NCST Investigation of the Champlain Towers South Collapse

Cross-Project Panel Theme 3: Failure Hypotheses

Glenn Bell, Fahim Sadek, Georgette Hlepas, Scott Jones, James Harris, Youssef Hashash

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

CTS Investigation: Failure Hypotheses

NIST

Failure Hypotheses

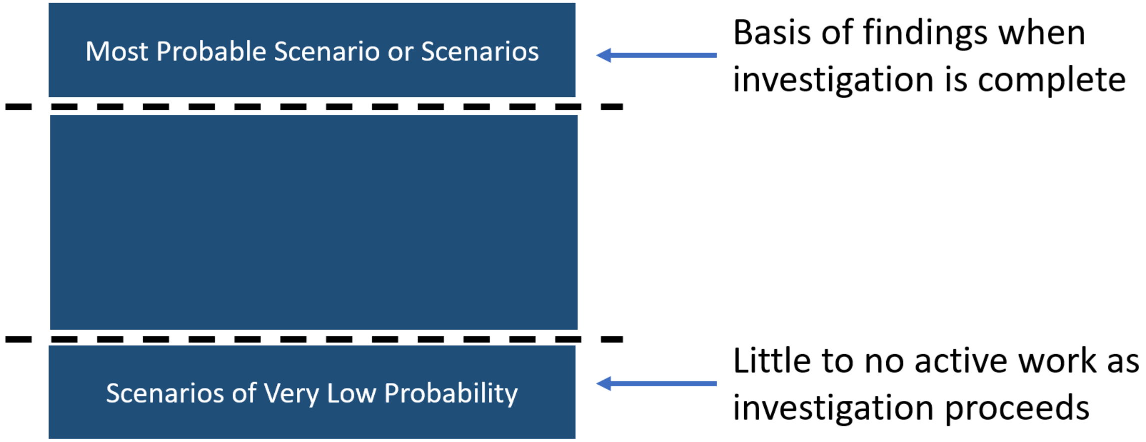
A failure hypothesis is an investigative supposition about **where and how the failure occurred** with likely **causes and contributors**.

(Similar terms: *Potential Failure Scenario, Failure Theory, Failure Supposition, Potential Failure Mode*)

- ❖ There are hypotheses about the **initiation** of the failure and the **progression** of the global collapse.
- ❖ The investigation holds about **two-dozen initiation hypotheses**.
  - ➢ Each hypothesis may have many potential initiation points.
    - ➢ Collectively there are **hundreds of possible failure initiation points** in the structural and geotechnical elements.

CTS Investigation: Failure Hypotheses

Assess the probability of each hypothesis



List of Hypotheses Ordered by Probability, High to Low

CTS Investigation: Failure Hypotheses

NIST

Assess the probability of each hypothesis

- Collect and analyze evidence of all types
- Perform analyses and tests

Most Probable Scenario or Scenarios

Basis of findings when investigation is complete

Scenarios of Very Low Probability

Little to no active work as investigation proceeds

List of Hypotheses Ordered by Probability, High to Low

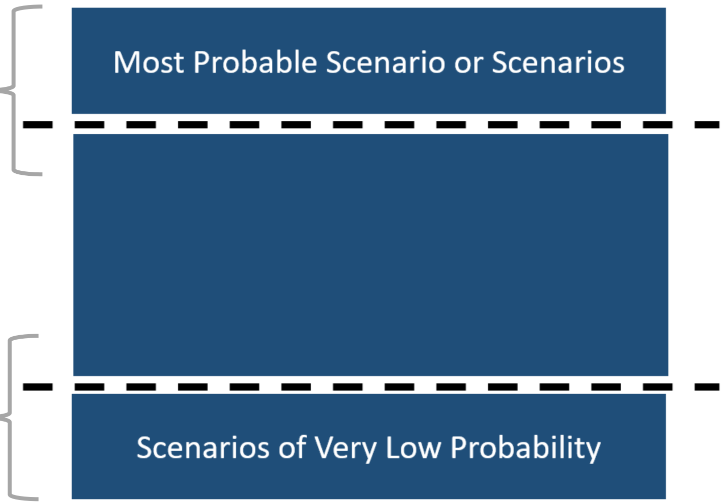
Evidence For *vs.* Evidence Against

CTS Investigation: Failure Hypotheses

1. Introduction
   Glenn Bell

2. Examples of hypotheses currently assessed as higher likelihood
   - ***Pool Deck Slab-Column Connections***
     Fahim Sadek, Georgette Hlepas, Scott Jones
   - ***Columns Along South Edge of Tower***
     Jim Harris, Scott Jones

3. Examples of hypotheses currently assessed as lower likelihood
   - ***Formation of Karstic Features and Differential Settlement***
     Youssef Hashash
   - ***Tower Columns Above the First Story***
     Glenn Bell



List of Hypotheses Ordered by Probability, High to Low

Pool Deck Slab-Column Connections

Fahim Sadek, Georgette Hlepas, Scott Jones

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CTS Investigation: Pool Deck Slab-Column Connections

Description: Failure of the connection between slab and column, causing the slab around the column to drop. Failure may be preceded by cracking, large movements, and yielding or fracture of reinforcement in the slab. Such failure can initiate cascading failures through the entire slab.

Objective: To examine the likelihood that partial collapse of the CTS building initiated at a pool deck slab-to-column connection

Source: NIST

CTS Investigation: Pool Deck Slab-Column Connections

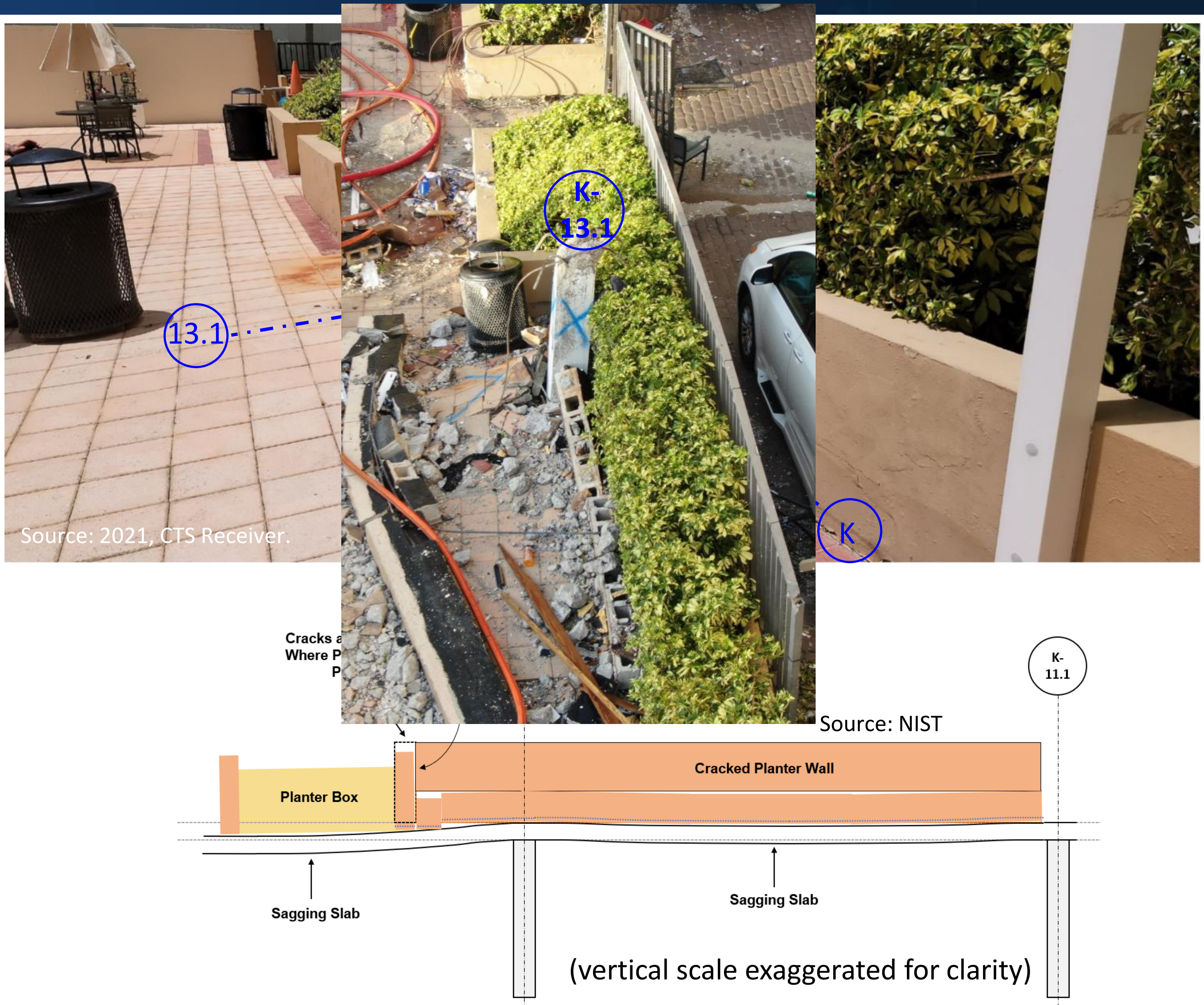
NIST

Evidence for:

- Damage to planter boxes observed prior to collapse
- Slab failure and sagging pattern
- Corrosion
- Exposure of slab to water and chlorides
- Parking Garage Ramp and 87 Park NW videos showing that collapse of the pool deck slab preceded tower collapse
- Knocking noises reported by some residents prior to collapse may indicate fracture of reinforcement
- Eyewitness accounts indicating location and extent of failure of pool deck slab

Evidence against:

- Eyewitness accounts of noises from above the 1st story prior to the collapse of the pool deck, tower vibrations, and cracking prior to tower collapse



CTS Investigation: Pool Deck Slab-Column Connections

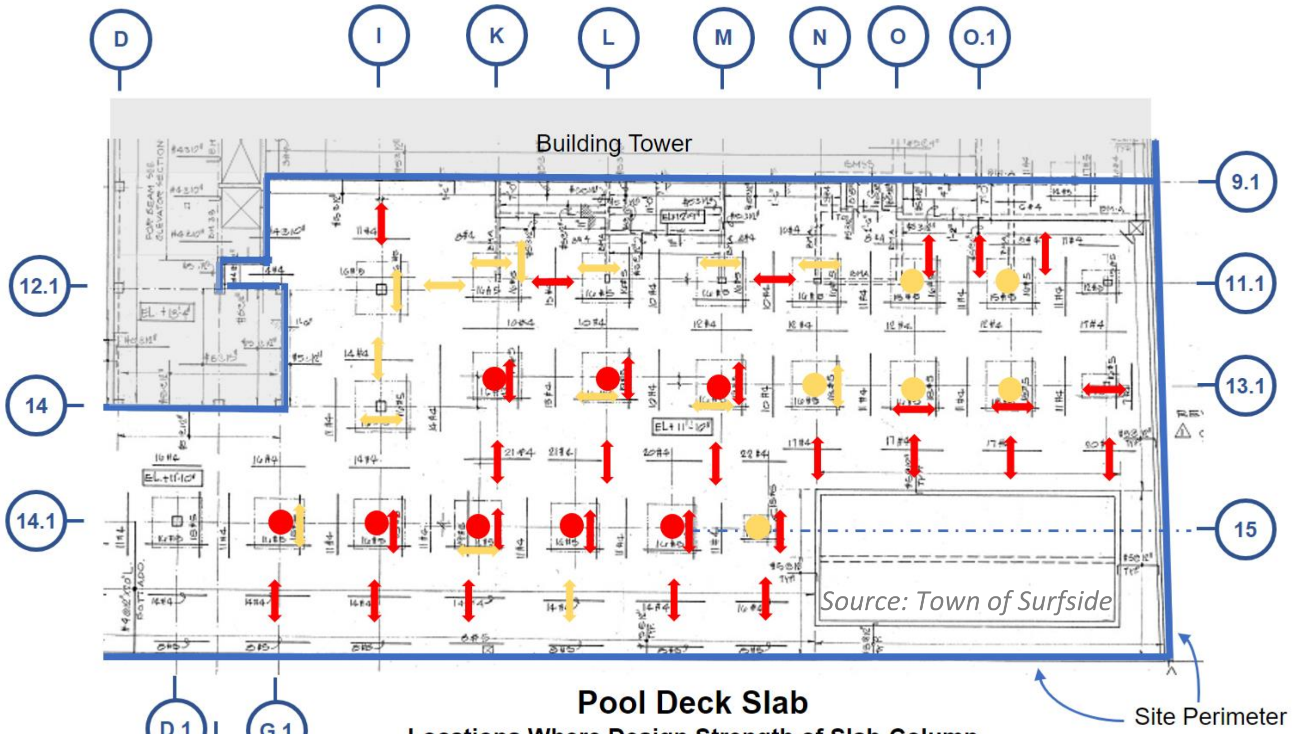
Potential Causes and Contributors:

(1) Design and construction factors

- *Design deficiencies in pool deck:* High DCRs (demand/capacity ratios) in connections, in particular, along Grid Lines 13.1 and 14.1
- *Deviations in pool deck construction from design documents:* Lower top bars, wider top bar spacing, 25 % of reinforcing bars not passing over columns
- *Added super-imposed dead loads:* Heavier planters, added fill and paving

(2) Material degradation effects

- *Effects of corrosion*
  - Analysis shows that bottom reinforcement was highly stressed under dead loads, thus corrosion-induced loss of cross section could lead to failure/fracture of these bars.
  - Loss of or reduction in flexural capacity at midspan increases reinforcing bar stresses and strains in top bars over adjacent columns. Top bars are also susceptible to corrosion and could yield or fail.
  - This increases slab movements and crack width in the critical shear perimeter, eventually leading to a punching failure.
- *Possible concrete degradation*



Pool Deck Slab
Locations Where Design Strength of Slab-Column Connections and Slab Flexure Do Not Meet Original Code (DCR > 1.0)

Figure Legend

	Location of Understrength	
Degree of Understrength	slab-column connections	slab flexure
severe	● (red)	↔ (red)
moderate	● (yellow)	↔ (yellow)

Source of underlying original design drawing: Town of Surfside

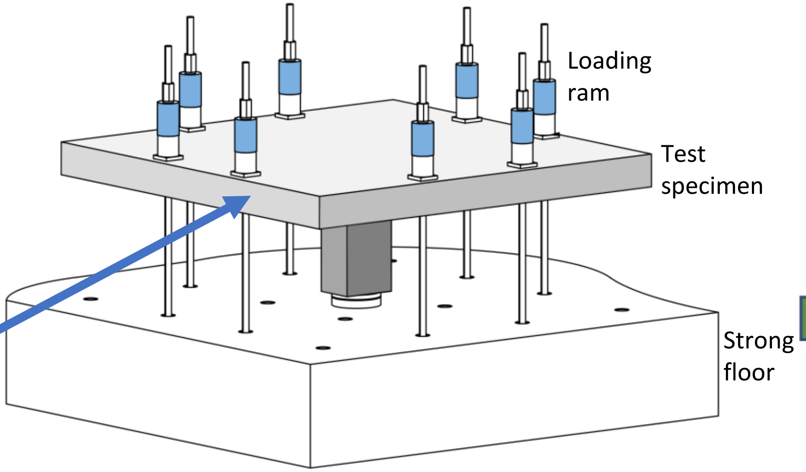
PRELIMINARY ANALYSIS RESULTS

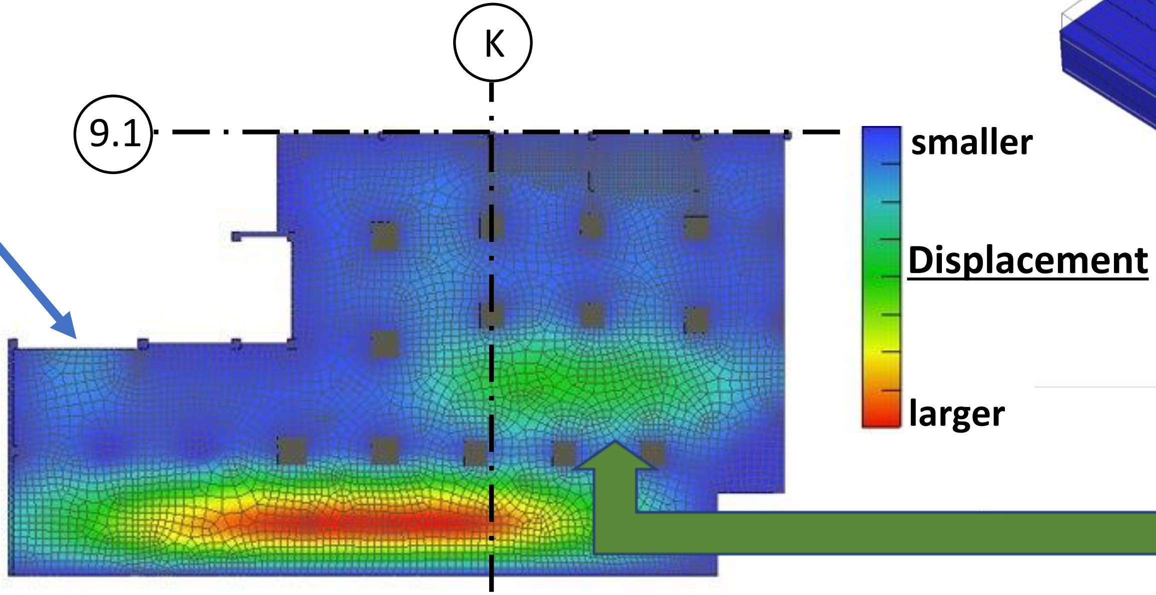
CTS Investigation: Pool Deck Slab-Column Connections

Approach:

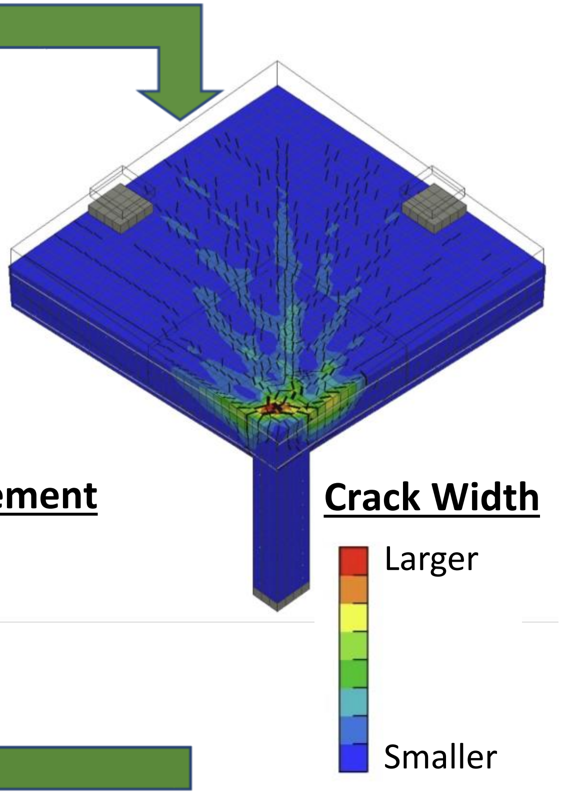
- Examine available evidence
- Evaluate materials degradation
- Conduct structural testing
- Perform computational modeling

Source: 2021, CTS Receiver
Annotated by NIST



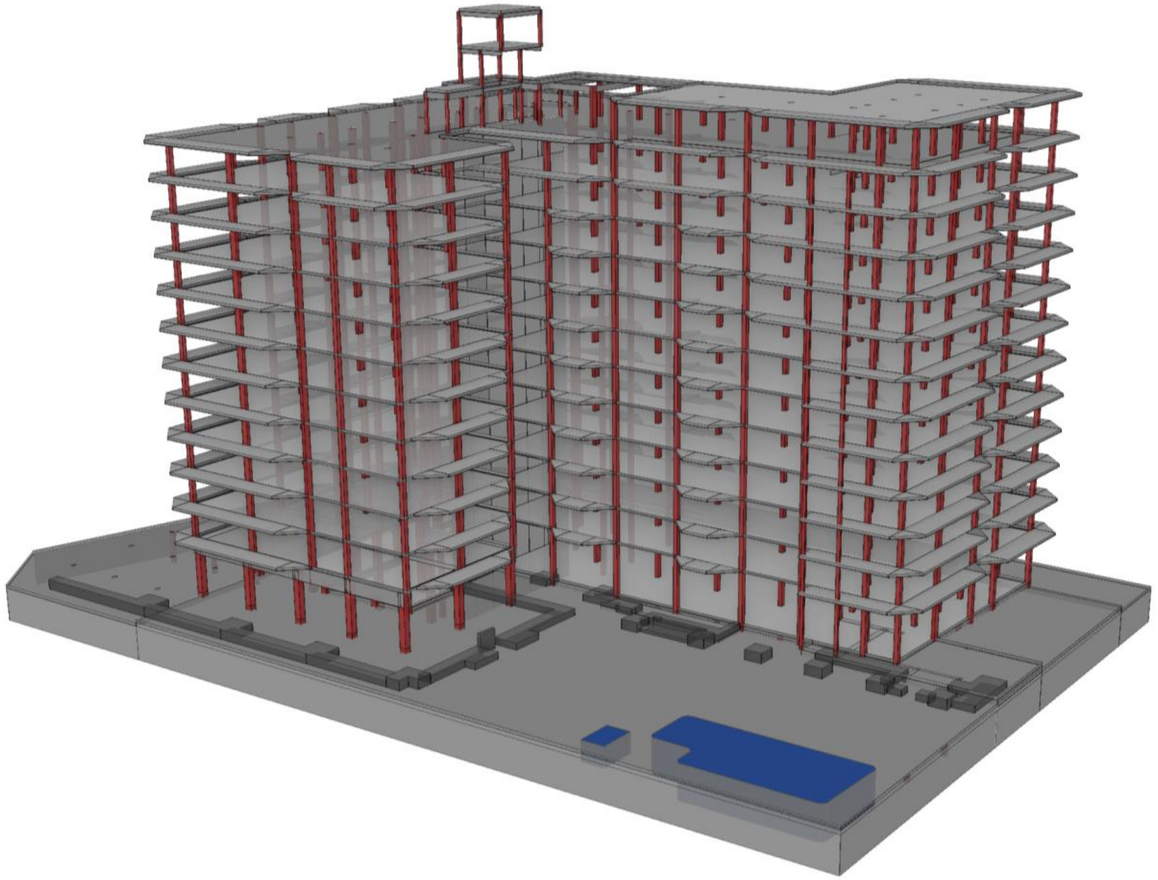


Source: NIST using ATENA software



Source: NIST using
ATENA software

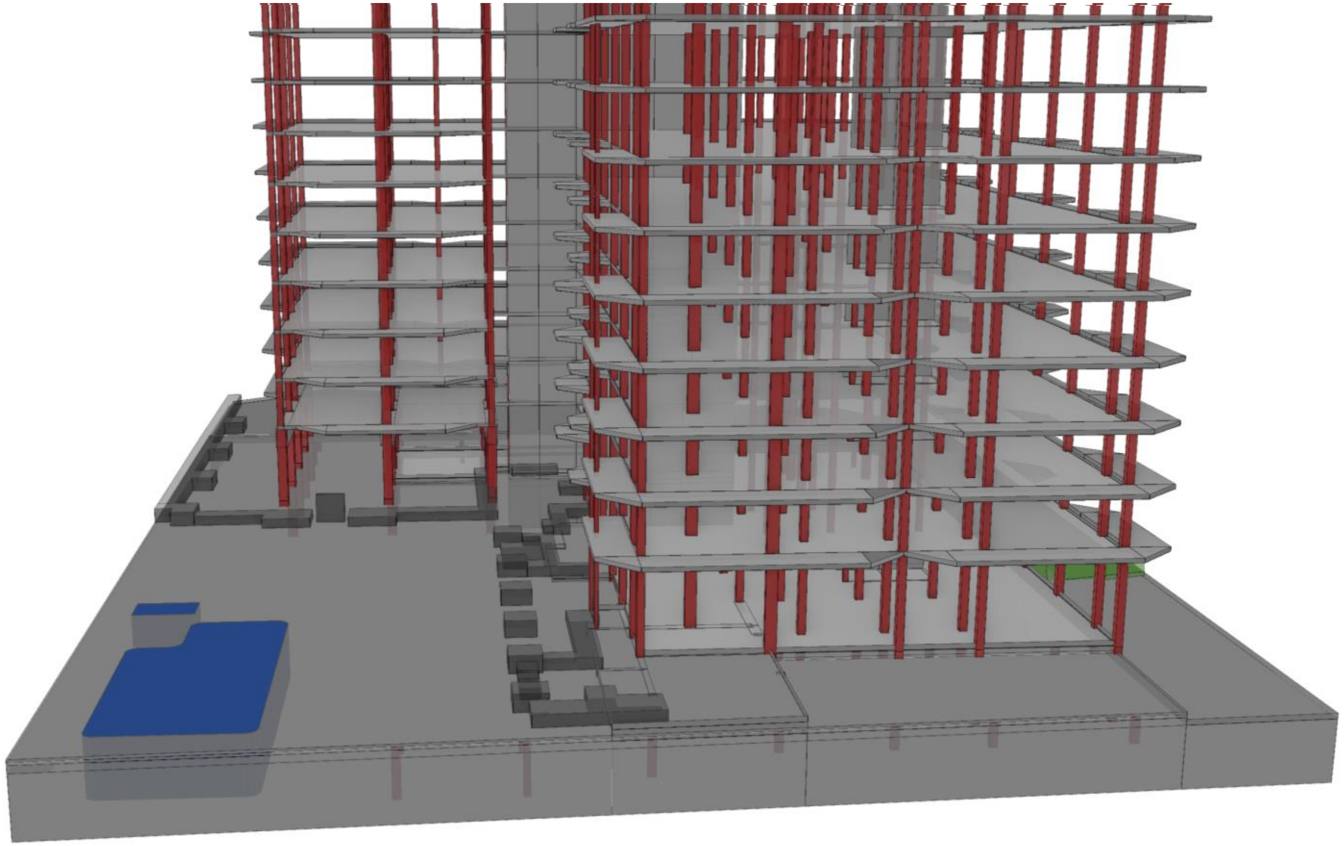
Putting the Puzzle Pieces Together



Relating the Information

- **Videos & Photos**
- **Reports**
- **Drawings**
- **Test results**
- **Measurements**

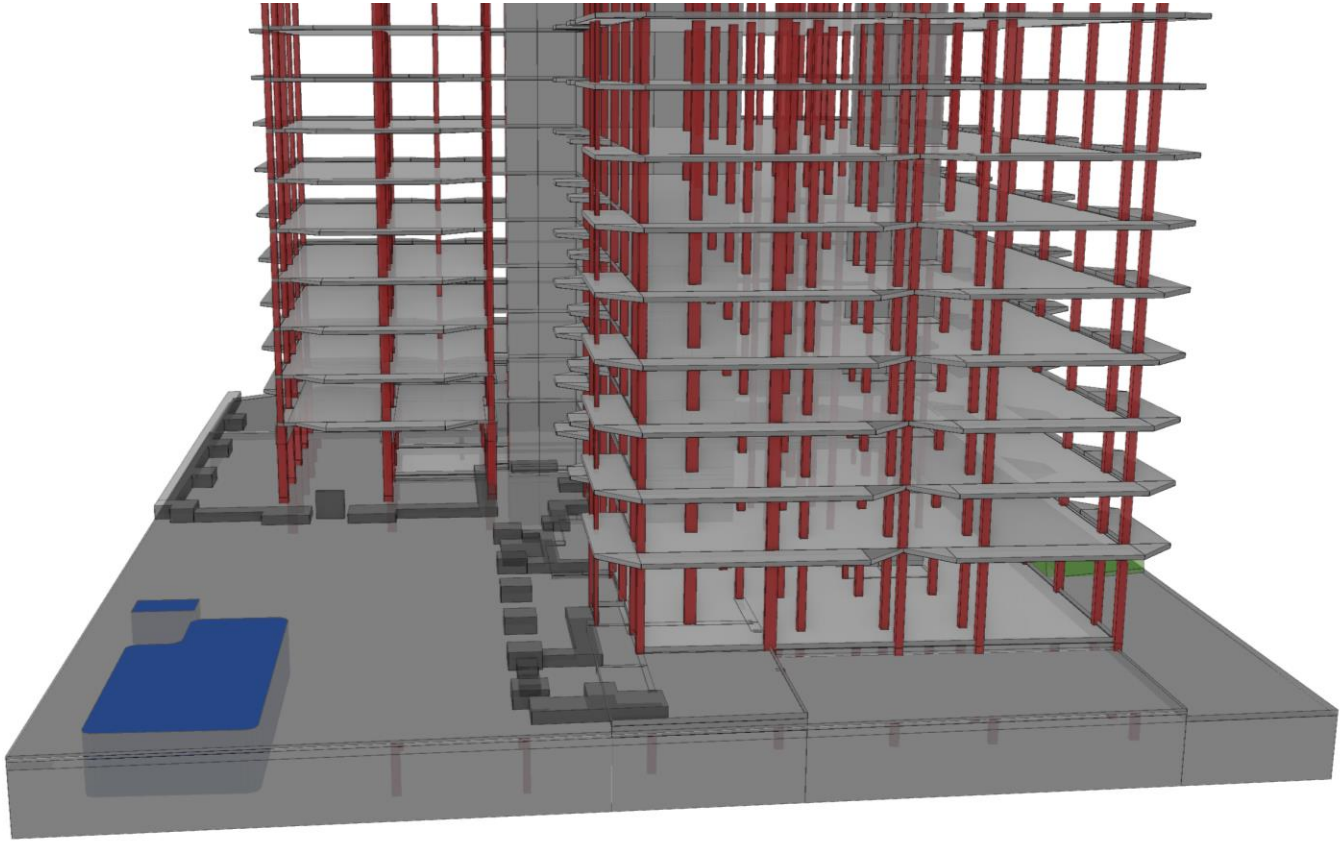
Failure of Pool Deck Slab-Column Connections



Pre-Collapse Geospatial Model

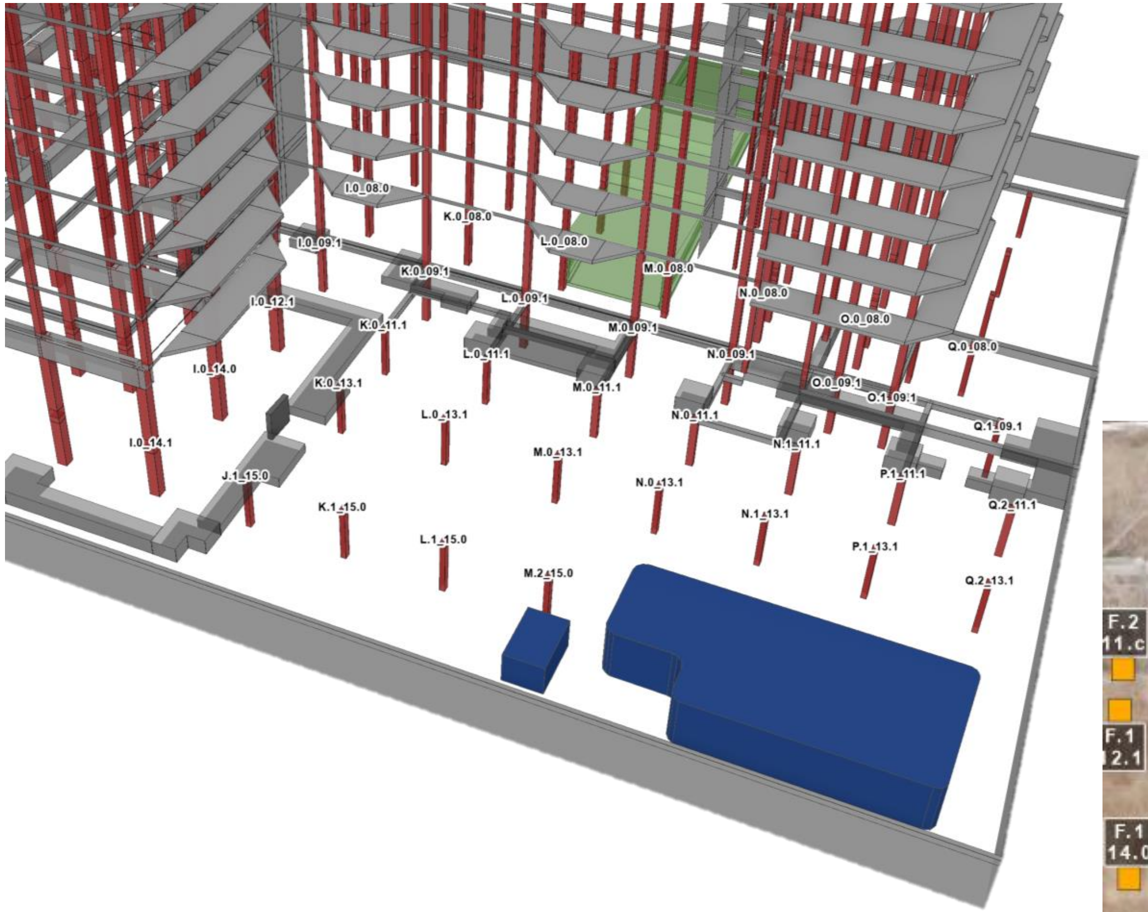
Post-Collapse Photo

Data Related to Pool Deck Slab-Column Connections

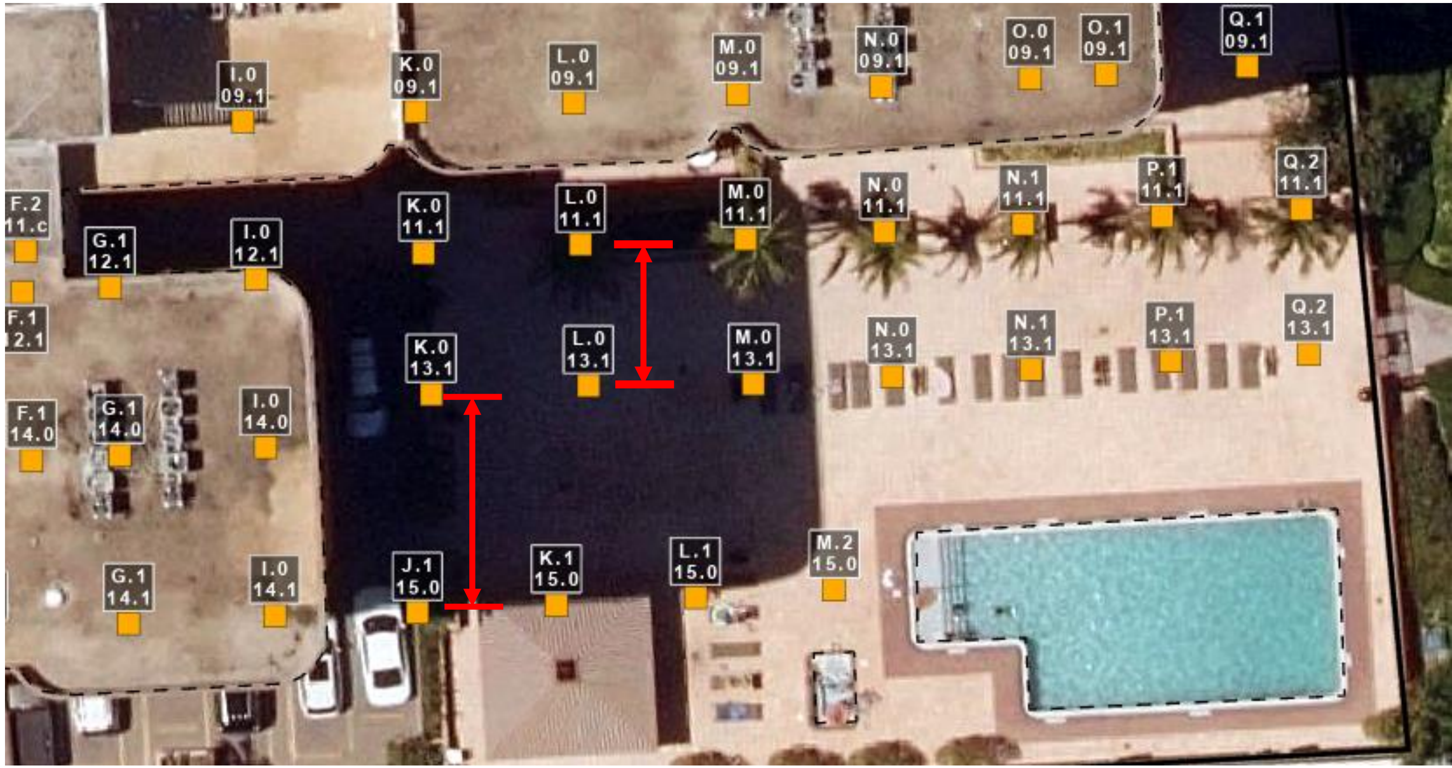


- **Columns**
- **Pool deck**
- **Planters**

Column Locations and Spans



Source: Miami Dade County Open Data Hub 2017 Aerial (background); NIST Annotation

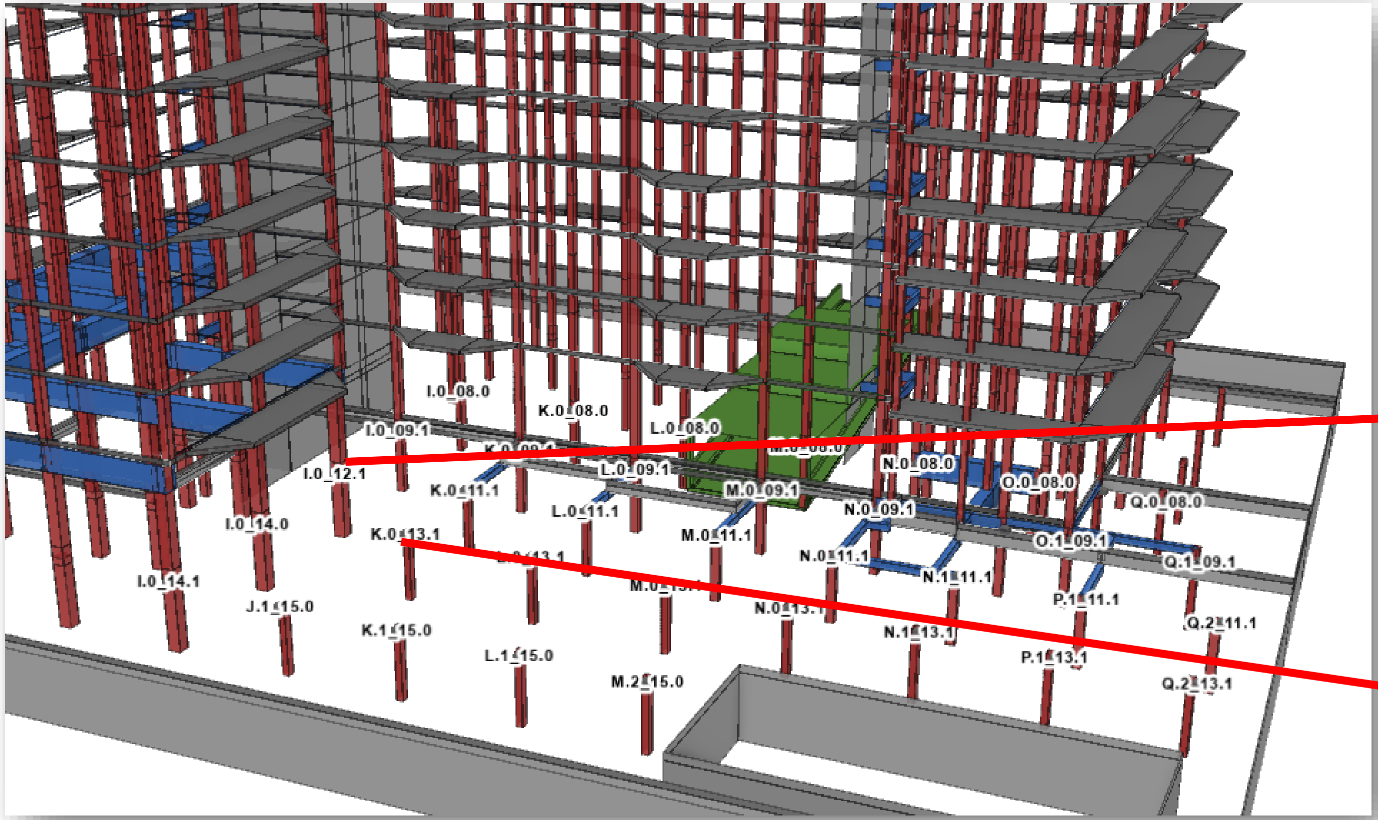


Preliminary Results of Pool Deck Code Check

	Location of Understrength	
egree of erstrength	Slab-Column Connections	Slab Flexure
Severe		
oderate		

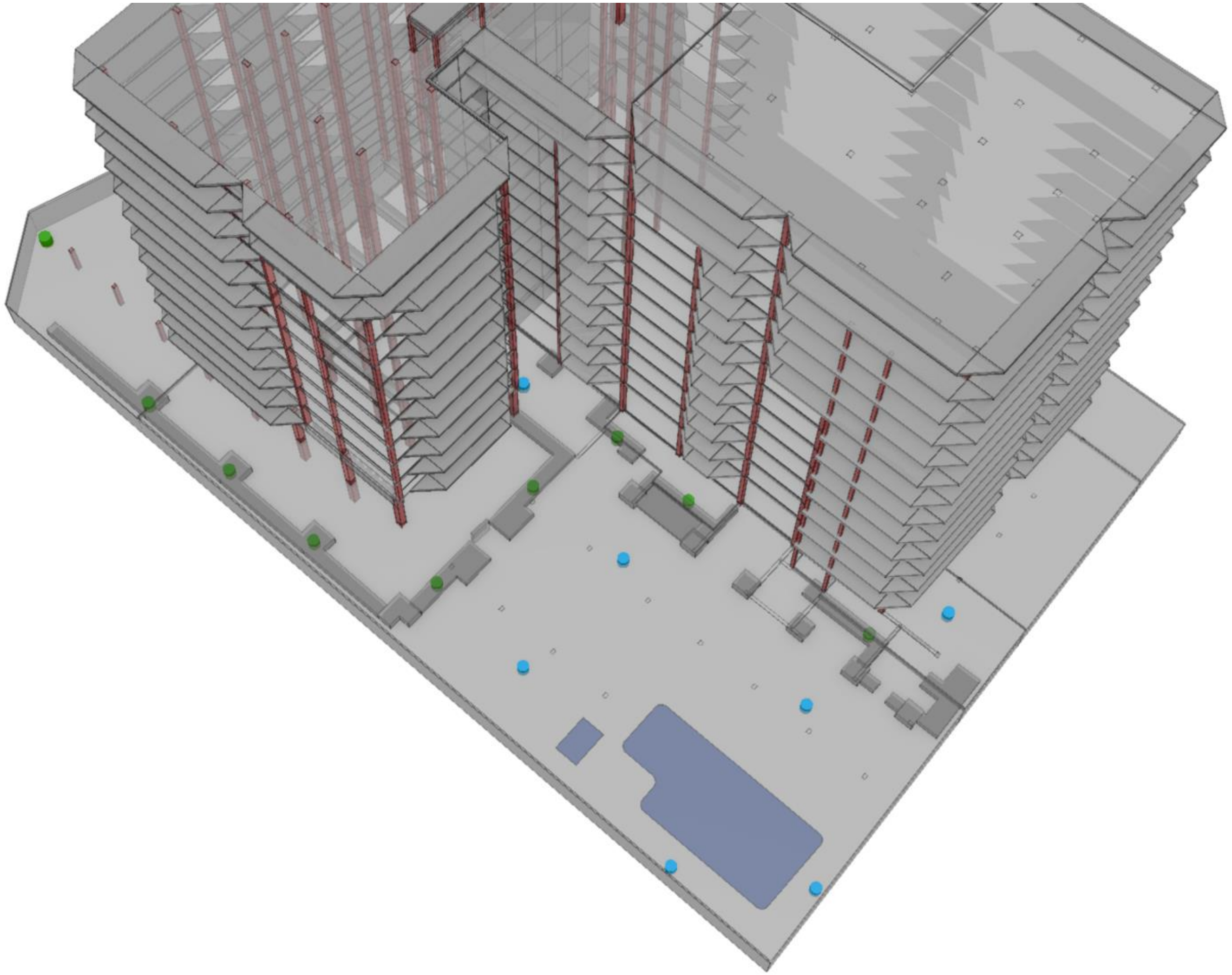
PRELIMINARY ANALYSIS RESULTS

Reinforcement Bar Spacing and Corrosion



Source: 2021, NIST

Pool Deck Drain Locations

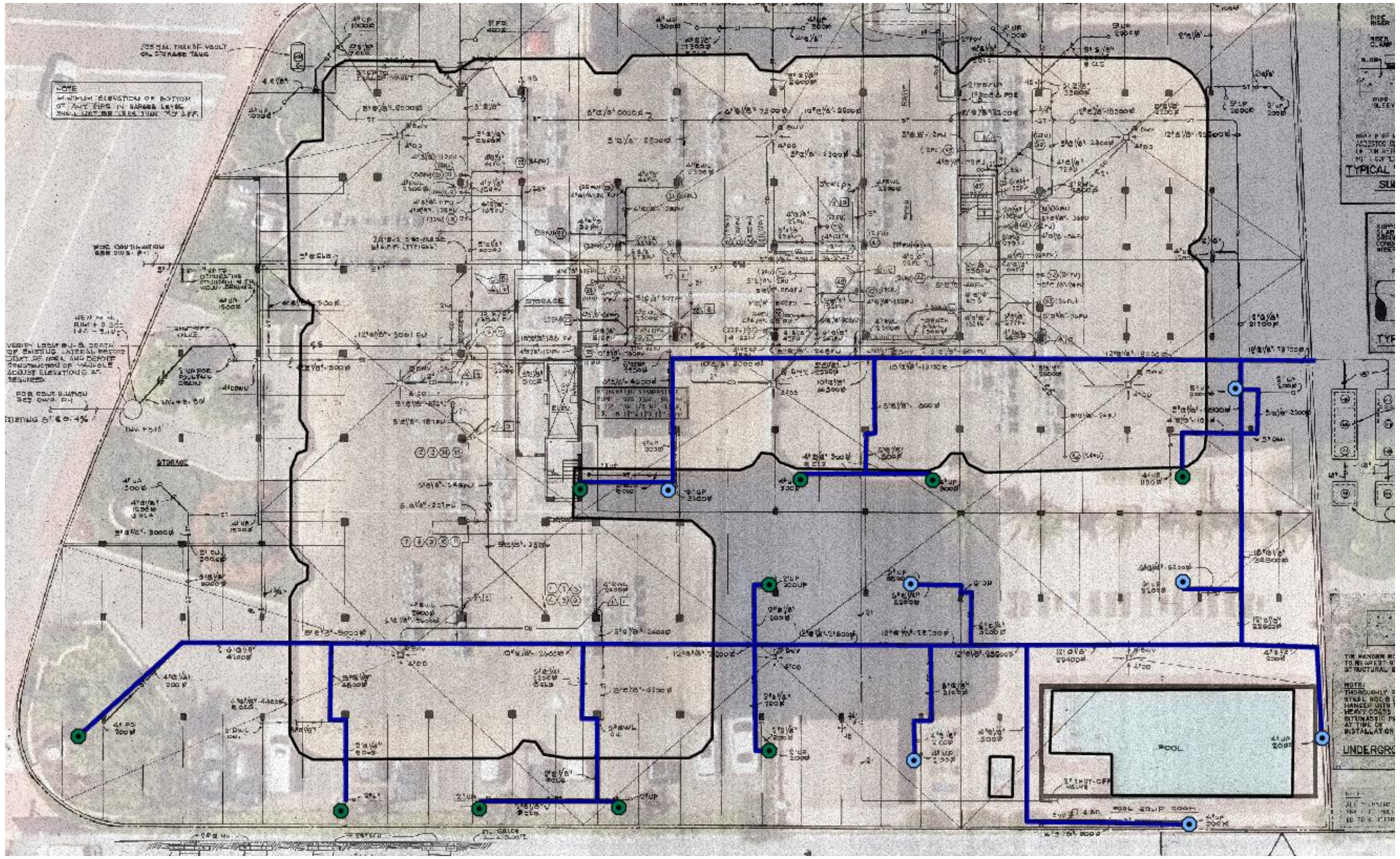


Blue = Floor drains

Green = Planter drains

As-Designed Pool Deck

NIST



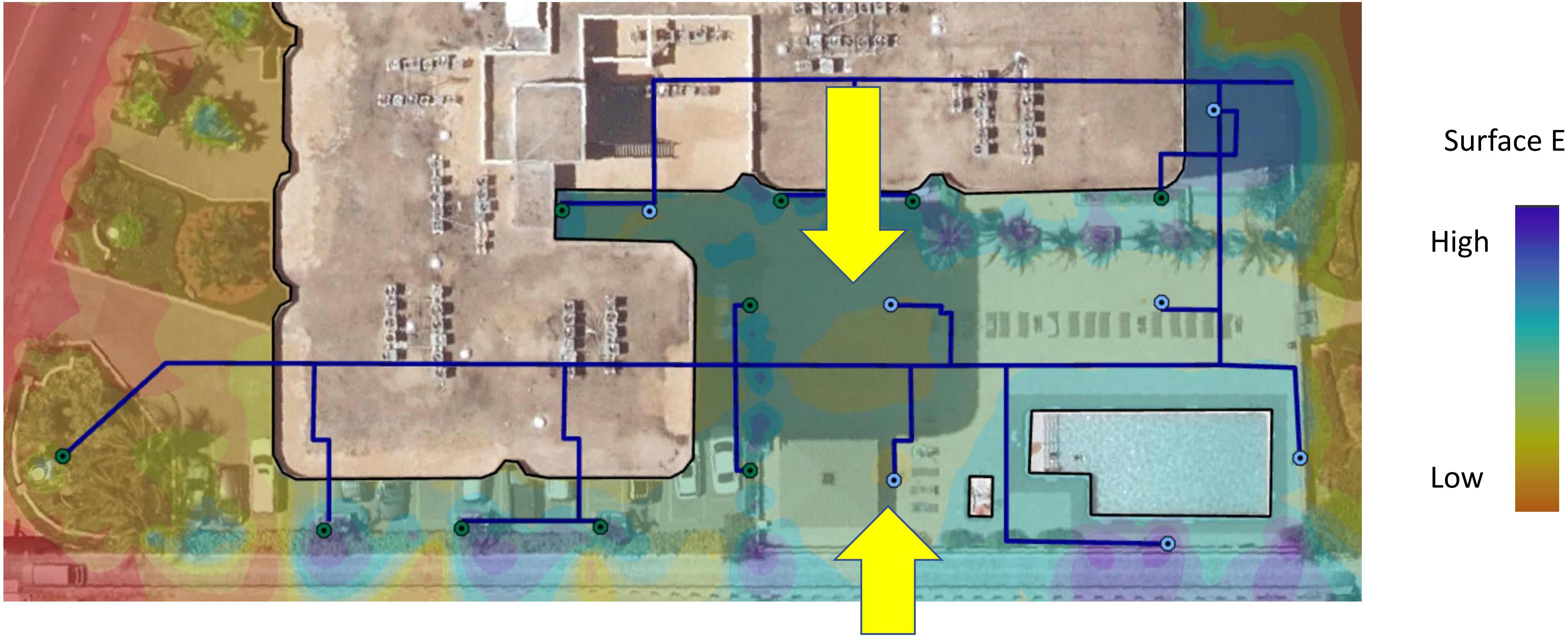
Sources: Miami Dade County Open Data Hub 2017 Aerial (background); Town of Surfside (foreground plumbing design drawings); NIST annotation

Original Plumbing Design Drawings

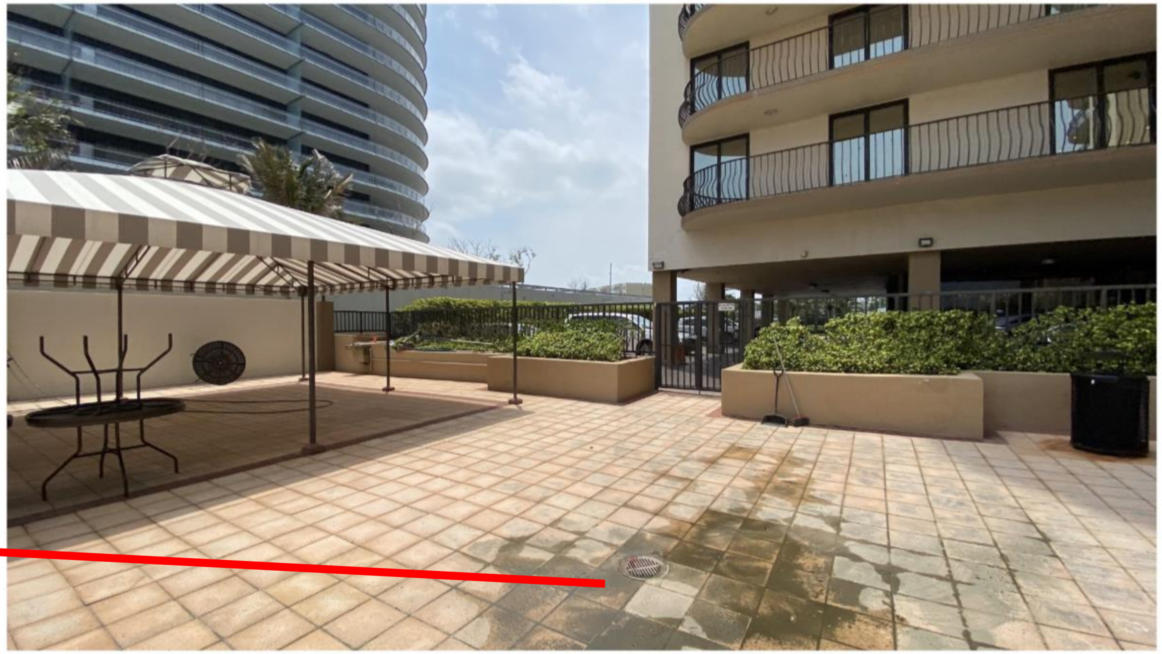
- **Pool deck design to slope to drains**
- **Drain plumbing connections**

Pool Deck Topographic Map Based on 2020 Level Survey

Sources: Miami Dade County Open Data Hub 2017 Aerial (background); 2020 Boundary Survey, CTS Receiver. NIST Annotation



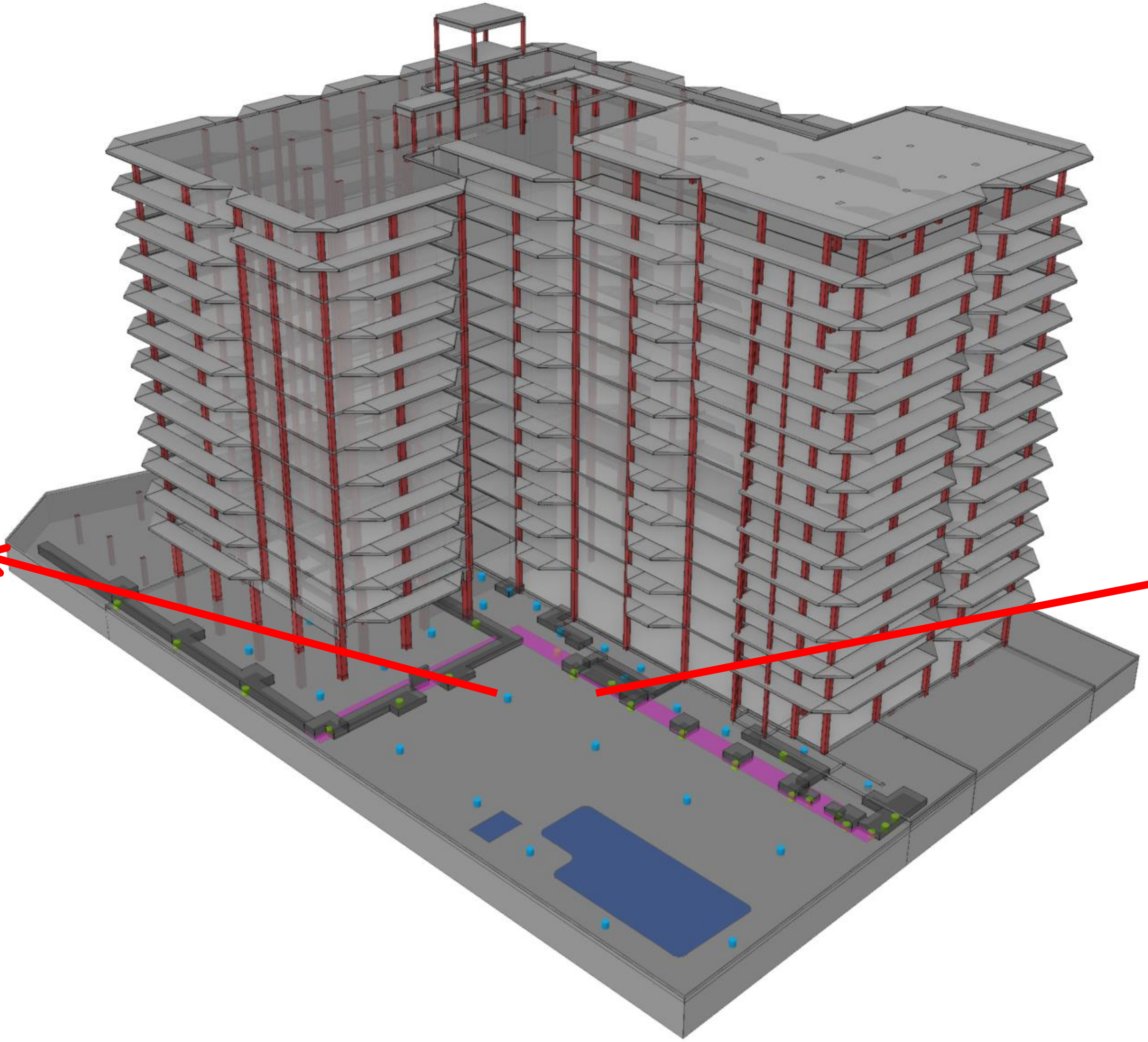
Pool Deck: Low Area and Ponding

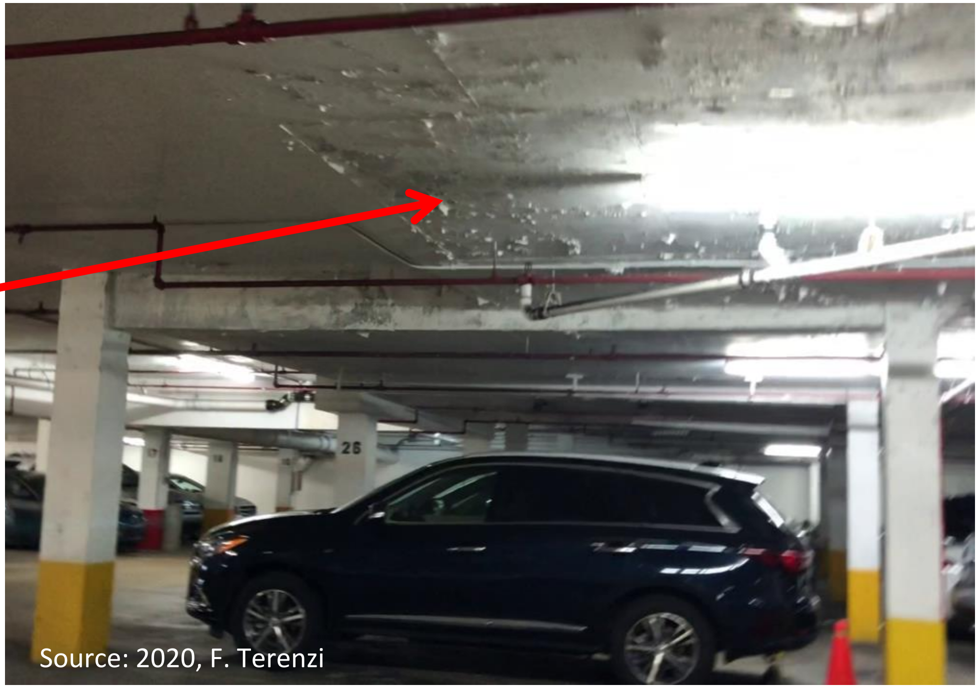


Source: 2020, CTS Receiver

Pool Deck: History of Seepage In Garage

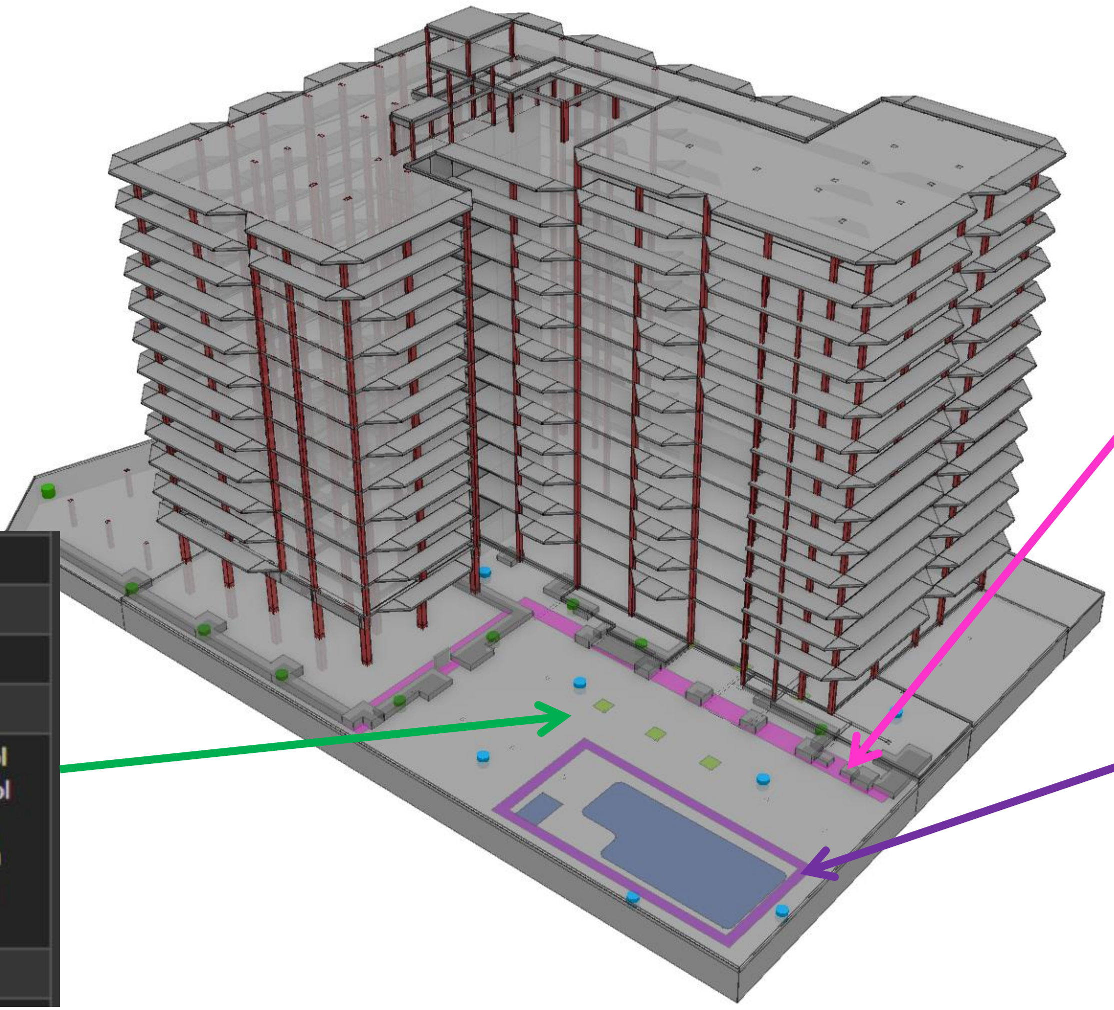
Source: 2020, CTS Receiver





Source: 2020, F. Terenzi

Pool Deck: Leaking Around Pool



Location	Pool Deck
Floor	1
Date	2/14/2012
Type	Leak/Water Damage
Observation	Repair planters leaking into parking garage.
Repair	Seal cracks

Source: 2012, CTS Receiver

Location	Pool Deck
Floor	1
Date	6/1/1997
Type	Leak/Water Damage
Observation	Significant resealing effort of pool deck "sealing all cracks in the pool deck and parking garage and for waterproofing". Complaints from unit 509 led to repairs in parking garage ceiling near space 25.
Repair	Replaired waterproofing

Source: 1997, CTS Receiver

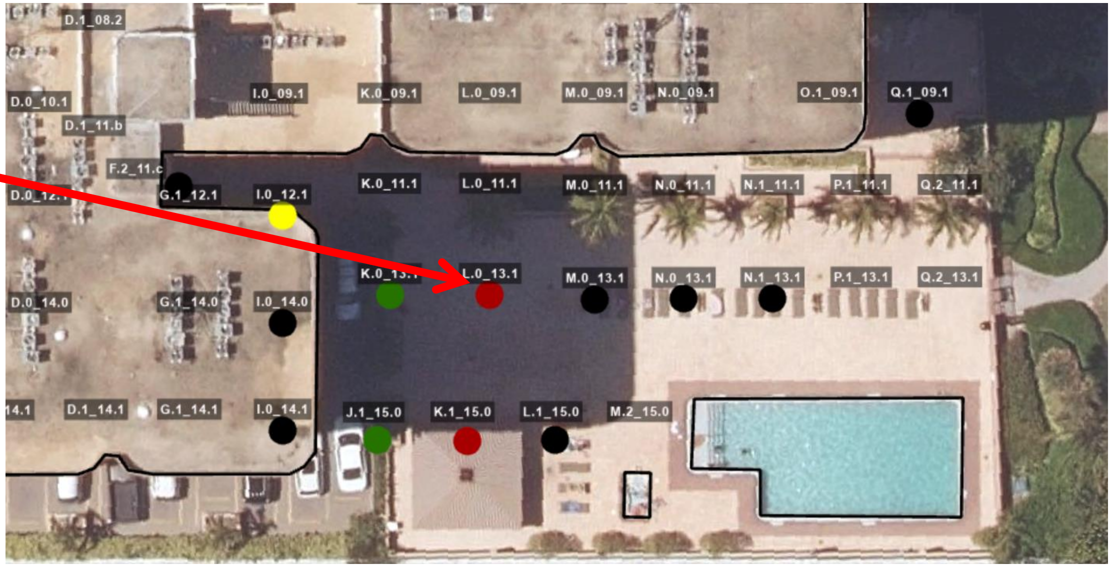
Location	Pool Deck
Floor	1
Date	4/16/2013
Type	Concrete Damage
Observation	Removed damaged pavers and substrate surrounding the pool. "There are three separate areas in the garage where drain pipes are leaking" ; in process of getting repair proposals.
Repair	Replaced with new pavers and substrate

Source: 2013, CTS Receiver

Pool Deck Columns: Chlorine and Efflorescence

Source: 2020, CTS Receiver

Source: Miami Dade County Open Data Hub 2017 Aerial (background); NIST Annotation

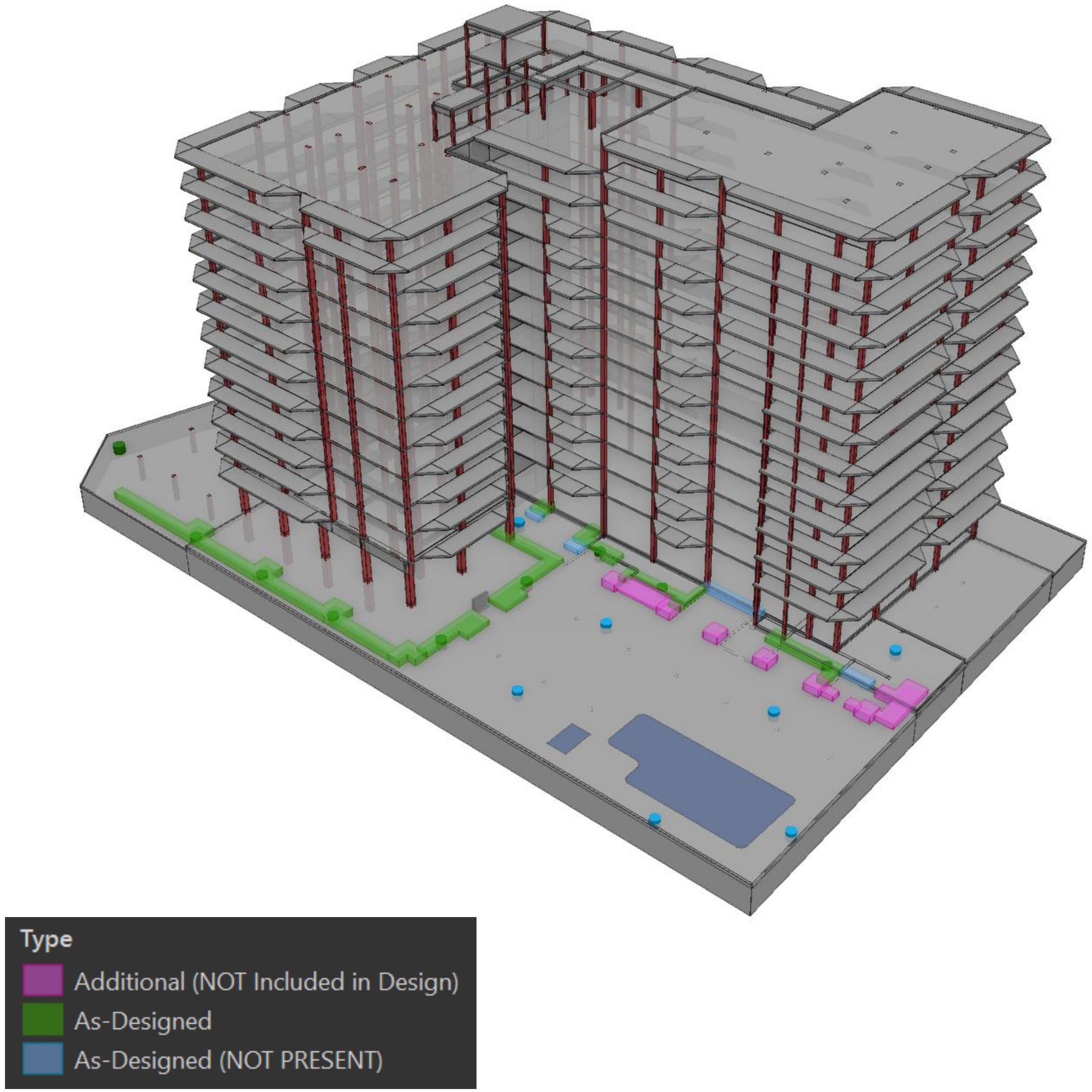


Chlorine Relative %
Red = Higher
Yellow = Middle
Green = Lower

Efflorescence Relative Amount
Red = Higher
Yellow = Middle
Green = Lower
Black = Undetected

PRELIMINARY ANALYSIS RESULTS

Planter Location Plan vs. Actual



Source: 2012, Used with Permission

Note: Palm trees not present at time of collapse

Planter Location Plan vs. Actual

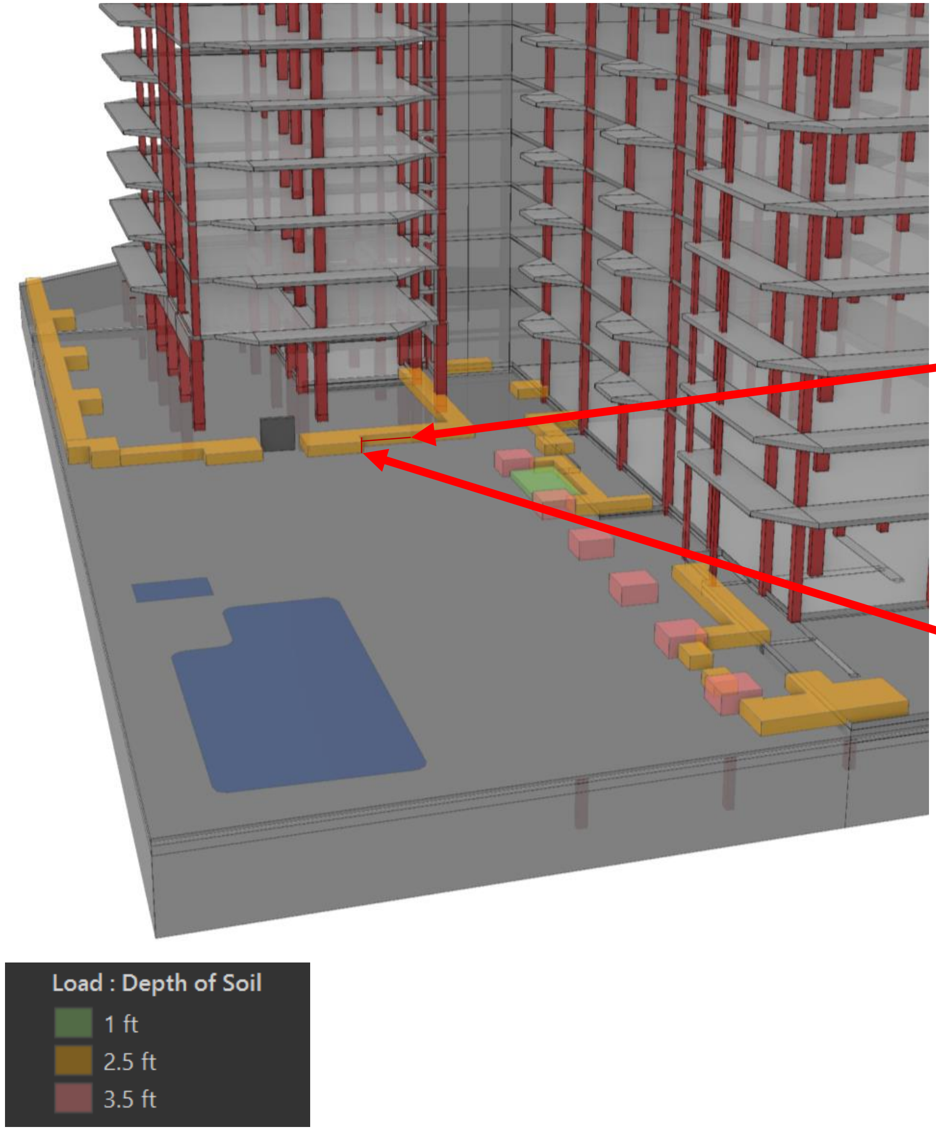
Type

Additional (NOT Included in Design)

As-Designed

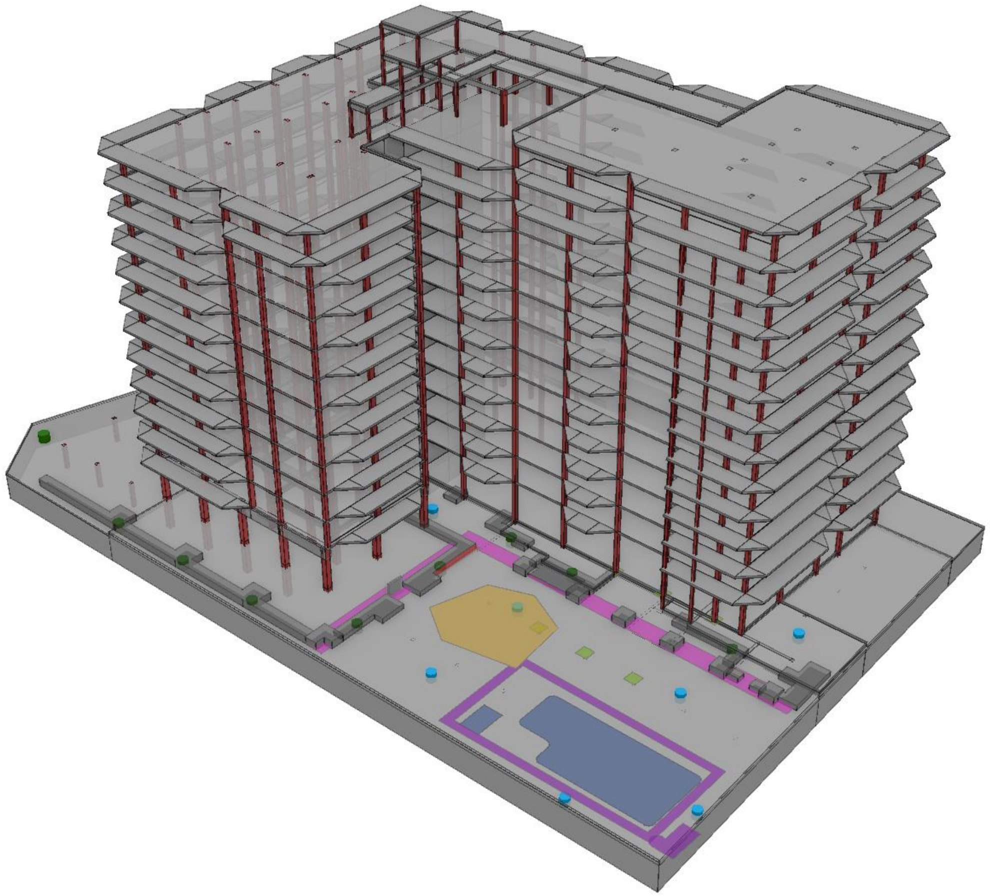
Planter Loadings

Planter Distress – Cracks/Displacement in Planter Wall



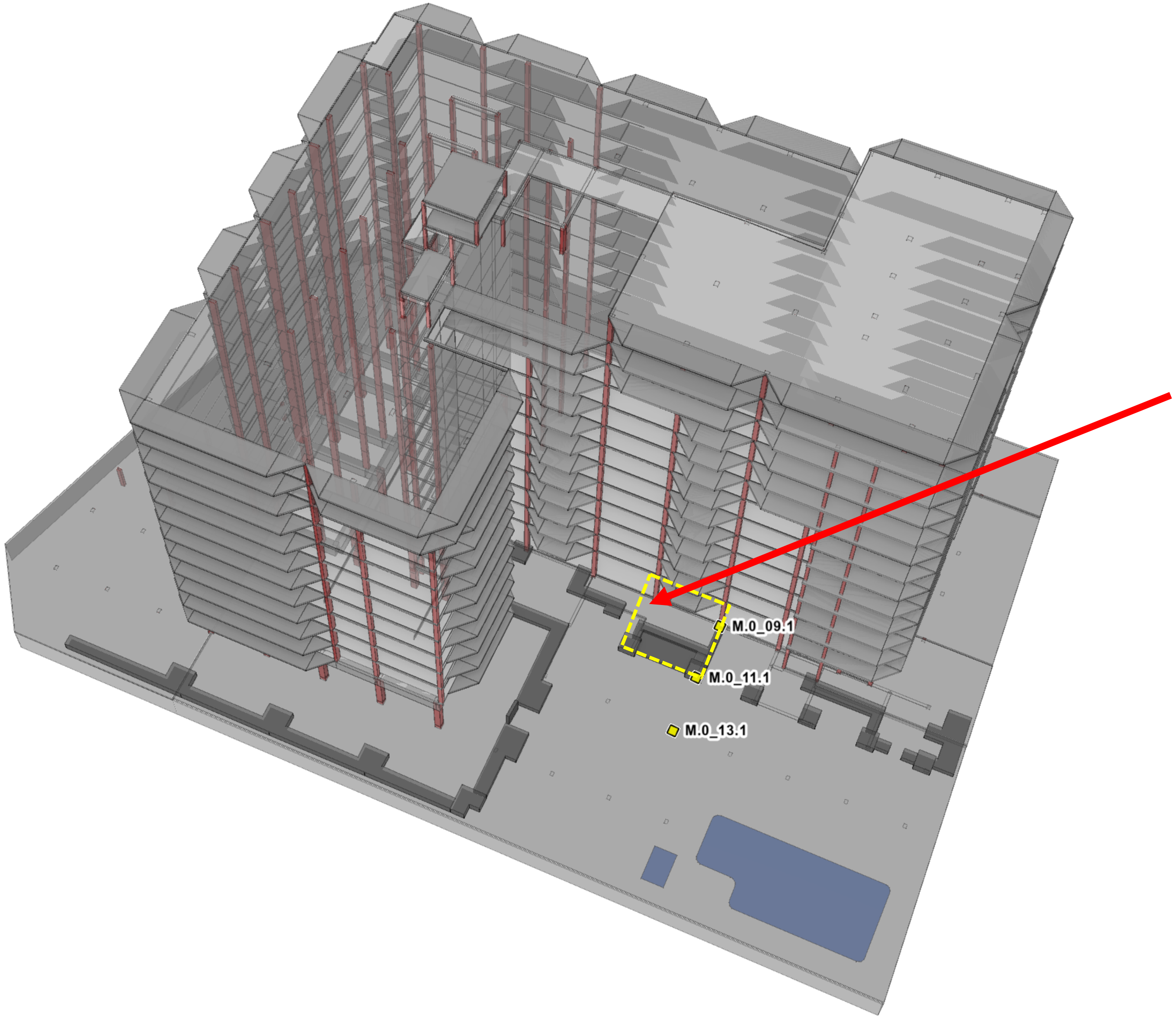
Source: 2021, CTS Receiver

Relating Multiple Pre-Collapse Data Sets



Source: Miami Dade County Open Data Hub 2017 Aerial (background); NIST Annotation

Pre-Collapse Data

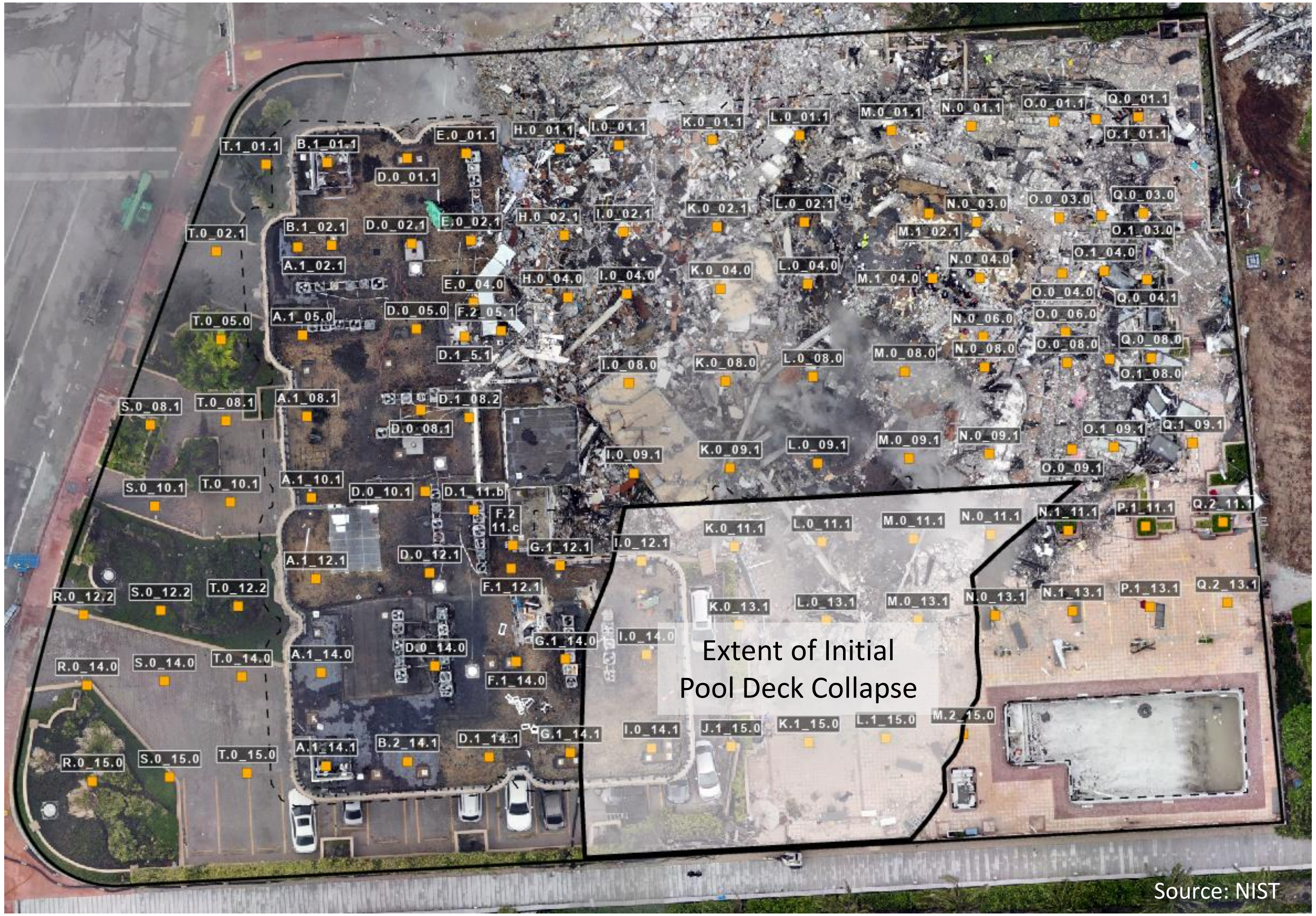


Source: 2021, S. Nir and G. Nir

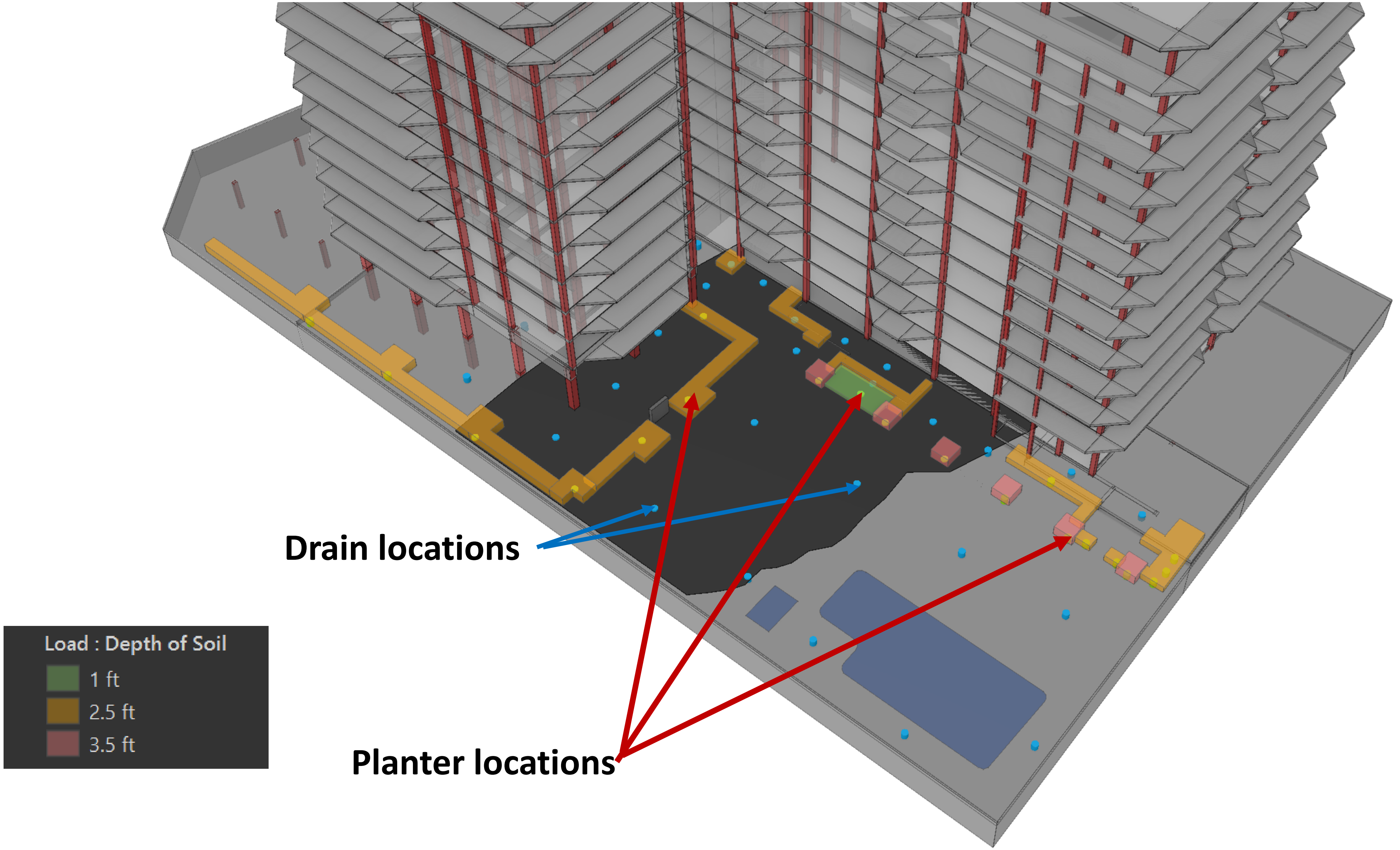
Post-Collapse Data

Source: NIST

Post-Collapse Data: Highlighted Extents of Initial Collapse



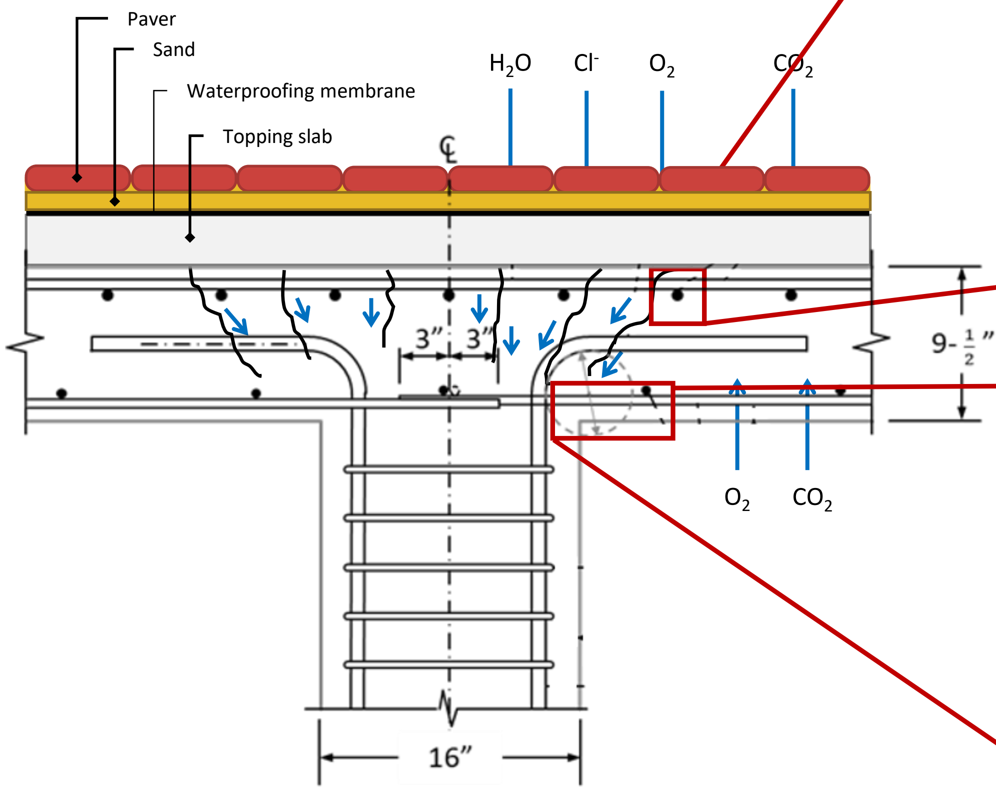
Multiple Data Sets Related to the Pool Deck Area Combined

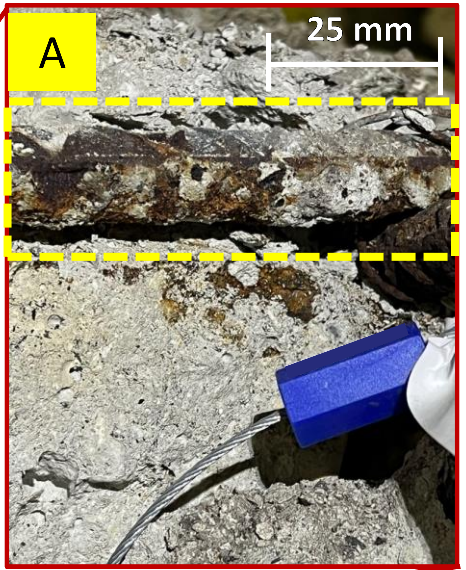


CTS Investigation: Degradation Mechanisms in Pool Deck Slab-Column Connections

Degradation Mechanisms

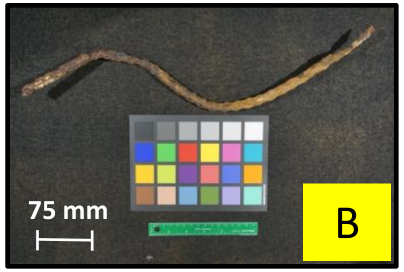
1. Cracking creates a "highway" for Cl^-, H_2O, and CO_2 to reach reinforcing bar causing corrosion
2. Concrete microstructure altered by the environment, changing mechanical properties

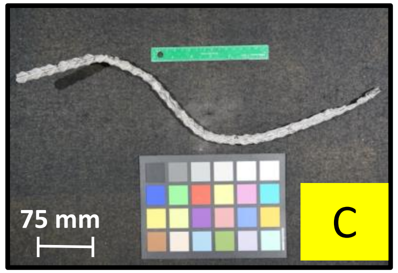


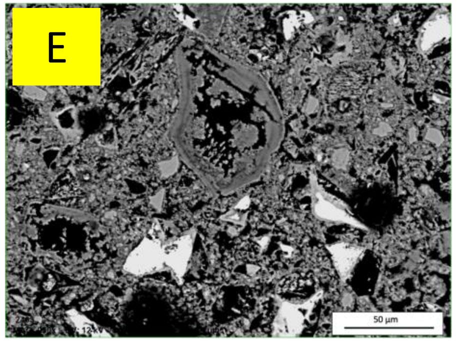


1. Reinforcing bar corrosion

- Corroded reinforcement in slab (A)
- Reinforcement before (B) and after (C) cleaning







2. Concrete degradation

- Specimen extracted from slab near column (D)
- Microstructure characterized by high porosity (black regions at E)

Source for all images: NIST

PRELIMINARY ANALYSIS RESULTS

Columns Along South Edge of Tower

James Harris, Scott Jones

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
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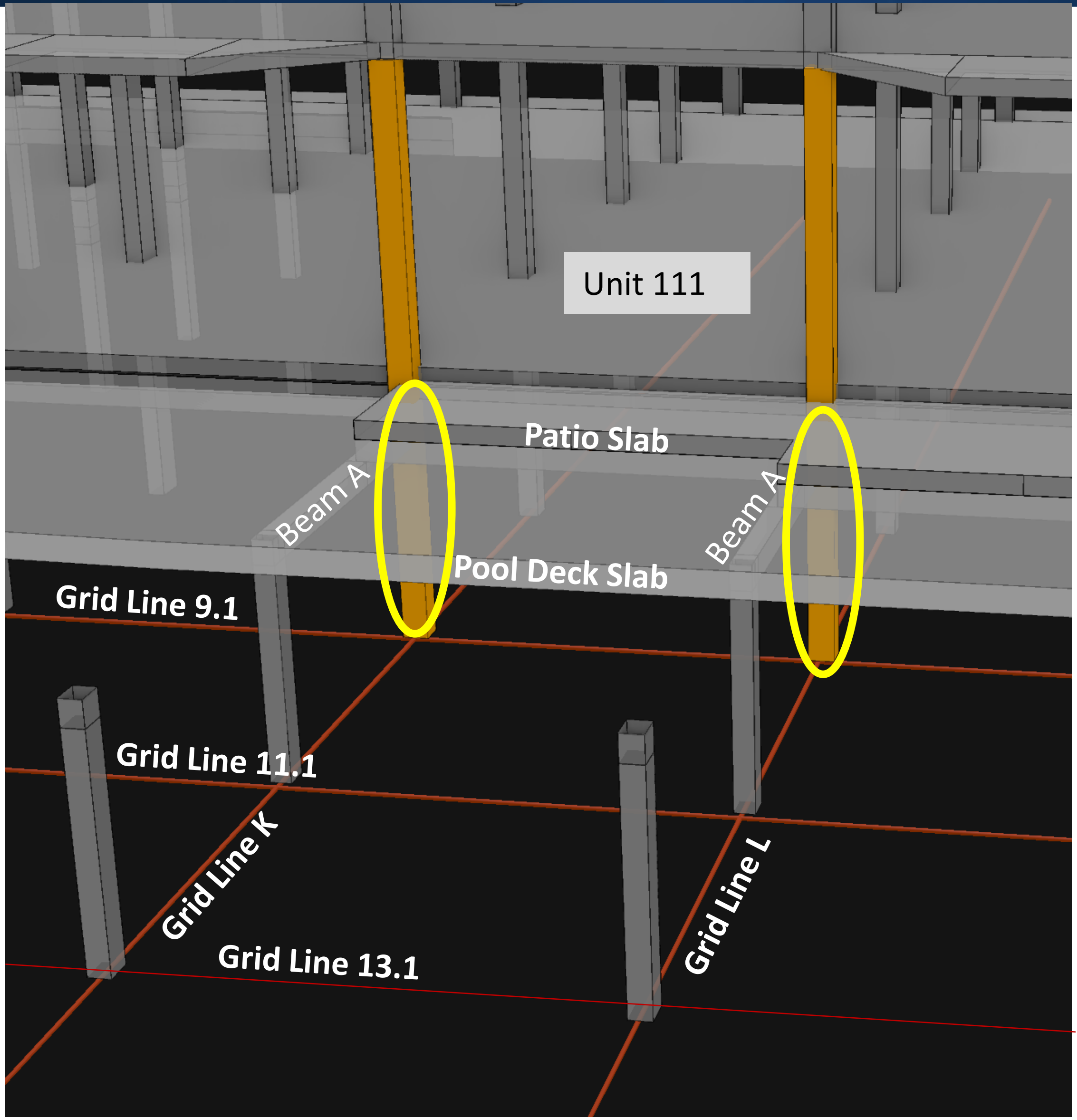
CTS Investigation: Columns Along South Edge of Tower



Description of Structure

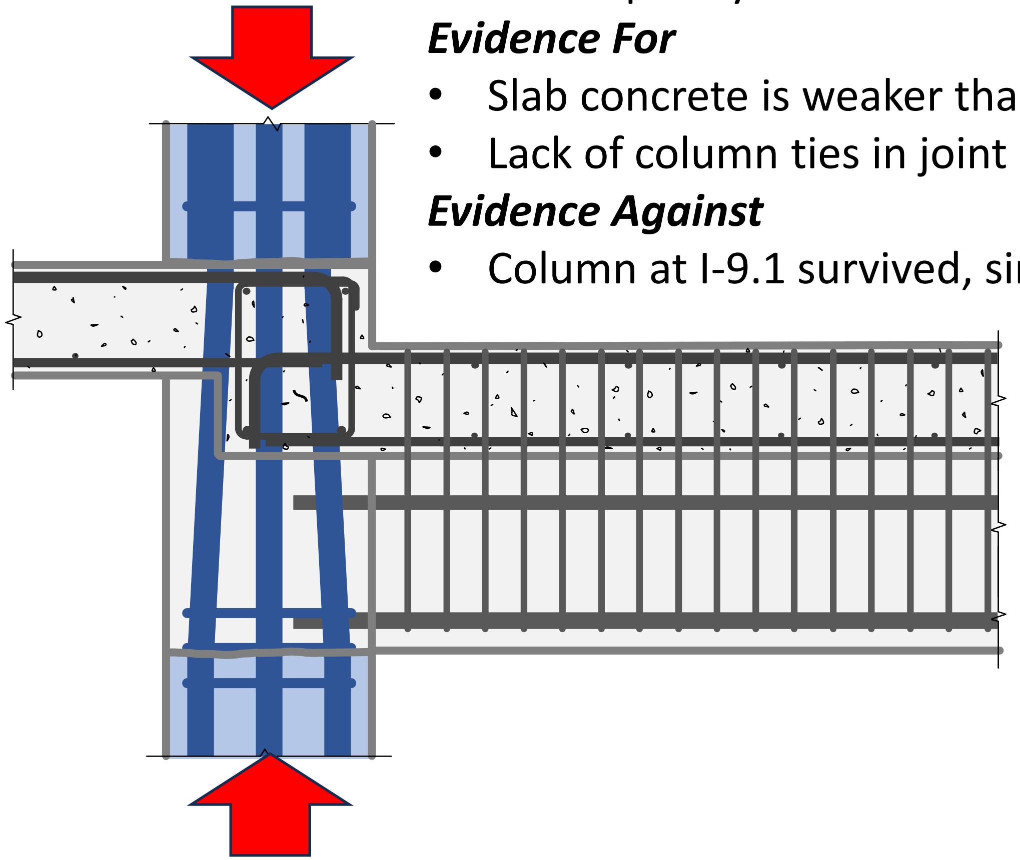
Structural Columns at Grid Lines K and L along the South Edge of the Tower

- Unit 111's patio is 7 in down from interior floor.
- The pool deck is another 11 in down from the patio. (Shown terminating at Grid 11.1 for clarity of structure below)
- The slab drop beams run along each step.
- Additional beams (Type A) extend from south face of tower to the next row of columns under the pool deck.

CTS Investigation: Columns Along South Edge of Tower

Description of Three Failure Initiation Possibilities

All three possibilities lead to shortening of column and redistribution of load elsewhere.



Failure Initiation Possibility #1: crushing in weak and poorly confined column/slab/beam joint:

Evidence For

- Slab concrete is weaker than column concrete
- Lack of column ties in joint

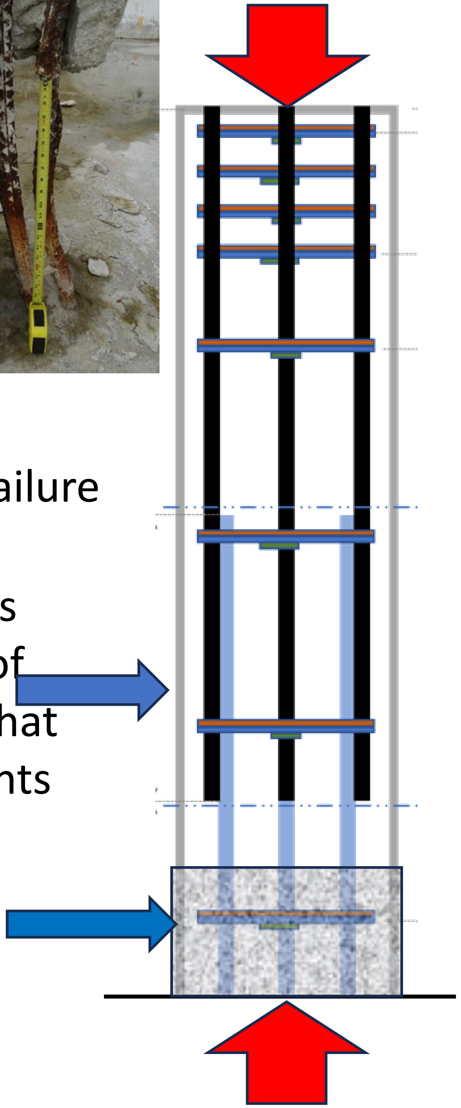
Evidence Against

- Column at I-9.1 survived, similar load

Failure Initiation Possibility #2: partial failure at improper lap splice:

Evidence For: measurements

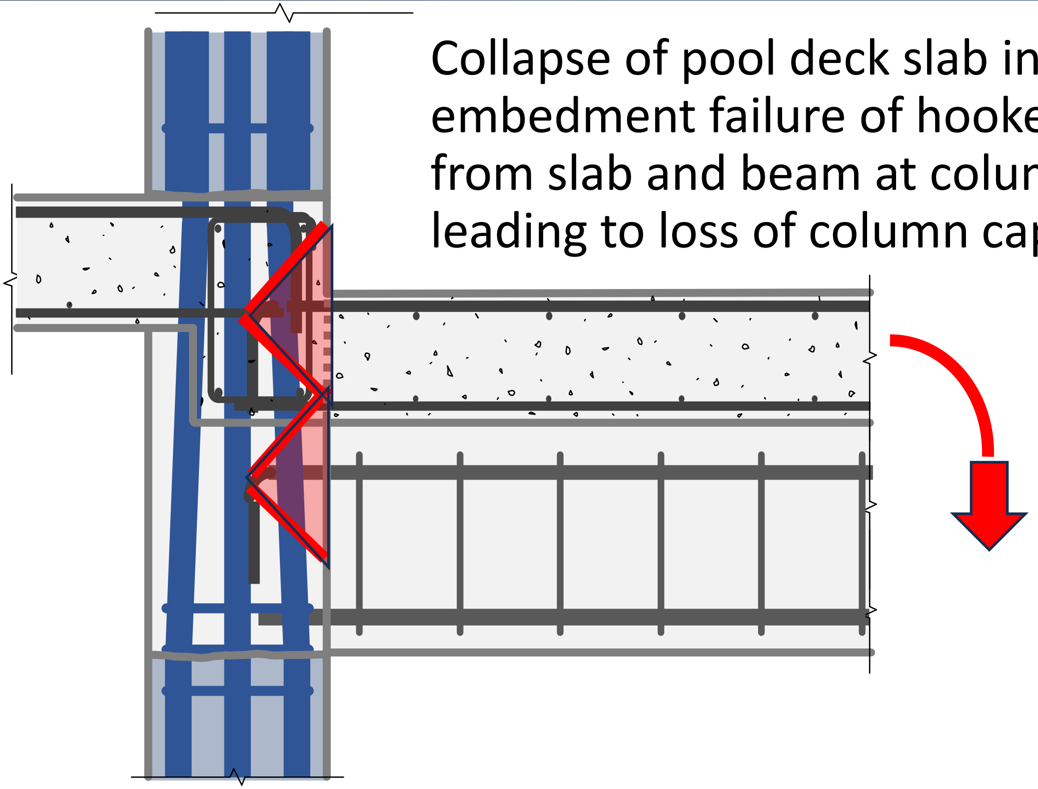
Evidence Against: survival of columns with short splices that permitted such measurements



Failure Initiation Possibility #3: crushing in deteriorated concrete at bottom of column in basement

Source for all images: NIST

CTS Investigation: Columns Along South Edge of Tower

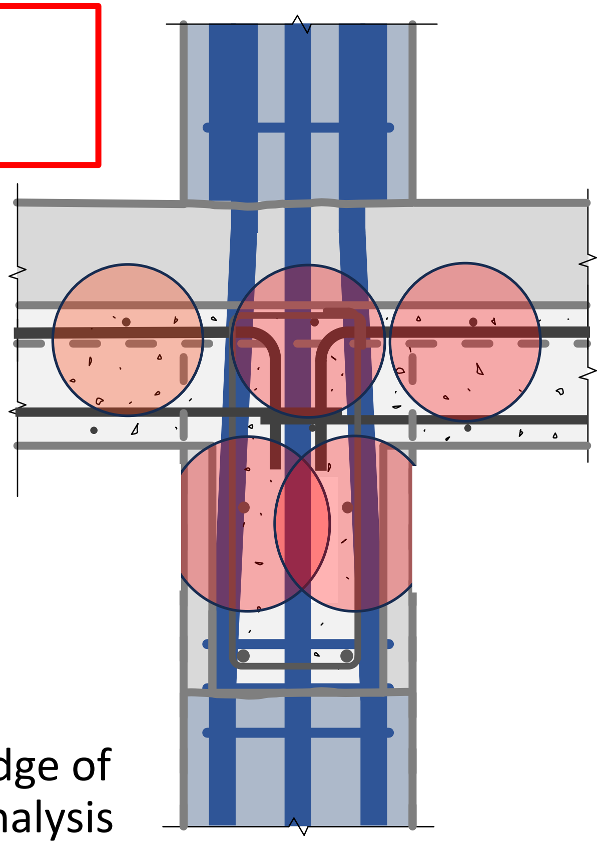


Collapse of pool deck slab initiates embedment failure of hooked bars from slab and beam at column, leading to loss of column capacity.

Description of Failure Progression Hypothesis

Important Issues

- Position of ends of hooked bars
- Strength of concrete
- Position of column reinforcement (vertical and ties)
- Column ties in joint
- Corrosion of reinforcement



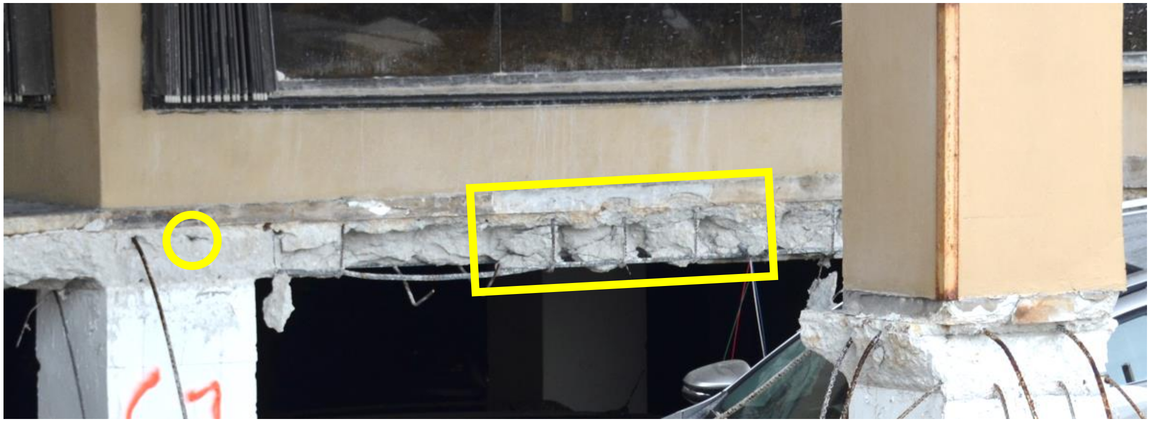
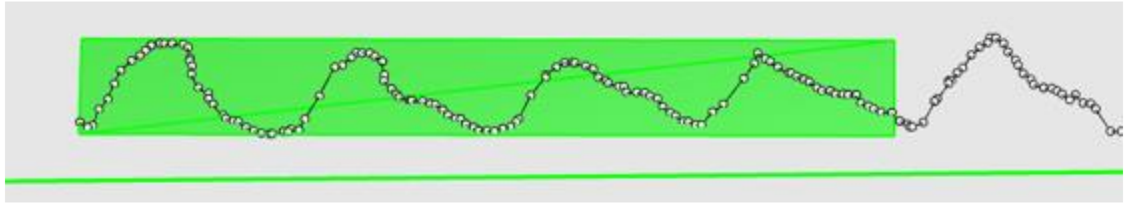


Image (at left) of similar condition at edge of portion that did not collapse. Image analysis of area in yellow box led to the profile (below) of concrete left after bars pulled out.



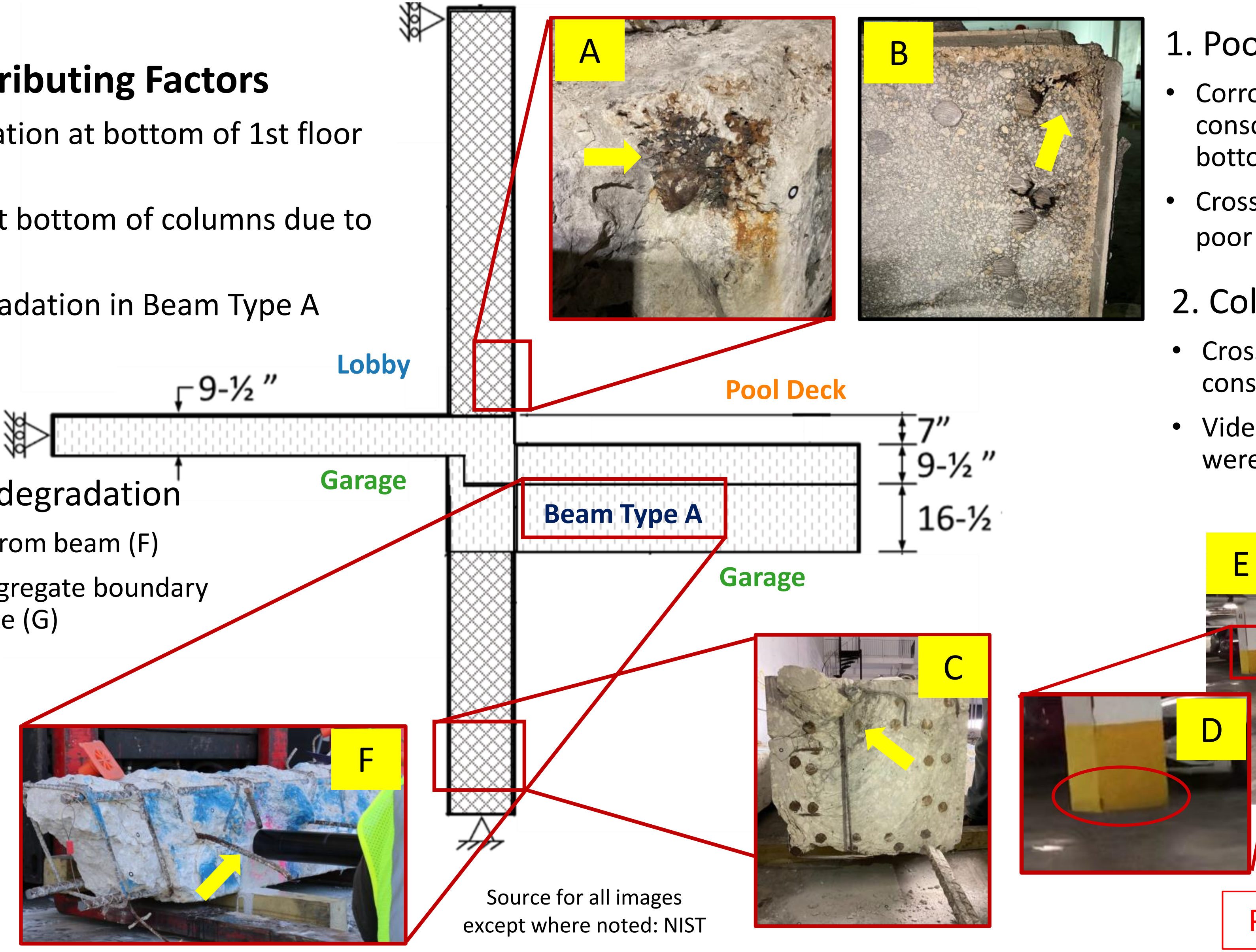
Source for all images: NIST

CTS Investigation: Potential Causes and Contributors to Failure at Columns Along South Edge of Tower

NIST

Potential Contributing Factors

1. Poor consolidation at bottom of 1st floor columns
2. Degradation at bottom of columns due to flooding
3. Concrete degradation in Beam Type A



1. Poor consolidation

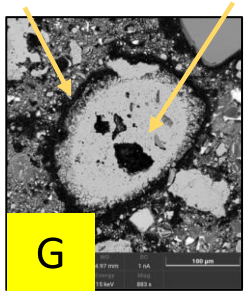
- Corrosion resulting from poorly consolidated concrete at the column bottom (A)
- Cross section of a second column showing poor consolidation at edge (B)

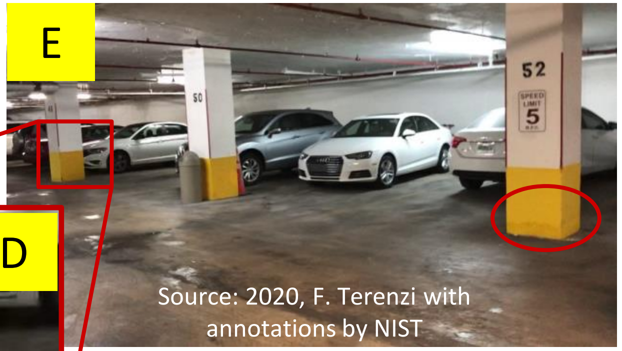
2. Column degradation

- Cross section of a column showing poor consolidation (C)
- Video evidence suggests that columns were repeatedly exposed to water (D & E)

3. Beam Type A degradation

- Core extracted from beam (F)
- Porous paste aggregate boundary and altered paste (G)





Source: 2020, F. Terenzi with annotations by NIST

Source for all images except where noted: NIST

PRELIMINARY ANALYSIS RESULTS

Formation of Karstic Features and Differential Settlement

Youssef Hashash

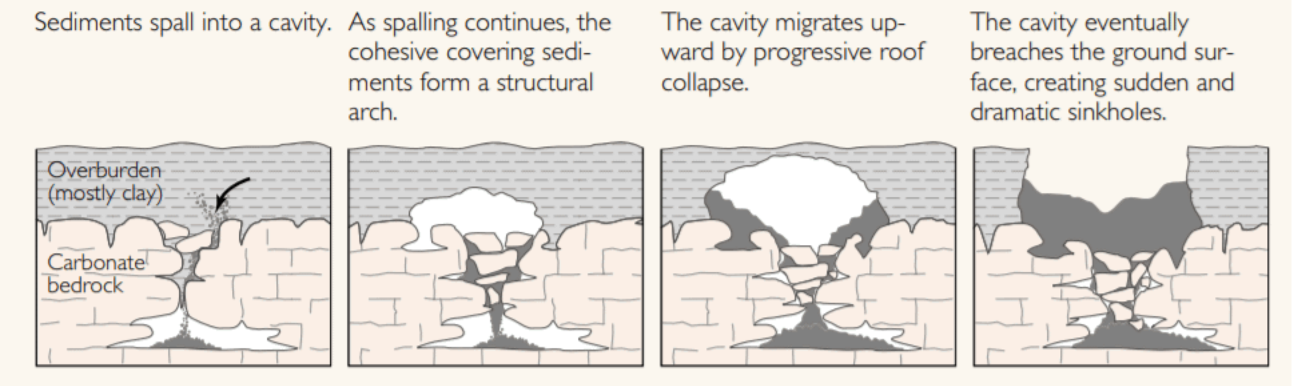
CTS Investigation: Formation of Karstic Features and Differential Settlement

Description

- Potential presence of karstic features and their impact on the CTS foundations
- Potential differential settlements and their impact on the slab-column connections of the pool deck

CTS Investigation: Karstic Feature Formation Potential at CTS Site

- Foundations at CTS bear on limestone strata
- Limestone has the potential for karstic feature formation (e.g., large voids or sinkholes that undermine pile foundations)



Source: USGS
Public Domain: https://www.usgs.gov/media/images/cover-collapse-sinkholes-can-open-suddenly

Failure hypothesis	Damage Related to Karstic Features: Did a large enough void or a sinkhole develop under the foundation, leading to loss of support, initiating failure in any of the foundations?
Goal	Evaluate direct and indirect evidence for damage related to karstic features, if present, and the potential for karst formation in limestone at the site.

CTS Investigation: Post-Collapse Observations and Measurements

NIST

Visual Observation of Basement Slab

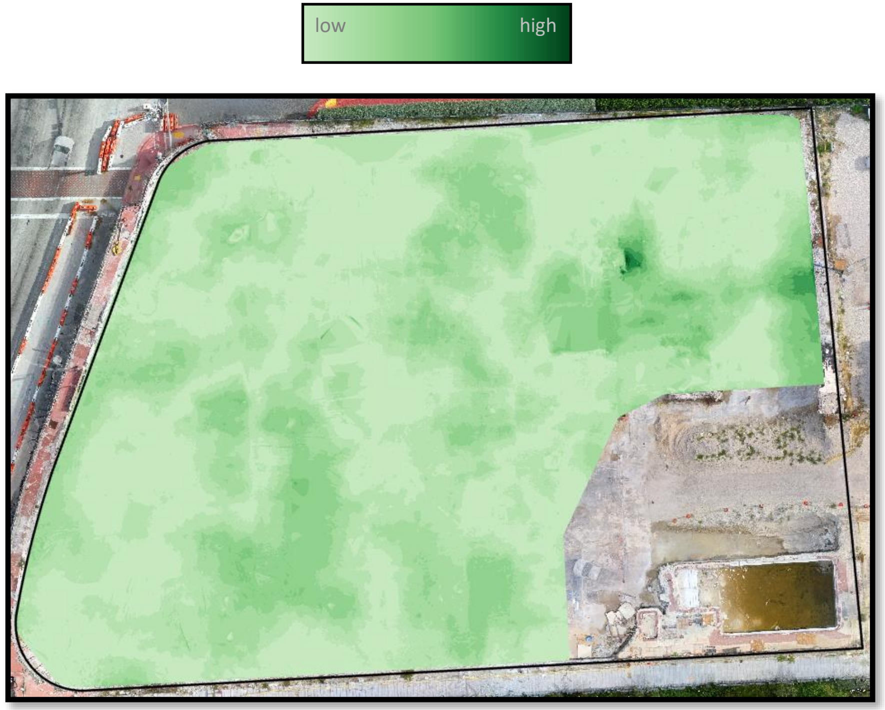
- Absence of gross damage
- Cracking in the Basement slab around east shear wall most likely induced during collapse sequence

Source: NIST

Level survey of Basement slab shows mostly level slab without sudden changes in elevation.

2021 USACE Survey

Deviation from mean elevation



PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Post-Collapse Site Investigations

- 70 boreholes and cone penetrometer tests
- No evidence of large, persistent karstic voids

Source: NIST

Pile Load Testing

Source: NIST

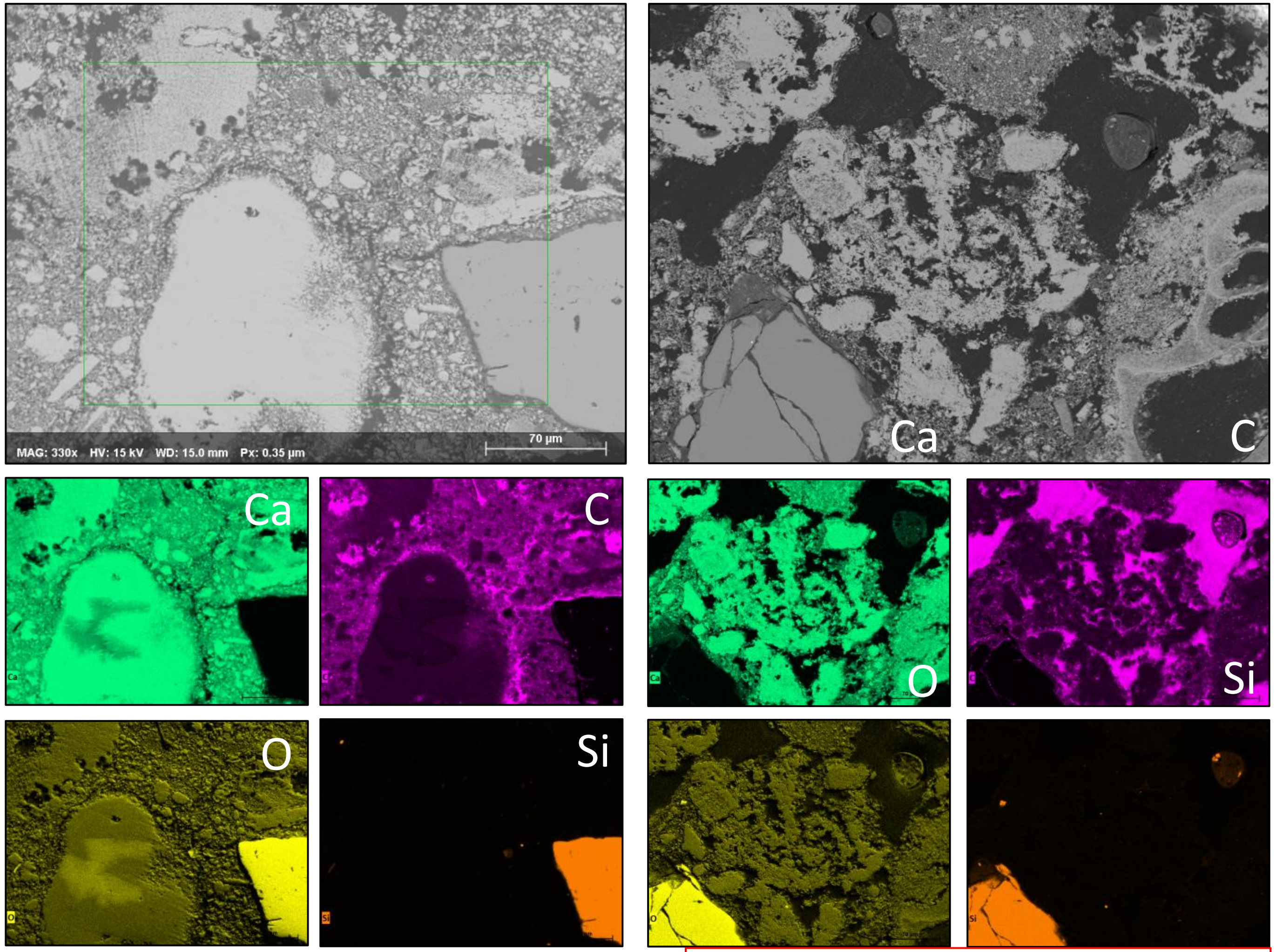
PRELIMINARY ANALYSIS RESULTS

Karstic Feature Formation Potential: Laboratory SEM & EDS Results

NIST

- SEM: Scanning Electron Microscope
- EDS: X-ray (Energy Dispersive Spectrometer)
- SEM images and EDS / element maps confirm heterogeneity in composition and texture
- Large calcite / aragonite and quartz grains present
- While carbonate grains and matrix show signs of dissolution, presence of dissolution fronts and void space is limited
- **Intact quartz grain boundaries confirm insolubility (lack of potential to form large scale voids)**

Sample depth range 25 ft-26 ft | **Sample depth 36 ft**



Source all images: NIST

PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Preliminary Evaluation of Potential for Karstic Feature Formation

NIST

Evidence For

- CTS site is underlain by limestone
- Limestone may develop solution or karst features

Evidence Against

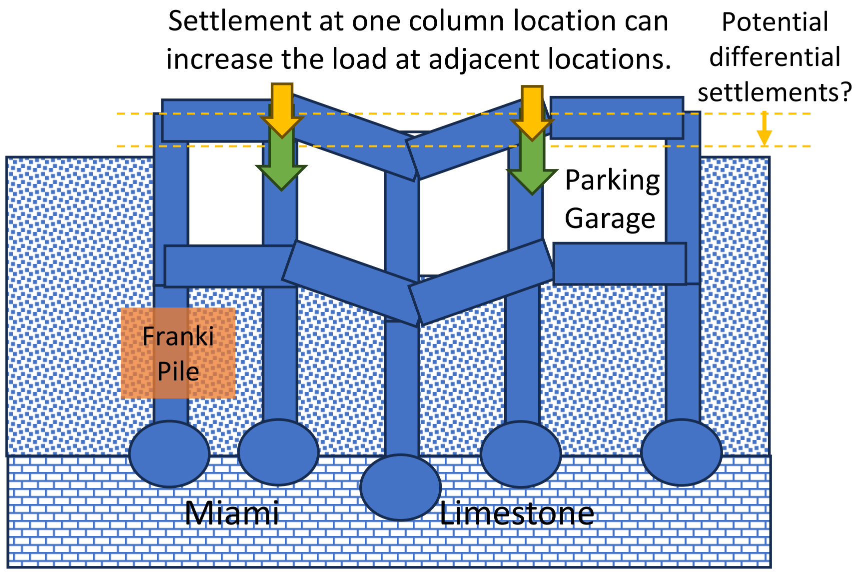
- As detailed in the literature, the Miami Limestone in south Florida, inclusive of CTS site, is characterized by **scattered concentrations of quartz sand and cemented limey sandstones / siliceous limestone**
- **High concentrations of quartz**, as found in CTS soil samples, in "limestone" lower the solubility potential of the local bedrock and **hinder karst feature formation** at the CTS site
- Boring logs show **no evidence of large-scale karstic features**
- Relevant evidence from the post-collapse investigation and laboratory testing **does not indicate damage** in the **basement or foundations** that could be attributed to karstic feature(s) formation at the site

Preliminary finding: Karstic feature formation scenario has very low probability

PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Structural Damage due to Potential Differential Settlements

- Foundations at CTS bear on sands and soft limestone strata
- Foundation elements have the potential to move differentially



Failure hypothesis

Damage Related to Differential Settlements

Did foundation elements settle differentially, leading to increased load on slab-column connections in the pool deck and contributing to an initiation of the collapse?

Goal

Evaluate the evidence of differential movements and the potential damage to the pool deck superstructure

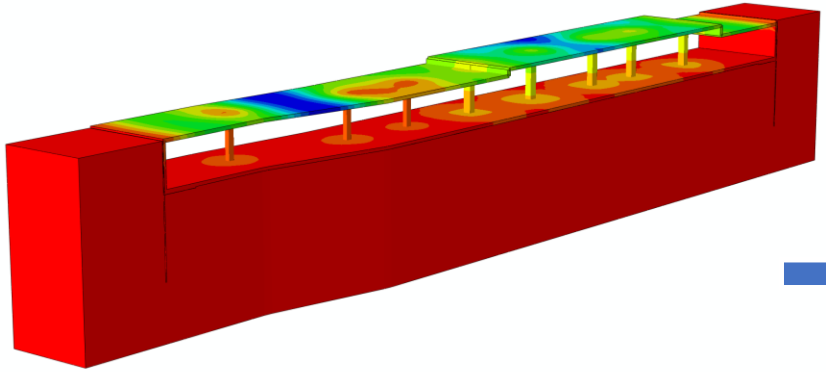
CTS Investigation: Observations and Evaluation of Differential Settlement Potential

Site-Specific Pile Testing

Source: NIST

Two pile load tests in pool deck area by NIST showed that these piles were able to adequately carry estimated design loads with limited deformations.

Pile Settlement Evaluation



Preliminary numerical analyses and calculations using empirical methods showed settlements within the range anticipated based on the site-specific pile load testing for the estimated structural loads.

Preliminary Evaluation

Estimated potential differential settlements under structural loading are on the order of **1/4 in.** The following slide presents an analysis of differential settlements on the structure.

1/4 in

3/4 in
(diameter of a penny)

Source: U.S. Dept. of Treasury. usmint.gov/learn/coin-and-medal-programs/coin-specifications

PRELIMINARY ANALYSIS RESULTS

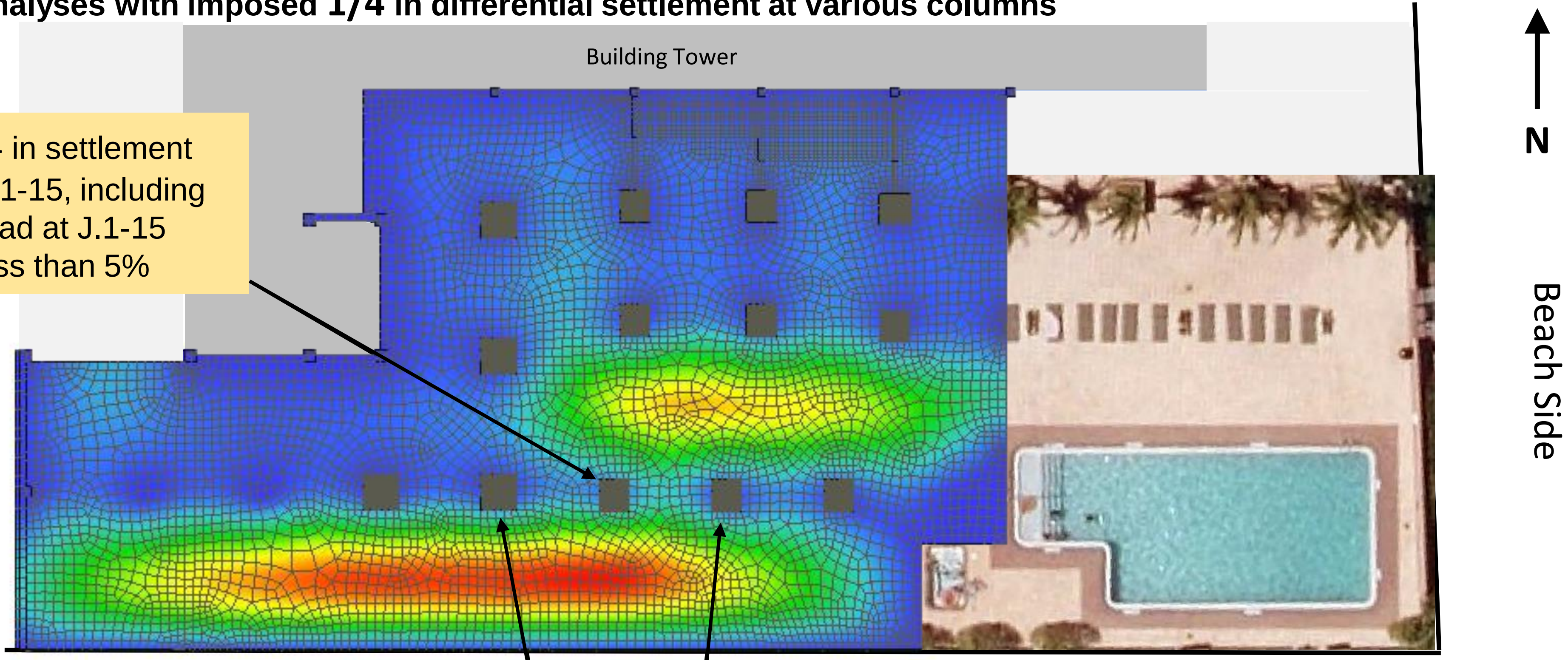
CTS Investigation: Structural Impact of Differential Settlement Potential Under the Pool Deck

NIST

Pool/Drive/Park Deck Structural Model

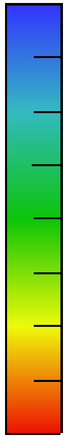
Analyses with imposed 1/4 in differential settlement at various columns

Example: 1/4 in settlement imposed @ J.1-15, including creep. The load at J.1-15 reduces by less than 5%



Source: Miami Dade County Open Data Hub 2017

Displacement



The loads at adjacent locations I-14.1 and K.1-15 increase by less than 5%.

Source: NIST using ATENA software

PRELIMINARY ANALYSIS RESULTS

Preliminary evaluation: 1/4 in differential settlement has minimal impact on pool deck structure

CTS Investigation: Preliminary Evaluation of Differential Settlement Potential

NIST

Evidence For

- Slight variations in basement slab level
- Minor cracking

Evidence Against

- Visual evidence shows minor cracking in the slab and level survey shows a mostly level slab without abrupt changes in elevation
- Post-collapse pile load testing show very low deformation potential
- Numerical modeling shows very small differential settlement potential that has minimal impact on the column-pool deck slab connection

Preliminary finding: Differential settlements scenario in the pool deck has very low probability

PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Path Forward for Potential Geotechnical/Foundation Contributors to Failure

NIST

While these failure hypotheses are currently rated as having low likelihood, we continue evaluating other potential geotechnical contributors to the failure:

- Continued evaluation of the interaction of the Pool Deck with the south Basement wall
- Continued evaluation of impact of construction including vibrations from neighboring sites

These are currently being examined via empirical and SSI modeling

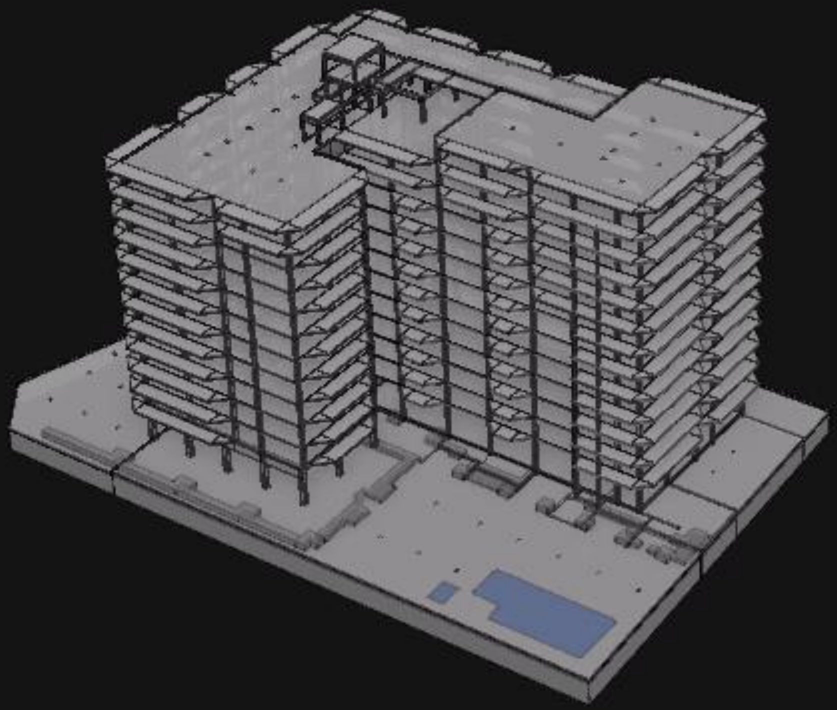
Tower Columns Above the First Story

Glenn Bell

NATIONAL INSTITUTE OF
STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Description: Failure of one of the tower columns above the first story

Objective: To examine the likelihood that partial collapse of the CTS building initiated at one of the tower columns above the first story



CTS Investigation: Tower Columns Above the First Story

NIST

Loads at Time of Collapse

- Actual live loads at time of collapse lower than required building code design loads
- Wind modest

PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Tower Columns Above the First Story

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Structural Design

(conditions without wind)

- Shorter story heights > lower slenderness
- Design strength generally well within building code. Modest understrength in limited areas.

PRELIMINARY ANALYSIS RESULTS

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Concrete Materials Testing to Date

(limited tests from tower columns above the 1st story)

- Average strength exceeds specified design strength
- But large variability

PRELIMINARY ANALYSIS RESULTS

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- Less reinforcement congestion suggests fewer consolidation problems
- Some incidence of short lap splices and member misalignments

PRELIMINARY ANALYSIS RESULTS

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Deterioration

- Generally, less severe environmental exposure than columns at the Basement & 1st stories, e.g.,
  - Pool deck/planter conditions at Grid Line 9.1
  - Water exposure at Basement floor

PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Tower Columns Above the First Story

NIST

Evidence Against = White / Evidence For = Yellow

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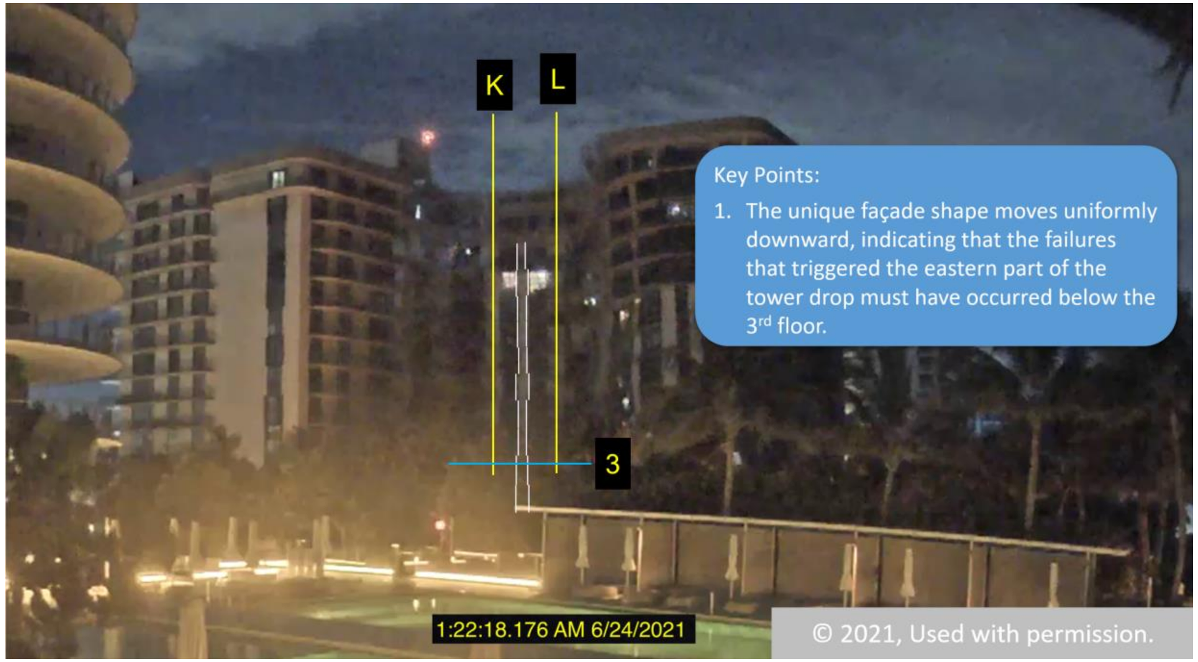
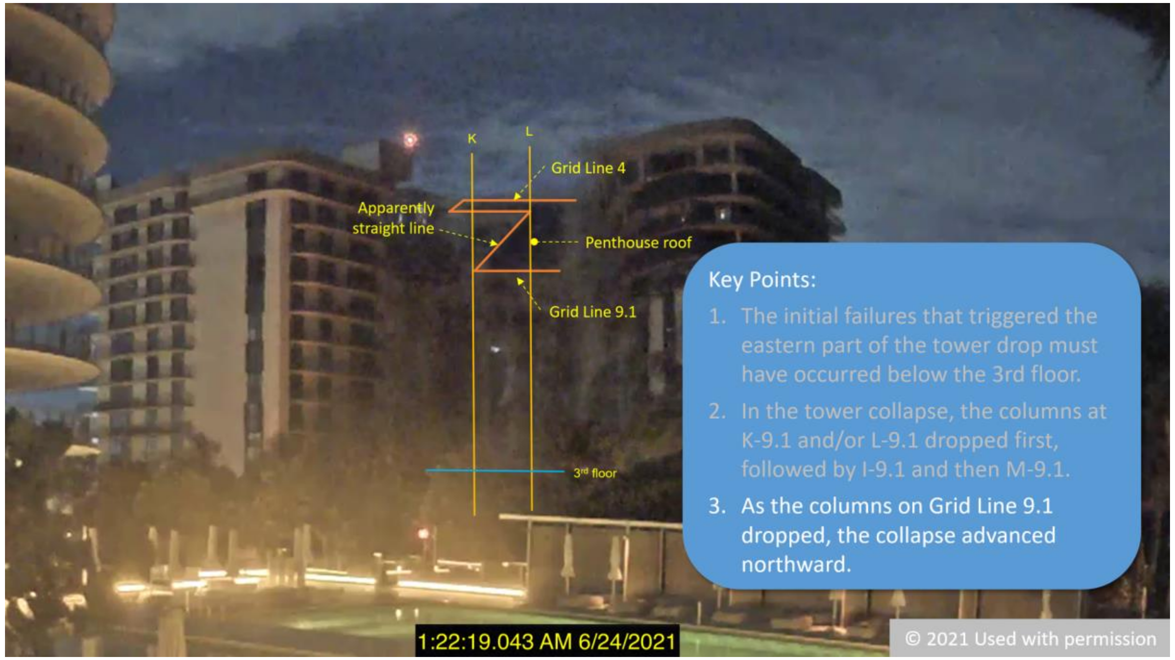
PRELIMINARY ANALYSIS RESULTS

CTS Investigation: Tower Columns Above the First Story

Evidence Against This Hypothesis



The individual stories of the tower columns at K-9.1 & L-9.1 dropped in unison above the 2nd story



Penthouse roofline shows Grid Line 9.1 dropping in advance of Grid Line 4

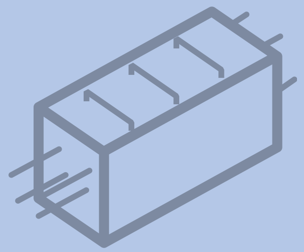
PRELIMINARY ANALYSIS RESULTS

Questions?

Theme 1: *Timeline and Evidence Collection*

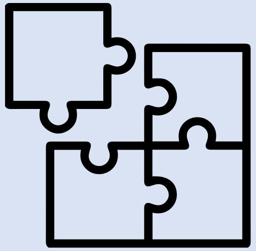
Judith Mitrani-Reiser, N. Emel Ganapati, David Goodwin, Christopher Segura, Jonathan Weigand, Kam Saidi, Jack Moehle

Theme 2: *Analysis and Testing Updates*



Fahim Sadek, James Harris, Christopher Segura, Kenneth Hover, Jack Moehle, Sissy Nikolaou,

Theme 3: *Analysis of Failure Hypotheses*



Glenn Bell, Fahim Sadek, Georgette Hlepas, Scott Jones, James Harris, Youssef Hashash