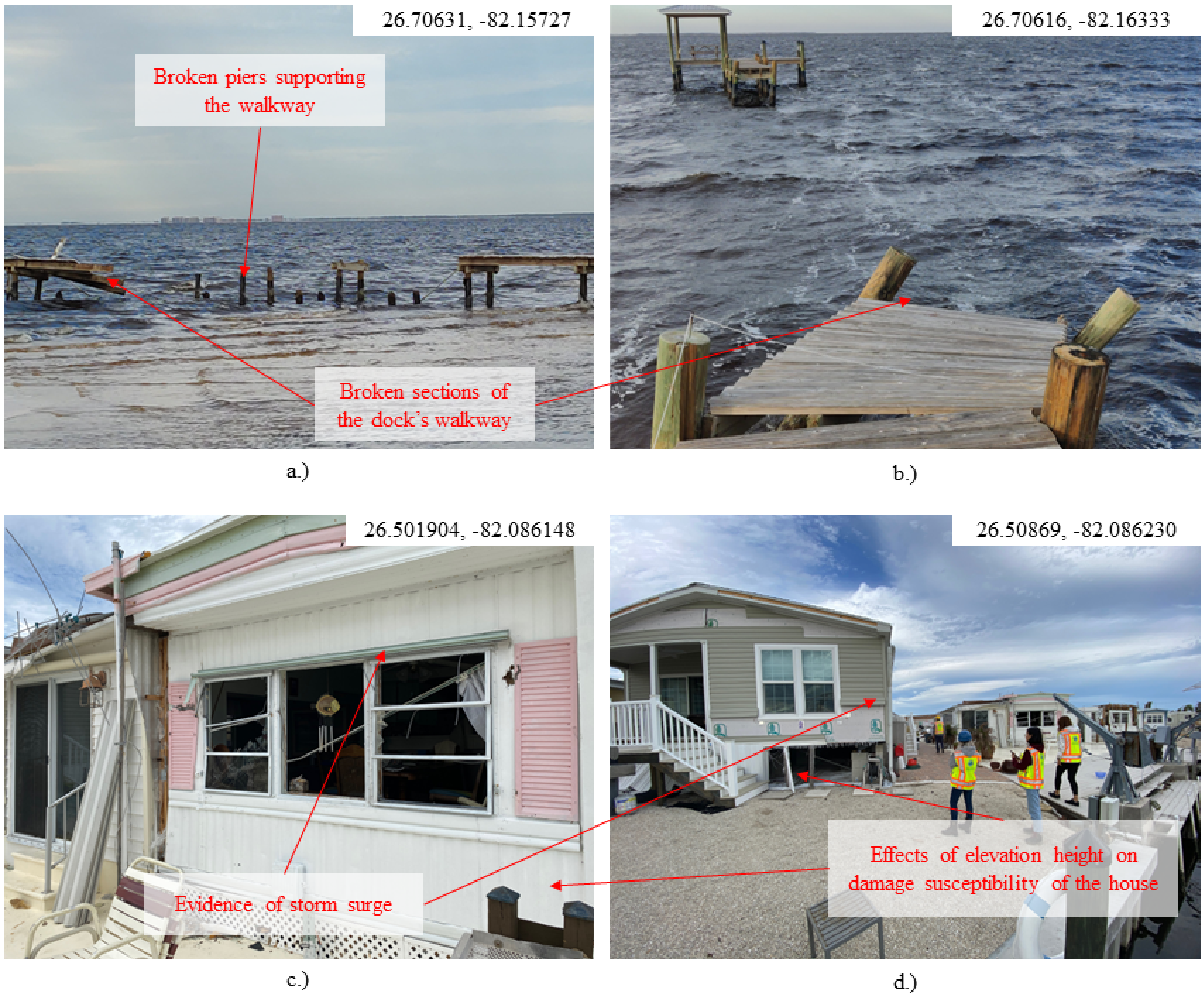


Figure 4.13: Ground photo of a broken dock in Bokeelia (top) and housing destruction in St. James city (bottom): (a) broken sections of the walkway is shown to be a cause of pillars breaking in half or being picked up at the base by the wave power; (b) closer look at the broken sections of the dock's walkway showing complete submergence of the supporting pillars; (c) evidence of storm surge in St. James City as damage was observed to go up to the top rim of the windows for houses that were on the same elevation; (d) for houses that were elevated higher, less damage was seen to be slightly above the lower rim of the windows approximately 6 feet high.

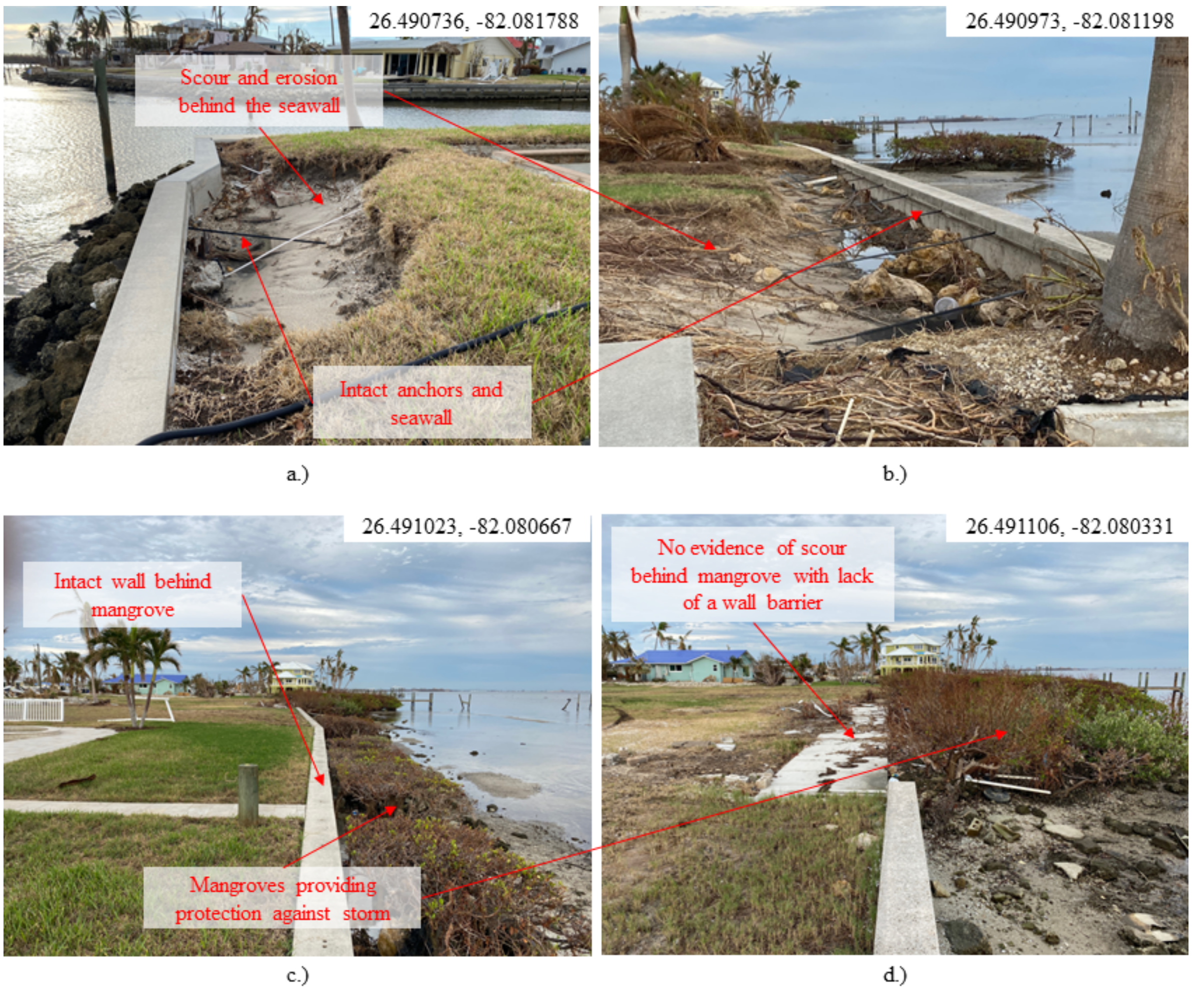


Figure 4.14: Ground photos St. James City: (a) scour behind the seawall noting that the sewall itself and the anchors are intact and no mangrove is present; (b) another instance of no mangrove being present and the seawall and anchors being intact with scour behind them; (c) no scour is present behind the seawall in lieu of protection from mangrove; (d) another example of mangrove protecting against scour where there is no sign of scour even where there is no seawall

4.3 Cape Coral

Cape Coral is a city located in Southwest Florida, situated on the Gulf of Mexico. The area is characterized by flat terrain, sandy soil, and a low-lying topography. The soil in Cape Coral is predominantly sandy, which is typical of many coastal areas. The soil is formed from weathered shell and limestone, with some areas having a higher concentration of organic material due to the presence of mangroves and other vegetation.

The geology of Cape Coral is heavily influenced by the region's unique history. The area was once a shallow sea that was filled with sediment over millions of years, leading to the formation of limestone and other sedimentary rocks. The region's geologic history has also led to the development of sinkholes, which are common in the area due to the dissolution of limestone by acidic groundwater. This might explain some of the extreme erosion the GEER team observed in this area which was described as erosion-induced sinkholes as shown in figure 4.15.

Figure 4.15a-b depicts a failed retaining wall which has led to extreme erosion causing a depression in the soil. The GEER team also observed subsurface irrigation systems which may have played a role in weakening the soil in this area.

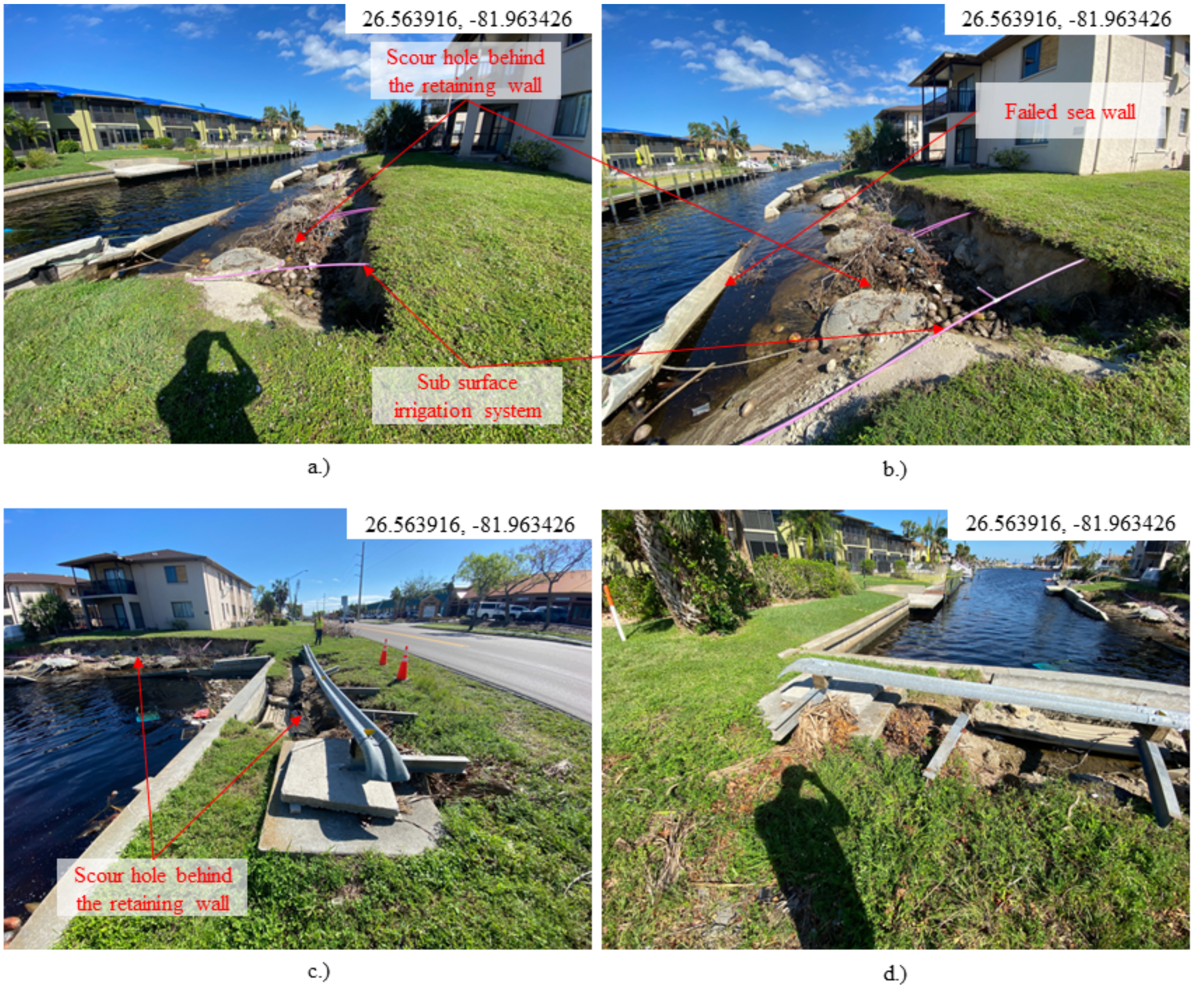


Figure 4.15: Ground photos of erosion-induced sinkholes at Cape Coral: (a) failed retaining wall on the side of the canal causing extreme ground depression and failed anchor rods with visible subsurface irrigation system; (b) a closer look at the same site; (c) top of the canal where much less soil erosion is present and the retaining wall has not failed; (d) behind the retaining wall at the top of the canal, showing some ground depression due to the erosion caused presumably by the drainage system

Subsurface irrigation pipe systems can weaken the soil and increase the potential for erosion-induced sinkholes. This is because the pipes are installed underground and release water directly into the soil, which can saturate the soil and cause it to become loose and unstable. Over time, this can lead to soil subsidence and the formation of sinkholes. Additionally, subsurface irrigation systems can also cause the soil to become more compacted, as the weight of the soil and vegetation above the pipes can compress the soil. This can reduce the soil's ability to absorb water and nutrients, and also make it more prone to erosion.

Another major component of this site's observed ground depressions could possibly be the drainage system implicated in the canal. When water flows through drainage pipes in a canal, it can cause erosion in the soil behind the retaining wall. This is because the water flow creates a vacuum effect, which pulls soil particles from behind the retaining wall and into the canal. As the soil erodes, it creates voids or empty spaces that weaken the retaining wall's stability. Over time, these voids can become larger and eventually lead to a failure of the retaining wall as shown in figure 4.16c-d where the retaining wall has failed, resulting in further erosion and potential sinkhole formation. Additionally, the presence of excess water from the canal can also increase soil saturation, leading to decreased soil strength and stability, which can also contribute to the potential for erosion-induced sinkholes. Figure 4.15c-d depicts a small erosion which was presumably caused by the drainage system behind the top retaining wall. These drainage pipes can be found on the side and top retaining wall as shown in figure 4.16a-b and in figure 4.17a-b respectively. Figure 4.17c shows a breakage in the other side of the canal where there is no drainage system present.

Figure 4.16: Ground photo of the erosion-induced sinkhole on the right side of the canal: (a) drainage pipe is visible and might have been the primary cause of the failure at this section (b) drainage pipe in the vicinity of the cavity created by erosion; (c) failure of the retaining wall as a result of the vacuum effect of the voids created in the soil; (d) back of the failed retaining wall showing the breakage and displacement

The failure of the retaining wall in this canal highlights the complex interplay between natural and human-induced processes that can result in significant environmental and infrastructure damage. Analysis of the site reveals that the initial cavity in the soil created due to the water vacuum effect was predominately the cause of failure in this area. The formation of voids and cavities weakens the soil's structural integrity, making it more susceptible to erosion and collapse. Moreover, the soil's weakness from the subsurface irrigation system intensified the erosion process, which in combination with the voids created in the soil due to the presence of the drainage pipes, created a chain of events that ultimately led to the failure of the retaining wall. Had the primary reason for the incident, the initial cavity created by the water vacuum effect, was not present as shown in figure 4.17c, the subsequent erosion and structural failure could have been prevented shown in figure 4.17d.

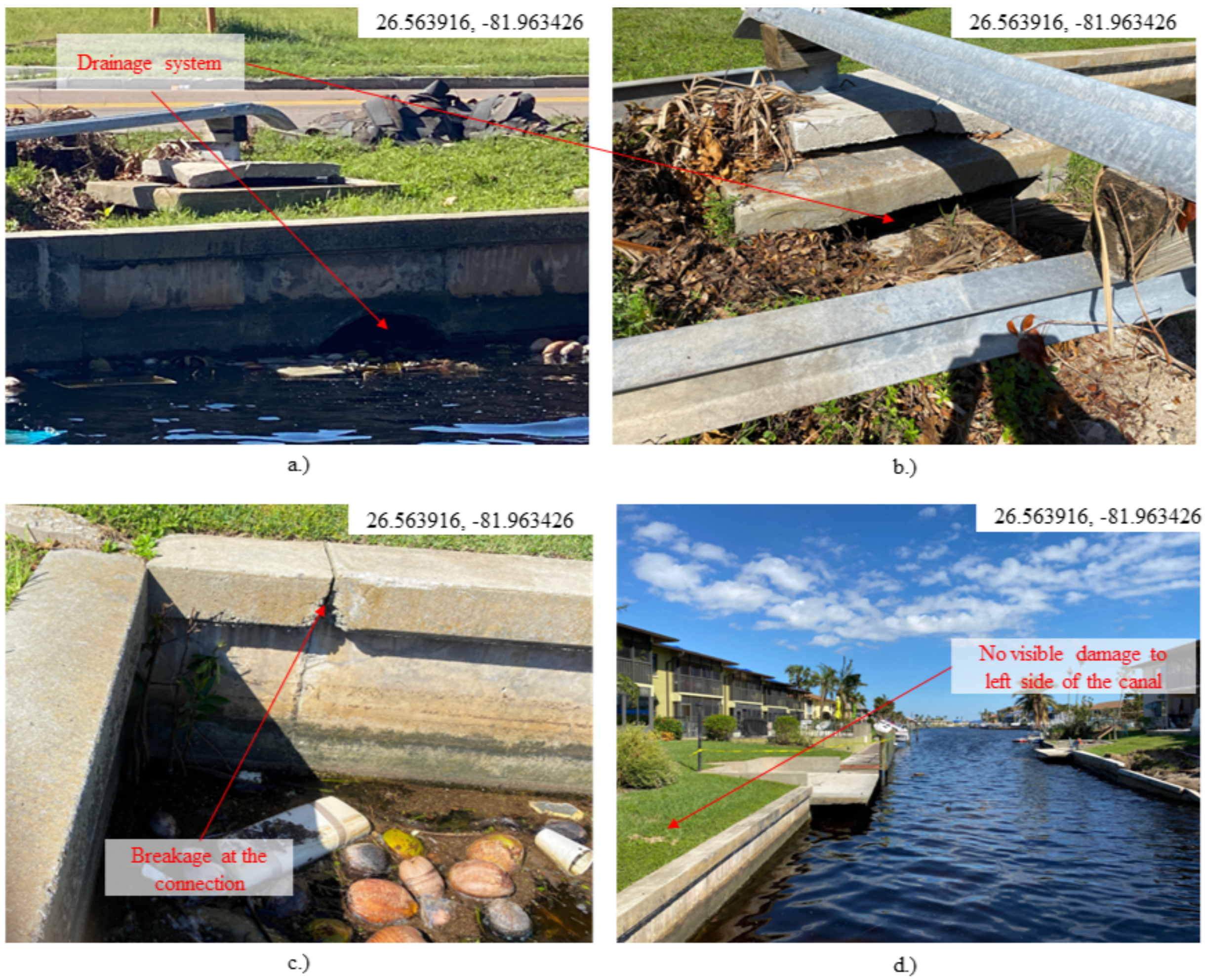


Figure 4.17: Ground photos of the top side of the canal (top) and left side of the canal (bottom): (a) drainage system at the top of the canal; (b) initial cavity created by the presence of the drainage; (c) small breakage due to compounding water pressure on the retaining wall and no sign of a drainage system present on the left side of the canal; (d) left side of the canal showing no sign of erosion

Figure 4.18 shows a terrestrial LiDAR image taken at the site where the magnitude of this event is more visible.

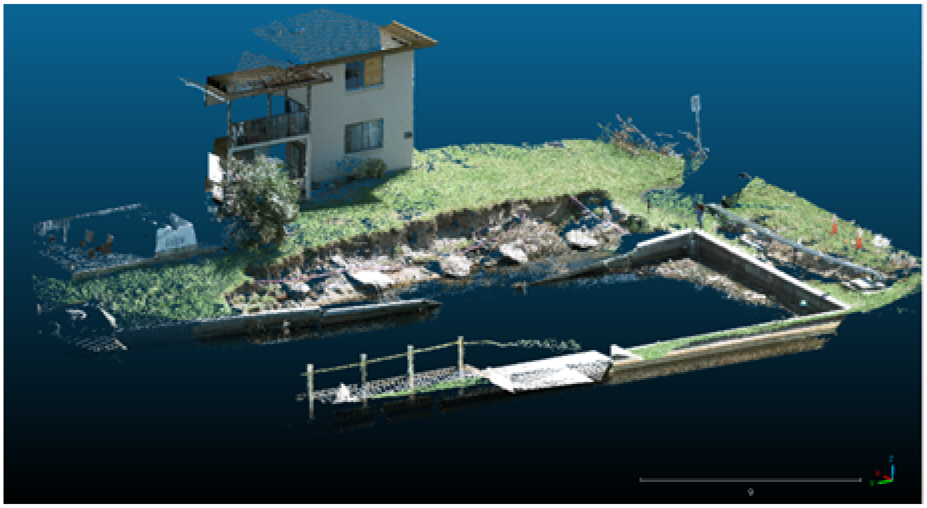


Figure 4.18: Cape Coral: Terrestrial LiDAR scan of a canal retaining wall in a residential neighborhood. Coordinates 26.564127, -81.963464

GEER team also observed massive sediment transportation in the canal which is depicted in figure 4.19. In the case of the retaining wall failure, the sediment transport analysis showed that the path of the storm was directly in the canal. The water flow and associated sediment transport were intensified in this particular location, which could have contributed to the erosion and failure of the retaining wall. The depth of sediment to the water surface was measured as shown in figure 4.19c-d.

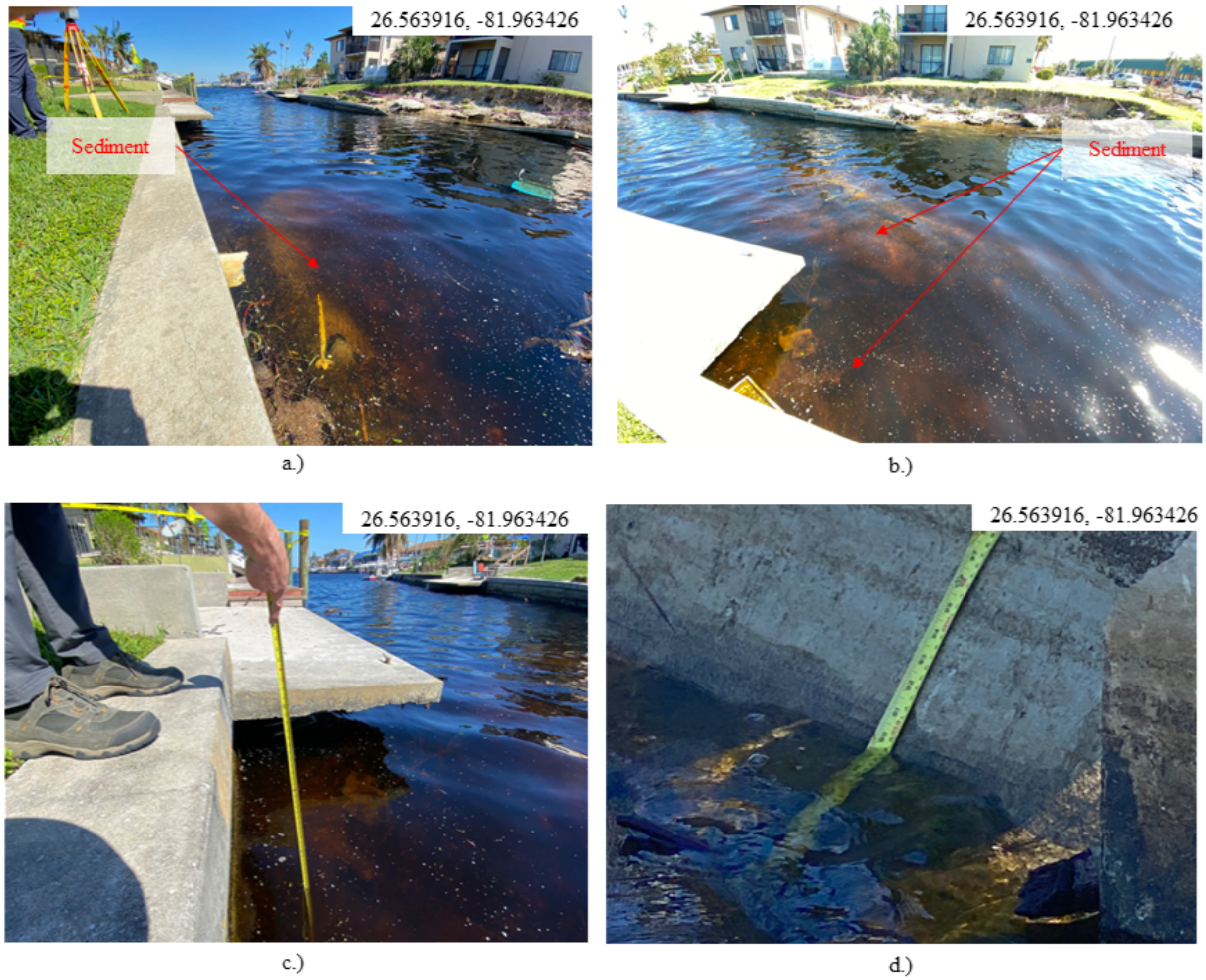


Figure 4.19: Post-hurricane sediment transport analysis of a canal in Cape Coral showing significant accumulation of sediment, indicating the path of the storm

In addition to the retaining wall failure due to soil erosion, the GEER team also observed two other types of failures in Cape Coral after the hurricane. The first type of failure was related to the uprooting of trees, where the roots of the trees were pulled out of the soil, resembling a foundation uplift failure which is shown in figure 4.20a. This type of failure occurs when the soil supporting the foundation is unable to resist the uplift forces acting on it. In this case, the water table rose to such a high level that the soil lost its bearing capacity, causing the roots to be pulled out of the ground.

The second type of failure observed by the GEER team was related to guy wire anchor rods, which are designed to provide stability to tall structures such as transmission and communication towers. During the storm surge, the tremendous force of the water acted upon the anchor rod and the soil surrounding it, causing it to move and detention shown in figures 4.20a,c,d. This type of failure highlights the power of the storm surge, which can cause even large and stable structures to become unstable and potentially collapse. The GEER team observed that for some utility poles, the base was eroded which could increase the chance of collapse of the utility pole in future extreme events if not fixed as shown in figure 4.20b. The team also noticed that some of the guy wire anchor rods were dislodged and detensioned about 8 inches during the hurricane, indicating the great force being exerted on the rod and the surrounding soil which is shown in figure 4.20d.

Figure 4.20: Bearing capacity and stability failure in Cape Coral: (a) overturned trees and detensioned guy wire anchor rod resulting in a stability failure of the utility pole; (b) erosion around the base of the pole; (c) closer look at the detensioned anchor rods; (d) anchor rod dislodged approximately eight inches from it's original location due to extreme force of the storm surge.

Inspecting Cape Coral, the GEER team did not observe any other types of geotechnical failure other than the previously mentioned ones. However many detached roofs and overturned boats were observed in the Bimini Basin and Four Freedom Park as shown in figure 4.21a-b. The sidewalk was detached from the retaining wall and the lower ground in the Basin and looking at the cross-section of it, many cracks were noted as it is depicted in figures 4.21c-d. It is undecided if the displacement of the sidewalk occurred due to Hurricane Ian.

Figure 4.21: Ground images of Four Freedoms Park: (a) Overturned boats as a result of extreme water surges and wind power along with slight displacement of the sea wall along the side walk; (b) due to Hurricane Ian's powerful winds, roof panels came off as evidence of a structural failure; (c) closer look at the displacement of the sea wall; (d) the displacement also came from the base where there were stairs.

Storm surge typically carries large amounts of water, waves, and debris onto coastal areas. When the surge recedes, it leaves behind debris that can get caught in trees as shown in figure 4.22. The height and pattern of the debris marks on trees can indicate the maximum level reached by the storm surge. In Cape Coral the marks show a storm surge of close to 6 feet in the area which is corroborated by the eye witnesses and residents.

Figure 4.22: Evidence of the storm surge in Cape Coral: (a) debris marks on trees measuring at 72 inches (b) closer look at the debris marks

4.4 Downtown Fort Myers

The Centennial Park was surveyed near Downtown Fort Myers as shown in figure 4.23a through f. The damage was mostly observed in boats which were washed ashore during the storm and some piers which were completely destroyed. Figure 4.23a and 4.23d shows the damage to the shore railings but no significant damage was observed due to geotechnical failure. Upliftment of ground was observed near the parking lot as shown in figure 4.23b. Boats were greatly damaged as shown in figure 4.23c and 4.23e. The pier was observed to be damaged with the foundation being severely destructed as shown in figure 4.23f.

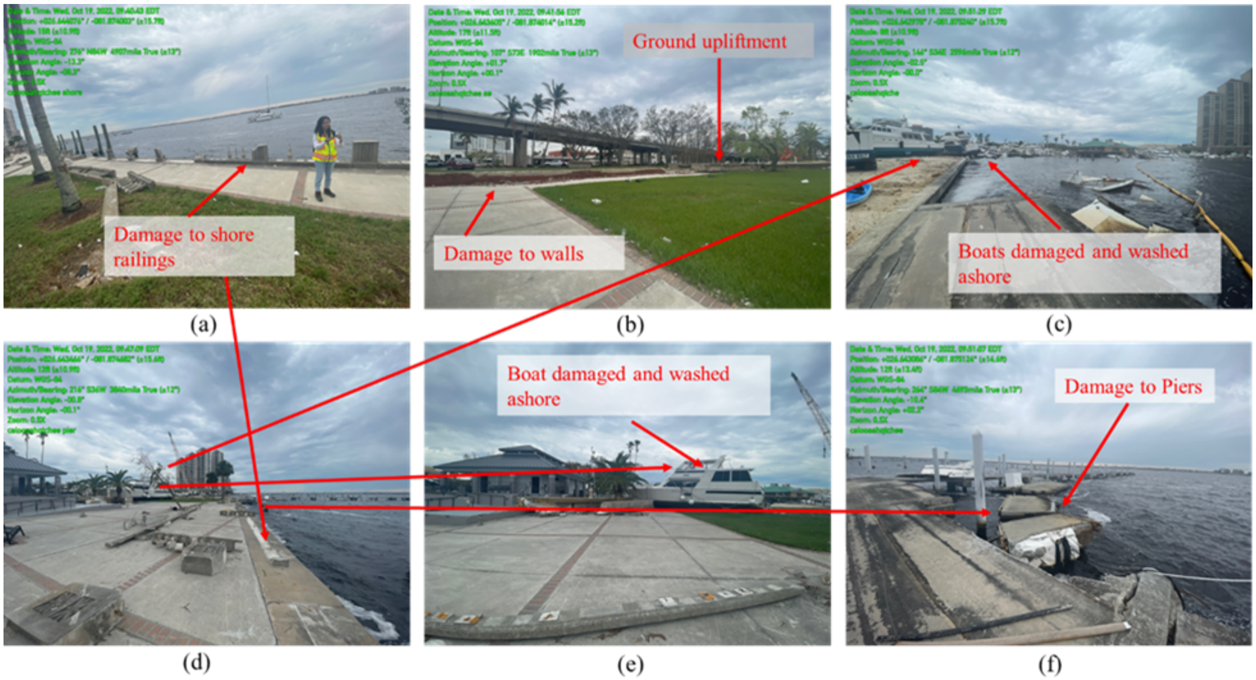


Figure 4.23: Surveying around Centennial Park, Downtown Fort Myers: (a) Damage to shore railings; (b) Ground upliftment and damage to walls near the Cleveland Avenue; (c) Damaged boats washed ashore due to the storm; (d) Damage to railings; (e) Boat damaged and washed ashore; (f) Damage to piers with severe damage to the foundation. Coordinates: 26.64375, -81.87416

In Addition to Downtown, Beckler Riverside area, which is along the Caloosahatchee River, was surveyed for damage as shown in Figures 4.24a through 4.24d. Figure 4.24a shows the satellite image of the area before the storm. It can be observed from Figure 4.24b that there was a wall failure accompanied by soil erosion. The Pier was completely damaged and washed away but the foundations were intact installed in place as observed from Figure 4.24c. More soil erosion was observed across the shoreline as depicted in Figure 4.24d.

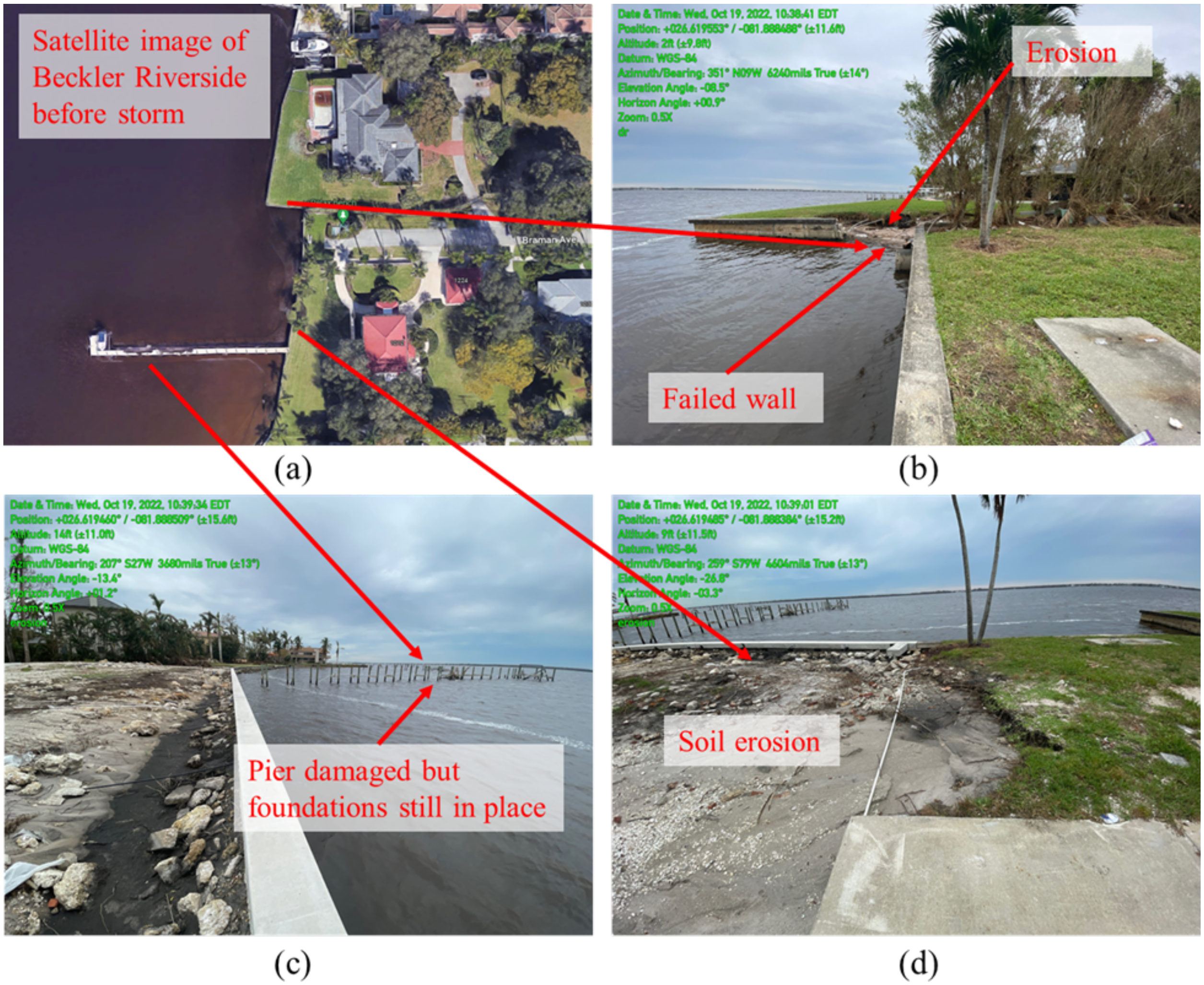


Figure 4.24: Surveying around Beckler Riverside along the bank of Caloosahatchee River: (a) Satellite image of the area before the Hurricane (b) Failing of wall and washing away of soils; (c) Pier completely washed away with foundations still intact ; (d) Soil erosion along the coast. Coordinates: 26.61952, -81.88840

4.5 Fort Myers Beach

Fort Myers Beach is a town located on Estero Island, a barrier island off the southwest coast of Florida. The island is part of a system of barrier islands that line the Gulf of Mexico, known as the barrier islands of Lee County. These islands are composed of sand and shell fragments and were formed during the last ice age when sea levels were much lower. As the climate warmed and the glaciers melted, sea levels rose and the islands were separated from the mainland.

Geologically, the area is also known for its karst topography, which is characterized by sinkholes and underground drainage systems. This type of landscape is formed by the dissolution of limestone bedrock, which is prevalent throughout the region. The porous nature of the limestone allows water to percolate through the rock, creating underground streams and caves. In some cases, the collapse of underground cavities can lead to sinkholes, which can pose a hazard to infrastructure and property.

The impact of Hurricane Ian on Fort Myers Beach is illustrated in Figure 4.25, which shows a before-and-after comparison. Notably, the figure highlights the location of an erosion-induced sinkhole, as shown in Figure 4.25a. However, the majority of the damage observed on the beach was related to structural damage caused by the hurricane.

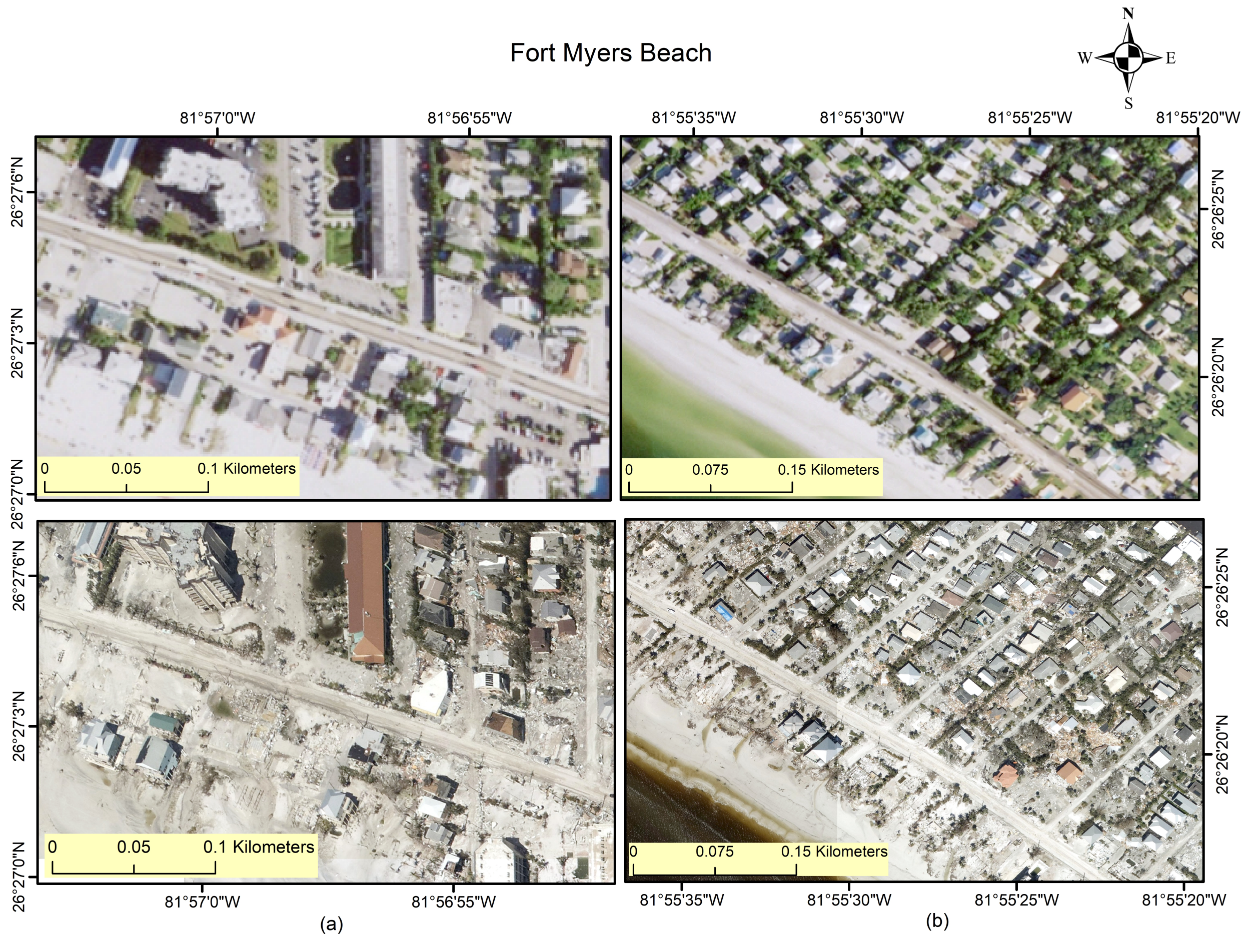


Figure 4.25: Overview of Fort Myers Beach

This island sustained extensive damage due to Hurricane Ian in the form of debris litter over the beaches, washing of boats ashore and building being completely vanished. Smaller buildings were impacted the most as they were deposited elsewhere after being carried away by the flood water. The survey was performed along the coast as shown in figures 4.26a through f. Figure 4.26a shows that most of the small buildings were completely obliterated. Soil erosion was also observed which made the foundations visible. Scouring of soil around the stone columns was also observed as depicted in figure 4.26b. However, the stone columns were still in place with no visible damage. Some of the stone columns were tilted due to the flood and erosion as shown in figure 4.26c. Figure 4.26d shows that the buildings were severely damaged with great quantities of soil being eroded. The water level was noted as shown in 4.26e. Figure 4.26f shows another case of soil erosion which caused the tilting of pole.

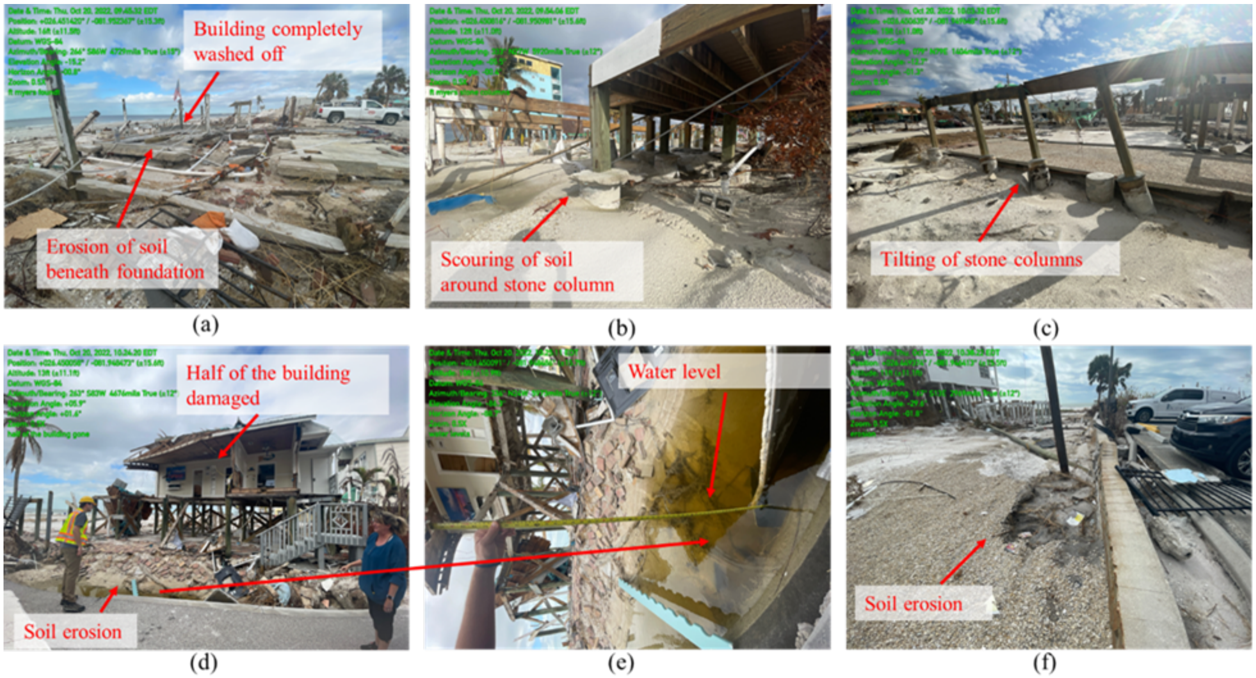


Figure 4.26: Surveying in Fort Myers Beach along the coast: (a) Buildings being completely washed off and soil erosion around the foundation (b) Scouring around the stone columns; (c) Tilting of stone columns and possible signs of erosion; (d) Damaged building and extreme soil erosion; (e) Survey of water levels near the building; (f) Soil erosion possibly causing tilting of pole.Coordinates: 26.44966, -81.94872

Other areas along Fort Myers beach were also surveyed and are depicted in figures 4.27a through f. Figure 4.27a depicts the formation of sinkhole due to saturation and liquefaction of the soil. This resulted in tilting of a pole. Soil erosion was observed beneath and around the foundations as shown in figure 4.27b and c. Differential settlement and tilting of columns was observed in some buildings as shown in figure 4.27d. It was interesting to note that for most of the buildings the first floor was completely washed away but damage to the upper levels was not that substantial. The Black Island Bridge was also surveyed and was observed to be in a stable state as shown in figure 4.27e. However, upon closer observation some of the bolts were detected to be damaged therefore, the connections of the bridge were weakened.

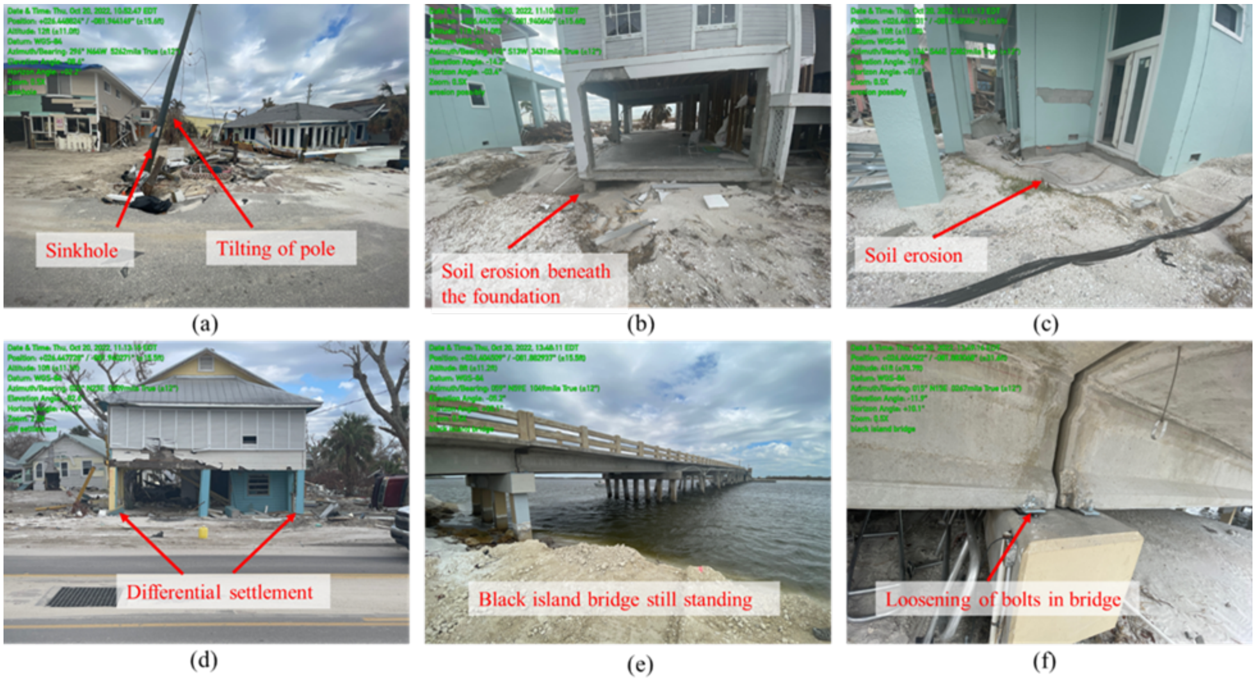


Figure 4.27: Surveying in Fort Myers Beach: (a) Formation of sinkholes and tilting of pole (b) Soil erosion beneath and around the foundation; (c) Soil erosion; (d) Differential settlement causing damage to the building; (e) Black Island bridge intact after the hurricane; (f) Loosening of bolts in the bridge.Coordinates: 26.45121, -81.95105

Several sinkhole formations were also observed throughout Fort Myers beach as shown in Figure 4.28a through f. Figure 4.28a shows a large sinkhole which affected a huge area. Multiple sinkholes were observed adjacent to the buildings as shown in Figure 4.28b and c. Water sinkholes were formed as a result of the hurricane as observed from Figure 4.28d which affected the overlying building and its foundation as depicted in Figure 4.28e. In some cases, such as Figure 4.28f, the sinkholes were large enough to engulf a part of the building.

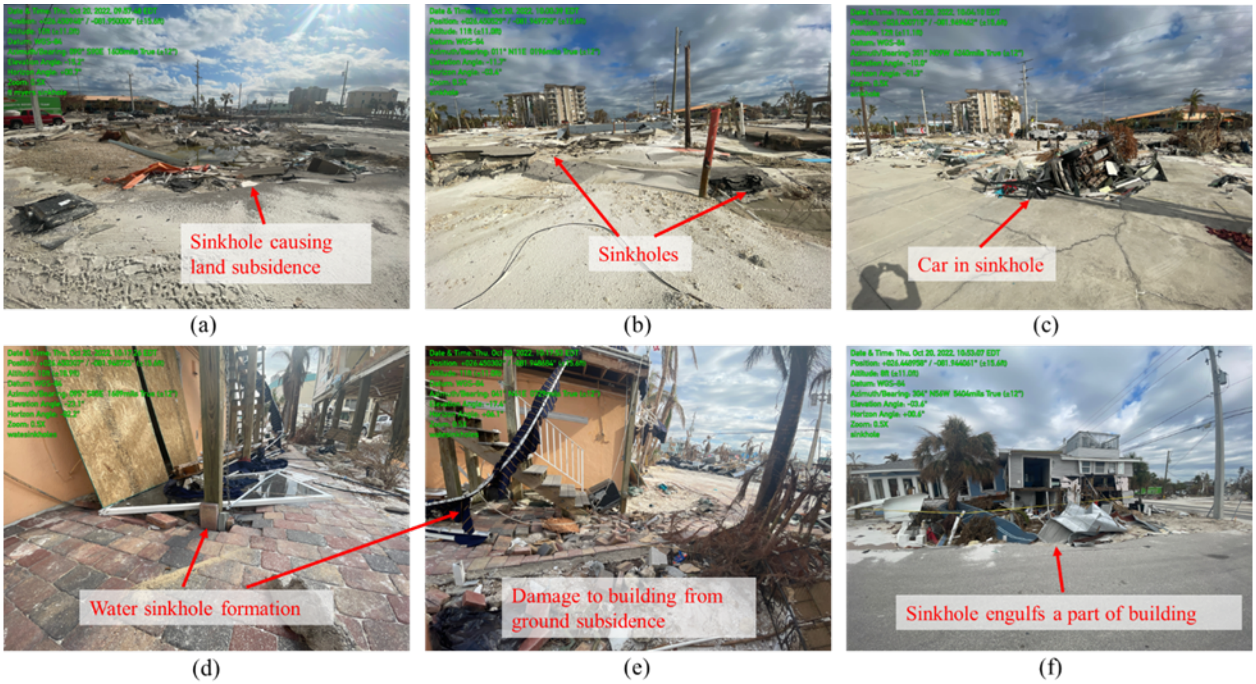


Figure 4.28: Surveying Fort Myers Beach: (a) formation of sinkholes resulting in land subsidising; (b) ground depressions as a result of cavity formation in the soil under the pavement; (c) sinkhole formation under a residential house causing cavity underneath the walk way and foundation of the house which in turn left the column's footing exposed; (e) structural damage to the building was observed which was due to the differential settlement caused by cavities formed; (f) extreme erosion and scour causing ground depression underneath the houses foundation, completely engulfing the middle of the house. Coordinates: 26.44742, -81.93963

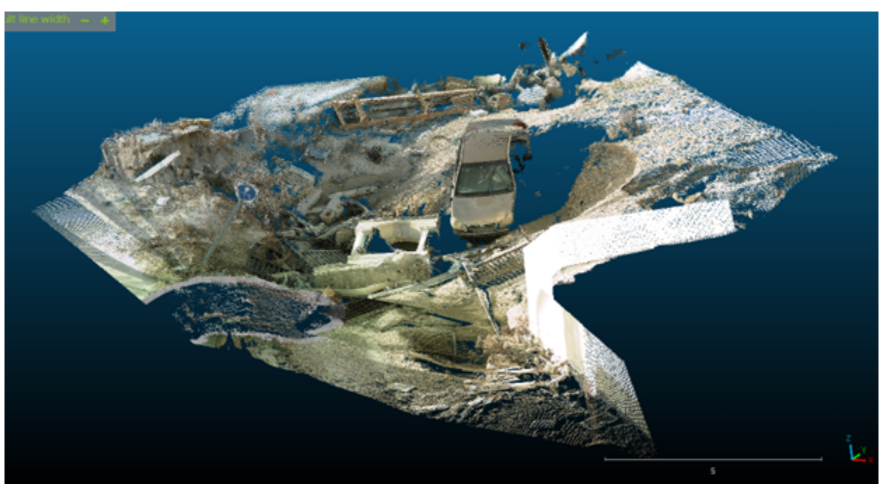


Figure 4.29: Terrestrial LiDAR scan of depression feature adjacent to road and apartment building. Coordinates 26.446486, -81.937939

Surveying the south east end of the Fort Myers Beach, the GEER team observed many ground deoressions and land subsidies resemebling sinkholes caused by sever erosion and scour particularly close to the buildings on shoreline. Figure 4.30 and 4.31a-b depict an erosion induced sink hole caused by the powerful storm surge of Hurricane Ian. The forceful waves and water currents erode the ground beneath the buildings foundations as shown in figures 4.30b-d, leading to the formation of sinkholes as the support for the building collapses and cavities form below the foundation as shown in figure 4.30b. Sediment transportation, especially in excessive amounts, can have significant geotechnical implications and adverse effects on the stability of the surrounding environment. As shown in figure 4.30c, these excessive amount of sediment can impact the stability of foundations supporting buildings. When sediment is eroded from beneath a foundation, the support and bearing capacity of the soil are compromised. This can lead to differential settlement, uneven stress distribution, and structural damage, ultimately jeopardizing the stability and integrity of the entire structure.

In the aftermath of Hurricane Ian, the GEER team observed an area of highly saturated sand resembling quicksand as shown in figure 4.31c due to heavy rainfall and flooding. In these saturated conditions, the soil became temporarily weakened and lost its ability to support weight. This in return created soft or muddy ground that may resemble quicksand-like conditions. This was a very isolated condition as it is assumed that this soft ground is not true quicksand but rather a result of the temporary saturation of the soil. While people may experience difficulty extracting their feet from this softened ground, it is undecided if this condition has the same characteristics as true quicksand. Quicksand typically forms in specific geological environments with the right combination of loose, fine-grained sediment and high water content. It is relatively unstable and prone to liquefaction under stress or disturbance. Highly saturated soil that behaves like quicksand can result from excessive water saturation due to factors like heavy rainfall or flooding. While it may exhibit quicksand-like behavior, the stability and degree of liquefaction can vary depending on the specific soil composition and water content. Highly saturated soil that behaves like quicksand exhibits similar characteristics of low strength and fluid-like behavior but may have a slightly higher viscosity compared to true quicksand. It may exhibit a "quicksand-like" behavior when loaded or disturbed but may not flow as freely as true quicksand.

The GEER team observed another concerning situation in the south east end of the island during their assessment of residential buildings' foundation, extreme scour and erosion underneath the foundation was discovered, leading to the exposure of the footings and cavities created below the foundation causing breakage. This finding raises significant geotechnical issues and indicates potential geotechnical failure. This is shown in figures 4.32, 4.33, 4.34, and 4.35. With the soil eroded, the stability and load-bearing capacity of the soil supporting the structure is undermined. Furthermore, the exposed footings depicted in figures 4.32b-c, 4.34b, 4.35, and specially disconnected footing shown in 4.33 are particularly problematic as they can no longer rely on the surrounding soil for proper support and distribution of loads as the scour and erosion create voids or cavities beneath the footings, reducing the effective bearing area. As a result, the load-bearing capacity of the footings decreases, leading to increased stresses and potential settlement or failure. Furthermore, the uneven scour and erosion patterns can cause differential settlement resulting in an uneven distribution of loads, leading to structural distortion, cracking, or even collapse. Moreover, the extreme transportation of sediment from the shore exacerbates the geotechnical challenges.

The influx of sediment can lead to the formation of empty cavities below the foundation. These cavities as shown in figures 4.32b-d, 4.34, 4.35 and figure 4.33b, when unsupported, further reduce the load-bearing capacity of the soil and increase the risk of foundation failure.

Figure 4.36 depicts a sea wall failure where the anchor rod has corroded and broken at the connection. Figure 4.36b shows an anchor system which could resemble the tie-back and deadman weight system however, it seems that this system was not installed correctly. The anchor, tie-back, or deadman system was probably not adequately designed or constructed to withstand the expected loads and forces and with extreme corrosion of the anchor rod inside of the concrete beam at the connections, it failed under the stress. This could occur if there were errors in the calculations, poor material choices, lack of experience, or substandard construction practices.

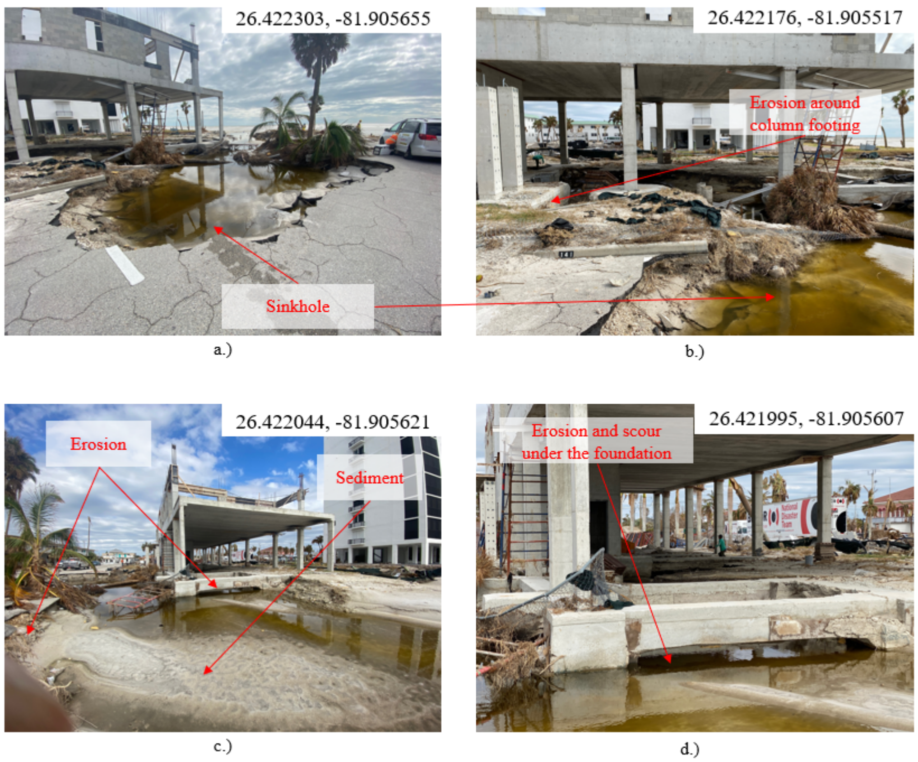


Figure 4.30: Ground images of failures observed in south east end of the Fort Myers Beach island, near Sunset Condominium: (a) Sinkholes caused by extreme scour and erosion resulting in the ground depression underneath the paved driveway and foundation of the skeleton of a new building; (b) extreme scour underneath the foundation of the building resulted in exposure of the footing of the load bearing column; (b) ground photo capturing the depth and size of the sinkhole formed by extreme erosion and scour. Notable, exposed load-bearing column footings reveal the building's vulnerability to water's path, evident form the transported sediment; (c) ground photo of the transported sediment depicting path of water; (d) erosion and scour underneath the shallow foundation of the building

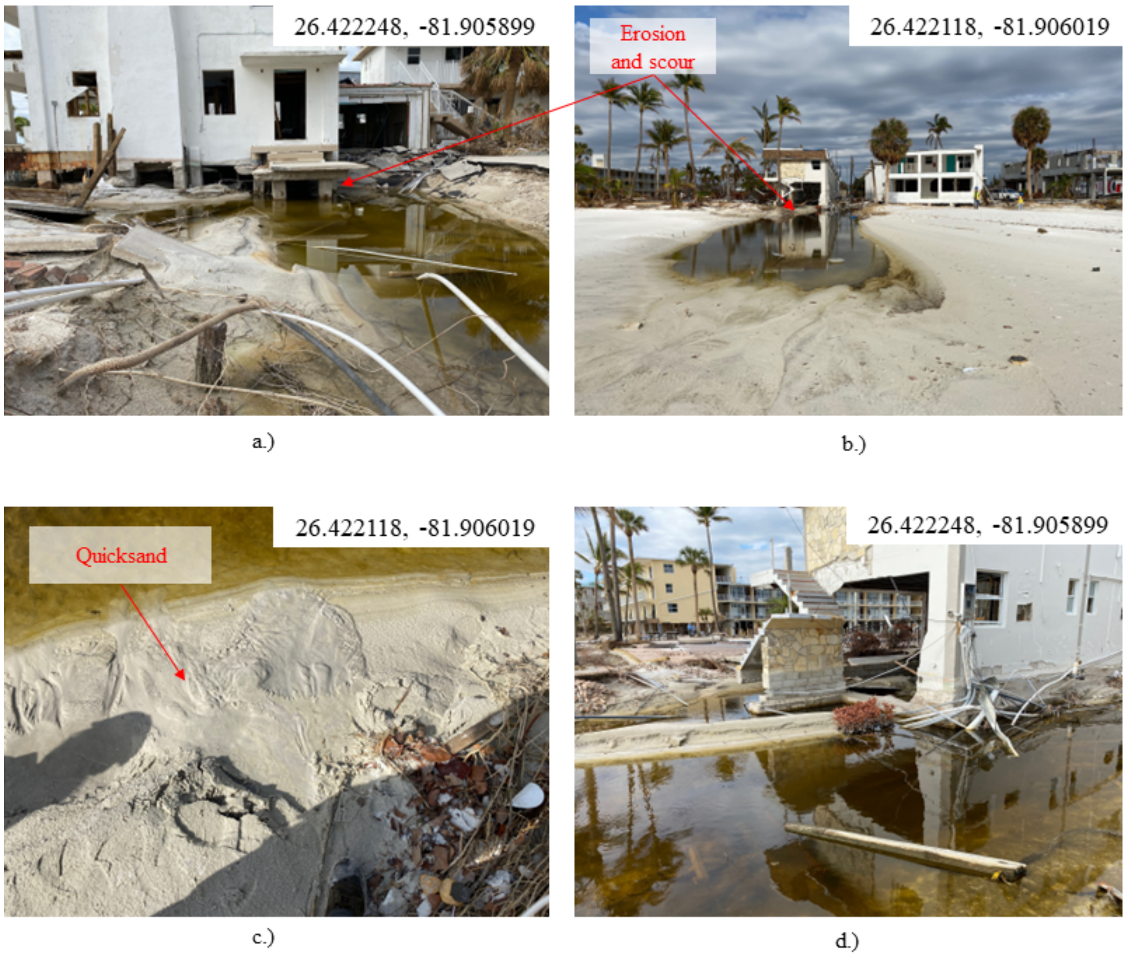


Figure 4.31: Ground images of failures observed in south east end of the Fort Myers Beach island, near Sunset Condominium: (a) erosion and scour underneath the buildings' foundation creating a ground depression filled with water and sediment transported by storm surge resembling a sinkhole; (b) path of water and sediment transported by storm surge depicting that the eroded areas were a result of a direct impact of the waves; (c) soil liquifaction or commonly known as quicksand was observed in the outer banks of the water path; (d) erosion and scour underneath the foundation of a house resulting in a ground depression engulfing the house and exposing the footings and foundation of the house

Figure 4.32: Ground images of failures observed in south east end of the Fort Myers Beach island, near Sunset Condominium: (a) erosion and scour underneath the foundation of the house; (b) closer look below the foundation showing extreme erosion and sediment transport; (c) exposed footing due to extreme erosion; (d) sediment transport below the foundation of the house

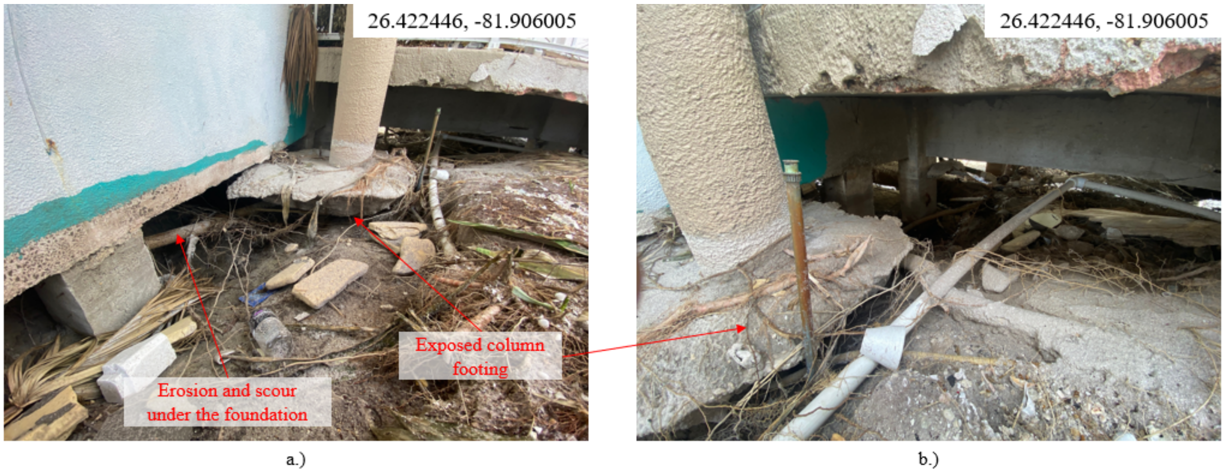


Figure 4.33: Ground images of failures observed in south east end of the Fort Myers Beach island, near Sunset Condominium: (a) Exposed footing of the stairways column and erosion below the foundation of the house; (b) closer look below the foundation showing the transported sediment and exposed footing

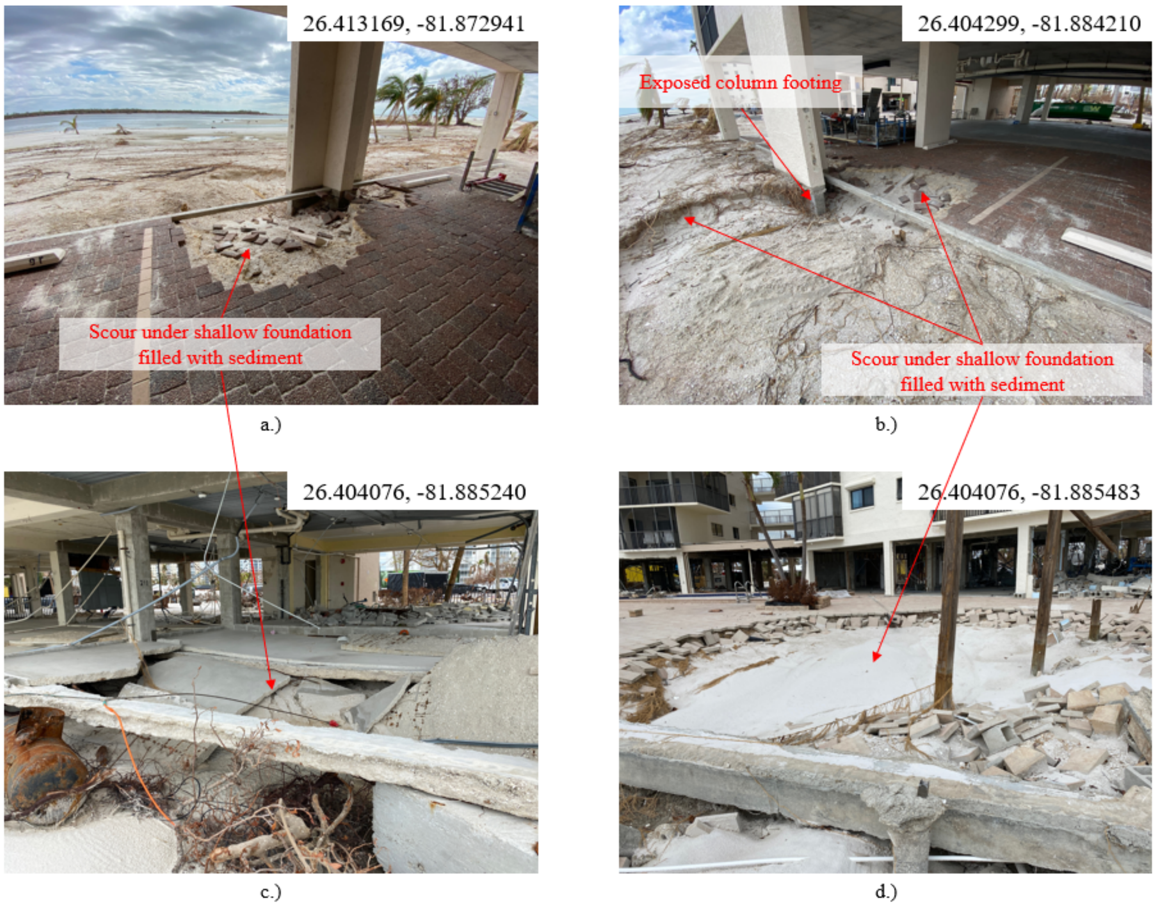


Figure 4.34: Ground photos of failures observed in south east end of the Fort Myers Beach island, at Carlos Point Condominium Associates: (a) erosion below the foundation of the condominium caused land subsidies which were filled with sediment transported by the storm surge: (b) exposed footings of a column and more scour underneath the shallow foundation causing cavities filled with sediment; (c) scour below the shallow foundation resulting in a cavity leading to a loss of support, cracks, and breakage; (d) scour underneath the foundation of the building causing the same breakage and cracking issues as cavities emerge and creates a ground depression resembling a sinkhole.

Figure 4.35: Ground photos of failures observed in south east end of the Fort Myers Beach island, at Carlos Point Condominium Associates: (a) ground photos of the erosion beneath the foundation depicting the scope of eroded area; (b) ground photo of the underneath the foundation depicting the exposed footing

Figure 4.36: Southern end of the Fort Myers Beach: (a) ground photo depicting a broken anchor of a sea wall showing the tie-back used in the anchor system; (b) ground photo of the anchoring system showing cross beam tie backs and dead man weights

The north-west end of the island was also visited by the GEER team. The northern end exhibited substantially less damage than the southern end. This area also had sink holes caused by erosion, although they were far less numerous and larger in scope. Figure 4.38c shows drone photos of ground depression filled with water and debris that was observed by the team as shown in the terrestrial LiDAR scan in figure 4.39, and ground photos shown in 4.38c-d. Figure 4.37 shows the path of water from the shoreline splitting into two routes, one going behind the a residential building (figure 4.37a) exhibiting a lower speed and power meditated by the mangroves obstructing the path of water. The other path is coming from the right of the adjacent residential building approximately 105 feet apart. After traveling for approximately 345 feet, the waves took a turn to the left and joined with the other water route. Erosion of the sandy beach from this dynamic water flow can be seen via UAV images in Figure 4.37.

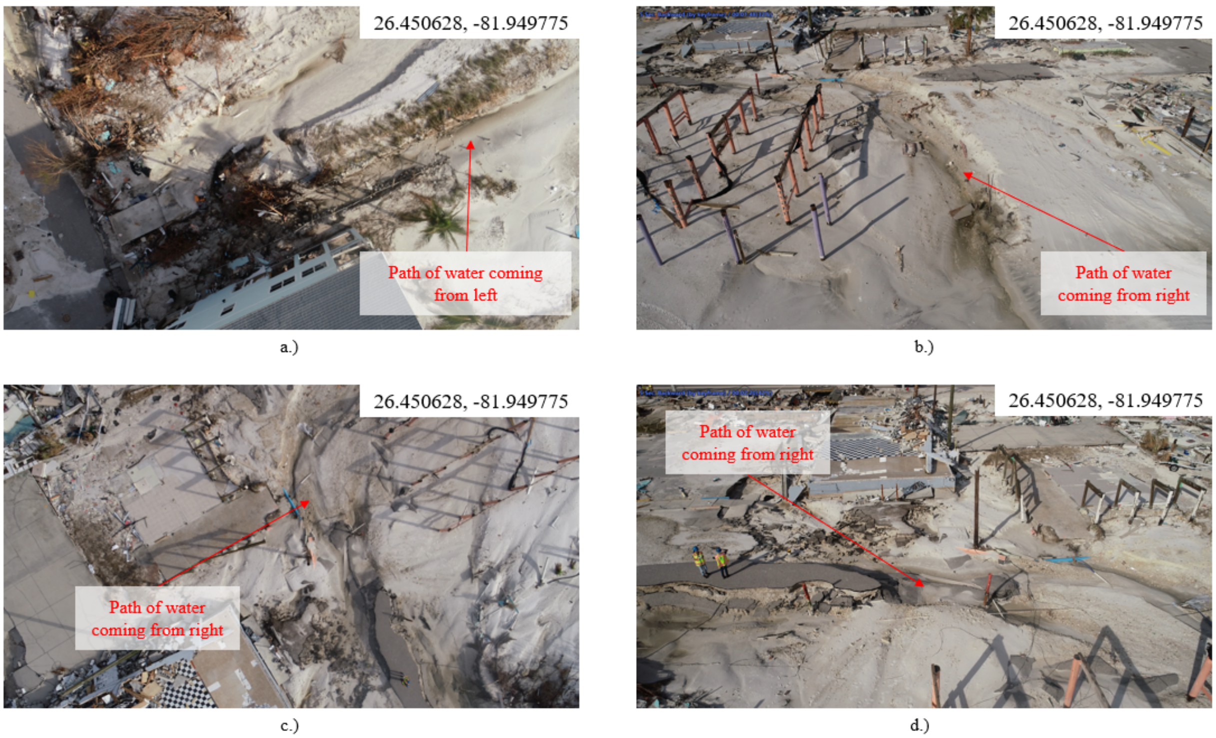


Figure 4.37: Drone images of failures observed in north west end of the Fort Myers Beach island: (a) image showing the path of water starting from the shoreline carrying a sizable amount of sediment from the left side of the building causing less damage in comparison to water coming from the right side in presence of mangroves; (b) water coming from the shoreline on the right side of the area of interest and hitting the first set of buildings, leaving only the piling of the houses behind; (c) the waves taking a turn to left and carrying the debris towards the next row of the buildings causing more damage; (d) path of water coming from the right side of the area of interest causing scour and erosion, joining with the water coming from the left side which in return caused more powerful storm surges resulting in damages in greater magnitude

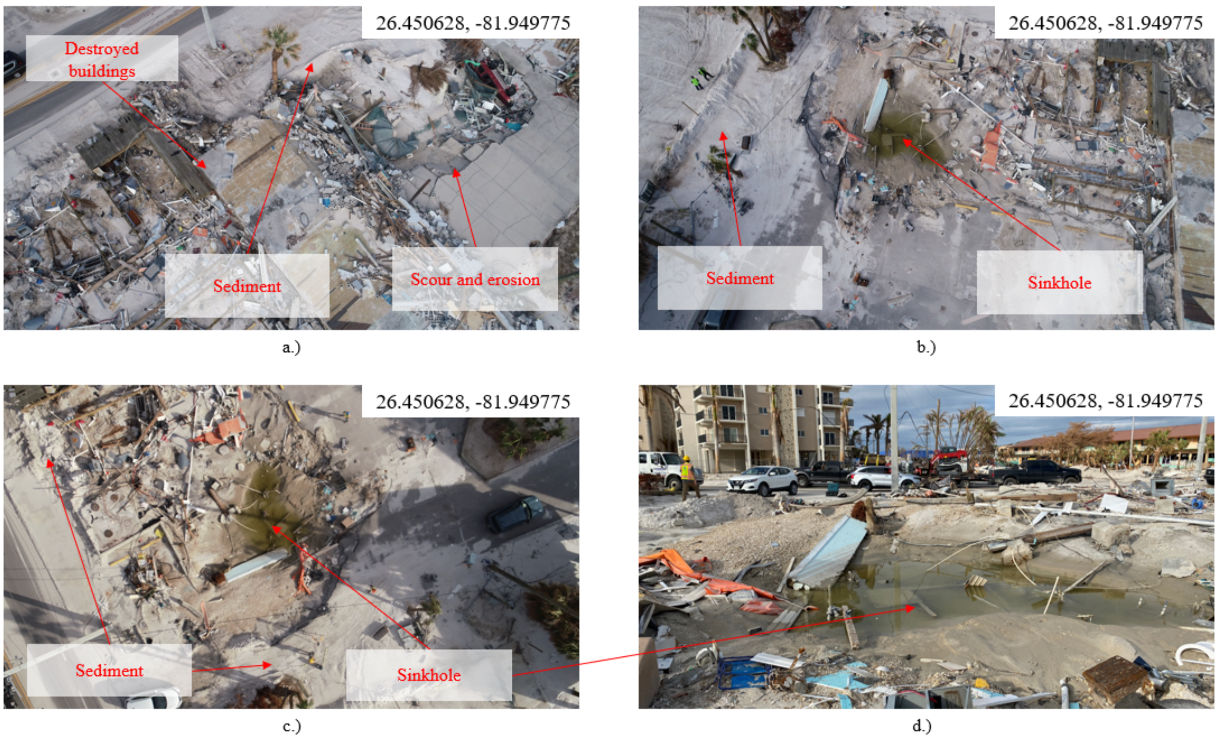


Figure 4.38: Drone images of failures observed in north west end of the Fort Myers Beach island: (a) image of the sediment transported and debris left from the buildings destroyed by storm surge. scour caused a ground depression near the driveway of the adjacent building; (b) sediment transported by the storm surge is shown and the sinkhole in place where a shop used to be; (c) ground depression filled with water and sediment resembling a sink hole where a shop used to be; (d) ground image of the sink hole presumably caused by erosion and scour resulted by powerful storm surges

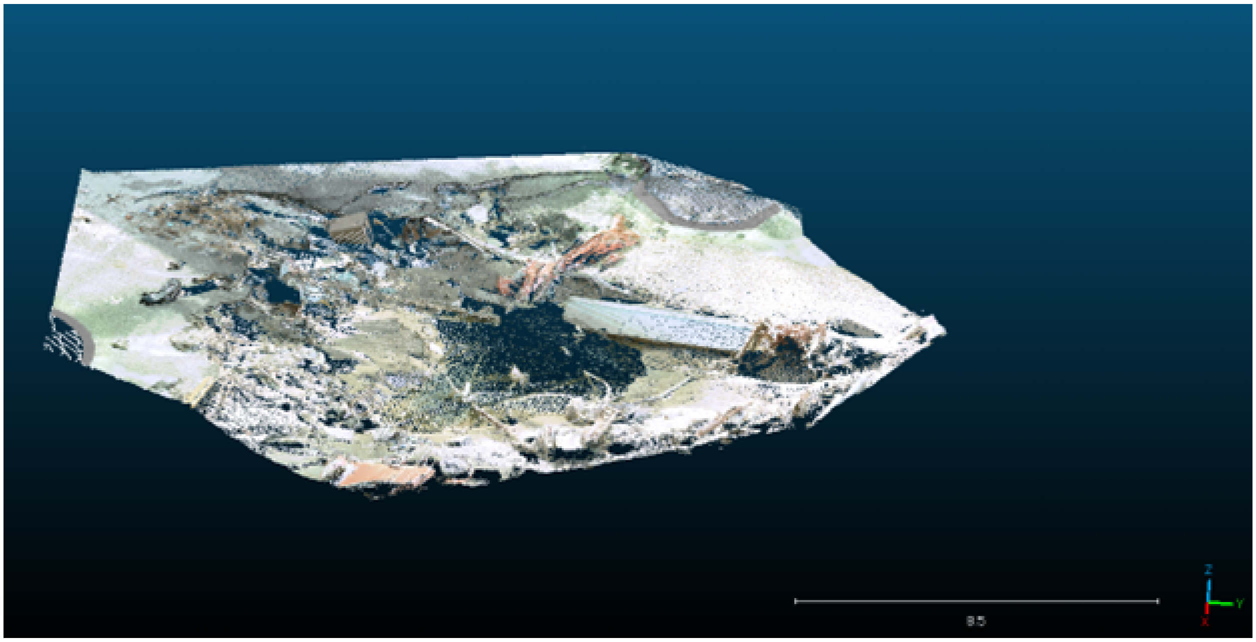


Figure 4.39: Terrestrial LiDAR scan of depression feature adjacent to road. Coordinates 26.450556, -81.949677

More erosion underneath the foundations was observed in north west end of the island along with immense amount of sediment transportation. Erosion and scour left cavities underneath the foundation, exposing the footings of the piles. The residential house standing on the piles was completely washed away by the storm and left only the pilings behind showcasing that the connection at piles had failed which is corresponding to the observations so far.

Figure 4.40: Ground photos of failures observed in north west end of the Fort Myers Beach island near Pelican Watch Condominium: (a) scour and erosion under the shallow foundation of a building; (b) Close up photo of damage to shallow foundation

Surveying along the Estero Blvd, the GEER team observed houses that have slid off of their foundations causing the house to collapse. Figure 4.41 shows one commercial building that has shifted approximately 3.5 feet in the front and 1 feet from the left side. In figure 4.42, the house has slid approximately 1 feet on the front and 2 feet on the side. Figure 4.42d shows the movement of the house was from the the left side of the house and ho This could be caused by the power of the storm surge in accompany with debris which ultimately can subject the structure to intense lateral forces that exceeded the foundation's capacity to resist movement. It is worth noting that the excessive erosion around the foundation of the house shown in figure 4.41 may have also be a contributing factor to the soil losing its stability and create hydrostatic pressure against the foundation and cause it to move. Figures 4.42b,c show that the house has moved substantilly given that the skeleton has either been removed and top parts of the mat foundation is exposed. Moreover, in figure 4.42d, it can be observed that the house's skeleton has passed the foundation area of the original position.

Figure 4.41: Ground photos of the failures adjacent to Estero Blvd in Fort Myers Beach: (a) photo of a shop building depicting erosion beneath the foundation; (b) sliding of the front of the building as a result of the scour and erosion behind the building, beneath the foundation; (c) scour underneath the foundation at the back of the building causing a cavity and engulfing the back of the building; (d) image showing the left side of the building sliding

Figure 4.42: Ground photos of the failures adjacent to Estero Blvd in Fort Myers Beach: (a) front of the residential building showing that foundation has slid; (b) right side of the residential building showing that foundation has slid; (c) right side of the residential building showing that foundation has slid; (d) left side of the residential building showing that foundation has slid

4.6 Caloosahatchee River

Located on Florida's southwest coast, the Caloosahatchee River (figure 4.43) Estuary spans 105 km from Lake Okeechobee to San Carlos Bay, and flows into the Gulf of Mexico near Fort Myers, Florida. Originally sinuous, the river's source was near Lake Flirt, around 2 miles east of La Belle, Florida. The estuary is 42 km long and has a long, narrow shape. In terms of hydrology, the region faces significant challenges such as extreme high flows during the wet season and very low flows during the dry season. The high flows may adversely affect oyster and marine SAV species in the lower estuary by altering the salinity regime and light environment through colored dissolved organic matter, sediment resuspension, and turbidity.

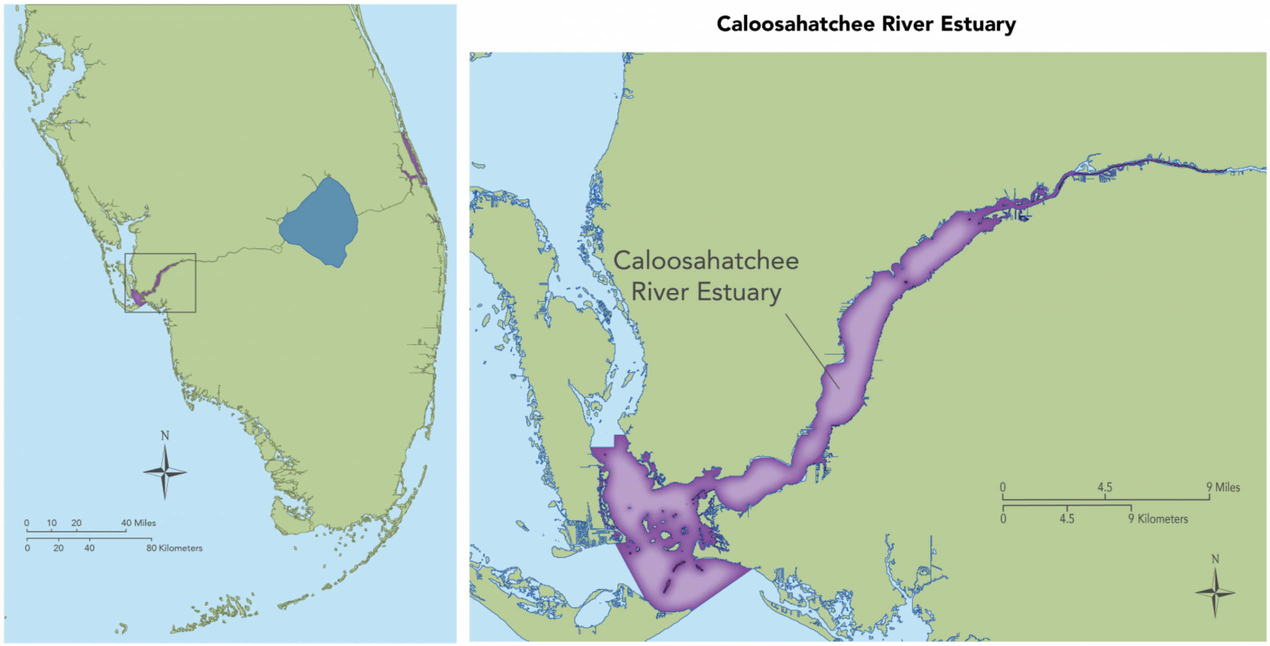


Figure 4.43: Photo of Caloosahatchee River Estuary by South Florida Water Manangement District (SFWMD)

During a hurricane, the gage height and estuary or ocean water surface elevation values tend to rise significantly due to the strong winds and heavy rainfall. The gage height in ft from Caloosahatchee River at S-79 measuring 9.29 ft on September 28, 2022 (figure 4.44) is an indication of the water level in the river. This is another evidence showing that Hurricane Ian caused intense rainfalls that resulted in a large amount of water flowing into the river, thereby causing the gage height to rise. Moreover, strong winds caused great storm surges, which also contributed to the rise in the gage height. The rise in gage height during Hurricane Ian can caused flooding in low-lying areas, posing a threat to both human life and infrastructure.

Similarly, the estuary or ocean water surface elevation above NAVD 1988 in ft from Caloosahatchee River, measuring 7.44 ft on September 28, 2022 (figure 4.45) is also indicative of the water level in the river. The estuary or ocean water surface elevation rose significantly due to the high winds and waves. The strong winds can also cause the waves to crash onto the shore with tremendous force, causing significant damage to coastal infrastructure.

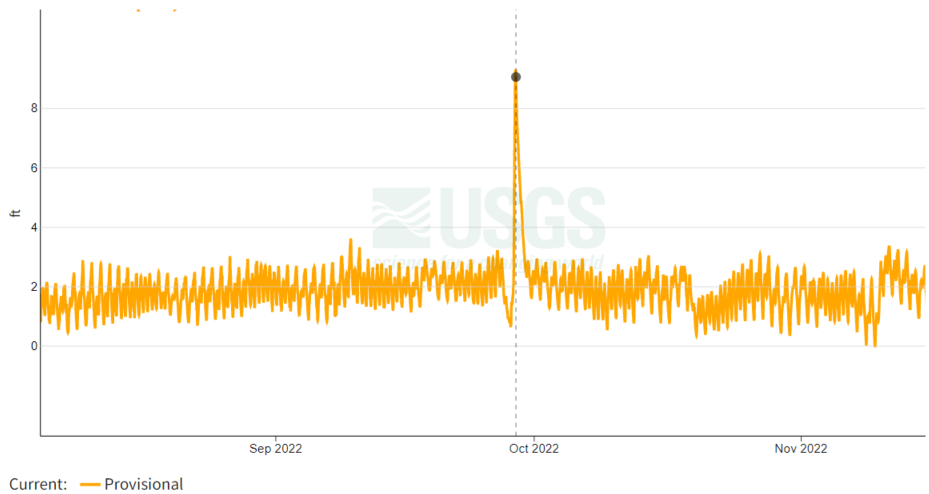


Figure 4.44: Gage height in ft from Caloosahatchee River at S-79, measuring 9.29 ft on September 28, 2022, at 08:30:00 PM EDT. Coordinates: 26.72173, -81.69314

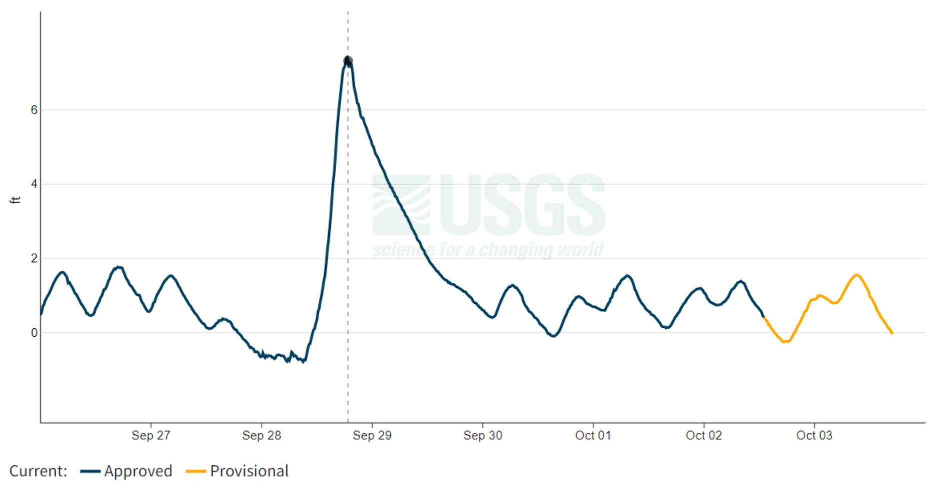


Figure 4.45: Estuary or ocean water surface elevation above NAVD 1988 in ft from Caloosahatchee River, measuring 7.44 ft on September 28, 2022, at 06:30:00 PM EDT. Coordinates: 26.53611, -81.94619

The Caloosahatchee River and bridges traversing the river were surveyed on October 19th, beginning where the mouth of the river enters San Carlos Bay and ending in the town of LaBelle. Along this route, the flooding effects on nine bridges and bank erosion were documented. At the time of the visit, these bridges showed no sign of any damage. The U.S. 41 bridge had no observable effects, but was closed for on November 1st due to washout of fill material. It is unclear if this was related to any lingering effects from Hurricane Ian. Adjacent to the U.S. 41 bridge, the Edison bridge also showed no signs of any damage.

Figure 4.46: Caloosahatchee Bridge showing no sign of damage. Coordinates: 26.64413, -81.87405

Figure 4.47: Fort Denaud Swing Bridge showing no sign of damage. Coordinates: 26.74411, -81.51015

Seminole Gulf Railway (SGLR), a Class III shortline freight railroad that is an important supply line for Southwest Florida, is one of the entities that has been severely impacted by the hurricane. Hurricane Ian caused extensive damage and destruction to at least six rail bridges, requiring an estimated $28 million in repairs, and effectively cutting off the region's only link to the North American Rail Network.

Figure 4.48, a satellite image depicting the Caloosahatchee railway system crossing Beautiful Island reveals the conditions before and after the hurricane's impact, highlighting the damage caused to the railway. As shown in figure 4.51, the storm pulled the tracks off of the piles and into the Caloosahatchee. Figure 4.50, shows the photogrammetry model of the damages transversing over Beautiful Island taken by the GEER team.

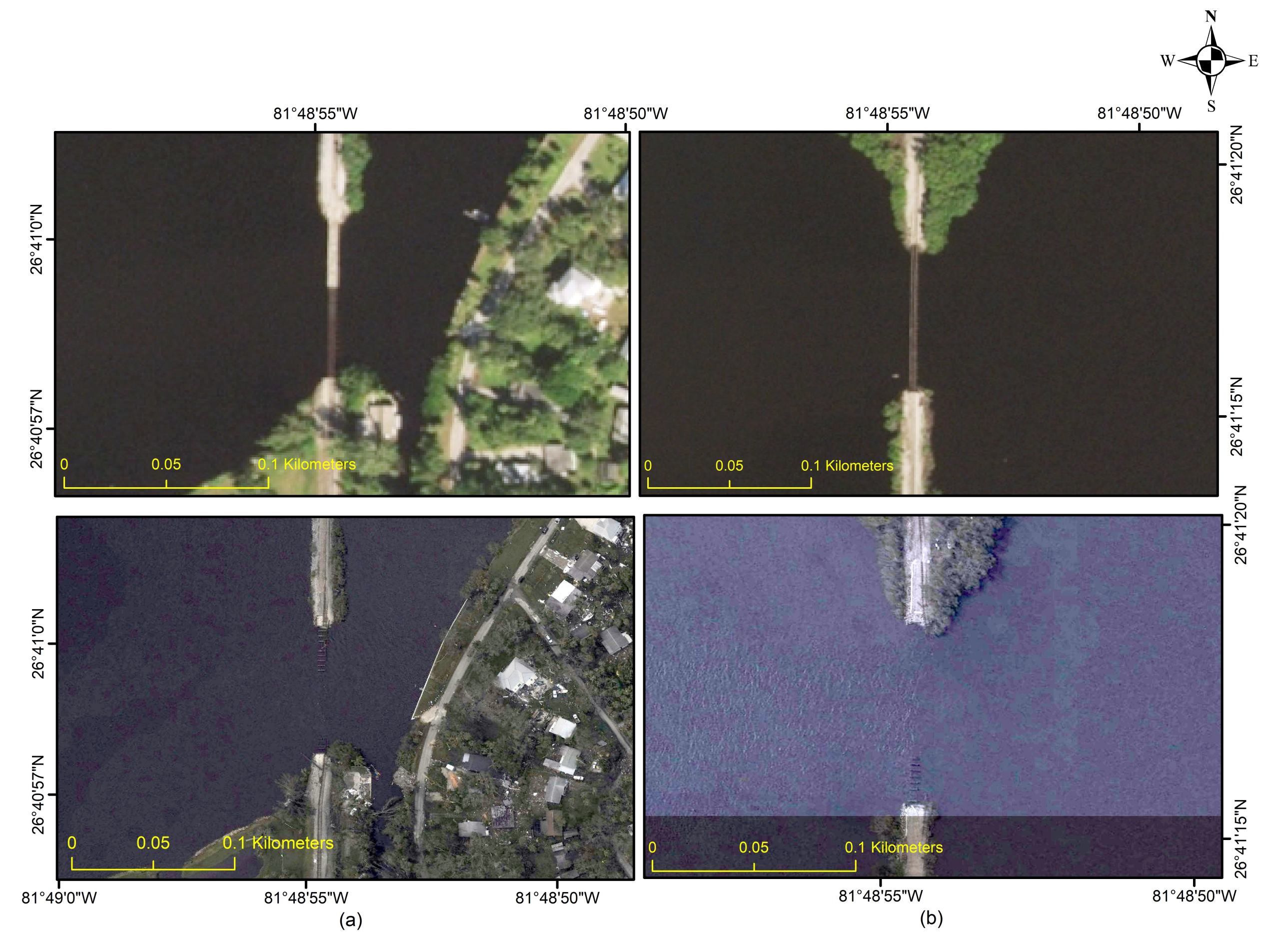


Figure 4.48: Satellite Images of Beautiful Island Rail Bridge before and after Hurricane Ian

The rail bridge connects three islands to the mainland of Ft. Myers, spanning four sections of the Caloosahatchee River. When intact, this railway brings supplies, including building materials, to the Ft. Myers area. These supplies are vital for the recovery and rebuilding effort. The total affected length of the Caloosahatchee River System of bridges was reported to be 2,043 feet.

Robert Fay, who owns and operates the railway, expected bridge reparations to take a month and a half once funding is secured. However, by November 29, bridge repairs had not yet begun.

Figure 4.49: Beautiful Island Rail Bridge on November 29. Coordinates: 26.6928137, -81.8124748

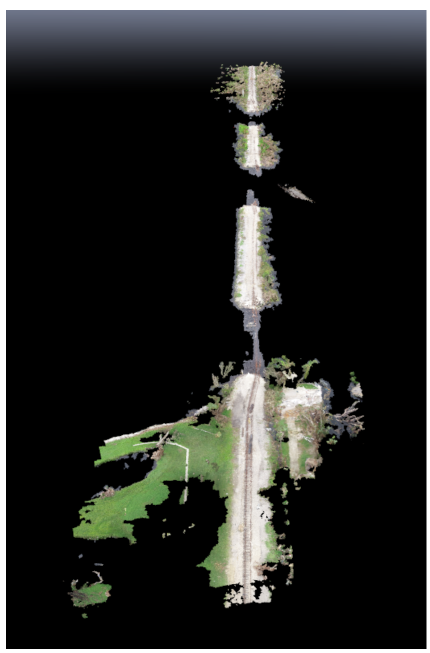


Figure 4.50: Structure from Motion photogrammetry model of rail bridge failure across the Caloosahatchee River. Coordinates: 26.6922922, -81.8123293

a.) b.)

Figure 4.51: Beautiful Island residential area: (a) Railroad cross beam carried by waves through a house garage. Coordinates: 26.682601, -81.814131; (b) Destroyed garage due to wave power and impact of railroad cross beam debris. Coordinates: 26.682601, -81.814131

4.7 Peace River

The bridges and piers along Peace River are investigated, starting from Punta Gorda and ending at Arcadia. Figure 4.53 shows the disaster reconnaissance route along Peace River. The GEER team observed surface erosion by the riverside of Peace River at Punta Gorda. Around the same location, damaged fishing pier was found, however, no scour or sinkhole were observed. No geotechnical or structural damages were found when driving towards the inland area. Figure 4.52 shows some of the observations in this area.

a.) b.) c.)

Figure 4.52: Observations along Peace River: (a) Surface erosion along the riverside of Punta Gorda, Coordinates: 26.93235, -82.05837; (b) Broken pier along the riverside of Punta Gorda, Coordinates: 26.93351, -82.05694; (c) No damage observed at Barron Collier Bridge, Punta Gorda, Coordinates: 26.93689, -82.05460

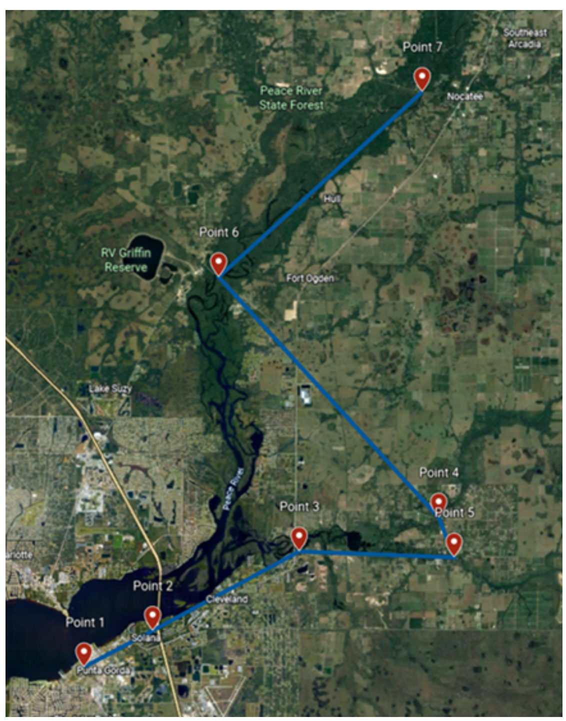


Figure 4.53: Disaster reconnaissance route along Peace River with several inspection points

4.8 Sanibel Island

Sanibel Island is a barrier island located on the southwestern coast of Florida, USA. It is part of Lee County and covers an area of 33.4 square miles. The island is connected to the mainland via the Sanibel Causeway, a three-mile bridge that spans San Carlos Bay. The Sanibel Causeway, a vital link between mainland Florida and Sanibel Island, suffered significant damage which is shown in satellite photos in figure 4.54 and aerial drone shots in figure 4.55. The causeway underwent extensive construction work after being hit by Hurricane Ian. Unfortunately, this meant that the GEER team was unable to visit the island on two occasions, which were scheduled for October 21 and November 29 dates. It is worth noting that while the Sanibel Causeway was reopened on October 19, access was limited to only a select group of individuals, including residents, construction workers, insurance personnel, and reporters. Unfortunately, surveying teams were not granted access and were unable to conduct a thorough assessment of the damage caused by Hurricane Ian. This presented additional challenges for the GEER team in gathering accurate data on the extent of the damage on Sanibel Island. Despite these limitations, the remote survey conducted by the team provided useful information.

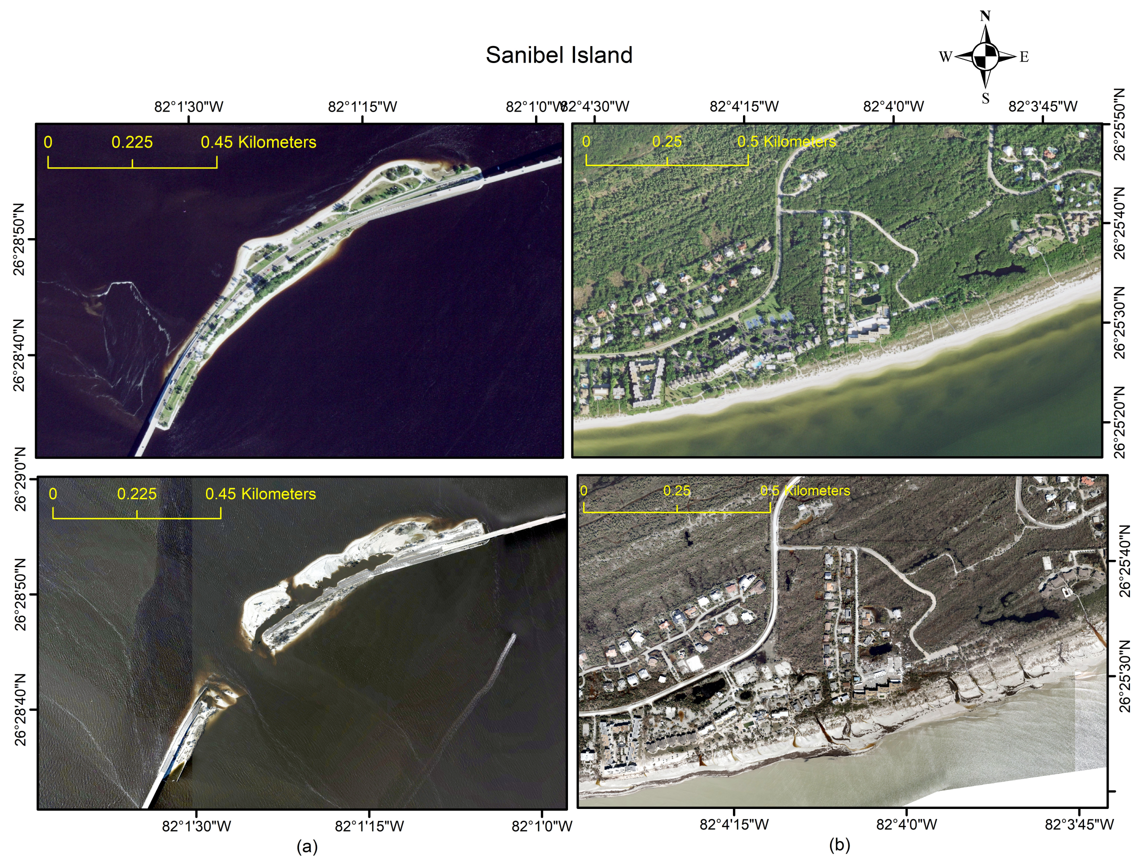


Figure 4.54: Satellite photos of some damages in Sanibel Island (top vs. bottom) a.) Sanibel Causeway and b.) Shoreline of Sanibel Island

Figure 4.55: Drone photos of Sanibel Causeway: (a) picture taken on Friday, Sept. 30, 2022, by Ricardo Arduengo from Agence France-Presse; (b) picture taken on Thursday, Sept. 29, 2022, by Wilfredo Lee, distributed by the Associated Press; (c) picture taken on Thursday, Sept. 29, 2022, by Wilfredo Lee, distributed by the Associated Press; (d) picture taken on Thursday, Sept. 29, 2022, by Joe Raedle. Coordinates: 26.48339, -82.01301

The team made use of various resources, such as satellite images, aerial drone photos, ground photos provided by the US Geological Survey, and reports from on-site reporters and construction companies. While not being able to conduct an in-person survey presented its own set of challenges, the GEER team was able to gather enough data and information to create an assessment of the damage caused by the hurricane.

The remote survey conducted by the GEER team provided valuable insight into the extent of the damage caused by Hurricane Ian on Sanibel Island. The data and information gathered from various sources indicated that the damage was similar to what the team observed in other affected areas. Most of the damage was structural in nature, with houses being completely washed away, broken piers and piles, extreme scour and beach erosion and sediment transport being the most common forms of damage.

One of the most common types of damage caused by Hurricane Ian was flooding, and Sanibel Island was not immune to this type of damage. The heavy rainfall and storm surge caused significant flooding throughout the island, damaging or destroying buildings and infrastructure. The flooding also caused erosion and damage to the island's beaches, further exacerbating the structural damage caused by the hurricane.

Hurricane Ian also caused the structural collapse, and Sanibel Island experienced several instances of structural collapse. The damage caused by the hurricane was so severe that many buildings on the island were leveled to the ground. The collapse of these structures required extensive repairs or rebuilding efforts, further adding to the economic toll of the hurricane on the island. In addition to the structural damages observed on Sanibel Island, it was apparent that beach erosion had occurred across the shoreline. This erosion was particularly pronounced along the walkway paths of houses, where the waves and storm surge had eroded the sand as shown in figure 4.56.

Figure 4.56: Effects of Hurricane Ian on Sanibel Island's shoreline: (a) pre-hurricane satellite photo; (b) post-hurricane satellite photo showing extreme beach erosion more pronounced on the path of the walkways; (c) ground depression and accumulation of water. Coordinates: 26.42657, -82.10010

CHAPTER 5
SUMMARY AND DISCUSSION

5.1 Retaining Walls

Retaining walls are essential structures in geotechnical engineering used to prevent soil erosion and landslides. However, many retaining walls during the disaster reconnaissance failed due to poor construction and design practices. The most common type of failure was structural failure, which occurs when the wall breaks at its connections. This can happen due to insufficient structural support, such as the lack of reinforcement in the concrete or inadequate compaction of soil behind the wall during construction. Structural failures are often caused by human error or oversight during the construction phase.

Another common cause of retaining wall failure was erosion, which can create cavities in the soil behind the wall. When water accumulates in these cavities, it creates a vacuum effect that can weaken the soil and cause the retaining wall to fail. Poor drainage, improper grading, and the use of the wrong type of backfill material can also lead to erosion and cavity formation. Over time, the soil pressure on the wall may become too great, and it may collapse under its weight.

During the mission, many retaining wall failures were present in Pine Island, Matlacha Island, Fort Myers, Cape Coral, and Downtown Fort Myers, which was a combination of both. This can occur when a retaining wall is constructed on soil that is already prone to erosion. If the wall is not built correctly, the weight of the soil and water can cause it to fail. Additionally, poor drainage and inadequate grading can exacerbate the erosion process, causing the retaining wall to break down over time. Proper construction and design practices, including the use of high-quality materials, proper compaction, and adequate drainage, can help prevent retaining wall failures due to poor construction and erosion.

5.2 Scour and Erosion

One of the major causes of damage during Hurricane Ian observed bt the GEER team was erosion and scour, which lead to ground depression, cavities in the soil, and erosion around the foundation of houses, causing them to collapse. Erosion and scour occurred due to the impact of the hurricane, which caused waves, wind, and rain to erode the soil and remove sediment from the ground.

Ground depression was a common result of erosion and scours. When the soil was eroded, it can create a depression in the ground where the soil has been removed. This depression can be dangerous for buildings and structures, as it can cause the foundation to sink or become unstable. This can result in the collapse of the building or structure, especially during a hurricane when the force of the winds and water is at its strongest.

Cavities in the soil are another common result of erosion and scour during a hurricane. When the soil is eroded, it can create voids or cavities in the ground where the soil has been removed. These voids can weaken the soil and make it more susceptible to collapse. The voids can also cause sinkholes to form, which can be extremely dangerous for people and vehicles.

Erosion around the foundation of houses was also a common result of erosion and scour during Hurricane Ian. When the soil is eroded, it can remove the support for the foundation of a house, causing it to become unstable. This can lead to the collapse of the house or damage to the foundation. The erosion around the foundation can also cause the house to shift or settle, leading to structural damage and potential collapse.

The impact of the hurricane on the soil also caused liquefaction to occur. This happened when the soil was saturated with water and was subjected to strong vibrations or shaking, such as those caused by a hurricane. Liquefaction can cause the ground to sink or become unstable, which can result in the collapse of buildings and structures.

In order to prevent erosion and scour during a hurricane, it is important to take measures to protect the soil and prevent it from eroding. This can include using retaining walls or other barriers to prevent soil erosion, as well as planting vegetation and mangroves to stabilize the soil. Additionally, proper construction techniques can help to prevent the failure of structures during a hurricane, such as ensuring that the foundation is properly constructed and that the building materials are appropriate for the expected wind and water loads.

5.3 Foundations

Observations of damage to building foundations were rare. The GEER team observed two minor instances of scour to building foundations along Fort Myers Beach. Additionally, the connections between foundation and frame were a common point of failure in residential structures on Pine Island. By in large, building foundations were not observed to be a common point of damage or failure following Hurricane Ian.

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