Overview

Limestone is hard, solid rock. It is expected to exhibit short-term settlement during and immediately after construction but not long-term settlement because the load is carried by the rock matrix and not by the water occupying the pore spaces. However, satellite-based Interferometric Synthetic Aperture Radar (InSAR) observations of Miami Beach, FL show long-term settlement of ~6 cm in radar line-of-sight direction (10 cm vertical displacement) over a 5+ years period after the construction of several multi-story coastal structures. We propose a multi-disciplinary research program to investigate the mechanisms of this unexpected long-term settlement consisting of (i) the acquisition of InSAR data, (ii) the drilling of sediment cores, (iii) geotechnical testing and experiments, and (iv) numerical modeling of flow of granular matter. The shallow limestone in South Florida is weak because it is young, porous, permeable coralline limestone riddled with voids and vugs. Our research approach is to identify long-term settlement using InSAR, to drill sediment cores in the areas of strong settlement, and to investigate the samples in the geotechnical laboratory for their creep and settlement potential. We will conduct sustained loading experiments to determine whether settlement is due to compression of the limestone or compression of the embedded sand. Assuming the latter, we will investigate why creep compression continues for years. We will conduct experiments on sand samples from the sediment cores to investigate the time dependency of creep compression under sustained loading. We will test whether the combination of sustained and dynamic loading (from the new structure and construction-related vibrations) induces secular creep of the sand. We will reproduce the laboratory-measured creep using numerical simulations of the flow of granular media (sand) using finite and discrete element modeling approaches and non-local constitutive relations. The overall objective is to accurately predict the InSAR observations of settlement based on laboratory-measured geotechnical properties.

Intellectual Merit

This project investigates the surprising observation of long-term settlement of young coralline limestone.

Broader Impacts

Some of the world's major cities are built on young coralline limestone including the Floridian metropolises of Miami, Tampa and Orlando. This project will demonstrate the value of the InSAR technique to the construction community for understanding settlement as well as for monitoring the structural integrity of high-rises. This project supports a postdoctoral researcher and a graduate student and will lead to the introduction of InSAR observations into the Civil Engineering curriculum.

Collaborative Research: Understanding settlement of young coralline limestone containing interbedded sand layers using InSAR observations

Falk Amelung and Esber Andrioglu, University of Miami, FL

Khaled Sobhan, Florida Atlantic University, Boca Raton, FL

Project goals: Obtain subsidence data using InSAR. Drill sediment cores. Experimental and numerical investigation of the long-term settlement mechanism.

Funding request: Drilling of sediment cores. 2 years support for postdoctoral fellow and grad. student.

1. Project overview

Limestones are strong, highly permeable rocks. The construction of a high-rise on limestone is thought to be associated with short-term settlement (often termed immediate settlement; it includes the elastic component), but not with any long-term settlements, which typically occur in "soft" compressible medium undergoing primary and secondary consolidation. However, space-based interferometric synthetic aperture radar (InSAR) observations of coastal high-rises in Miami Beach, FL reveal up to 10 cm of subsidence occurring over several years following the construction (described below). Is this long-term settlement a consequence of the underground lithology such as weak limestone or thick sand layers? Is this settlement exacerbated by the employed construction techniques such as vibrations and/or groundwater pumping? The observed subsidence was not anticipated. It is concerning because it can impact the structural integrity of both newly constructed buildings and existing, nearby structures.

The bedrock in Miami Beach is young, porous, permeable coralline limestone riddled with dissolution features (vugs), cavities, collapse features (sink holes), and contains embedded sand layers. Assuming that the observed subsidence of buildings is not the result of deformation of the structural piles, we suggest four possible mechanisms for the subsidence: (1) slow crushing of the limestone under the base of the piles by brittle or ductile creep within the rock matrix leading to the reduction of void space, (2) consolidation/compression of the crushed limestone under the piles, (3) creep of the sand layers under sustained loading and/or due to construction-related vibrations, (4) same as (3) but of the crushed limestone under the piles. Given the physical strength of limestone, we consider explanation (3) the most likely. Particularly surprising is the observation that subsidence continues for 5+ years after construction, i.e. after the construction-related disturbances ceased. In order to explore the mechanisms of subsidence in young coralline limestone we formulate the *two hypotheses* of this proposal:

"Hypothesis 1: Subsidence in young coralline limestone environments is due to creep deformation and settlement of the interbedded sand layers."

"Hypothesis 2: Creep deformation of interbedded sand layers is exacerbated by the combination of sustained loading by a new structure and construction-induced vibrations."

To test these hypotheses we have designed a research program consisting of InSAR data analysis, sediment core collection, laboratory geotechnical testing, laboratory experiments on scaled models, and numerical modeling. Our *research strategy* is to first test whether pure coralline limestone (without embedded sand layers) exhibits any slow compression behavior under simulated building loads. This is a test for hypothesis 1. Assuming that we don't find any evidence for creep in limestone, i.e. that hypothesis 1 is confirmed, we then will investigate how deformation in the interbedded sand layers can explain the InSAR-observations of settlements of tall buildings. Is creep deformation due to the sustained (static) loading by the building, due to the dynamic loading by construction-related vibrations, or both? The *overall objective* of the proposed project is to develop an approach to predict settlements of sand-layer-containing limestone given the thickness and properties of the interbedded sand. To prove the proposal hypotheses we will pursue the following five specific aims:

Aim 1. Measuring subsidence using InSAR. We will characterize the spatial and temporal patterns of construction-induced subsidence of coralline limestone in the Miami Beach, FL area using persistent scatterer InSAR from Sentinel-1 and TerraSAR-X SAR data obtained using a phase-linking approach. In addition, we will obtain InSAR data for high-rise construction on young coralline limestone elsewhere in the world lacking embedded sand layers (in Jeddah, Saudi Arabia and Coral Gables, FL). The absence of construction-induced subsidence in sand-poor environments would support our hypothesis that subsidence is the result of compaction of the interbedded sand.

Aim 2. Retrieving sediment cores. We will collect sediment cores and borehole loggings for 3 locations in the Miami Beach area with different subsidence signals. These cores will inform us (i) on how widespread embedded sand layers and large cavities are, (ii) on differences in the subsurface geology such as the sand layer thicknesses and large cavities between the sites, (iii) provide specimens for geotechnical testing, and (iv) provide structural information for the numerical settlement simulations. The sediment cores will be supplemented by geological information from the pre-construction geotechnical exploration borings (geotechnical reports).

Aim 3. Measuring rock and sand properties. Using the collected sediment cores we will measure in the laboratory (i) the strength of the limestone (unconfined compressive strength, shear strength, Young's modulus), (ii) the physical/mechanical characteristics of crushed limestone which potentially could contribute to creep settlement, (iii) the properties of the embedded sand layers (classical grain size and grain shape analysis, measure the shear strength and creep), and (iv) the limestone's ability to creep and to be crushed under sustained loading lasting several weeks to months. The questions to address are (1) whether the young limestone compresses and/or crushes under the induced stresses from a multi-story high-rise building load, (2) whether the crushed limestone shows any long-term creep compression, and (3) the sand's potential for settlement under the building load and/or vibrations from nearby construction. If the experiments do not show any long-term compression behavior of the limestone proper, this supports our hypothesis that subsidence is due to compression of the interbedded sand layers.

Aim 4. Experimental and numerical investigation of settlement. We will conduct sustained, vibratory, and combined loading experiments on the retrieved sand samples to investigate whether the combination of a building load and vibrations is particularly effective in inducing settlement (proposal hypothesis 2). We also will develop finite element simulations of sand layer compression in response to building and vibrational loads using independent and coupled models. These efforts are aimed to understand why creep continues for 5+ years after a surface load has been emplaced and in which cases creep is exacerbated by vibrations. The objective of this activity is to more accurately predict the settlements based on geotechnical tests and measurements.

The proposed project will lead to an improved understanding of long-term settlement of young, sand-layer-containing, coralline limestone. It could lead to changes of the pre-construction geotechnical exploration practices in young coralline limestone environments in order to better capture the properties that determine long-term settlements. Furthermore, the project will introduce the construction community to the power of the InSAR technique to monitor subsidence during and after construction, and the structural integrity.

The interdisciplinary nature of the research team consisting of geophysicists and a geotechnical engineer requires clarifications about the terminology. We use the terms *subsidence* and *settlement* interchangeably. We use the term *creep* for slow and progressive deformation with time but distinguish between *creep due to static loading* and *creep due to dynamic loading.* Static loading is by the new building. Dynamic loading by construction-related vibrations. Creep and subsidence due to dynamic loading is sometimes referred to as *dynamic settlement*.

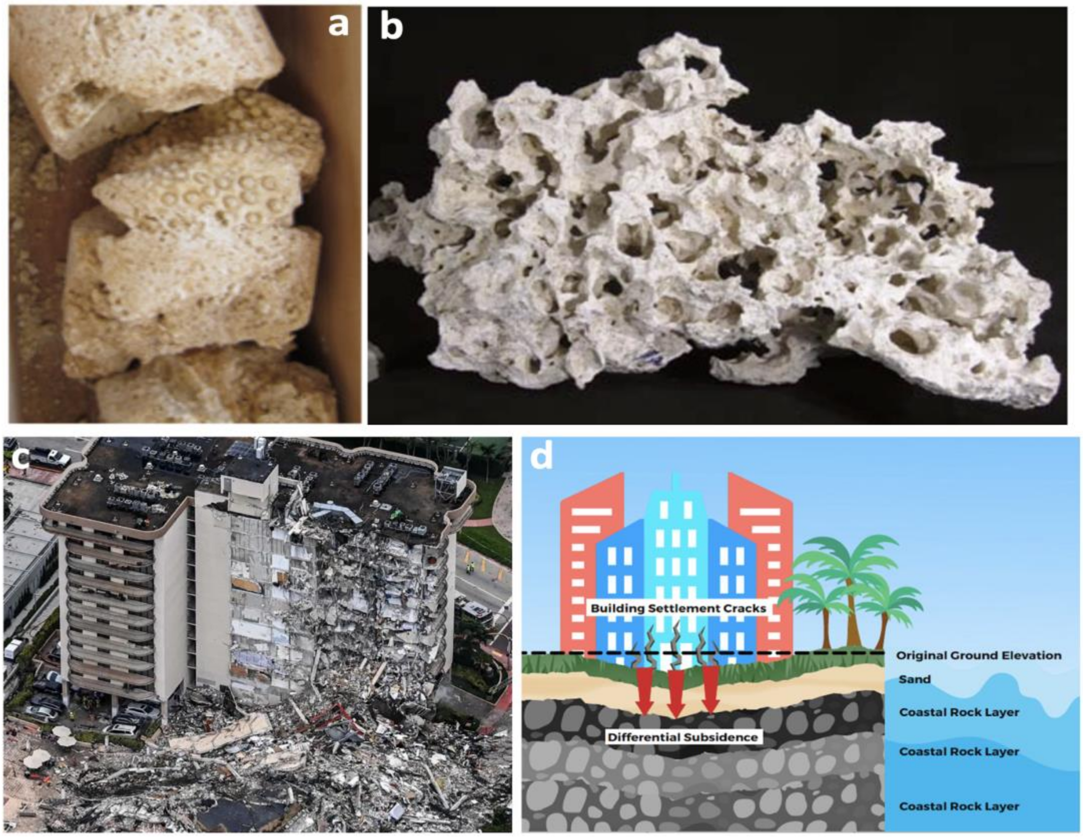

Fig. 1. *(a) Cavities in coralline limestone from Jeddah, Saudi Arabia (from Seng et al., 2020) and (b) Miami, FL (from Cunningham et al., 2009). (c) Miami Beach condominium that collapsed in June 2021. (d) Illustration of settlement cracks in high-rises subject to differential subsidence. We will investigate subsidence of young, cavity-ridden limestone that could threaten the structural integrity of the built-upon high-rises.*

2. Significance

Settlement of young coralline limestone. Limestone has the property to slowly dissolve when exposed to freshwater, which is why limestone features abundant cavities (possibly meter-sized) (Fig. 1a-c). In geologically persistent coastal environments young coralline limestone can contain sand. Understanding how both, the cavities and the interbedded sand layers contribute to building settlement is important for some of the world's major cities that are built on young coralline limestone, including Jeddah (Saudi Arabia), Kuala Lumpur (Malaysia), Santo Domingo (D.R.) and the Floridian metropoleis of Miami, Orlando, Tampa and Jacksonville.

InSAR monitoring of coastal high-rises. After the 2021 collapse of the Champlain Towers South in Surfside, FL (Fig 1), the overwhelming concern for the residents of condominiums along the US coast is whether the structures they live in are safe. Although deferred maintenance and poor design were the primary culprits for the collapse, sea level rise (salt water intrusion and corrosion damage), storm surge events and subsidence all could have contributed to compromise the structural integrity of the building. It was already found before the collapse that the area was undergoing subsidence in teh 1990s (Fiaschi & Wdowinski, 2019). Satellite-based InSAR has the potential not only to provide observations to understand settlement, but also to monitor and assess the structural health of the building stock.

Relevance to Engineering of Civil Infrastructure program. The proposed project addresses two priorities of the ECI program. (i) We will conduct fundamental research on how construction interacts with the natural environment (the limestone basement) using experimental and computational methods. (ii) Scientific understanding of the subsidence of coastal structures will contribute to the welfare of coastal communities.

3. Preliminary results: Subsidence in Surfside, FL

The proposed project is motivated by InSAR data of the cities of Surfside and Bal Harbour, Miami Beach, FL, showing subsidence centered on two newly constructed high-rise complexes of up to 1 cm/yr velocity in radar line-of-sight (LOS) direction, corresponding to 1.4 cm/yr vertical velocity (Fig. 2, Structures A and B). The InSAR data were obtained using a new InSAR phase linking approach that exploits both persistent and distributed scatterers using 2016-2021 data of the European Sentinel-1 SAR satellite (see section 6.1).

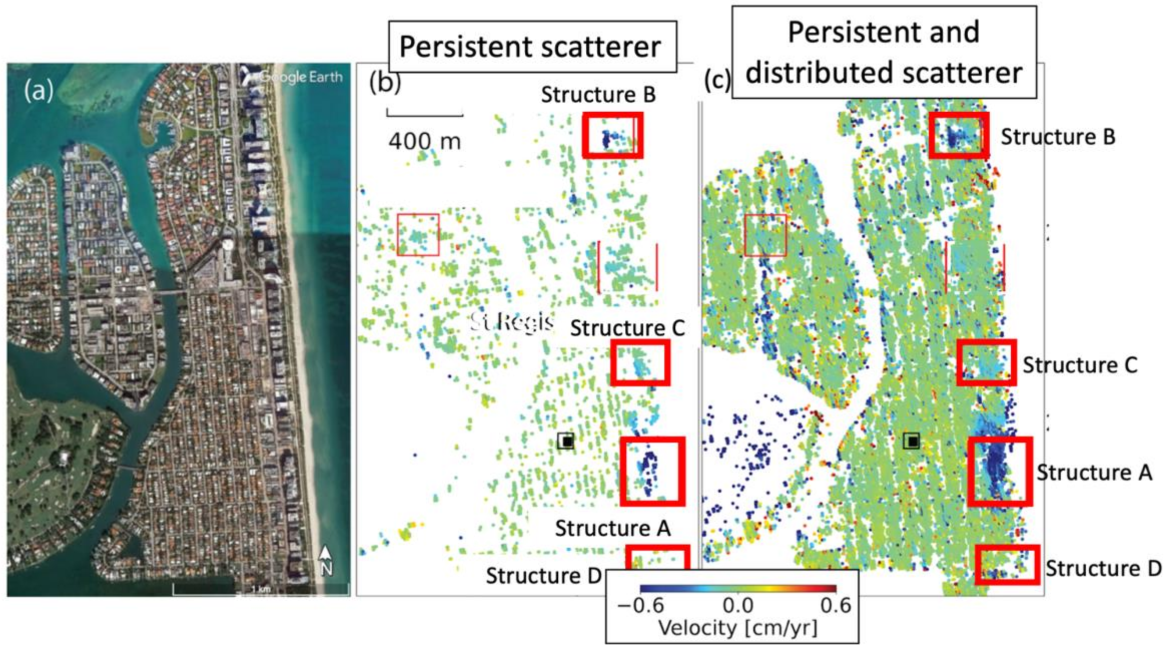

Fig. 2. Persistent and combined persistent and distributed scatterer radar line-of-sight (LOS) velocities for northern Miami Beach, FL, from 2016-2021 Sentinel-1 data. 1 cm/yr LOS velocity corresponds to 1.4 cm/yr subsidence.

The InSAR data for structures A and B reveal the spatial and temporal details of subsidence (Figs. 3, 4). In the area of Structure A not only the new buildings subsided, but also the abutting properties (see distributed scatterers in Fig. 3B). The displacement time series for two persistent scatterers located on the rooftops show that subsidence was rapid until early 2018 (~4 cm/yr in LOS direction) when it leveled out (Fig. 3E). The total differential displacement between the two scatterers was ~2 cm in LOS direction. In contrast, Structure B which is located ~1.5 km further north subsided over the entire 5 year study period at constant rates of up to 7 mm/yr in LOS direction. The differential velocity between two rooftop scatterers ~90 m apart is 3.5 mm/yr in LOS direction (Fig. 4), corresponding to 5 mm/yr subsidence. Differential settlement at this rate will lead after 10 years to 5 cm differential displacement which likely will cause damages to the structure

Examination of optical Google Earth imagery for Structure A shows that a new high-rise was constructed in 2018 in the second next lot to the south (Fig. 3C, D). This suggests that the subsidence of Structure A is the result of the construction of the nearby structure, possibly vibrations from sheet pile installation. However, this mechanism does not explain the subsidence at Structure B because there was no nearby construction.

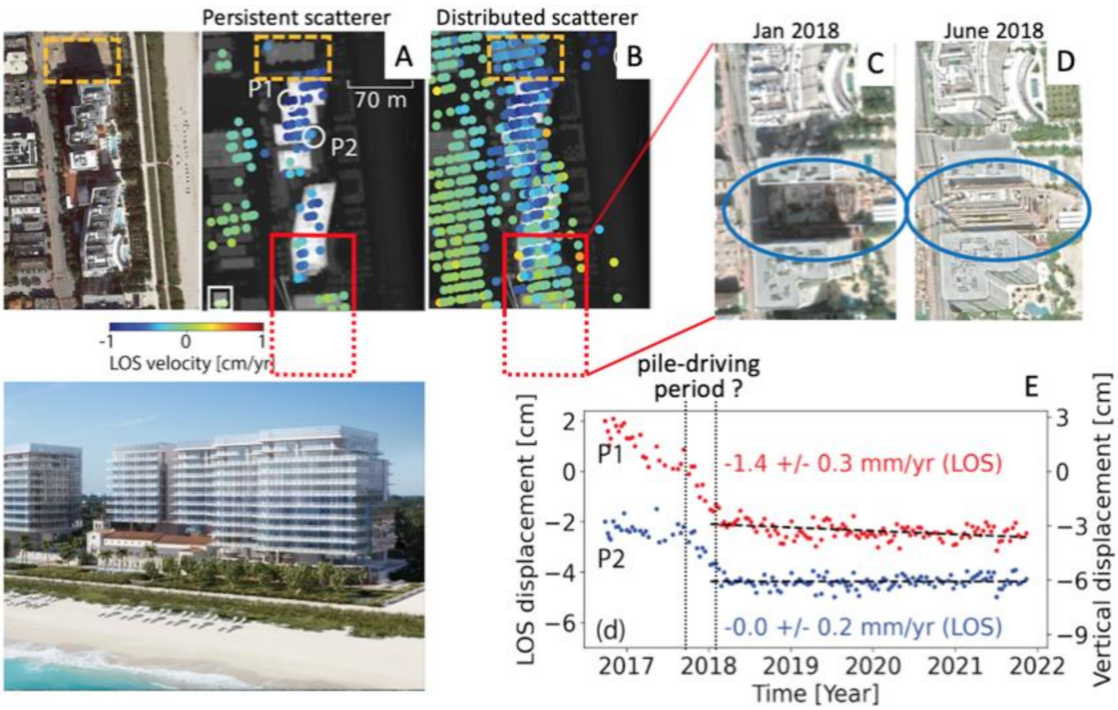

Fig. 3. *A,B) Subsidence velocity of persistent and distributed scatterers for Structure A which was completed in 2016 (see Fig. 2 for location). E) Displacement time series for 2 roof-top scatterers. C, D) Optical imagery from Google Earth showing that a new high-rise was constructed to the south in early 2018, suggesting that the 4 cm/yr LOS velocity until early 2018 could be caused by disturbances from this construction.*

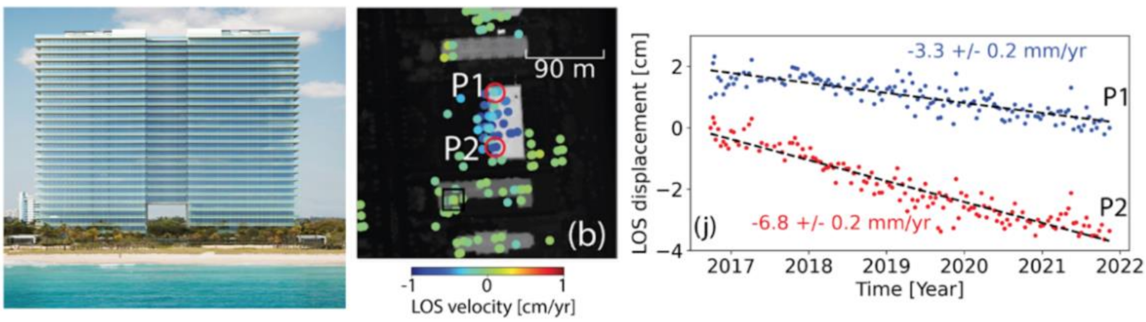

Fig. 4. *(Center) Subsidence of persistent scatterers in the area of Structure B which was also completed in 2016 (see Fig. 2 for location). (Right) Displacement time series for two persistent scatterers on the rooftop. The difference in LOS velocity between the two scatterers is 3.5 mm/yr in LOS direction, corresponding to 5 mm/yr in vertical direction*

4. Specific research questions

The specific research questions addressed in this project are:

1. What is the physical settlement mechanism of young coralline limestone? Is subsidence the result of deformation of the limestone? Mature limestone is known to be deforming by ductile or brittle creep at pressures >125 MPa (5 km overburden) but not at the low stresses from a multi-story building. Could young coralline limestone deform at stresses induced by a building?

Did the piles crush the limestone under their bases? Is this crushing instantaneous or does it take a few years to complete? Does the crushed limestone exhibit primary consolidation? Alternatively, subsidence is due to creep of the sand layers embedded in the limestone (our proposal hypothesis). While the 2-year subsidence at Structure A suggests settlement of sand (Fig. 3), the steady subsidence of Structure B (Fig. 4) suggests primary consolidation.

2. Why does subsidence continue for years after construction? Assuming that we see creep within the embedded sand layers, is this creep a response to static loading (the new building), dynamic loading (vibrations from construction), or both? Can such particle rearrangement continue for years once initiated? When will it stop? How does the settlement response depend on the thicknesses of embedded sand layers (considering both scenarios: sand layers penetrated by the foundation impacting the side friction resistance and sand layers underlying the tip of the foundation impacting tip resistance)?

3. How to predict settlement of sand-layer containing limestone? An important objective is to determine how the geotechnical findings from (1) and (2) can be used to accurately predict the time-dependent settlement. Is there an appropriate numerical modeling approach for granular media to predict settlement in sand containing coralline limestone and to corroborate the observed subsidence?

5. Background and approach

5.1 Strength of young coastal limestone

The young coralline limestone in Miami Beach reflects 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 to surface water, aragonite is highly unstable and begins to dissolve. Over tens of thousands of years the aragonite transforms into the more stable calcite, leaving the limestone riddled with dissolution features (vugs), cavities and collapse features (sinkholes) (Fig. 1B), and susceptible to breakage of the cemented grain structure, and compaction (Cunningham, 2004; Nguyen et al, 2019). A central question is whether the vuggy limestone is weak and yields under the relatively small load of a multi-story high rise, or whether creep compression is limited to the embedded sand.

5.2 Mechanisms for long-term settlement

The three possible mechanisms that could cause the long-term settlement are summarized in Fig. 5. Long-term settlement is commonly due to the expulsion of water from the pore space (primary consolidation) but this mechanism is not at work in limestone which has a solid rock matrix. However, the crushed limestone under the base of the piles could potentially consolidate (Fig. 5A). Another possible mechanism is slow reduction of the void space of the limestone by ductile or brittle creep within the rock matrix (Fig. 5B). This mechanism is unlikely to apply because sustained loading experiments on limestone show creep behavior only for loads orders of magnitude larger than the loads of high-rise buildings (Baud et al., 2009). We will conduct sustained loading experiments to determine whether vuggy, coralline limestone exhibits creep under multi-story building loads.

Our hypothesis is that not the limestone but the interbedded sand layers are responsible for the settlement. Granular material can respond to both sustained, static loading by a new building and transient, dynamic loading by construction-related vibrations with rearrangement of the particles, a process known as creep (Fig, 5C). Particle rearrangement in response to dynamic loading is sometimes referred to as dynamic settlement. Fig. 6 illustrates how cyclic shear strain leads to changes in the particle packing including the closure of voids (Youd, 1977). Several case histories of vibration-induced dynamic settlement in shallow foundations have been reported in the literature even at low vibration levels (0.02 – 0.1 in./s), and at long distances from the source of vibration especially in low plasticity sands and silts and in loose collapsible soils and granular fills (Kaminetzky, 1991; Feld and Carper, 1997; D'Appolonia, 1971; Svinkin, 2004, 2008; Siskind, 2000; Hunt (1986); Lacy and Gould, 1985).

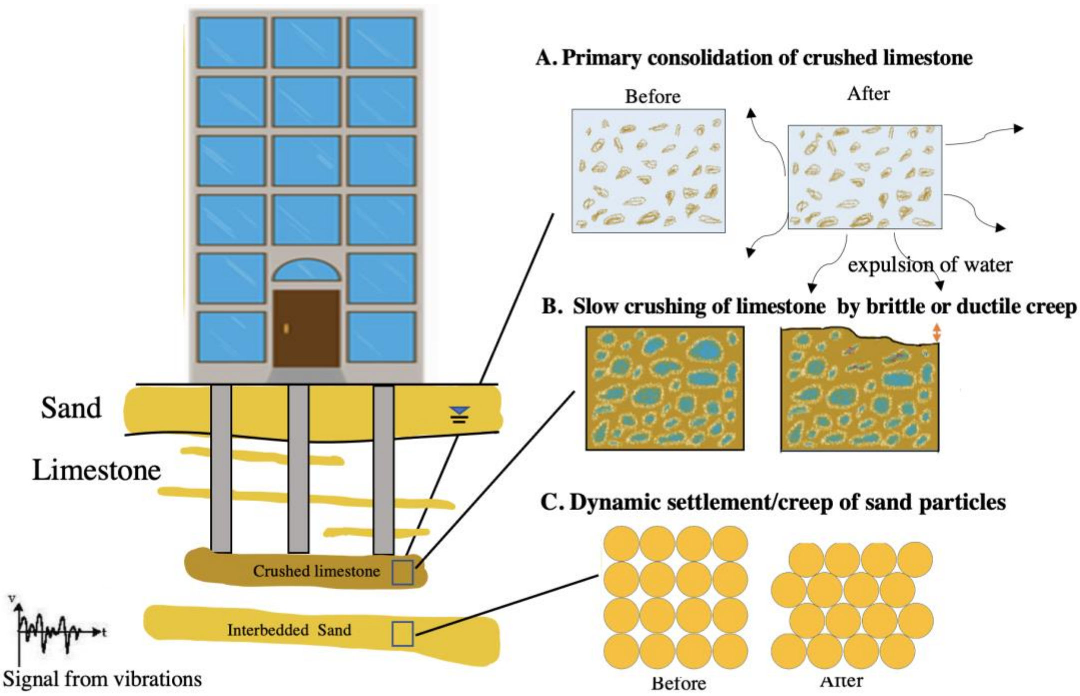

Fig. 5. *Cartoon of possible settlement mechanisms: (A) primary consolidation of crushed limestone (B) creep of limestone reducing void space (crushing), (C) creep of sand by rearranging the grain packing. The proposal hypothesis is mechanism C: rearrangement of the sand particles associated with volume reduction of the sand layer.*

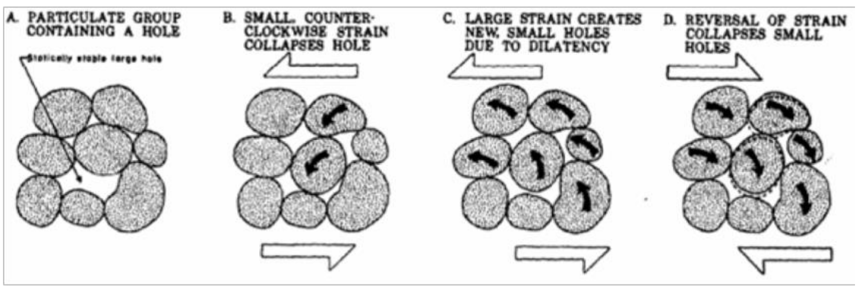

Fig. 6. *Schematic showing how the accommodation of shear strain by sand particles leads to the closure of holes in the packing and to volume reduction of the sand (from Youd, 1977).*

5.3 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, then the phase linking is performed for each distributed scatterer using the full complex coherence matrix containing the wrapped phase values using a hybrid approach consisting of maximum eigenvalue maximum likelihood phase linking (Ansari et al., 2018) and classic eigenvalue decomposition (Fornaro et al., 2015). The latter is used for pixels with a non-invertible covariance matrix. Then the phase is unwrapped by selecting an optimum unwrapping network of interferograms and the network is inverted for the time series. We will use single-reference networks which work well in urban settings. As the digital elevation model 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 (Yunjun et al., 2019) is that it identifies persistent scatterers and works at full resolution. The drawbacks are the computational expenses which are partly overcome by using a sequential processing technique (Ansari et al., 2017) and by using the NSF's ACCESS high-performance computing systems. We use JPL's ISCE software for SLC coregistration our MIAmi Phase Linking software in Python (MiaplPy) for phase linking, the only open source package implementing this approach (available from GitHub as github.com/insarlab/MiaplPy). A publication is accepted for publication (Mirzaee et al., 2022).

6. Proposed work

Task 1 - InSAR data acquisition

The first task is to better characterize the temporal and spatial subsidence trends. We will refine the InSAR data by selecting for each newly built coastal high-rise individual starting dates for the phase-linking analysis because scatterers appear only once a structure is completed and it's surface which scatters the radar signal back to the satellite is no further changed. For example, the building south of Structure A that was completed in 2019 (see Fig. 3c,d) will have persistent scatterers in a dataset starting in 2019 but not in the 2016-2022 dataset. With this approach we can better characterize the early settlement phase, and how far subsidence extends from the structure (100-200 meters for Structure A Fig. 3b). The latter provides clues on the depth of the compressing strata (a large subsidence footprint indicates compression of deeper layers)..

High-resolution TerraSAR-X. In addition to the openly available low-resolution Sentinel-1 data ($5*20m^2$ spatial resolution), we will analyze high-resolution TerraSAR-X data ($3*3m^2$ spatial resolution for stripmap mode), obtained through an approved research proposal with the German Space Agency DLR (2017-2021 data). For TerraSAR-X we expect a factor of ten higher persistent scatterer density.

Coralline limestone without embedded sand layers. To confirm our hypothesis that subsidence is the result of compression of the sand layers we will obtain InSAR data for new construction on young limestone that lacks sand layers. We will study ground displacement in the vicinity of new structures in downtown Miami built on top of the Miami Oolite, an up to 13 m thick solid limestone which is part of the Atlantic Coastal Ridge. The geotechnical reports will provide the information on how much sand the limestone contains. We also will study structures in Jeddah, Saudi Arabia which is characterized by a young coralline limestone similar to South Florida (Fig. 1) but to our knowledge does not contain any sand.

Task 2 - Collection of limestone cores and core logging

We will drill sediment cores near the three structures of interest (Structures A, B, and C, for an example see Fig. 7). We will use sonic drilling to collect solid, 4-inch cores with nearly complete core recovery in contrast to reverse-air circulation drilling for typical geotechnical exploration coring with 20-30% core recovery. For borehole logging we will apply a suite of methods, including optical imaging, density, resistivity and gamma-ray logging to be conducted by the borehole logging team of the Caribbean-Florida Water Science Center (CFWSC) of the U.S. Geological Survey based near Fort Lauderdale (e.g. Cunningham et al. 2009, 2012, 2018). This ensures that all logs will be available via the USGS data portal (see data management plan). We have budgeted for one core to ~100 meters and 2 cores to 60 meters. However, we hope that we can convince the local municipalities to fund additional core collections. The sediment cores will unequivocally show how much interbedded sand the limestone contains

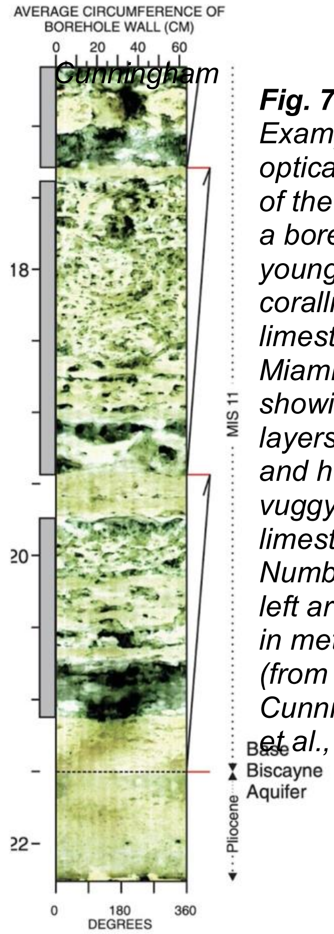

***Fig. 7**. Example of an optical image of the walls of a borehole in young coralline limestone in Miami, Fl, showing sand layers, voids, and how vuggy the limestone is. Numbers on left are depth in meters (from Cunningham et al., 2009).*

***Fig. 8.** Optical borehole log of a >1 ft thick sand layer at 202 ft depth in northern Miami Beach (3 km south of Structure D). Our proposal hypothesis is that the subsidence areas are underlain by similar sand layers which compress in response to combined static and dynamic loading.*

Task 3 - Estimate susceptibility for settlement by laboratory testing

Next we will determine in the laboratory the physical and mechanical properties of the young coralline limestone and of the embedded sand layers. Tall coastal towers are supported by deep foundations often consisting of groups of cast-in-place reinforced concrete piles supporting a column load transmitted from the superstructure to the underlying soil and rock. We will conduct standard geotechnical/materials testing of overlying soil and underlying limestone layers to measure the modulus of elasticity, the unconfined compressive strength and the shear strength (as appropriate) of the rock, of the crushed granulated rock samples generated during the coring process, and conduct grain size analyses and classifications of the interbedded sand (using the Unified Soil Classification System USCS/ASTM), all complementing and validating the site characterization data obtained from Standard Penetration Test (SPT) results given in typical geotechnical reports. One focus will be on determining the settlement parameters of the interbedded sand layers (both instantaneous and creep) through laboratory 1-D oedometer tests and establishing the relationship between creep strain rate and stress levels, the c_α/c_c ratio (where c_α and c_c are the secondary and primary compression indices, respectively), and the effect of fines content on the creep settlement parameters.

Another focus will be on determining whether the vibratory shear strain $\gamma = v_s/c_s$ induced in the granular material can trigger dynamic settlement. Here v_s is the particle velocity in the direction perpendicular to the wave motion and c_s the shear wave velocity. It has been proposed to quantify the hazard for dynamically induced creep by the shear strain (Fig, 9, Massarsch, 2000; Massarsch & Fellenius, 2014):

(1) γ <0.001%: particle rearrangements can't occur; no dynamic settlement.

(2) $\gamma \geq$ 0.01%: particle rearrangements and dynamic settlement possible.

(3) $\gamma \geq$ 0.1%: high likelihood for particle rearrangements and dynamic settlement.

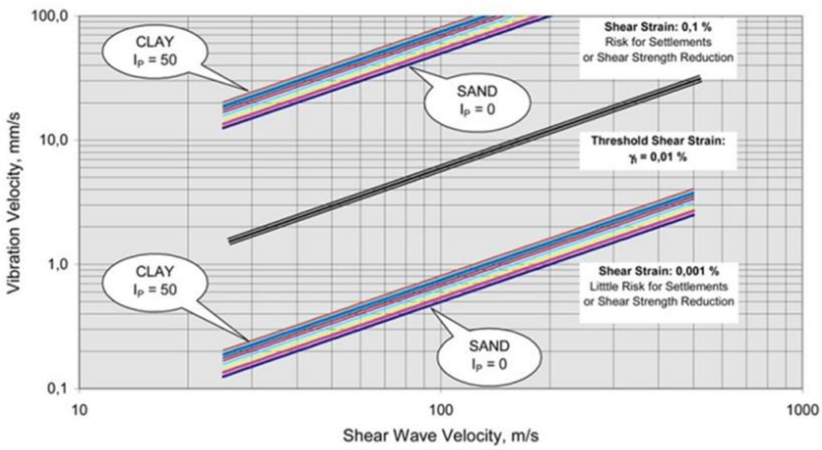

Figure 9: *Vibratory shear strain thresholds for particle rearrangement and settlement. Based on the measured/estimated shear wave velocity and measured vibration velocity we can assess the likelihood of settlement by particle rearrangement (from Massarch and Fellenius, 2014).*

Shear wave velocity can also be estimated from SPT N values (such empirical correlations are widely reported in the literature, e.g. Hussien and Karray, 2015), while construction vibration monitoring data measured during construction are available from the city government. Accordingly, Figure 9 can be used for assessing the hazard of dynamic settlement at a construction site.

Task 4 - Sustained and vibratory loading experiments in the laboratory

We will design and conduct long-term laboratory creep experiments on the retrieved rock cores with interbedded sands, determine the creep settlement parameters of the sand using oedometric loading (Levin, Vogt and Cudmani, 2019; McDowell and Khan, 2003) and under triaxial loading conditions (Kuwano and Jardine, 2002), characterize the rate of creep strain with stress levels, the c_α/c_c ratio, and the effect of fines content on the creep settlement parameters. Using a Shake Table (Fig. 11) we will conduct experiments to investigate creep and particle rearrangements due to applied vibrations in sand contained in a plexiglass chamber, with strains analyzed through digital image correlation techniques (Sobhan et al. 2008). Does creep continue after the vibrations have ceased? What determines the decay of the creep? The comparison of experiments under drained and undrained conditions will highlight the role of the pore fluids.

A top priority of this and the previous task is to find an explanation for the differences in observed settlement between Structures A, B and C (rapid, slow and very little settlement, respectively, see also task 6) in terms of the geotechnical properties of the sand (e.g. grain size distribution, fines content and/or sand layer thickness).

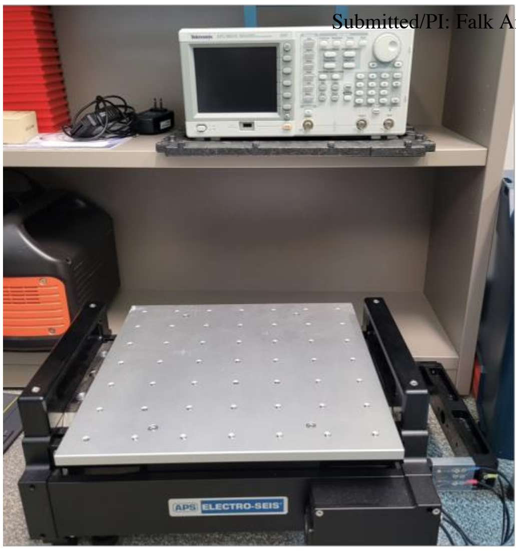

Figure 10. *Shake table in the FAU geotechnical laboratory. To investigate settlement under both static and dynamic loading we will place on the shake table a sand-filled tank with model footing foundations. We will conduct a series of experiments to investigate settlement as a function of the frequency and magnitude and of vibrations (peak particle velocity) and as function of the surface load.*

Task 5- Numerical modeling of settlement of granular material

After having established that settlement occurs in the embedded sand, we will conduct model simulations of compression creep. The deformation of granular media is complex because they can deform elastically like a solid but begin to flow like a fluid once a yield criterion is reached. The presence of pore fluids further complicates the matter (e.g. Zienkiewicz, et al., 1980, 1988).

We will use two different modeling approaches. First we will use discrete particle modeling approaches which are well suited for granular media. Second we will use a combination of discrete particle and continuum modeling. This modeling approach has been used successfully to simulate flow of granular matter through an hourglass (Kamrin & Koval, 2012), along inclined surfaces (Kamrin and Henan, 2015) and dynamic intrusion into granular matter (Agarwal et al., 2021).

Our strategy for this task is to first create a type experiment in the laboratory of vibration-triggered creep compression using idealized material (such as one or two-phase glass beads), labeled here for simplicity as “vibrations-triggered slow sinking building experiment”. We then will aim to reproduce this experiment using model simulations. We first will model static and dynamic loads independently and then use coupled loading models. Our hypothesis is that vibrations from construction achieve the yield criterion to initiate the fluid-like flow. The next step will be to run models with grain size distributions from the laboratory measurements under the presence of water.

We acknowledge that we have limited experience with this type of modeling, although the PI is a frequent user of finite element modeling approaches (e.g. Albino et al., 2018; Varugu & Amelung, 2021). Our approach will be to first establish the “vibrations-triggered slow sinking building experiment” and then to reach out to experts in modeling the flow of granular media. This project component will be the responsibility of the postdoctoral researcher.

Task 6 - Explaining the InSAR observations

Finally, we will use the geotechnical information retrieved from the sediment cores to determine the settlement of the group pile foundation systems both analytically (conventional geotechnical computations) and numerically. We will obtain vibration information and foundation designs from the local building departments (in Miami-Dade county it is public information). Can the InSAR-observed settlement at structures A, B and C be explained by a unifying model with varying model parameters reflecting lateral variations in the subsurface and/or creep parameters? Particularly insightful will be the comparison of the sediment cores and creep properties between structure B and C. Both structures were built in 2016. Structure A subsidence rapidly until 2018 (Fig. 3) whereas not Structure C does not show any significant subsidence. Is this difference caused by variations in the local geology (e.g. absence of sand layer under Structure C), construction practices (less vibrations at Structure C) or something else such as the pre-construction consolidation state of the soil?

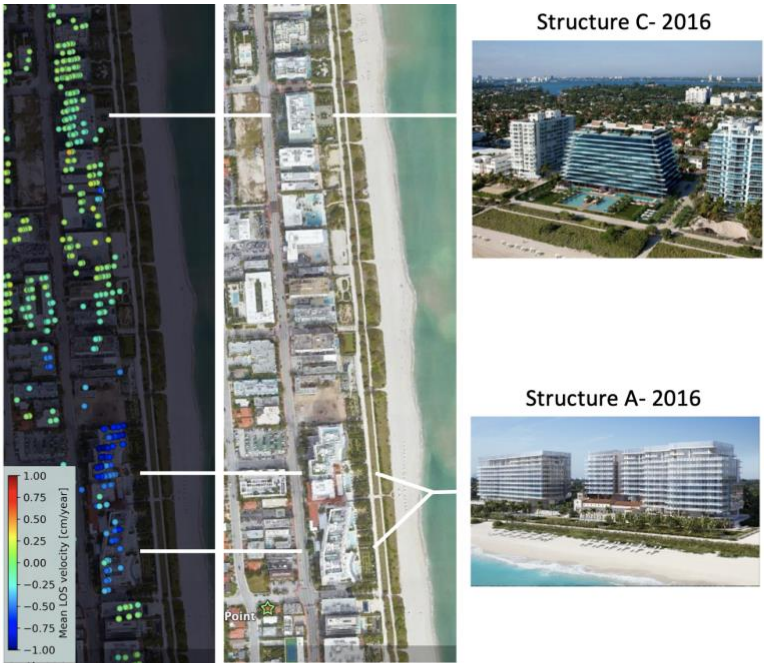

Fig. 11. *Difference in settlement between Structures A and C, both constructed in 2016. In contrast to Structure A, Structure C shows hardly any subsidence. We hypothesize this is due to the consolidation state of the soil at the time of construction. Structure C was built on the site of a 12-story building while Structure A was built on the site of a 1-story building. This suggests that the soil was already fully consolidated when Structure C was constructed.*

We also will use the learned lessons to investigate settlement in the vicinity of the collapsed condo. In 2016 the area was subjected to vibrations from sheet pile-driving for the construction of a new 20-story high-rise to the south (Structure D). Preliminary InSAR data show that the new tower and its surroundings is subsiding at a rate of ~1 cm/yr in LOS direction (1.4 cm/yr vertical) since at least 2019 (Fig. 12B,C). A previous study found for this area ~2 mm/yr subsidence in the 1990s (Fiaschi & Wdowinski, 2019). Geotechnical drilling found a five-feet thick sand layer at 67 feet depth (Fig. 12D; below the tip of the piles), suggesting slow creep compression of this layer.

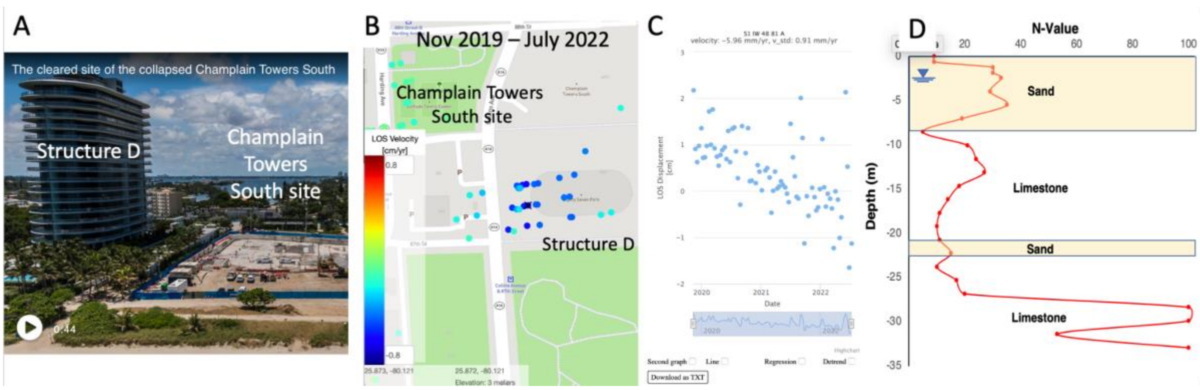

Fig. 12. *(A) Site of Structure B and the Champlain Towers South condominium in Surfside, FL, that collapsed in June 2021 (see Fig. 1). (B) InSAR velocity and (C) displacement time series showing 2 cm LOS displacement (2.8 cm subsidence) of the adjacent Structure D since its completion in 2019. (D) Lithology depth section and Standard Penetration Test (SPT) N-values. We hypothesize that slow creep in the sand layer at 22 m depth is responsible for the observed subsidence.*

7. Expected results and deliverables

- Characterization of construction-induced subsidence of young coralline limestone for several locations around the world using InSAR
- Sediment cores, borehole logs and geotechnical parameters for three Miami Beach subsidence hotspots.
- Identification of the settlement mechanism: creep of limestone or creep of sand.
- Approach to predict settlement in sand-containing coralline limestone environments
- Type laboratory experiment for a slowly sinking building in sand.
- Identification of applicable physics; numerical simulation of the processes.

8. Intellectual merit

The proposed project investigates the puzzling observation of long-term settlement of young coralline limestone. The project will answer three fundamental questions: (1) Is the long-term settlement of young limestone due to creep of the rock matrix or due to creep compression of the interbedded sand? (2) Is the long-term settlement driven by the combination of sustained loading by the new structure and by vibrational loading from construction activities? (3) How do granular media respond to the combination of sustained and vibrational loading?

9. Broader impacts

Understanding the settlement of young coralline limestone will benefit the Miami-Fort Lauderdale metropolitan area, the second largest residential high-rise construction market in the nation. The project could lead to new ordinances on geotechnical exploration and to limits on the peak particle velocity (PPV) for vibrations associated with construction. Furthermore, the project will introduce the InSAR technique to the local construction and regulatory communities as a new tool to monitor settlements and the structural safety of buildings. Finally, the scientific understanding of coastal subsidence will calm the minds of residents of coastal high-rises concerned about the structural safety of the buildings they live in.

Broader impact for education. We will develop a teaching module for InSAR-measured settlements based on the results of this project for undergraduate and graduate courses taught by Co-PIs (and non Co-PIs) in the Civil, Structural and Architectural Engineering departments at both FAU and UM (FAU courses such as CEG 4012: Foundation Engineering; CEG 6105: Advanced Foundation Engineering and Capstone Senior Design Series (CGN 4803C and 4804C). For example, the Foundation Engineering course involves a series of design tasks including settlement analysis. Settlement of deep foundations resting on sand-layer containing coralline limestone will be incorporated as design projects into this course. One student assignment will be to retrieve subsidence data from the OPERA website (see sect. 13) and to explain them using settlement calculations. This will directly contribute to the career readiness of new graduates, many of which will enter the South Florida engineering design/construction industry. Many of the students in the UM MSc program are already employed, ensuring the rapid spread of the new knowledge in the industry.

10. Outreach

The proposed project has two outreach components.

Engagement of local stakeholders. The success of our project requires the support of local stakeholders (municipalities including building department officials, Homeowner Associations, property managers) so that we will be granted permission for the drilling of the sediment cores on public land near the structures of interest. To engage the stakeholders we will convene at the beginning of the project an information session in the Northern Miami Beach area (preferably in the Surfside or the Bal Harbour City Hall). Online recordings of the presentations are a powerful tool to further disseminate the information. The research results will be shared in a follow-up session at the end of the project.

From research to applications. We will engage in a dialogue with the South Florida building department community to determine how their daily practice could benefit from our project, including changes to guidelines for geotechnical studies and construction inspections. Low hanging fruits include to require optical borehole logs for geotechnical reporting, and online dissemination of the reports and vibration information by the City. We will start this dialogue in year two of the project with a series of seminars to building department officials on preliminary research results. Although not a priority of this project we will offer to provide an assessment on the value of high-resolution InSAR for 30-year building recertification. After the condo collapse the structural safety of aging condos is a top concern for the municipalities.

11. Possible next steps

A possible – although unlikely – outcome of this project is that proposal hypothesis 1 is proven wrong, and that subsidence is the result of creep of the limestone. This then raises the question why limestone creeps under the load of a 12-story building. The strength of the limestone is not affected by saltwater intrusion from the rising seas because, as noted above, limestone is chemically stable in saltwater. A possible mechanism to weaken young limestone are physicochemical processes by microbes striving in the alternating salt- and freshwater environment. The contribution of biological processes to carbonate diagenesis is a research topic in the PI's department (Diaz et al, 2022).

12. Related projects and outlook

NASA's OPERA project. The proposed project will prepare the South Florida construction community to routinely updated InSAR data of the NASA/Jet Propulsion Laboratory (JPL) Observational Products for End-Users from Remote sensing Analysis (OPERA) project available in 2025. This project is led by previous UM graduates now employed at JPL (Fattahi, Yunjun, Mirzaee).

13. Project team and management

Project Team. The PIs of this project are Falk Amelung, Professor in the Dept. of Marine Geosciences at the University of Miami (UM) Rosenstiel School of Marine, Atmospheric and Earth Sciences (RSMAES), and Khaled Sobhan, Professor in the Dept. of Civil, Environmental and Geomatics Engineering at the College of Engineering at Florida Atlantic University (FAU) in Boca Raton, FL. Co-PI is Esber Andiroglu, Assoc. Professor in the Dept. of Civil and Architectural Engineering of the University of Miami. Amelung is an InSAR expert with >20 years of experience studying land subsidence, active volcanoes and tectonics with InSAR. Sobhan is a geotechnical engineer and the director of the FAU geotechnical laboratory. Andiroglu is a mechanical/architectural engineer specialized in sustainable design and construction with expertise in coastal resilience. Overall, Amelung will be responsible for the geodetic and geologic aspects of the project, Sobhan for the geotechnical aspects, and Andiroglu for outreach to local stakeholders. Amelung and Sobhan will oversee a postdoctoral researcher at UM (Dr. Aziz Zanjani) and a Doctoral student at FAU, respectively, who will conduct different aspects of the laboratory testing, experiments. The small distance between RSMAES and FAU (one hour drive) facilitates effective collaboration. Aziz Zanjani will be responsible for the settlement and granular matter modelling. Amelung will be responsible for the reporting to the NSF.

Collaborators. Our collaborator is Dr. Antonio Nanni, Chair of UM's Dep. of Civil & Arch. Engineering, who will help establish links with the local construction community.

14. Results from prior NSF support

Award ID 1838385: "Collaborative Research: Geodetic and seismic observations of volcanic unrest at Sierra Negra volcano, Galapagos Island", \$50,000, 7/1/2018 -6/30/2019 PI; co-PI: Peter LaFemina.

Intellectual merit and broader impacts: This proposal supported the repair and upgrade of the GNSS network of Sierra Negra volcano, and a photogrammetric survey of the trapdoor system. Publications: Bell et al. (2021), Gregg et al., (2022).

15. Proposed schedule

Q1: Outreach session; sediment core collection; low-res. InSAR in South Florida.

Q2: Laboratory geotechnical testing; high-res. InSAR in South Florida; explain InSAR observations.

Q3: Laboratory experiments; InSAR for Jeddah; discrete particle simulations.

Q4: Combined discrete particle and continuum simulations

References Cited

Albino, F. , Amelung, F., & Gregg, P. (2018). The role of pore fluid pressure on the failure of magma reservoirs: Insights from Indonesian and Aleutian arc volcanoes. *Journal of Geophysical Research: Solid Earth*, *123*. https://doi.org/10.1002/2017JB014523

Ansari, H., De Zan, F., Bamler, R., 2018. Efficient Phase Estimation for Interferogram Stacks. IEEE Trans. Geosci. Remote Sens. 56, 4109–4125. https://doi.org/10.1109/TGRS.2018.2826045

Ansari, H., De Zan, F., Bamler, R., 2017. Sequential Estimator: Toward Efficient InSAR Time Series Analysis. IEEE Trans. Geosci. Remote Sens. https://doi.org/10.1109/TGRS.2017.2711037

Anselmetti, F.S. and Eberli, G.P., 1993. Controls on sonic velocity in carbonates. *Pure and Applied geophysics*, *141*(2), pp.287-323.

Baud, P., Vinciguerra, S., David, C., Cavallo, A., Walker, E., & Reuschlé, T. (2009). Compaction and failure in high porosity carbonates: Mechanical data and microstructural observations. *Pure and Applied Geophysics*, *166*(5), 869-898.

Cunningham K., (2004) Application of ground-penetrating radar, digital optical borehole images, and cores for characterization of porosity hydraulic conductivity and paleokarst in the Biscayne aquifer, southeastern Florida, USA, *Journal of Applied Geophysics*, 55, 61-76

Cunningham, K. J., Sukop, M. C., Huang, H., Alvarez, P. F., Curran, H. A., Renken, R. A., & Dixon, J. F. (2009). Prominence of ichnologically influenced macroporosity in the karst Biscayne aquifer: Stratiform "super-K" zones. *Geological Society of America Bulletin*, *121*(1-2), 164-180.

Cunningham, K. J., & Florea, L. J. (2009). The Biscayne aquifer of southeastern Florida. *Caves and Karst of America*, *2009*, 196.

Cunningham, K.J., Walker, C., and Westcott, R.L., 2012, Near-surface, marine seismic-reflection data define poten- tial hydrogeologic confinement bypass in the carbonate Floridan aquifer system, southeastern Florida: Society of Exploration Geophysicists Annual Meeting, Las Vegas, NV, 6 p., accessed October 3, 2014 at http://library.seg.org/doi/ abs/10.1190/segam2012-0638.1.

Cunningham, K. J., Dixon, J. F., Westcott, R. L., Norgard, S., & Walker, C. (2018). *Three-dimensional seismic characterization of karst in the Floridan aquifer system, southeastern Miami-Dade County, Florida* (No. 2018-5117). US Geological Survey.

D'Appolonia, D. J., D'Appolonia, E., & Brissette, R. F. (1968). Settlement of spread footings on sand. *Journal of the Soil Mechanics and Foundations Division*, *94*(3), 735-760.

Diaz, Mara R., Gregor P. Eberli, and Ralf J. Weger. "Indigenous microbial communities as catalysts for early marine cements: an in vitro study." *The depositional record*(2022).

Emadali, L., Motagh, M. and Haghighi, M.H., 2017. Characterizing settlement of the Masjed-Soleyman embankment dam, Iran, using TerraSAR-X radar. *Engineering structures*, *143*, pp.261-273.

Feld, J., and Carper, K. (1997). *Construction failure*, 2nd Ed., Wiley, New York.

Ferretti, A., Fumagalli, A., Novali, F., Prati, C., Rocca, F., Rucci, A., 2011. A new algorithm for processing interferometric data-stacks: SqueeSAR, in: IEEE Transactions on Geoscience and Remote Sensing. https://doi.org/10.1109/TGRS.2011.2124465

Fiaschi, S., and S. Wdowinski. "Local land subsidence in Miami Beach (FL) and Norfolk (VA) and its contribution to flooding hazards." *Ocean & Coastal Management* 187 (2020): 105078.

Fornaro, G., Verde, S., Reale, D., Pauciullo, A., 2015. CAESAR: An approach based on covariance matrix decomposition to improve multibaseline-multitemporal interferometric SAR processing. IEEE Trans. Geosci. Remote Sens. 53, 2050–2065. https://doi.org/10.1109/TGRS.2014.2352853

Gregg, P. M., Zhan, Y., Amelung, F., Geist, D., Mothes, P., Koric, S., & Yunjun, Z. (2022). Forecasting mechanical failure and the 26 June 2018 eruption of Sierra Negra Volcano, Galápagos, Ecuador. Science Advances, 8(22).

Guarnieri, A.M., Tebaldini, S., 2008. On the Exploitation of Target Statistics for SAR Interferometry Applications. IEEE Trans. Geosci. Remote Sens. 46, 3436–3443. https://doi.org/10.1109/TGRS.2008.2001756

Guarnieri, A.M., Tebaldini, S., 2007. Hybrid Cramér-Rao bounds for crustal displacement field estimators in SAR interferometry. IEEE Signal Process. Lett. 14, 1012–1015. https://doi.org/10.1109/LSP.2007.904705

Hunt, R.E. (1986). *Geotechnical Engineering Techniques and Practices*, McGraw-Hill Book Company, New York.

Hussien, M. N., & Karray, M. (2015). Shear wave velocity as a geotechnical parameter: an overview. *Canadian Geotechnical Journal*, *53*(2), 252-272.Kaminetzky, D. (1991). *Design and construction failures: Lessons from forensic investigations*, McGraw-Hill, New York

Kuwano, R. and Jardine, R. J. (2002). "On measuring creep behavior in granular materials through triaxial testing," *Canadian Geotechnical Journal*, Vol. 39, pp. 1061-1074.

Kamrin, K. and Koval, G., 2012. Nonlocal constitutive relation for steady granular flow. *Physical review letters*, *108*(17), p.178301.

Kamrin, K. and Henann, D.L., 2015. Nonlocal modeling of granular flows down inclines. *Soft matter*, *11*(1), pp.179-185.

Lacy, H. S., & Gould, J. P. (1985, October). Settlement from pile driving in sands. In *Vibration Problems in Geotechnical Engineering* (pp. 152-173). ASCE.

Levin, F., Vogt, S., and Cudmani, R. (2019). "Time-dependent behavior of sand with different fines content under oedometric loading," *Canadian Geotechnical Journal*, Vol. 56, pp. 102-115.

Ma, P., Lin, H., Wang, W., Yu, H., Chen, F., Jiang, L., Zhou, L., Zhang, Z., Shi, G. and Wang, J., 2021. Toward Fine Surveillance: A Review of Multitemporal Interferometric Synthetic Aperture Radar for Infrastructure Health Monitoring. *IEEE Geoscience and Remote Sensing Magazine*.

Mirzaee, S. Falk Amelung, Heresh Fattahi (2022), Non-linear Phase Linking using joined Distributed and Persistent Scatterers, *Computer & Geosciences*, in press.

Massarsch, K. R., & Fellenius, B. H. (2008). Ground vibrations induced by impact pile driving. International Conference on Case Histories in (2008) - Sixth International Conference on Case Geotechnical Engineering ; https://core.ac.uk/download/pdf/229080669.pdf

Massarsch, K. R., & Fellenius, B. H. (2014). Ground vibrations from pile and sheet pile driving Part 1-building damage. Proceedings of the DFI- EFFC International Conference on Piling and Deep Foundations, Stockholm, May 21-23, pp. 131-138.

McDowell, G. R. and Khan, J. J. (2003). "Creep of granular materials," *Granular Matter 5*, Springer-Verlag 2003, pp. 115-120; DOI 10.1007/s10035-003-0142-x.

Milillo, P., Bürgmann, R., Lundgren, et al. (2016). Space geodetic monitoring of engineered structures: The ongoing destabilization of the Mosul dam, Iraq. *Scientific reports*, *6*(1), pp.1-7.

Nguyen, T., McVay, M., Song, X., Herrera, R., Wasman, S. and Wang, K., 2019. Strength Envelopes of Florida Carbonate Rocks near Ground Surface. *Journal of Geotechnical and Geoenvironmental Engineering*, *145*(8), p.04019034.

Parkinson, R. W. (2021). Speculation on the role of sea-level rise in the tragic collapse of the Surfside condominium (Miami Beach, Florida USA) was a bellwether moment for coastal zone management practitioners. *Ocean & Coastal Management*, *215*, 105968.

Parsons, T. (2021). The weight of cities: Urbanization effects on Earth's subsurface. *AGU Advances*, *2*(1), e2020AV000277.

Perissin, D., 2010: https://www.sarproz.com/building-collapse/

Selvakumaran, S., Rossi, C., Marinoni, A. et al., 2020. Combined InSAR and terrestrial structural monitoring of bridges. *IEEE Transactions on Geoscience and Remote Sensing*, *58*(10), pp.7141-7153.

Siskind, D.E. (2000). *Vibration from Blasting*. ISEE, Cleveland. *Standard Specifications for Road and Bridge Construction*. (2013). Florida Department of Transportation.

Sobhan, K., Reddy, D. V., & Genduso, M. J. (2008). Permanent strain characterization in granular materials using repeated load triaxial tests and digital image correlation (DIC) technique. In *GeoCongress 2008: Characterization, Monitoring, and Modeling of GeoSystems* (pp. 181-188).

Svinkin, M. R. (2004). Minimizing construction vibration effects. *Practice periodical on structural design and construction*, *9*(2), 108-115.

Svinkin, M. R. (2008, August). Soil and structure vibrations from construction and industrial sources. In *Proceedings of international conference on case histories in geotechnical engineering, Arlington, VA, USA*.

Varugu, B., Amelung, F. Southward growth of Mauna Loa's dike-like magma body driven by topographic stress. *Sci Rep* **11,** 9816 (2021). https://doi.org/10.1038/s41598-021-89203-6

Youd, T.L. (1977). "Packing changes and liquefaction susceptibility." Journal of the Geotechnical Engineering Division, Proceedings of the American Society of Civil Engineers, Vol. 103, No. GT8, August 1977, pp 918-92

Yunjun, Z., Fattahi, H., & Amelung, F. (2019). Small baseline InSAR time series analysis: unwrapping error correction and noise reduction. Computers & Geosciences, 104331.

Zienkiewicz, O. C., Chang, C. T., & Bettess, P. (1980). Drained, undrained, consolidating and dynamic behaviour assumptions in soils. *Geotechnique*, *30*(4), 385-395.

Zienkiewicz, O. C., Paul, D. K., & Chan, A. (1988). Unconditionally stable staggered solution procedure for soil-pore fluid interaction problems. *International Journal for Numerical Methods in Engineering*, *26*(5), 1039-1055.