A. Project Summary

Proposal Title: Geological controls of construction-induced coastal subsidence

Following the tragic collapse of the Champlain South condominium tower in Surfside, Florida, in 2021 there are great concerns that a similar disaster could repeat at another complex. Preliminary InSAR time series have revealed widespread subsidence in Surfside, although not at the collapse site, which we attribute to new construction, raising the question whether ground subsidence combined with the rising seas could be a threat to the structural integrity of coastal highrises. We will develop InSAR persistent scatterer and distributed scatter displacement time series using Sentinel-1 for the southeastern US coast to search for construction-induced subsidence. For that we will develop a database of new construction from property tax rolls and building permit records and use data mining approaches to determine whether new construction was associated with subsidence. We will test the proposal hypothesis that construction-induced rock compaction occurs primarily in geological settings characterized by young limestone such as South Florida. We don't expect to see any construction-induced subsidence in the crystalline basement of the northeast and we expect to see little to no subsidence in the sandstones of the Atlantic and Gulf coastal plains. In addition we will conduct detailed studies of construction-induced subsidence at our home base in Miami to determine the causes of the observed subsidence (vibrations from pile-driving for foundation installation versus the static load of a building).

The deliverables of this project will be (1) a catalog of construction induced subsidence along the southeastern coast, and (2) a better understanding of the conditions for construction-induced subsidence to occur

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C. Project description

Proposal Title: Geological controls of construction-induced coastal subsidence

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Project goals: Detect construction-induced subsidence along the coast and to understand the causes.

Funding request: Support for one postdoctoral researcher and two graduate students.

1. Project Overview

The tragic collapse of the Champlain South condominium tower in Surfside, Florida, in June 2021 brought attention to the questions of the structural safety of Florida's aged (> 30 years) beach condominium buildings. While South Florida with its coastal limestone was thought to be immune from land subsidence, our new results using persistent scatterer InSAR for Surfside, FL, indicates that the construction of new high rises can be associated with subsidence by 10 cm or more of the high-rise and of the surroundings. Subsidence occurs for several years after construction and can be differential, potentially impacting the structural integrity of the high-rise and of adjacent buildings. Subsidence represents the compaction of the shallow limestone layers in response to an increase of the effective stress by adding a load to the surface. However, the process of construction-induced compaction of the rock matrix is not well understood. Compaction could be the result of the added vertical stress from the weight of the new building, or it could be facilitated by pile-driving vibrations from construction and/or by changes of the water table because of the rising seas. Alternatively, subsidence could reflect local geological peculiarities such as pockets of unconsolidated sand.

Here we propose a multi-disciplinary research program consisting of InSAR data analysis, data mining, and coastal geology to determine (i) how widespread construction-induced subsidence is along the US coast, (ii) the geological settings in which such subsidence primarily occurs, and (iii) the causes for the subsidence and implications on buildings. We also will conduct a research-to-application case study in Miami, FL, to demonstrate how InSAR subsidence information can serve to make coastal communities more resilient. The *central hypothesis* of this proposal is

"Construction-induced rock compaction and coastal land subsidence occurs primarily in geological settings characterized by young limestones."

This hypothesis is based on preliminary results for a coastal high-rise condominium building in Surfside, FL (the Surf Club Hotel) that underwent ~10 cm subsidence while a nearby coastal high-rise was being constructed (described below). In order to test our hypothesis we will pursue four specific aims:

Aim 1. Characterize construction-induced subsidence along the southeastern US coast. We will develop persistent scatterer and distributed scatterer InSAR data for the southern and eastern US coasts in order to identify construction-related subsidence in the towns and cities. For this purpose, we will develop a database of new construction (location, dates, height, nominal weight, type, and depth of foundation) using publicly available building design and construction permit records in collaboration with the local Building and Zoning Department at each local jurisdiction. We also will use data mining approaches to test whether the new construction is associated with InSAR subsidence signals and determine the magnitude and spatio-temporal patterns. We then will use this information to develop incidence and density maps of construction-induced subsidence along the southeastern coast.

Aim 2. Impacts of the rising seas on construction-induced subsidence. To understand whether salt water intrusion exacerbates construction-induced subsidence, we will systematically compare construction-induced subsidence in coastal and inland areas. Stronger construction-induced subsidence in coastal areas would indicate an influence of sea level rise, although care has to be taken to account for variations in types of structural foundations, construction density, and high-rise height. Inland metropolitan areas built on similar limestone lithologies include Nashville, TN, and Orlando, FL. Although not the primary objective of this project, we will in addition investigate potential correlation between storm events (tropical storms, hurricanes, and floods) and construction timelines in order to understand potential impacts of events while construction was underway.

Aim 3. Impact of the geology. To understand whether construction-induced subsidence is a coastal limestone phenomenon, we will systematically compare cities built on young coastal limestones with cities built on hard crystalline rock, such as Manhattan Island, NY, and Washington, DC. While we do not expect to see any subsidence in the latter two cases, actual InSAR observations are required to drive this message home. The analysis of New Orleans, LA, will show whether sandstones exhibit construction-induced subsidence. We will also study cities on other young coastal limestones around the world such as Cancun in Mexico, Santo Domingo, Dominican Republic, and Kuala Lumpur, Malaysia, to further test our hypothesis that construction causes young coastal limestone to compact

Aim 4. Improving the resilience of the Miami built environment. For our home base in Miami, FL, we will conduct a proof-of-concept study to demonstrate how the satellite-based subsidence information can lead to a more resilient coastal built environment. For this purpose, we will acquire high-resolution TerraSAR-X InSAR data and share the subsidence information with the local stakeholders such as construction companies, homeowner associations, and the City/County Building Departments. We will work with these stakeholders to (i) understand the causes of the observed subsidence, (ii) assist in interpretation of data generated and development of mitigation strategies against differential settlement, and (iii) investigate and encourage construction practices that minimize the induced subsidence. In particular, we will conduct a detailed study of the subsidence associated with the construction of a new high-rise next to the Surf Club Hotel that is being built in an area known for exhibiting the construction-induced subsidence.

The proposed project will be *transformative* because it will lead to (1) a re-evaluation of pile-driving guidelines for coastal construction, (2) the routine use of InSAR to monitor subsidence during construction, and (3) use of InSAR for structural integrity monitoring of coastal high-rises long after construction. This project is of *high value to NASA* because it will demonstrate how investments in Earth Observation can increase coastal resilience.

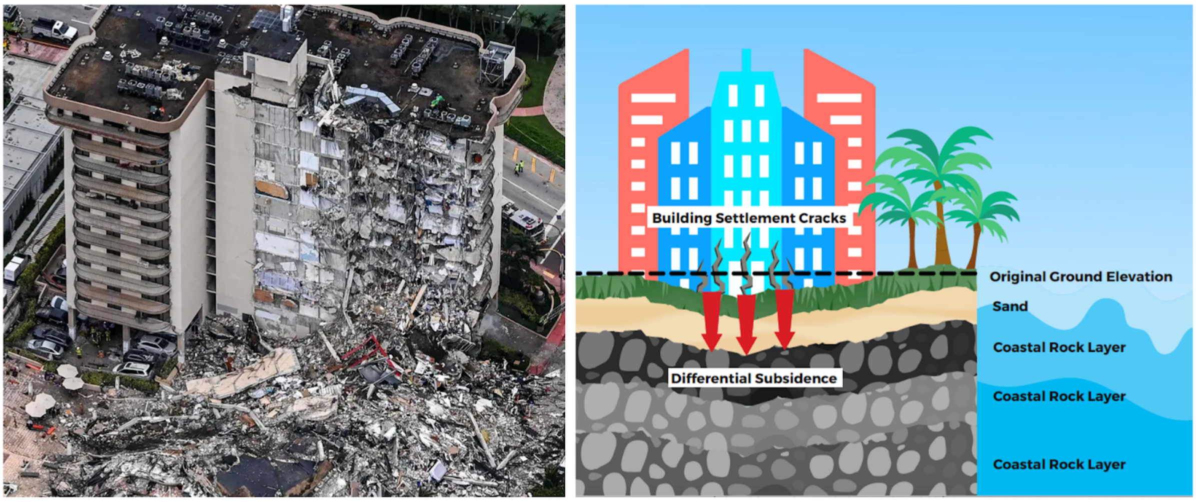

Fig. 1. *(left) Champlain Towers South in Surfside, FL, that collapsed in June 2021. (right) An illustration of settlement cracks in high-rises caused by differential subsidence.*

2. Significance

Structural integrity of coastal high-rises. After the 2021 collapse of the Champlain Towers South in Surfside, FL, the overwhelming concern for the residents of coastal condominiums in South Florida and elsewhere along the US coast is whether the structures they live in are safe. There is increasing evidence that deferred maintenance and poor design are the primary culprits for the collapse. However, (i) subsidence that typically occurs in the early years since construction, (ii) sea level rise / storm surge events, and (iii) pile-installation induced vibrations from nearby construction activities may well have contributed to compromise the structural integrity of the building. A previous InSAR study showed that the Champlain Towers South building was subsiding by a few mm/yr in the 1990s (Fiaschi & Wdowinski, 2019). A confirmation of the proposal hypothesis which establishes a connection between construction-based subsidence and geological attributes, viz., that construction-induced subsidence is limited to coastal limestones, will put at ease the minds of residents in US coastal areas where the basement rock is different from the young limestones of South Florida.

InSAR monitoring of the coastal built-environment. The Champlain Towers South collapse highlighted the need for new technology to monitor and assess the structural health of coastal condominium high-rises and to improve county protocols for building recertification. While various types and cracks are often observed in much of the built environment, it is important to distinguish potential hazards associated with differential settlements compounded by geological subsidence. With public safety as the top priority, the desired long-term outcome of the proposed project is the establishment of InSAR technology as a new economically viable tool for stakeholders to monitor and assess the structural safety of the building stock, and to retrofit and preserve the affected properties. InSAR has been previously used to study building collapses (Perissin, 2010), and to monitor critical infrastructure (Mililo et al., 2016; Emadali et al., 2017; Selvakumaran et al., 2020).

Regulating coastal condominium construction. Currently, Florida and other states lack regulations about subsidence in properties abutting new construction because this topic has not been investigated and not recognized as a hazard. The proposed project could lead to new regulation limiting pile-driving vibrations, and to minimize the impact of differential subsidence on adjacent buildings.

Fig, 2. *Example of a coastal development in Miami Beach, FL. Routine full-resolution InSAR monitoring can detect differential subsidence of buildings and contribute to the early detection of settlement cracks or structural damages caused by the rising seas.*

3. Relevance to NASA

Research solicitation. The proposed project addresses the solicitation's goal to better understand how key physical factors of the coastal environment such as the geological setting interact with human activities to compound the effect of the rising seas on coastal communities.

OPERA project and NISAR. The proposed project will introduce the value of InSAR ground displacement data to the coastal construction community (construction companies, building departments, and homeowner associations) and make them potential end-users for regularly updated InSAR displacement time-series data products of the Observational Products for End-Users from Remote sensing Analysis (OPERA) project, expected to be operational in 2025. It is worth noting that this end-user community requires full-resolution data products obtained from phase linking instead of the commonly used multi-looked data products obtained using the classic small baseline approach.

4. Preliminary Results

The proposed project is motivated by 2016-2021 Sentinel-1 InSAR data from phase linking (persistent and distributed scatterer) of the cities on northern Miami Beach island, FL, showing several subsidence hotspots of up to 1 cm/yr velocity in radar line-of-sight (LOS) direction (corresponding to 1.4 cm/yr vertical velocity because the radar does not look vertical) (Fig. 3). The subsiding areas are centered on newly constructed coastal high-rise buildings, suggesting that construction of the latter was the cause of the subsidence.

A zoom-in into the Surf Club Hotel area shows that both the new building and its immediate surroundings are subsiding (Fig. 4A), as revealed by persistent scatterers located on the roof of the building and one scatterer located next to the west of the building. The more dense distributed scatterers (Fig. 3) further confirm that the properties abutting the building are subsiding. Displacement time series for two roof-top persistent scatterers show that the subsidence was rapid until early 2018 (4 cm/yr in LOS), when the rate abruptly decayed (Fig. 4B). Examination of optical Google Earth imagery shows that during the early period the deep foundation of a nearby high-rise was being constructed (Fig. 4C, D). This strongly suggests that subsidence is related to the construction of the foundation. A field examination revealed that this building has a lowered ground floor, indicating that sheet piling was installed to protect against the entry of water. The vibrations from sheet pile driving could have facilitated the compaction of the underlying rock. For this project we will retrieve the records on foundation type (pile-driving versus auger-cast piles) and the dates of pile installation in order to refine the temporal correlation between pile installation and subsidence. This type of records relevant to this study are archived at building departments.

While uniform subsidence does not pose hazards to the structural integrity of a building, differential subsidence can cause settlement cracks (Fig. 1). The Oceana condominium complex further north exhibits 3.5 mm/yr differential LOS velocity (Fig. 5). If subsidence continues at this rate, there will be 5 cm differential vertical displacements after 10 years, which will likely cause damages.

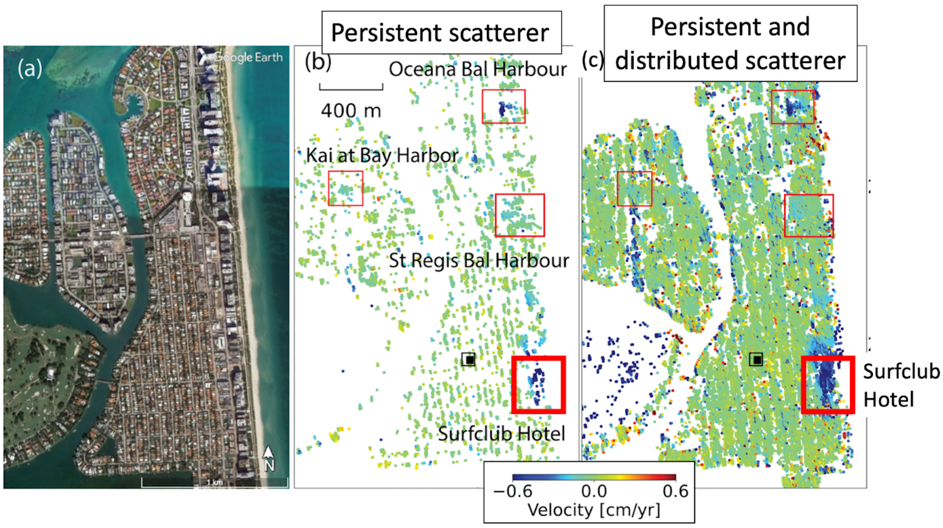

Fig. 3. *Persistent and combined persistent and distributed scatterer radar line-of-sight (LOS) velocities for Surfside and northern Miami Beach Island, FL, from 2016-2021 Sentinel-1 data. 1 cm/yr LOS velocity corresponds to 1.4 cm/yr subsidence because the radar does not look vertical. This project will show whether construction-induced subsidence hotspots occur everywhere along the US coast or only in coralline limestone settings.*

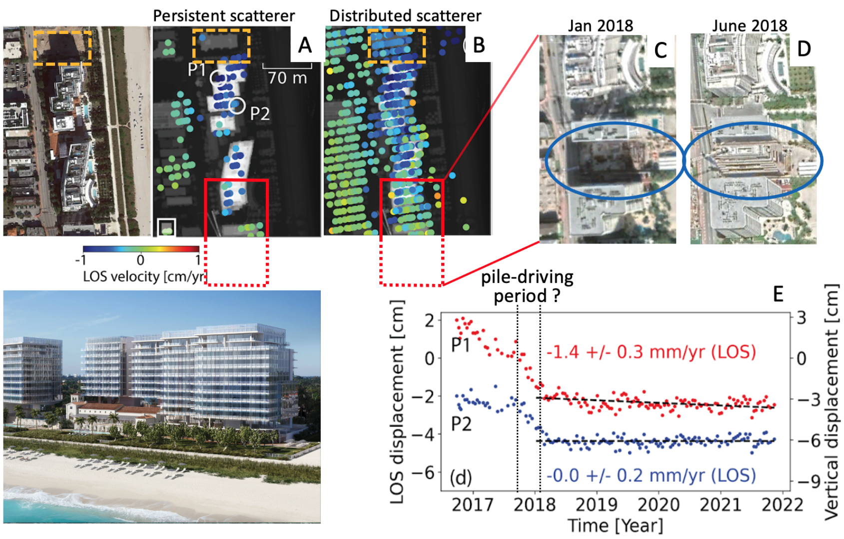

Fig. 4. *A,B) Subsidence velocity of persistent and distributed scatterer in the Surf Club Hotel area l. E) Displacement time series for 2 roof-top scatterers. The subsidence rate is 4 cm/yr LOS velocity until early 2018 when the rate declined. C, D) Optical imagery from Google Earth showing a new high-rise was constructed in early 2018 (the Arte condominium). This suggests that the 2017 subsidence was caused by pile installation. The construction of the Surf Club Hotel was completed in 2016 (see Fig. 3 for location). Dashed orange rectangle: high-rise of Fig. 9.*

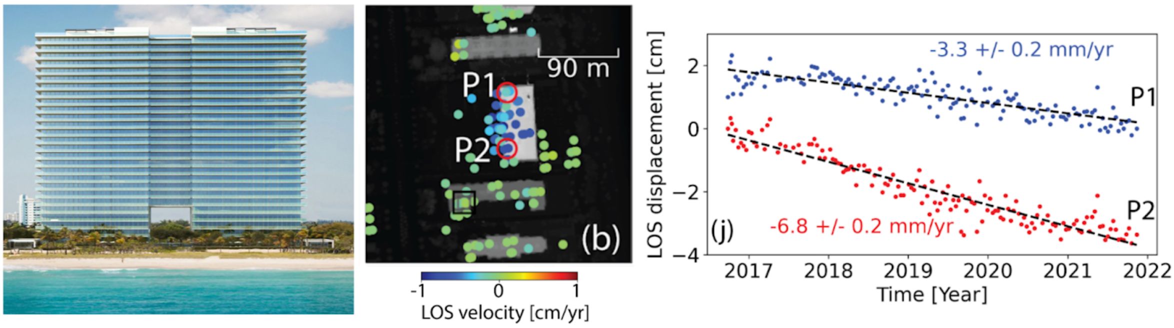

Fig. 5. *A) Subsidence of the Oceana condominium complex which was completed in 2016 (see Fig. 3b for location). 3.5 mm/yr differential LOS velocity corresponds to 5 mm/yr differential vertical velocity.*

5. Background

5.1 US coastal geology

The geologic history of Eastern North America is one of active mountain building followed by weathering erosion and sedimentary deposition. We can subdivide the eastern U.S. into three broad physiographic regions: (1) the Appalachians and Inland Basins, (2) the Atlantic Coastal Plain, and (3) the Florida Platform (Fig. 6). More or less continuous sedimentation for 100 million years on the coastal plains and the adjacent continental shelves has created an up to 10,000 meters thick clastic sediment pile. In contrast, the Florida platform was much of its history isolated from the Appalachians by a deep channel and accumulated tropical shallow water limestones in a setting much like the modern Bahamas. Once the channel was filled, siliciclastic sediments were transported south onto the Florida Platform.

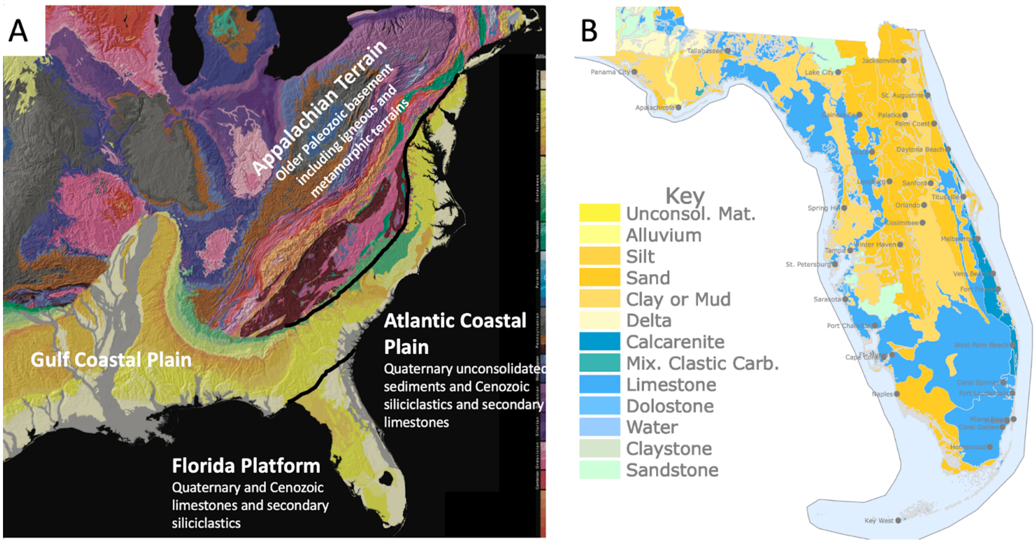

Fig. 6. *A). Simplified geologic map and generalized terrains of the Eastern U.S. and B) of the State of Florida. This project will reveal whether construction-induced subsidence is prevalent only in limestones (blue colors in B) and/or also in siliclastic deposits (orange colors in B), and whether it is a coastal phenomenon. We don't expect to see any construction-induced subsidence in the northeast because crystalline basement rock can't compact.*

The modern superficial lithologies reflect this complex geologic history. Whereas the northeast of the US is characterized by hard igneous and metamorphic rocks, the Atlantic Coastal Plain features sediments originating from clastics, sand, silt, mud, and gravel. On the Florida platform the modern coastal sedimentation reflects a gradient with more sand and siliciclastic deposition to the north with limestones dominating from South Florida to the Florida Keys. Central and western Florida received less siliciclastic sediments and is characterized by superficial limestone much older than in South Florida. The proposed project will show whether only the young south Florida limestone or also the older limestones and/or the siliciclastic coastal sediments are susceptible to construction-induced subsidence.

5.2 Strength of young coastal limestone

The shallow subsurface limestones in South Florida including in Miami Beach reflect marine deposition from coral reefs and lagoon deposits to oolitic sandy shoal deposits. These limestones were all originally composed of an aragonitic mineralogy. When exposed to fresh groundwater or surface water, aragonite is highly unstable and begins to readily dissolve. Over tens of thousands of years the aragonite transforms into the more stable calcium carbonate mineral calcite. This diagenetic process leaves the limestone riddled with dissolution features (vugs), cavities and collapse features (sink holes) (Cunningham, 2004).

In sediment core material from an area south of Surfside we have identified intervals with extensive vugs and larger dissolution features (Fig. 7). These features leave the now rubbly limestone susceptible to secondary collapse and compaction. This compromised integrity of the limestone became a significant issue during the drilling of the Miami port tunnel in 2010-2013 which revealed large voids in the highly porous limestone under Biscayne Bay that needed to be grouted prior to boring. Compaction of these voids could be an explanation for the observed subsidence.

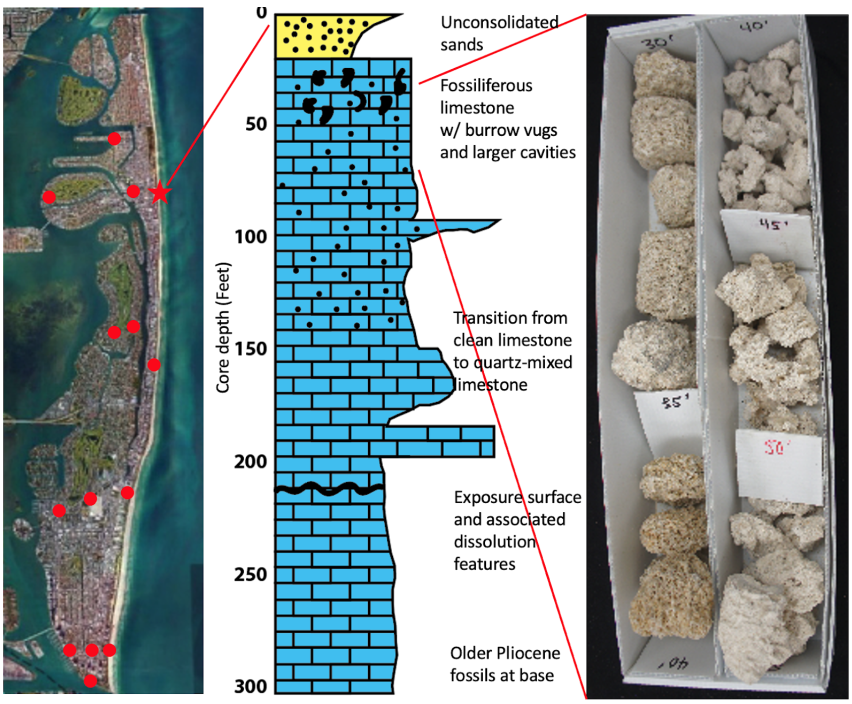

***Fig.** 7. Sediment core (300 ft long) from the coralline limestone in northern Miami Beach close to the Surfside subsidence hotspot. Compaction of cavities could be causing the observed subsidence. The City of Miami Beach drilled 13 sediment cores (stored at the University of Miami) that could help to explain local variation in construction-induced subsidence.*

5.3 Effects of sea level rise on limestone dissolution

Parkinson (2021) showed that the frequency of tidal events reaching the elevation of underground parking garages in the subsurface in Miami Beach tripled by a factor of 3 in the past decade-and-a half. The interface between the infiltrating salt water and the overlying freshwater lens has been shown to be one of the most corrosive environments to the dissolution of young limestones and to cause extensive formation of flank margin caves in coastal limestones (Cunningham 2004). The rise and fall of the water table in response to tides and fluctuations in surface precipitation may also serve to flush sediments out of the dissolving limestone and further enhance porosity formation and degrade rock strength. In addition, although not the primary topic of this proposal, the increase of salt water intrusion frequency could compromise existing infrastructure because the chemistry of salt water is particularly corrosive to concrete and iron and can directly attack aging structures that extend beneath the water table.

5.4 Building settlement

Land subsidence is the sinking of the ground which can occur naturally or because of human-induced activities. Building settlement is the downward movement of the ground (soil) when a load is applied to it. The load increases the vertical effective stress exerted onto the ground, which, in turn, results in strain causing the ground to move downward. Most buildings settle over time during the first few years after construction. Uniform settlement, i.e. when the entire foundation settles at a constant rate, does not result in damage to the structure that is typically evident with cracking. However, differential settlement due to differential compaction of the underlying ground can result in significant damage of the foundation or any other structural and non-structural elements of the building. Differential settlement can also cause tilting of both the foundation and the structure. Famous examples are the leaning tower of Pisa, and, more recently, the Millenium Tower in San Francisco.

5.5 Deep foundations and pile driving

Impact of construction activity during installation of deep foundations may also be a significant factor to consider when evaluating geological subsidence. Deep foundations for high rise buildings often consist of a series of structural columns, defined as piles, constructed or inserted into the ground to transmit loads to a lower level of subsoil. Similarly, sheet piles installed in linear configuration are also often used as retaining walls for sub-grade level building construction. Construction methods for pile installation are primarily defined in two categories: precast piles driven into ground by pipe hammer or cast-in-place piles which are bored by mechanical auger. While the driven piles are generally less expensive, vibrations during driving are often a concern for adjacent buildings when constructing in urban communities (Massarsch & Fellenius, 2008; Massarsch & Fellenius, 2014).

5.6 Building and construction information

Significant amount of relevant data can often be obtained on the built environment from publicly available building department records. Such data includes site specific geotechnical reports, building structural and foundation design plans, permit review/approval records by governing municipality and inspection records detailing the construction timelines which are pertinent data for correlating with InSAR time series data for a given site under investigation. However, only limited information such as the year of construction completion, the number of units and the square footage of units is readily available via Advanced Programming Interfaces (APIs) from the tax rolls. Obtaining the relevant data can require significant efforts, including specific building-by-building record requests commonly associated with fees.

6. Approach

6.1 InSAR full-resolution data from phase linking

We obtain InSAR time series data from the SAR image stack using a phase-linking approach (Guarnieri & Tebaldini, 2007; Guarnieri & Tebaldini, 2008), also known as SqueeSAR (Ferretti et al., 2011) which exploits the signals from both the persistent scatterer (PS) and distributed scatterer (DS). In this approach, the first data processing step is to find for each pixel the set of self-similar pixels. Next the phase linking is performed for each distributed scatterer using the full complex coherence matrix containing the wrapped phase values. Instead of phase triangulation of the original SqueeSAR approach, we use a hybrid approach consisting of maximum eigenvalue maximum likelihood phase linking (Ansari et al., 2018) and classic eigenvalue decomposition method (Fornaro et al., 2015), which is used for pixels with a non-invertible covariance matrix. The next processing step is to unwrap the phase by selecting an optimum unwrapping network of interferograms and invert for the unwrapped phase time series which is then converted to the displacement time series. For this project we will use single-reference networks which work well in urban settings and because phase-unwrap errors are not propagated. In urban environments where the digital elevation model used may not contain buildings, the geolocation of the pixels is corrected using the estimated topographic residuals used. The main advantages of phase linking compared to the classic small baseline approach (as implemented in our MintPy software; Yunjun et al., 2019) is that (i) it identifies persistent scatterers, and (ii) it provides spatial detail by multi-looking of only self-similar neighbors. The drawbacks are that it is computationally expensive, a problem which is partly overcome by using a sequential processing technique (Ansari et al., 2017) and high-performance computing.

Phase linking approaches are not widely used by the community because of the lack of publicly available software. For this project we will continue the development of our open-source MIAmi Phase Linking software in Python (MiaplPy) which fills this gap (available at https://github.com/insarlab/MiaplPy). A publication is in preparation. The OPERA project is evaluating MiaplPy. For SLC coregistration we use JPL's ISCE software.

6.2 Identifying construction-induced subsidence

While various topographical, hydrological, climatic, geological, and anthropogenic factors can impact ground subsidence (Naghibi, et al, 2022), within the context of our work, we will be concerned with only local construction-related anthropogenic activities. The approach we intend to take is to link ground displacements of a particular pixel (provided by PS-InSAR vertical velocity and displacement results) to construction-related activities (e.g., pile driving) at nearby properties. To be more specific, our stated hypothesis is that subsidence at a pixel near or on high-rise H is caused by its construction provided the subsidence correlates in time with the construction. Thus, as much as possible, we intend to rely on construction permit records. If we need to resort to tax records when permit records are unavailable/inaccessible, we will take into account that construction began 1-3 years prior to the construction completion year reported in the tax rolls.

To identify construction-induced subsidence, we will leverage methods of time series template matching. Of particular interest to us are work related to order-preserving pattern matching where one abandons discretization of the time series -- which may lead to loss of important information -- and instead attempts to match local ‘trends’ in a time series to a template (Kim et al, 2014, Wu, et al, 2022). Subsidence of a building caused by construction-related activities nearby exhibit a characteristic pattern of approximately linear decrease (starting at the start date of construction of the nearby property) followed by a near-stable steady-state value (see Figs 4 and 5). However, with the absence of specific information on the duration of the downward trend in the pattern and its slope, and also the uncertainty regarding the exact start date of construction of a high-rise -- dates in permit records may not be exact -- we intend to use multiple templates of varying parameters (related to slope and duration of downward trend) in our work. In essence, this involves matching multiple templates with each time series associated with the subsidence of a particular location. This process then generates ‘scores’ corresponding to each template leaving us with the task of choosing a ‘winner’ which would hint at the time at which the downward linear trend in subsidence began and its duration.

The task of choosing the ‘winner’ template however is not straightforward: noise inherent in the PS-InSAR results, and the uncertainties associated with the templates (e.g., the exact start date of construction), renders it difficult to select *one* ‘winner’ when the scores lie within a narrow interval of values. We have previously employed the Dempster-Shafer belief theoretic framework to resolve such issues allowing for a more informed and reasonable decision (Napoli, et al, 2015). We will leverage these results to tackle the task of selecting the ‘winning’ template in subsidence time series as well.

7. Proposed Work

Task 1 - Database of high-rise construction

We will generate a database of high-rise construction based on publicly available tax roll and building department information available from the local government agency offices (location, year of construction, footprint, geotechnical information, pile-driving versus auger-cast piling, weight or load, timing of pile installation). However, research is required on a practical approach to obtain this information because county databases are heterogeneous and foundation plans and permitting information are not available via APIs. The collection of all relevant information would require the investment of a substantial amount of work which is beyond the scope of this project. We have to make compromises between the completeness of the data and the efforts required to obtain them.

For the Miami case, however, we will do additional efforts, benefitting from the relevance of our project to the local community, and from preferred access, many of the staffers are our own graduates. We will explore the possibility of our graduate student conducting an Internship at the Miami-Dade County Building Department on a topic related to the proposed project.

Task 2 - InSAR displacement time series for the US coast

The next project task is to process the 8-year Sentinel-1 SAR data archive of the Southern and Eastern US coasts into persistent and distributed scatterer displacement time series beginning in 2015. We will start with Florida coastal cities and then move up along the coast to cover the Atlantic coastal plain including settlements on the North Carolina Barrier islands over Hampton Roads to the crystalline basement of Washington, DC, and New York City, NY, followed by the Gulf coast. In addition, we will obtain data for selected interior areas such as Orlando and Nashville for coast-inland comparisons. For data processing we use the computational resources of the NSF ACCESS (Advanced Cyberinfrastructure Coordination Ecosystem: Services and Support) and Frontera projects such as the Stampede2 supercomputer at the Texas Advanced Computing Center (TACC). All data products will be placed on the NSF's jetstream cloud computing system for storage which was designed for AI applications.

We will coordinate with JPL's Observational Products for End-users from Remote sensing Analysis project (OPERA) team on the requirements of the coastal construction user communities and data product formats. This will allow end users engaged for this project to seamlessly switch to OPERA data products when they go online in 2025. This effort will benefit from a graduate student (Sara Mirzaee) joining the OPERA team at JPL in Fall 2022.

New buildings. The dataset since 2015 will not contain any observations for new high-rises, because buildings constructed during the observation period do not maintain interferometric coherence. In order to obtain measurements for their roofs we will systematically process additional time series with starting date after construction was completed.

Task 3 - Identification of high-rise construction-induced subsidence

The next task is to link PS-InSAR vertical velocity and displacement results to construction-related activities at nearby properties. In particular, we will answer the following questions:

(a) Is the subsidence at a pixel on or near a high-rise H correlated with its construction? While we expect to rely mainly on construction permit records, when tax rolls need to be used, we need to be cognizant of when tax rolls reflect a property. This requires us to take into account that construction would have begun months or years ago (it usually takes 1-3 years from beginning of construction for a property to appear on the tax rolls).

(b) Is this subsidence correlated to construction-related activities nearby that pre- or post-date the construction of H? The fact that subsidence of a pixel near or on high-rise H could also have been caused by construction nearby that pre- or post-date the construction of H introduces a slight complication to our task.

To answer these questions, we will leverage work related to pattern matching in time series data. The database from task 1 informs us of the (approximate) start date of construction of a given high-rise H. We may then employ these pattern matching methods to seek whether it is likely that the subsidence at a pixel near or on H is, or is not, associated with construction-related activities nearby. This work would generate entries for each new high-rise on construction-induced subsidence, including the total vertical displacement (or absence thereof), the width of the affected area, and the temporal behavior (short-lived versus protracted). Using this catalog we will generate incidence maps of construction-induced subsidence which help to assess potential hazards (somewhat comparable to sinkhole incidence maps).

Task 4 - Correlation with geology

The next step is to retrieve for each new construction information on the bedrock geology from geologic maps and published reports such as those created by the State, the USGS and the water management boards in order to understand which geologic settings are susceptible for construction-induced subsidence. Is the 40 million-year old Ocala calcite limestone in west central Florida equally conducive to construction-induced subsidence and compactable as the young less than a million-year old limestones of South Florida? Do the siliclastic deposits which are widespread in the coastal plains exhibit compaction under the weight of new construction? We expect to identify coastal stretches without any construction-induced subsidence because the geological conditions are not conducive, which will be good news for these communities. We don't expect any construction-induced subsidence in the crystalline basement of Washington DC and New York City, and it is less likely for the sandstones under New Orleans, which this project task will confirm.

Task 5 - Cities on young coastal limestone around the world

While the relatively young coastal limestones of South Florida may be unique in the contiguous United States, they are globally common in the tropics. We will further test our hypothesis of construction induced subsidence by studying a number of coastal cities with young carbonate bedrock. A few well studied examples include San Juan, PR, Santo Domingo, DR, Cartagena, CO, and Kuala Lumpur, MY. For these areas we may not be able to apply our data mining approach because new construction information is more difficult to access, but archived Google Earth imagery allows us to identify new construction.

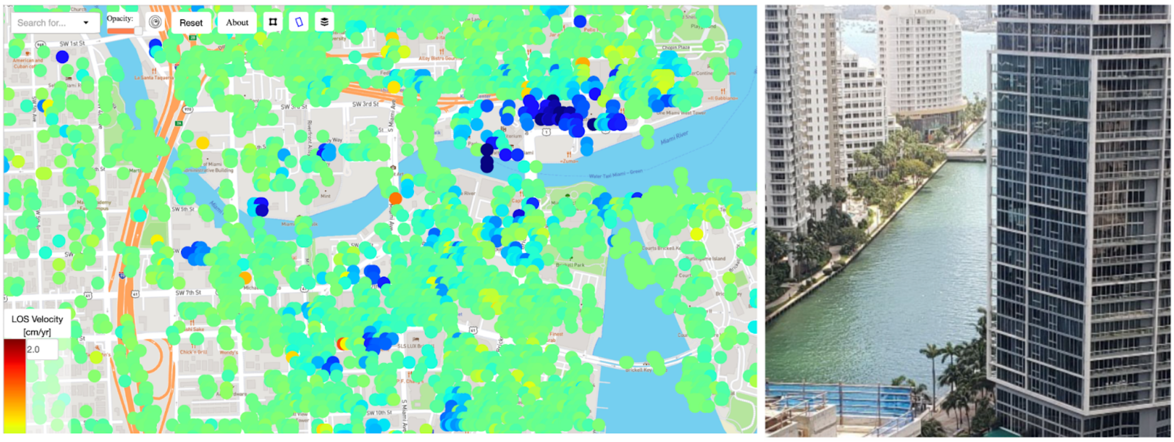

Fig. 8. (left) Preliminary InSAR LOS velocity map for the Brickell district in downtown Miami. (right) Example for residential high-rise buildings along the Miami river. The blue dots indicate subsiding pixels (>2 cm/yr).

Task 6 - Miami case study

In addition to the regional and global studies we will conduct a detailed study at our home base in Miami where construction-induced subsidence is surprisingly widespread (Fig. 8), and where building information such as type of foundation, pile installation dates, and geotechnical reports, all maintained by the Miami-Dade County building department is more accessible. We also will accompany the construction of new buildings with subsidence information from the start to completion by providing observations to stakeholders, and identify the reason for compaction.

In addition we will conduct an in-depth study of the Surf Club Hotel area. Based on the foundation plans and construction information we will assemble (i) a time series of piling installation at the various construction sites and (ii) a spatial-temporal surface loading model representing the rising buildings. Using this model we will examine how subsidence correlates with piling and building growth. Valuable new data will be provided by the ongoing and planned new construction of high-rise buildings just north and south of the Surf Club Hotel (Seaway Villas of Fig. 9; and between the Arte condominium and the Surf Club Hotel, see Fig. 4CD, respectively; construction of the latter is scheduled to begin in fall 2022). The geotechnical reports will provide information about lateral variations of the underlying geology.

TerraSAR-X. Whereas we will rely on openly available Sentinel-1 and NISAR data for the regional and global studies, for Miami we will use high-resolution TerraSAR-X data which have an order of magnitude better spatial resolution (2*2 and 3.5*3.5 m^2 for spotlight and stripmap mode, respectively; we have budgeted for it, Fig. 10). High resolution is particularly important for persistent scatterer analysis. We also will experiment with ICEYE and Capella Space imagery if it becomes available from NASA's Commercial Smallsat data acquisition program.

Fig. 9. *(left) Ongoing construction of the Seaway Villas in Surfside. (right) Artist's view of completed construction. The Villas are being constructed within the Surf Club Hotel subsidence hotspot (orange square in Figs. 4A,B) which is known to have subsided previously*

Task 7 - Differential building subsidence

A byproduct of the analysis is detected differential subsidence of coastal highrises that could indicate compromised structural integrity. This includes differential subsidence caused by the effects of saltwater intrusions from the rising seas. We will classify detected subsidence according to their severity and develop a protocol to alert the local building departments and/or property owners so that mitigation measures can be initiated. 8. Project Deliveries and Expected Results

- Full-resolution InSAR displacement time series for the southeastern coast
- Catalog and incidence maps of construction-induced subsidence along the southeastern coast
- Attribution of construction-induced subsidence to geological settings
- Insights on whether sea level rise compounds construction-induced subsidence.
- Global assessment of construction-induced subsidence in cities built on limestone.

Fig. 10. *High-resolution TerraSAR-X spotlight image which we will acquire for an in-depth study of Miami and Miami Beach.*

10. Project Team and Management

Project Team. The PI of this project is Falk Amelung, Professor in the Department of Marine Geosciences at the University of Miami (UM) Rosenstiel School of Marine and Atmospheric Sciences (RSMAS). The Co-PIs are Jim Klaus of the same department, Antonio Nanni and Esber Andiroglu, professors in the Dept. of Civil and Architectural Engineering and Kamal Premaratne a professor in the Dept. of Electrical and Computer Engineering. Amelung is the InSAR expert, Klaus is a coastal carbonate geologist, Nanni is a civil engineer specialized in structural analysis and design with focus on concrete-based systems. Andiroglu is a mechanical/architectural engineer specialized in sustainable design and construction with expertise in coastal resilience, and Premaratne's expertise lies in knowledge discovery from imperfect information and network science. The PIs and Co-PIs will oversee one postdoctoral researcher and two graduate students to be hired for this project, one in the College of Engineering and the other in the Dept of Marine Geosciences. The postdoctoral researcher will be responsible for the adaptation of the InSAR processing software and for the initial InSAR processing of the coastal regions. The engineering graduate student will be responsible for developing the new construction database and the data mining approaches. The geology graduate student will be responsible for the coast-inland comparisons, comparison with limestone environments around the world, and for the integration of the results in terms of the underlying geological setting. A computer science undergraduate student will assist with software development and computer visualization.

At RSMAS graduate students are supported for three years by a federal grant and for 2 years by the School. Although we request only 3 years of funding, the geology student will be working 5 years on this project.

Management. The team will have monthly all-hands-on-deck meetings in which the postdoctoral researcher and the two graduate students will present powerpoint presentations with updates on their respective projects. Furthermore, each student will have additional meetings with his/her primary advisor(s). Amelung strives for weekly individual meetings with all members of his research group.

Mentoring. The postdoctoral researcher will follow the University of Miami's postdoctoral mentoring program including outreach events to highschoolers. At the beginning of each project year Amelung holds a meeting focussing on how to achieve long-term career goals.

11. Related Projects

The proposed project will benefit from several research projects that our team is currently developing following the discovery of construction-induced subsidence at the Surf Club Hotel. This includes (1) the numerical modeling of the compaction of coralline limestone in response to vibrations from pile driving, including the prediction of the expected subsidence based on the geotechnical reports, and (2) the validation of InSAR subsidence with ground measurements using total station which will help the adaptation of satellite-based InSAR by the construction and regulatory community, and

12. Proposed Schedule

Yr 1: Development of the new construction database and of data mining software. Persistent and distributed scatterer analysis for Florida.

Yr 2: Generate initial construction-induced subsidence catalog using data mining. Data processing of the remaining coast and of initial TerraSAR-X data for Miami.

Yr 3: Development of geological background information and interpretation of incidence map in terms of geology. In-depth study of the Surf Club Hotel area. Comparison of limestone settings around the world.

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E. Data Management Plan

The Sentinel-1 SAR data used are open access. The TerraSAR-X imagery will archived at Unavco. Data older than 18 months are freely available from the DLR in response to research proposals.

We commonly make all InSAR data products openly available using our NSF-supported jetstream instance (https://js-104-223.jetstream-cloud.org/data/HDF5EOS/) and on our insar data portal (insarmaps.miami.edu). However, given the large amount of data produced by this project we only will make relevant data available that potentially show a signal. We also will closely collaborate with JPL's OPERA product to not duplicate their efforts and to only provide data that they don't provide (e.g. TerraSAR-X)

Like in all recent published papers by PI Amelung, all generated data products used in the interpretation will be published as a digital supplement.

F. Software Development Plan

For the InSAR analysis of this project we use our MIAmi PhaseLinking software in Python (MiaplPy). This software, although not completed, is already openly available on GitHub and has first users https://github.com/insarlab/MiaplPy. A paper is in preparation (Mirzaee et al., in prep.) PI Amelung is a strong supporter of open source software and aims to go a step further and publish software together with a scientific article describing the methods employed. We have done this with our previous software (Miami InSAR Time Series Tools in Python, MintPy, Yunjun, Fattahi and Amelung, 2019) which has developed into a true open source project with many developers including at JPL and the ASF. We hope that MiaplPy will follow this path.

We also will make the API software to generate a new construction database as well as the data mining software available on GitHub. Our goal is to provide software so that endusers can search for construction-induced subsidence using new data products produced by the OPERA project.

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