2026 GRIP Meeting

FDOT Project BED26 TWO 977-20:

Measuring Rebound and Evaluating Pile Resistance Using Ultra-High-Speed Photogrammetry

May 2025 – May 2027 | Project Manager: Rodrigo Herrera

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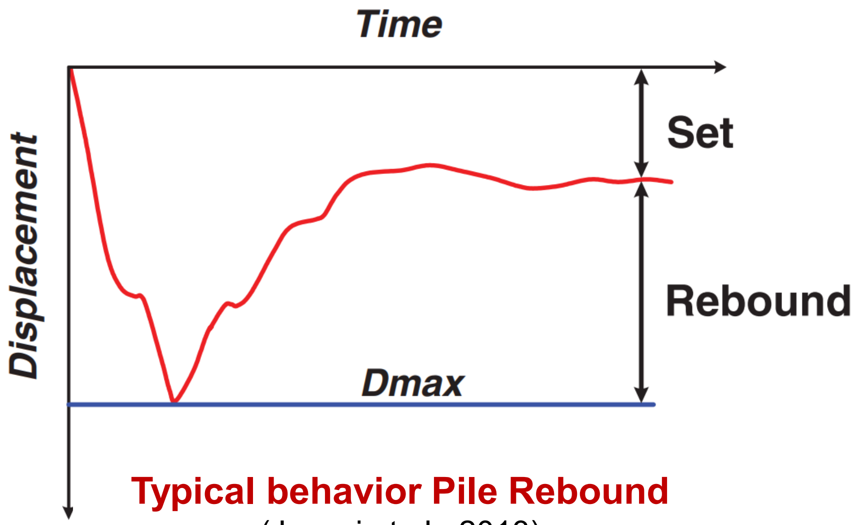
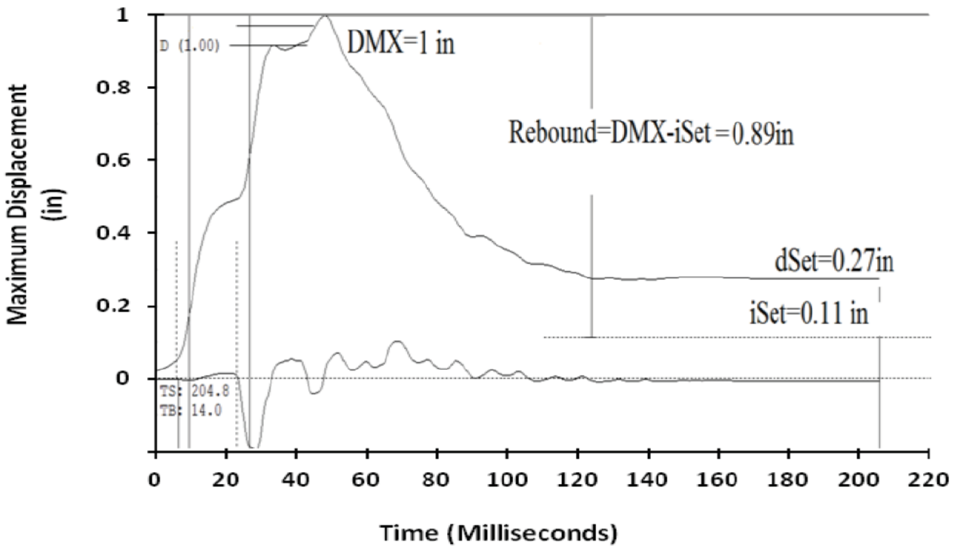
August 13, 2026 | SMO, Gainesville

Technical Background: Rebound



Typical behavior Pile Rebound
(Jausgi et al., 2013)



Typical PDA pile top displacement vs time from one hammer blow for an FDOT HPR site
(Consentino et al., 2020)

Pile rebound:

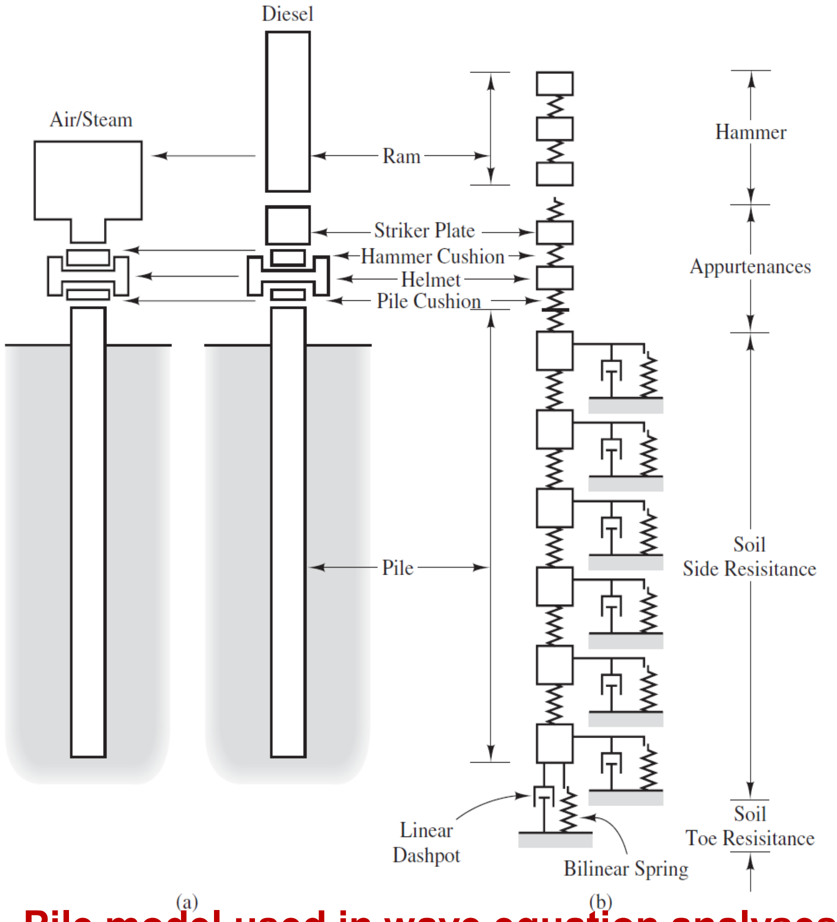
– Upward movement (elastic or plastic recovery) of a driven pile immediately after hammer impact during driving operations.
– Phenomenon influenced by the pile material properties, soil type, and pile-soil interaction mechanisms.

Previous studies:

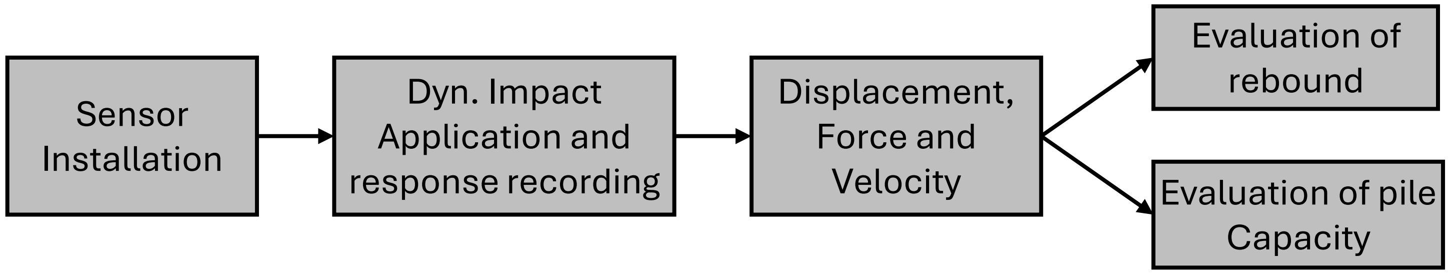
– Excessive rebound is found when (Jarushi et al., 2013; Hannigan et al., 1998):
  - Encounter with a very competent soil layer or rock.
  - High pore water pressures in cohesive soils.
  - Insufficient energy transfer during pile installation.
– Rebound has been monitored visually or using displacement sensors. Precise quantification remains difficult without high-resolution tracking (Cosentino et al., 2020).
– In problematic soils (e.g., clays with low permeability), rebound can mask actual pile behavior, leading to premature refusal or installation errors (Jarushi et al., 2013).
– Recent research highlights the importance of rebound (Reuter, 2019;Cosentino et al., 2010):
  - It affects drivability analyses and bearing capacity predictions.
  - It may result in overestimated capacity if ignored or misinterpreted.

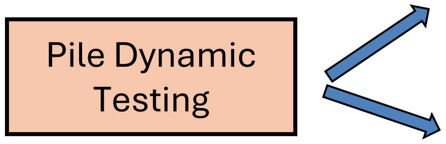
Technical Background: Pile Dynamic Test

- **Pile Dynamic Testing (PDT):**
  - Non-destructive method to evaluate load-bearing capacity during and after installation.
  - Based on Wave Equation Analysis, which models the stress wave propagation along the pile induced by an external dynamic load (Smith, 1960; Lee et al., 1988; Salgado et al., 2017).



Pile model used in wave equation analyses
(Coduto et al., 2016)





Embedded Data Collector (EDC)
- Sensors embedded during pile casting.

(McVay et al., 2009)

Pile Driving Analyzer (PDA)
- External sensors attached to the pile head.

(Pile Dynamics, Inc. 2000a)

Technical Considerations

- **Current Dynamic Testing Methods**
  - Pile Driving Analyzer (PDA) and Embedded Data Collector (EDC)
  - Require physical sensors either attached/embedded to pile
  - EDC is limited to specific pile types (e.g., cast-in-place concrete)
- **Photogrammetry Approach (Previous Studies)**
  - Previous studies using conventional cameras (≤ 60 Hz) show limitations in capturing fast dynamic responses; sensitive to vibration interference during measurements
- **High-Speed and High-Resolution Photogrammetry (Proposed)**
  - Proposed photogrammetry-based method enables non-contact, high-resolution monitoring with a sampling rate > 2,000-10,000Hz, allowing precise tracking of pile motion
  - Typical Pile Dynamic testing systems operate in the range of 2.5 to 10,000 Hz

Project Objectives

- To develop a **non-contact method using ultra-high-speed photogrammetry** to **measure pile displacements and rebound behavior** during driving operations across different pile types (e.g., precast concrete, steel pipe, H-piles).

- To evaluate the potential of imagen-based measurements for potentially **estimating pile capacity**, including comparisons with conventional methods.

- To provide **recommendations** for integrating photogrammetry into FDOT pile testing practices, particularly in scenarios where **sensor instrumentation** is limited.

Summary of Tasks/Deliverable Schedule

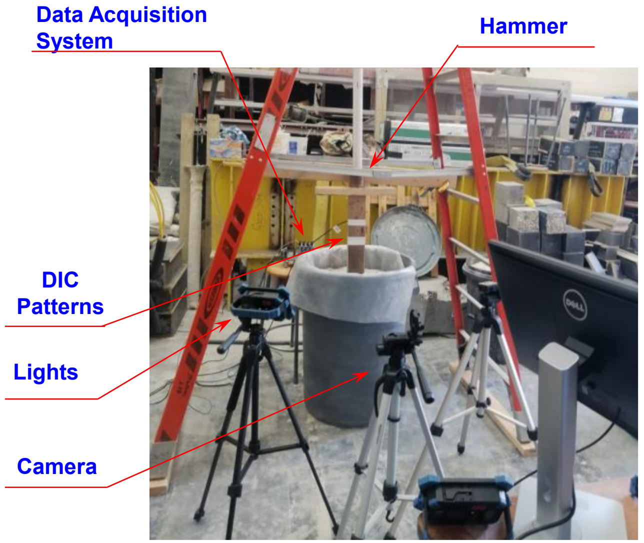
TASK AND ASSOCIATED DELIVERABLE	DATE
Kickoff teleconference	06/2025
Deliverable 1: A technical report presenting the results of the technical background on pile monitoring instrumentations, existing applications of ultra-high-speed cameras, image processing methods, and past case studies.	09/2025
Deliverable 2: Development of high-speed camera sensing system and data collection, and development of image processing algorithm for digital image correlation	02/2026
Deliverable 3: Small-scale rebound and pile resistance demonstrational testing in laboratory environment.	07/2026
Deliverable 4: Medium-scale physical model testing of rebound and pile resistance in high-bay structural laboratory.	12/2026
Deliverable 5: Full-scale field application and demonstration at selected pile driving sites	02/2027
Deliverable 6a Draft final report.	03/2027
Deliverable 6b: Closeout teleconference meeting and PowerPoint presentation	04/2027
Deliverable 7: Final report	04/2027

Presentation Overview

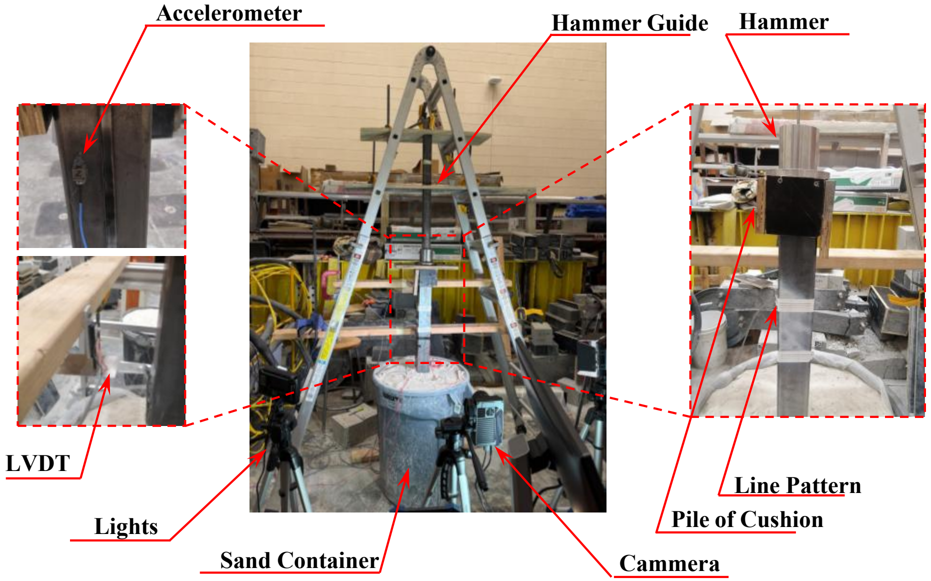
- **Project Introduction**
- **Review of Past Deliverables**
  - Deliverable 1: Technical Background and Preliminary Validation
  - Deliverable 2: Software and Preliminary Results
  - Deliverable 3: Small-Scale Rebound & Pile Resistance in Lab Testing
- **DIC Background and 2D-DIC**
- **Transformation from 2D-DIC to 1D-DIC**
- **Current Work: Medium-Scale Pile Tests**
- **Future Work**
- **Discussion and Comments from FDOT**

Deliverable 1: Technical Background and Preliminary Validation

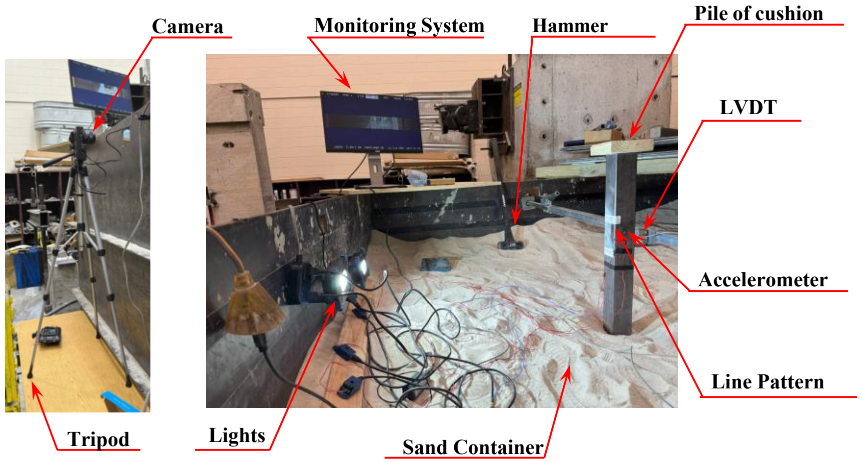
- **Conducted a Literature Review About**
  - High pile rebound (HPR), Pile Dynamic testing (PDA/CAPWAP), and Non-contact optical measurement techniques.
- **Preliminary Experimental Validation Using an area Scan Camera**



a) Wood pile in a bucket.



b) Steel pile in a large sand container (medium scale).



c) Steel pile in a large sand container (medium scale).

Deliverable 2: Software and Preliminary Results

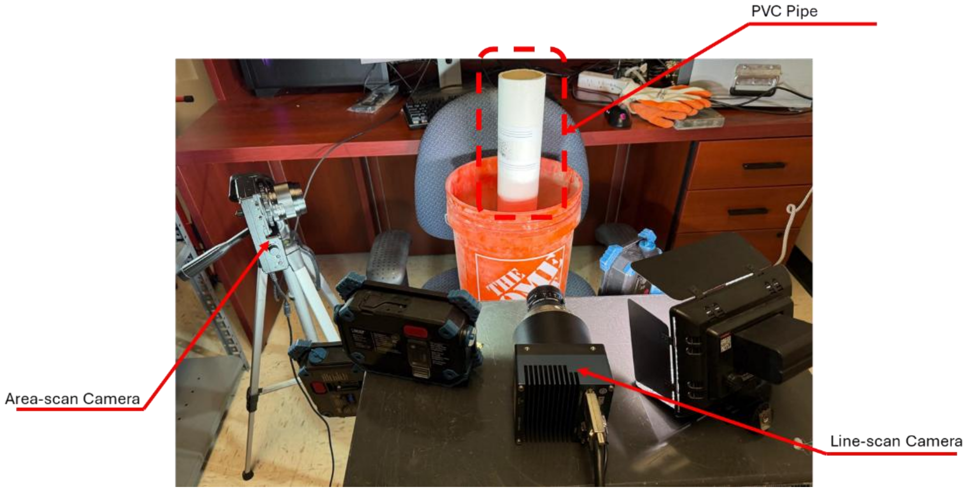
- **Hardware System for Image and Video Acquisition**
  – Hardware architecture, area- and line-scan imaging systems, camera calibration and data acquisition, and data management and future development.
- **Preliminary Experimental Tests: Wave Velocity in Piles**

Wave velocity ↑ **Wave velocity ↓**

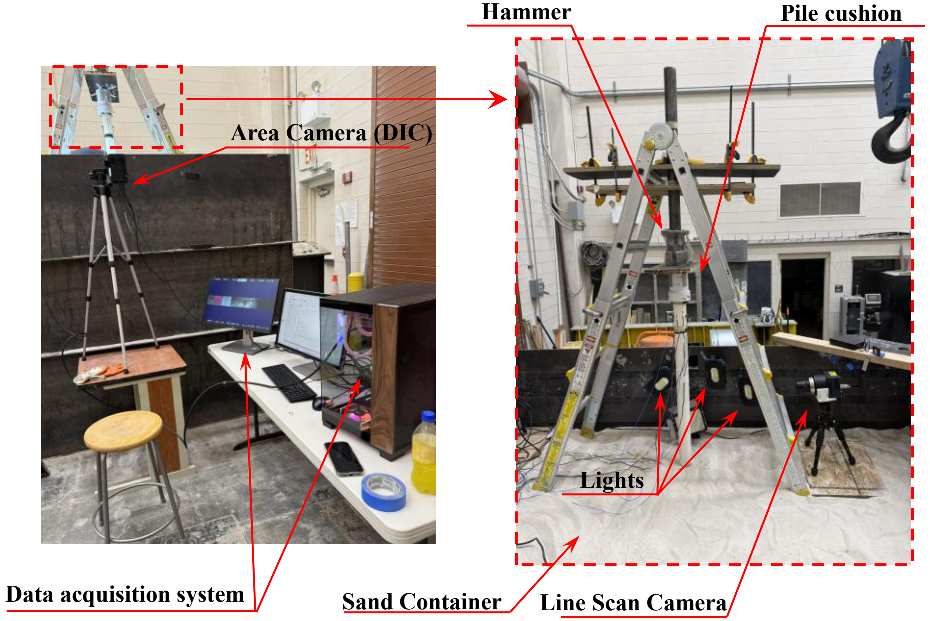
- **Development of a Force-Based Framework for Evaluating Pile Rebound Risk**
  – Relationship between pile resistance (static and dynamic) and pile driving force parameters

Deliverable 3: Small-Scale Rebound & Pile Resistance in Lab Testing

- **Developed the Line-Scan Camera System**
  - 3D printed mount, frame duplication correction, and data acquisition verification
- **Small and Medium Scale Testing Using the Line Scan Camera**



a) Small-Scale testing

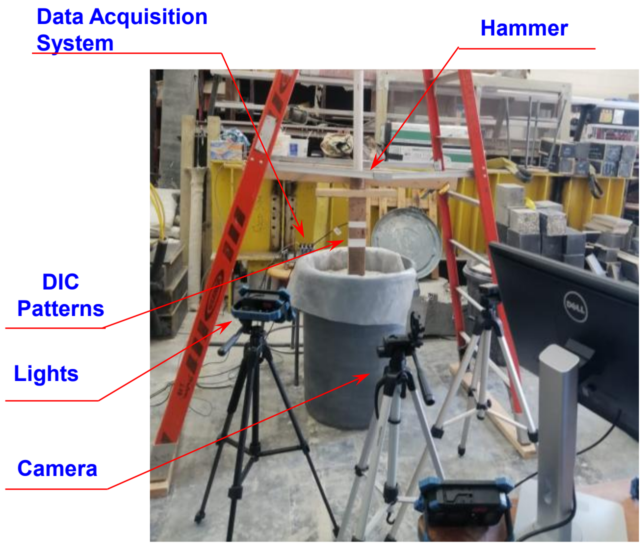


b) Medium-Scale testing

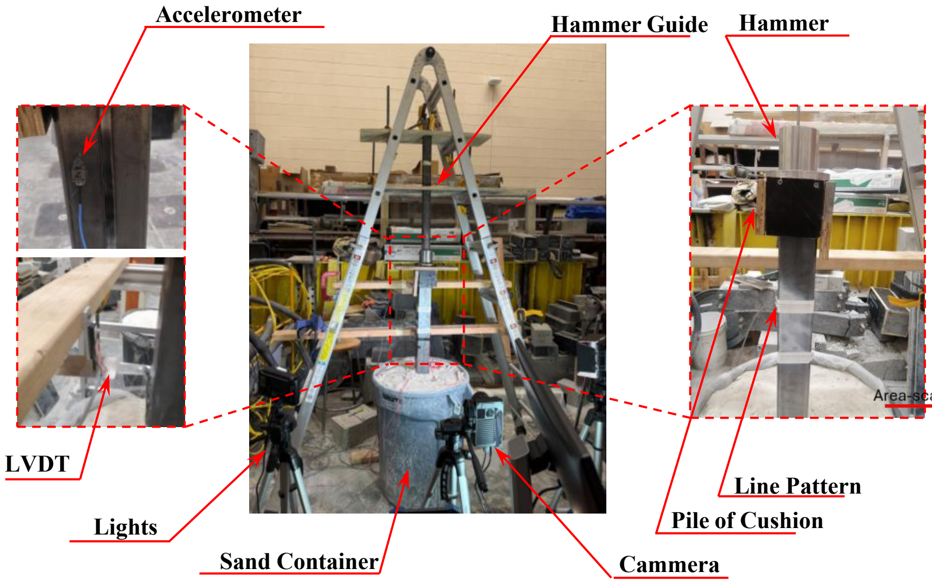
- **Update of the parametric analysis for the evaluation of pile rebound resistance components.**

Small-Scale Pile tests

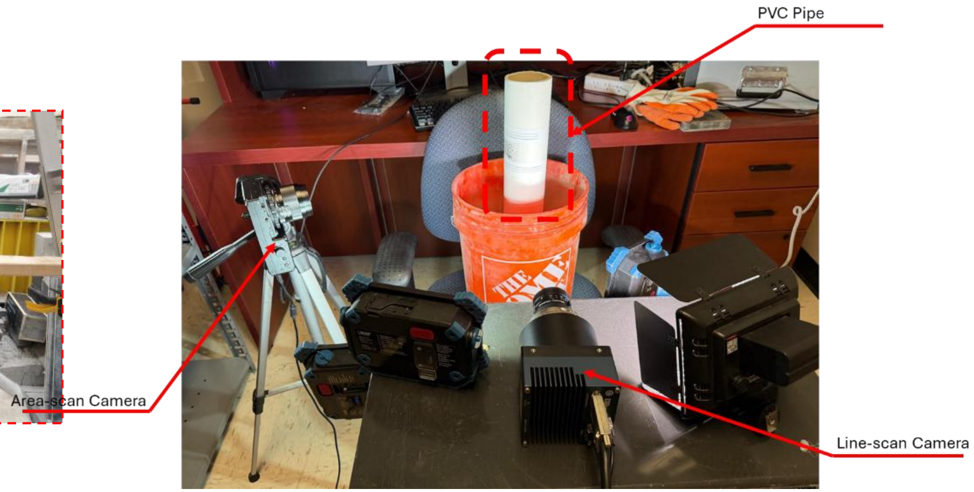
- **Progressive Development of the Experimental System**
  - Patterns evaluation, wave velocity, camera type, and hammer system.



a) Wood pile: Initial validation of displacement with Area Scan Camera.



b) Steel pile: Evaluation of displacement measurements using the Area Scan Camera.



c) PVC pile: Integration and verification of the Line Scan camera.

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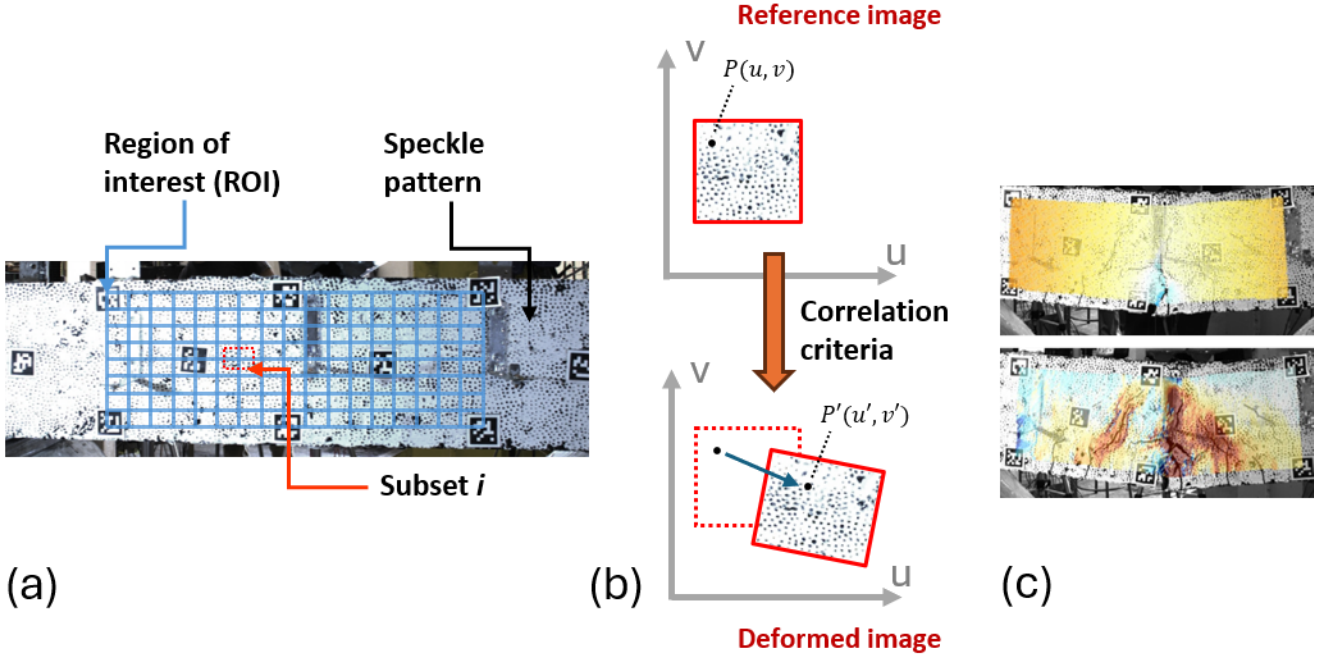
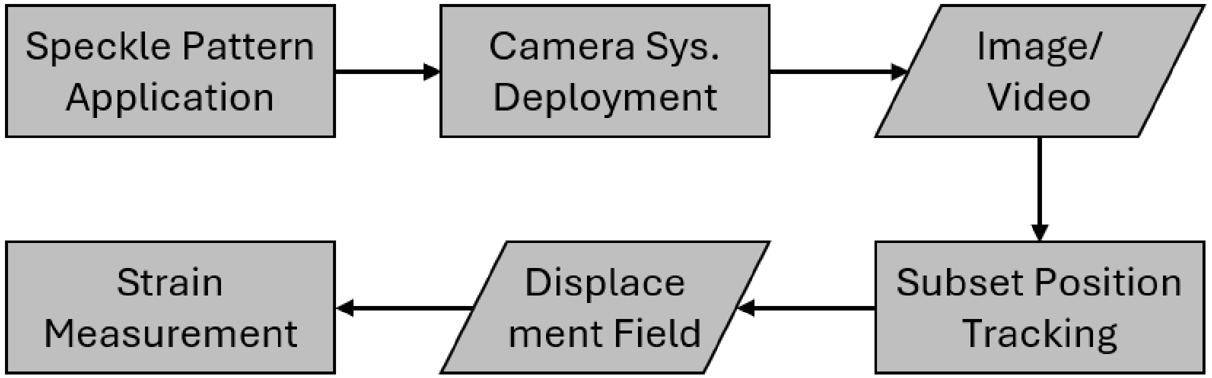
Digital Image Correlation (DIC): Background

- **What is DIC?**
  - Optical, non-contact full-field displacement/strain measurement
  - Tracks surface texture across image sequence
- **How it Works?**
  - Surface split into subsets (unique grayscale pattern)
  - Tracking pixel subsets between a reference and deformed image
  - Subset shifted over deformed image to find best match
  - Displacement = relative shift (reference → deformed)





Digital Image Correlation Flowchart

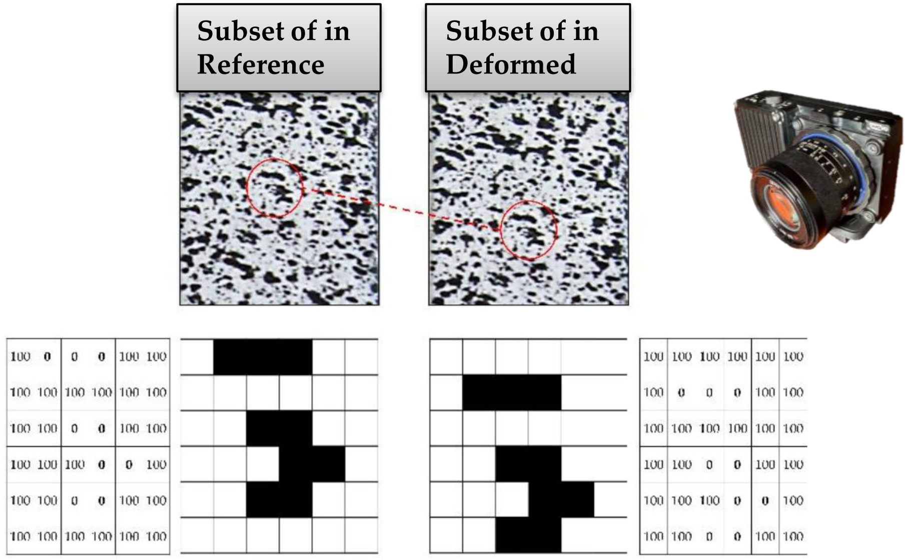
APOSTOLAKIS, G., MACKIE, K. R., IRANIPARAST, M. & SUN, P. P. 2024. UHPC girder multi-modal deformation measurements: Photogrammetry, physical sensing, and FEA. *Structures,* 70, 107790.

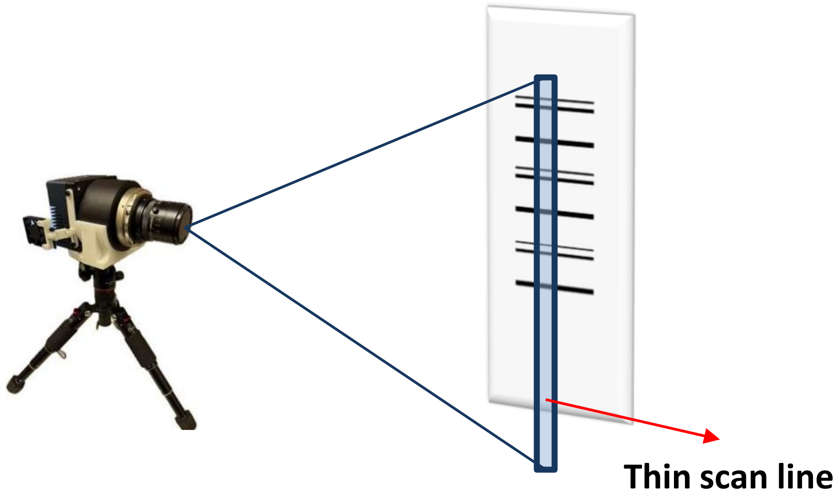
Subset Matching Criteria in DIC

- **Cross-correlation (CC) criteria identify the maximum similarity**
- **Sum of squared differences (SSD) criteria identify the minimum intensity difference**

Type	Formula
Cross-Correlation (CC) Family	
Direct CC	$C_{\text{CC}} = \sum f_i g_i$
Zero-Mean CC (ZCC)	$C_{\text{ZCC}} = \sum (f_i - \bar{f})(g_i - \bar{g})$
Normalized CC (NCC)	$C_{\text{NCC}} = \dfrac{\sum f_i g_i}{\sqrt{\sum f_i^2 \sum g_i^2}}$
Zero-Mean Normalized CC (ZNCC)	$C_{\text{ZNCC}} = \dfrac{\sum (f_i - \bar{f})(g_i - \bar{g})}{\sqrt{\sum (f_i - \bar{f})^2 \sum (g_i - \bar{g})^2}}$
Sum of Squared Differences (SSD) Family	
Direct SSD	$C_{\text{SSD}} = \sum (f_i - g_i)^2$
Zero-Mean SSD (ZSSD)	$C_{\text{ZSSD}} = \sum \left[(f_i - \bar{f}) - (g_i - \bar{g})\right]^2$
Normalized SSD (NSSD)	$C_{\text{NSSD}} = \sum \left[\dfrac{f_i}{\sqrt{\sum f_i^2}} - \dfrac{g_i}{\sqrt{\sum g_i^2}}\right]^2$
Zero-Mean Normalized SSD (ZNSSD) ✓ *used in this project*	$C_{\text{ZNSSD}} = \sum \left[\dfrac{f_i - \bar{f}}{\sqrt{\sum (f_i - \bar{f})^2}} - \dfrac{g_i - \bar{g}}{\sqrt{\sum (g_i - \bar{g})^2}}\right]^2$

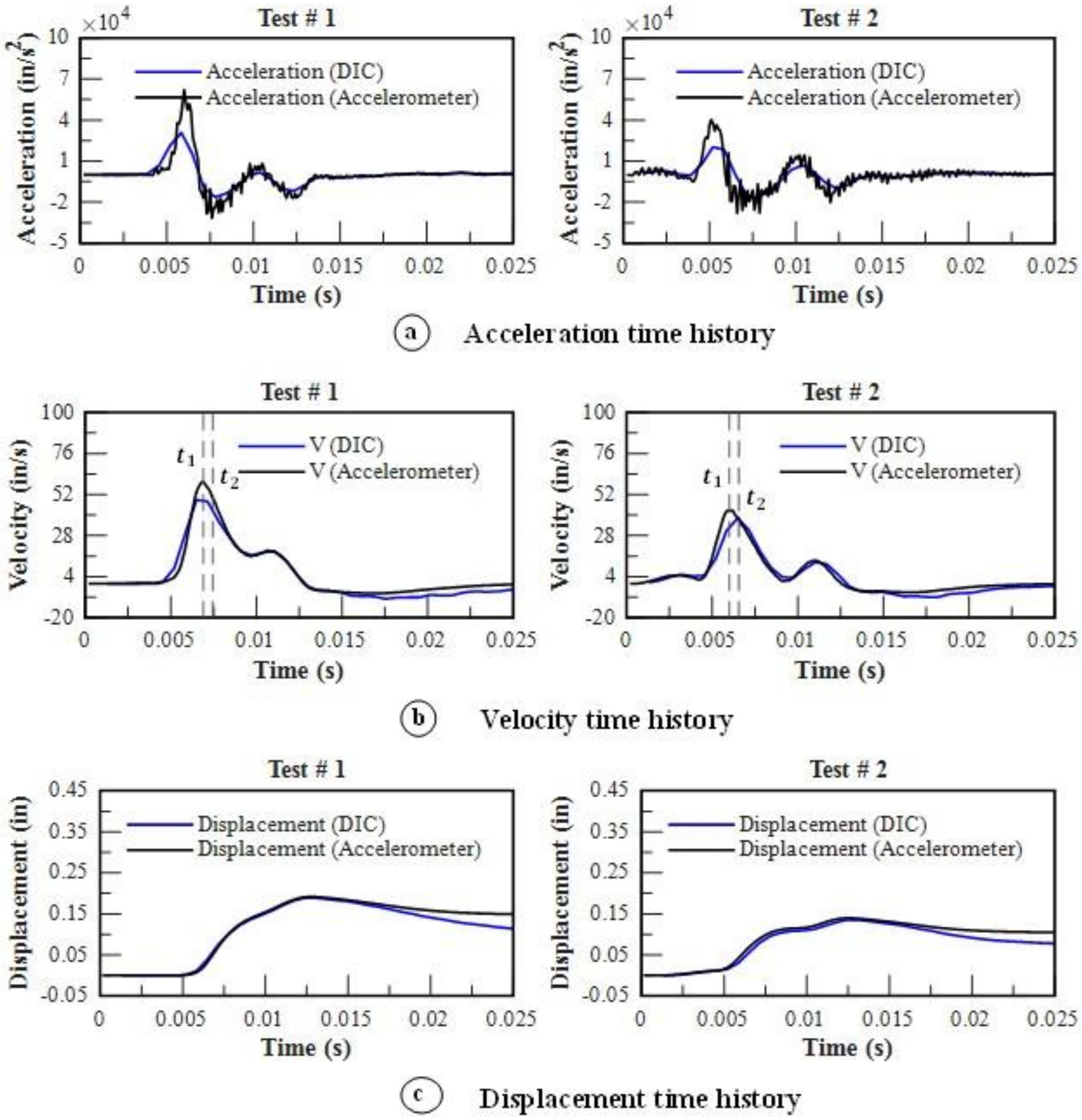
$f(x_i, y_i)$ and $g(x_i, y_i)$ denote the gray values of the i-th pixel in the reference and deformed subsets, respectively;
$\bar{f}$ and $\bar{g}$ are the mean gray values of the reference and deformed subsets, respectively.





Journey of 2D-DIC: Area-Scan Camera

- **Area-scan DIC captures full pile dynamics**
- **Sensing**
  - Freefly Wave ultra-high-speed CMOS
  - ZEISS Loxia 50 mm f/2 E-mount lens
  - Random speckle pattern+ 10 mm line patterns for calibration
- **Method: 2D-DIC**
  - MATLAB on open-source Ncorr engine
  - Subset-based correlation, sub-pixel interpolation
  - ZNCC criterion: robust to lighting and sharp peak
- **Validation**
  - Displacement → velocity → acceleration
  - Cross-checked vs. head accelerometer
  - Strong agreement on shape, peak timing, net displacement



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Why Moved from 2D-DIC to 1D-DIC?

2D-DIC

full-field, area-scan

- Correlate every subset across a 2D ROI
- Thousands of full frames per test
- Multi-GB recordings in seconds
- Heavy processing time and memory

→

1D-DIC

reduced-field, line-scan

- Correlate along one sensing line
- Records a single line, far less data
- Much faster to process
- Up to 60 kHz, finer temporal detail

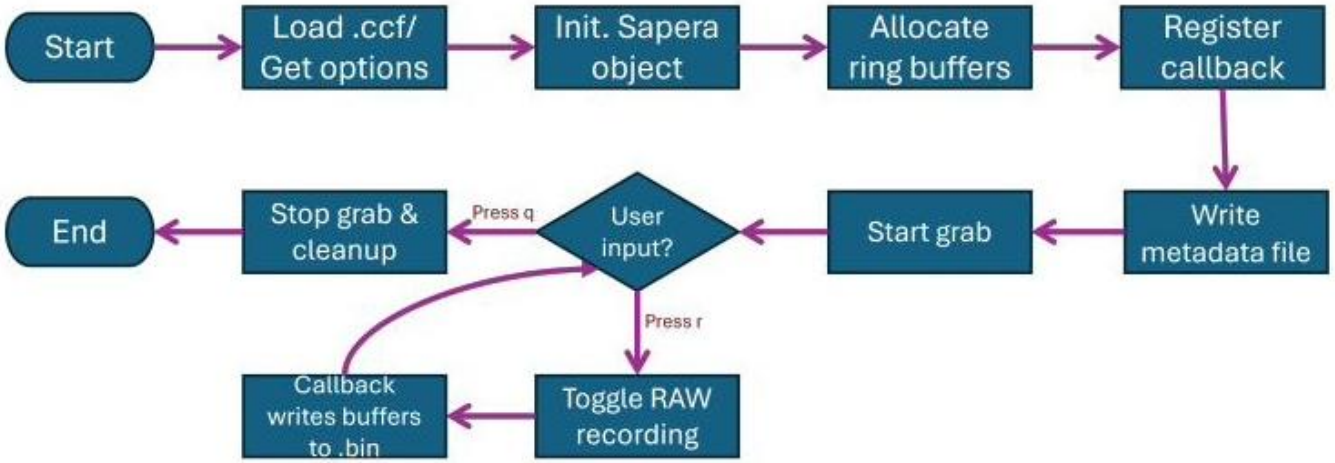
- **Key insight**
  - 2D field = more computation than axial motion needs
  - Line-based DIC → much less data (1D over 2D), much faster (collection 60kHz over 2kHz, processing x100), much higher temporal resolution (16K over 4K)

Journey of 1D-DIC: Line-Scan Camera (Totally Different Animal!)

Hardware

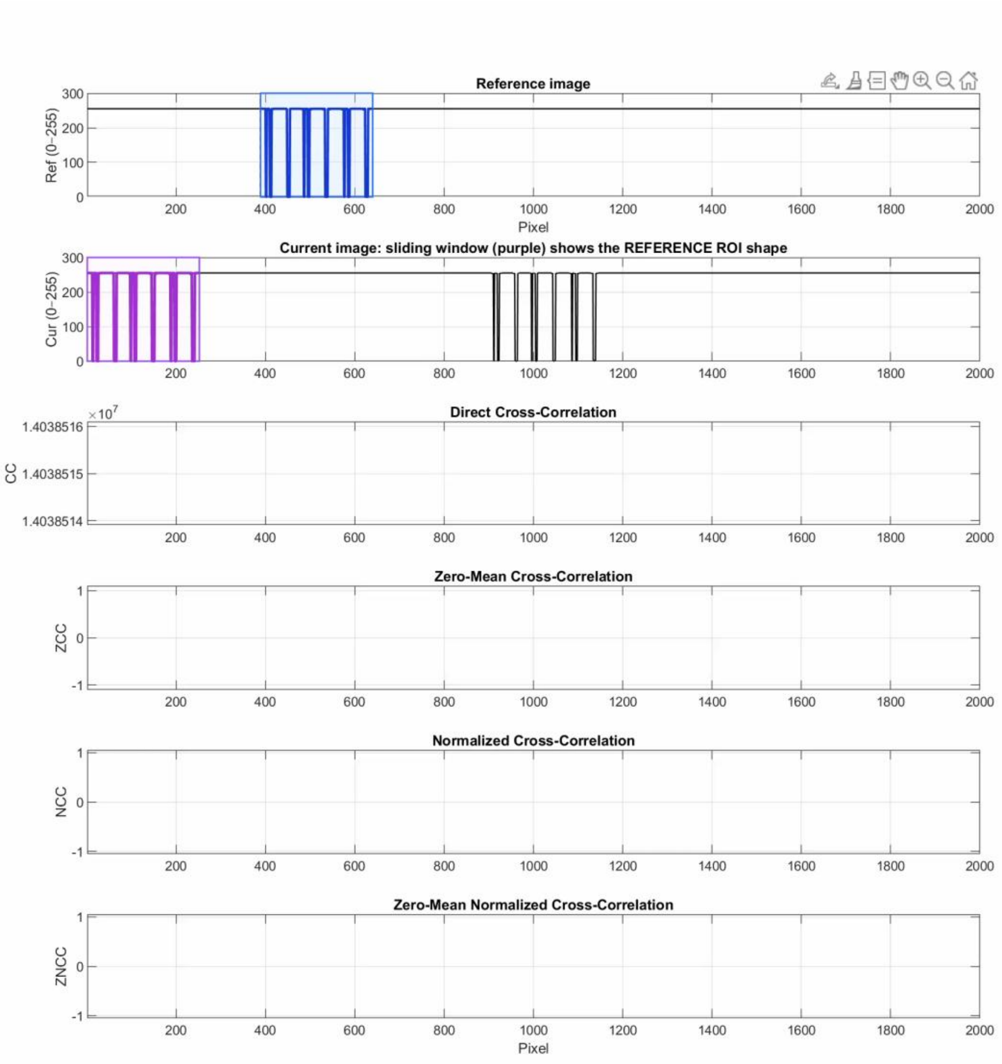
- **Teledyne DALSA**
  - Xtium-CLHS PX8 frame grabber
  - Camera Link HS (PCIe ×8, DMA streaming)
  - External active cooling

Software



- **GrabCPP**
  - Custom C++ on the Teledyne DALSA API
  - CamExpert sets camera config (.ccf) file
  - Save line pixel data as uncompressed .bin

1D-DIC Cross Correlation (CC): Line-Scan Camera



$$C_{CC} = \sum f_i g_i$$

Pros: Give local extremums
Cons: Sensitive to brightness

$$C_{ZCC} = \sum (f_i - \bar{f})(g_i - \bar{g})$$

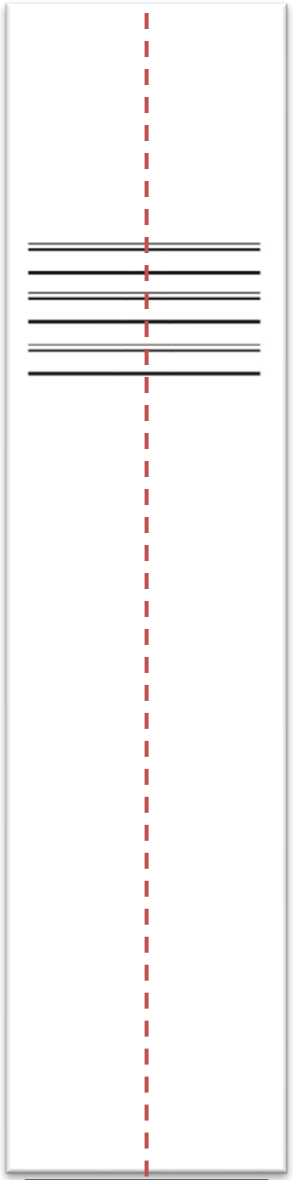
Pros: Removes brightness offset
Cons: Large/small intensity ranges

$$C_{ZCC} = \sum (f_i - \bar{f})(g_i - \bar{g})$$

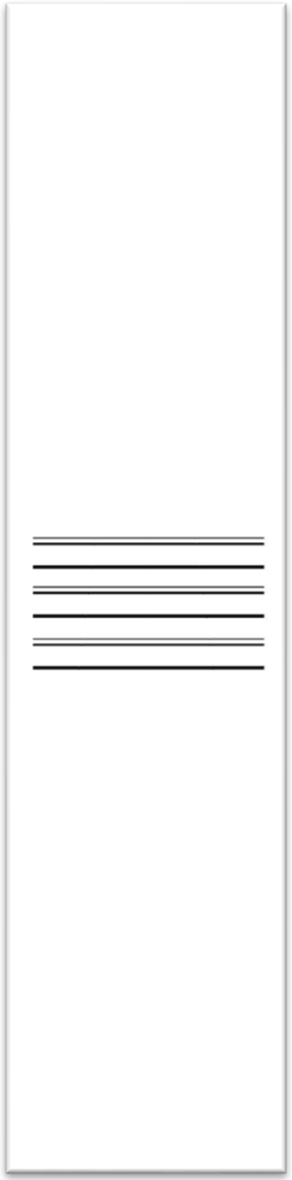
Pros: Independent of intensity
Cons: Baseline differences

$$C_{ZCC} = \sum (f_i - \bar{f})(g_i - \bar{g})$$

Pros: Give valuable range
Cons: Computationally expensive

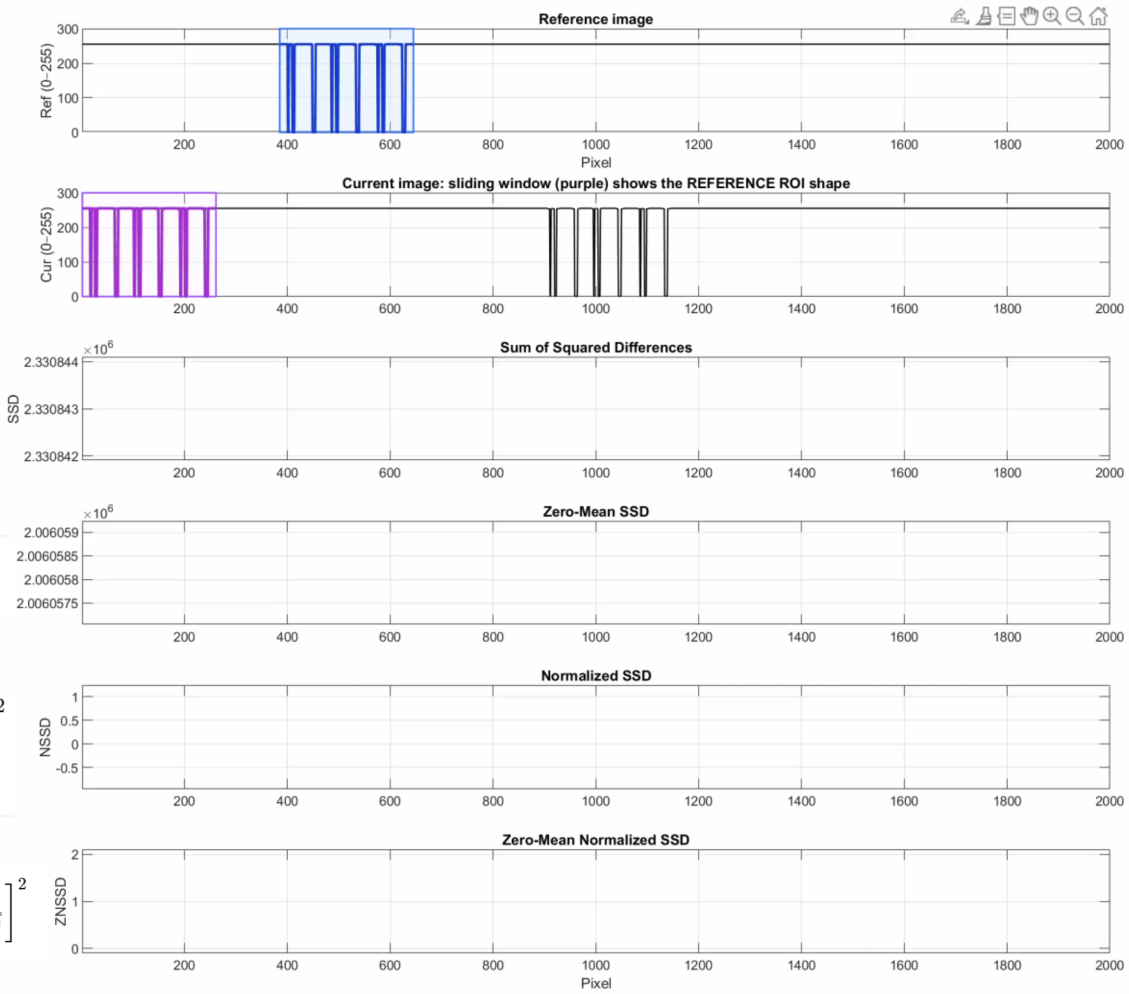


Reference image



Current image

1D-DIC Sum of Squared Differences (SSD): Line-Scan Camera



$$C_{\text{SSD}} = \sum (f_i - g_i)^2$$

Pros: Simple, local extremums
Cons: Large/small intensity ranges

$$C_{\text{ZSSD}} = \sum [(f_i - \bar{f}) - (g_i - \bar{g})]^2$$

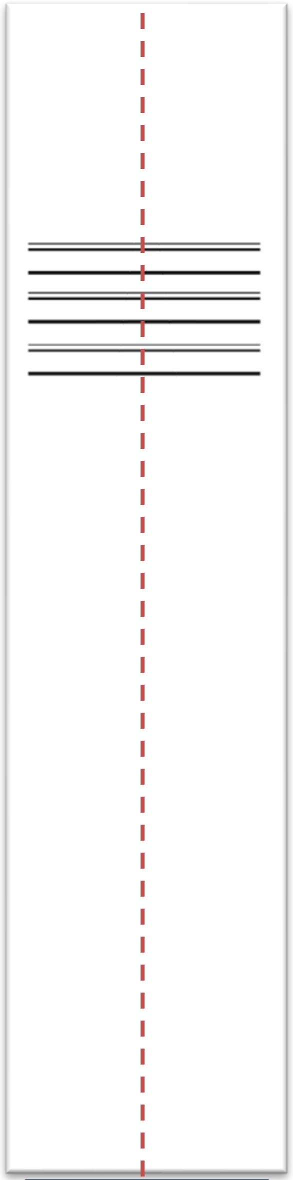
Pros: Removes brightness offset
Cons: Large/small intensity ranges

$$C_{\text{NSSD}} = \sum \left[\frac{f_i}{\sqrt{\sum f_i^2}} - \frac{g_i}{\sqrt{\sum g_i^2}} \right]^2$$

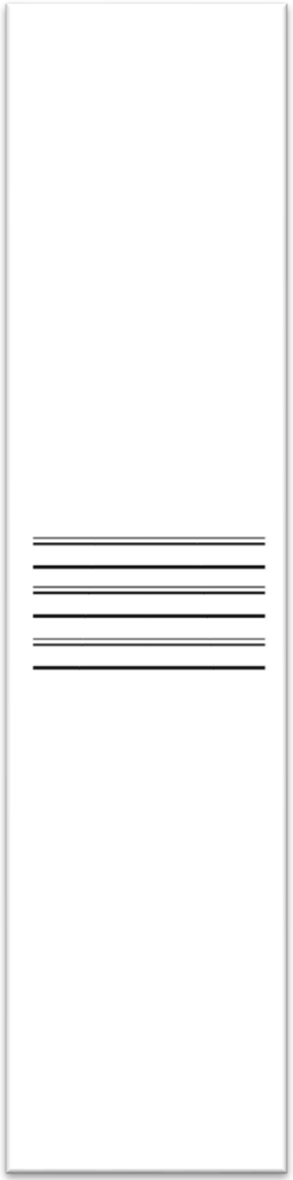
Pros: Scale invariant
Cons: Baseline differences

$$C_{\text{ZNSSD}} = \sum \left[\frac{(f_i - \bar{f})}{\sqrt{\sum (f_i - \bar{f})^2}} - \frac{(g_i - \bar{g})}{\sqrt{\sum (g_i - \bar{g})^2}} \right]^2$$

Pros: Give valuable range
Cons: Computationally expensive



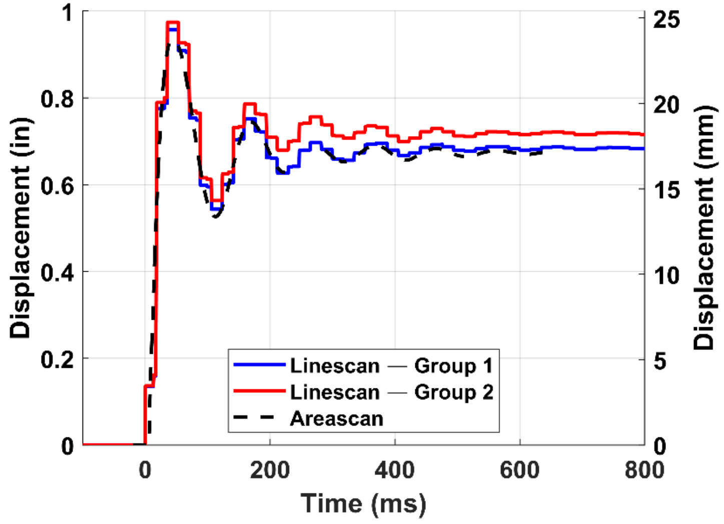
Reference image



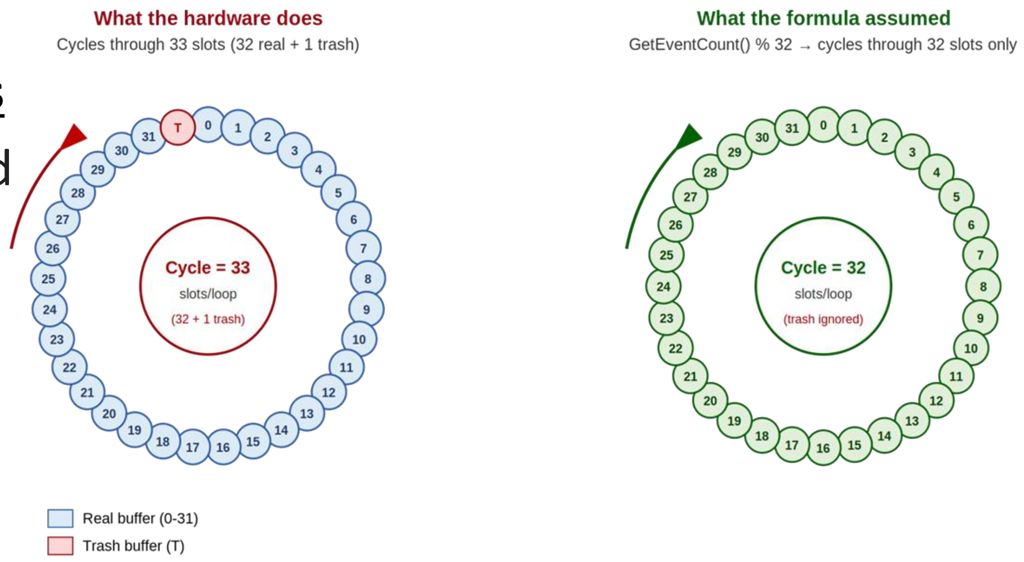
Current image

Journey of 1D-DIC: Stepped-Displacement Output

- **Staircase artifact in 1D-DIC output**
  - Flat zero intervals, then abrupt jumps
  - Inconsistent with real pile kinematics
- **Trouble shooting methods**
  - Pixel-to-length recalibration → no change x
  - DIC subset size adjustment → no change x
  - Speckle / surface texture re-check → no change x
- **Root cause: buffer-indexing bug in GrabCPP**
  - GrabCPP callback used idx = count % 32 slots
  - **SapBufferWithTrash adds 1 hidden trash slot → 33 slots**
  - Index drifts → stale frame re-written → ~97% duplicated

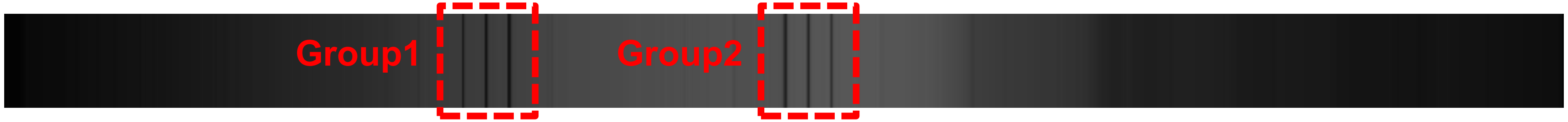


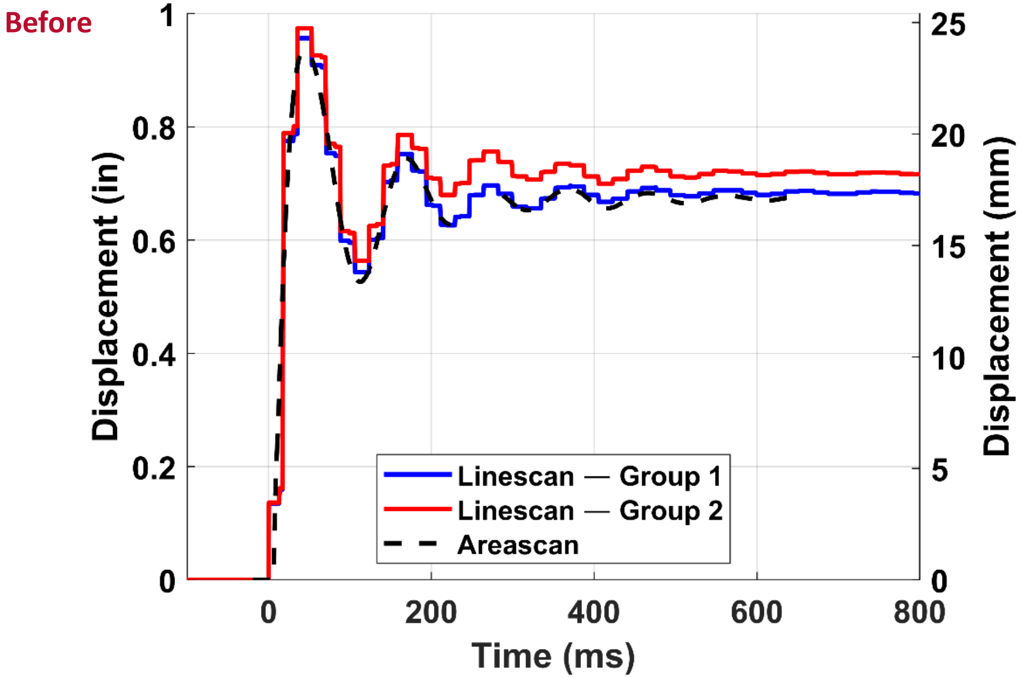
SapBufferWithTrash Function

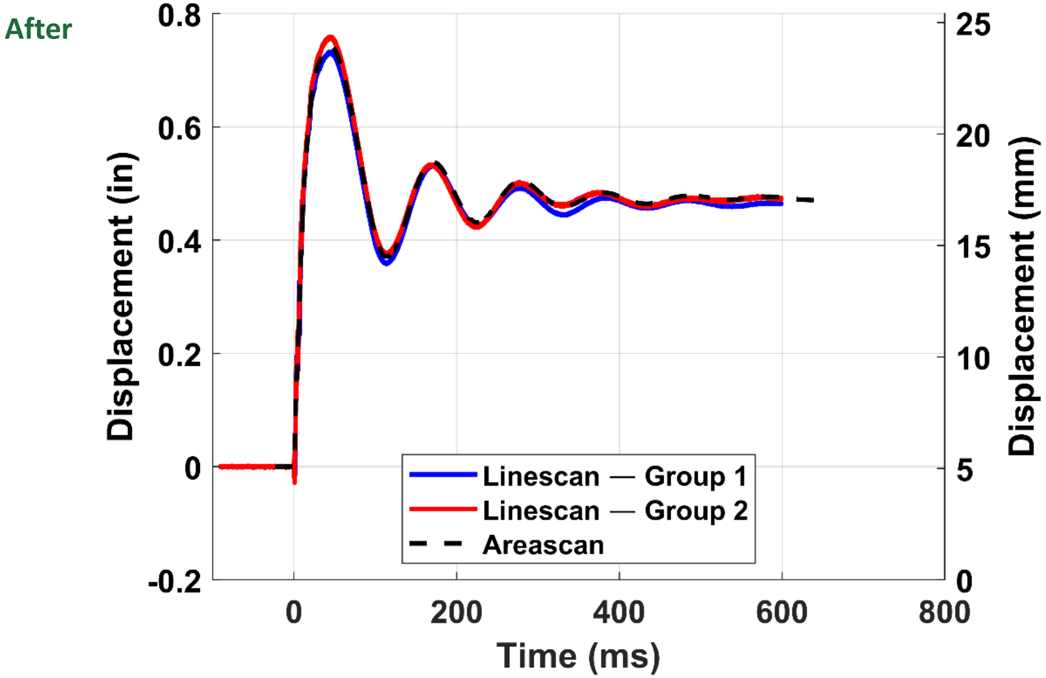


96.97%
Duplicated frame
↓
0.00%
after fix

Journey of 1D-DIC: Validation in Displacement







- **Validation evidence**
  - Two line-scan groups overlap the area-scan 2D-DIC reference across the full record
  - 0 duplicate frames out of 242,445 frames (0.0000%)
  - Line-scan reaches 18,848 lines/sec

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- DIC Background and 2D-DIC
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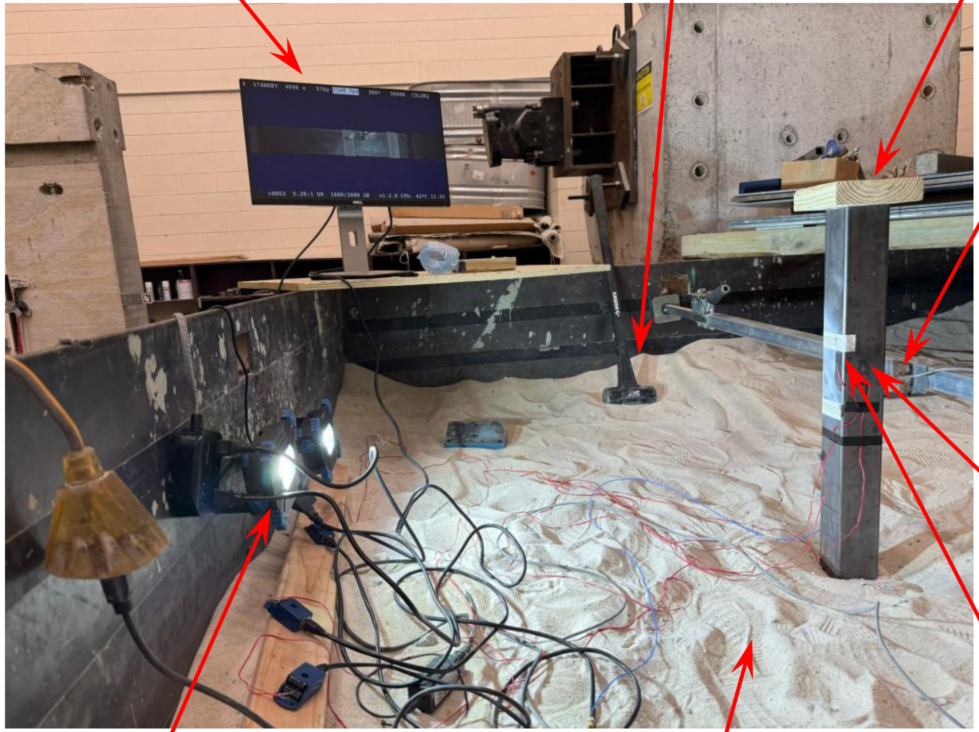
- **Current Work: Medium-Scale Pile Tests**
  - Sandbox Experiment: Displacement, Velocity, and Strains
  - Improved Experiment: “Hopkinson” Pile Test
  - Parametric Analysis for Evaluation of Pile Rebound Risk
- **Future Work**
- **Discussion and Comments from FDOT**

Current Work: Medium-Scale Pile Tests

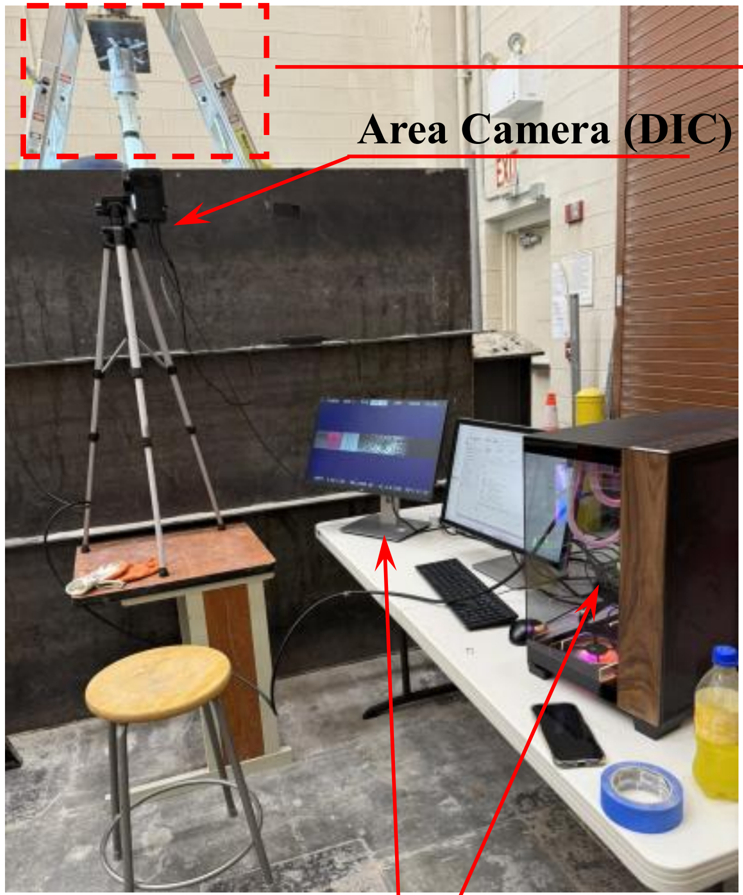
Progressive Development of the Experimental System

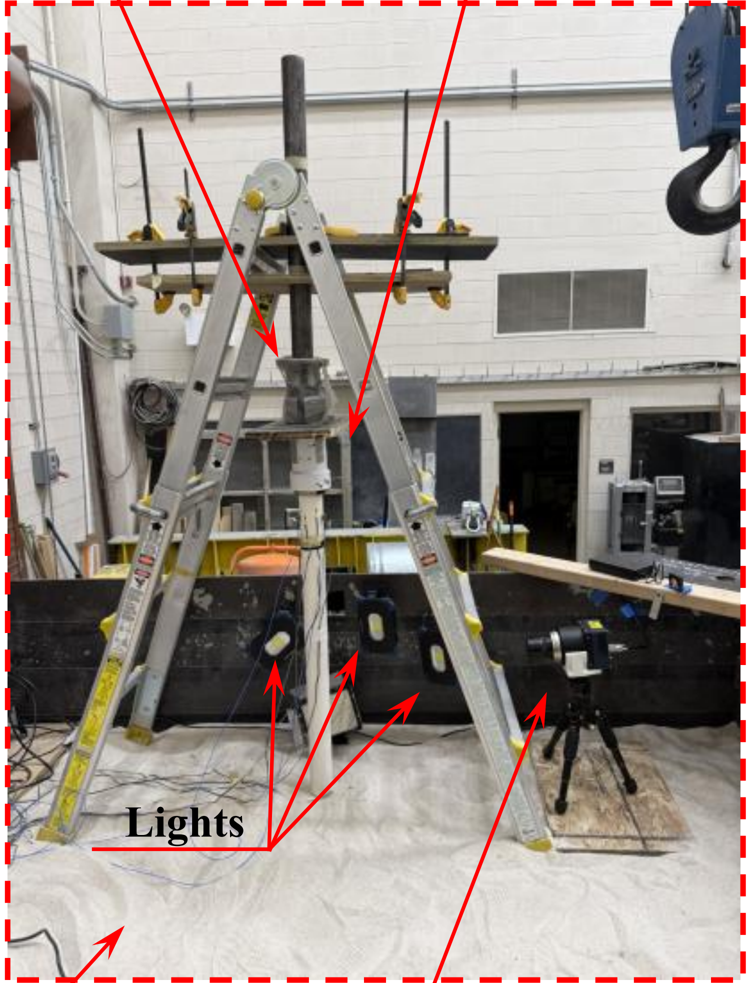
✓ Patterns evaluation, wave velocity, camera type, and sensor integration.



Steel pile: evaluation of displacement measurements using the area scan camera.

Current Work: Medium-Scale Pile Tests (PVC Piles)





Hammer

Pile cushion

Area Camera (DIC)

Lights

Data acquisition system

Sand Container

Line Scan Camera

PVC pile: integration and verification of the line-scan and area-scan cameras.

Measurement of Displacement and Velocity

DIC
Vision-Based

PDA
Acceleration-Based

DIC

Displacement:
- Surface-pattern tracking
- **Direct** displacement measurement
- Avoids integration-induced drift

Velocity:
- Differentiation of displacement
- May amplify measurement noise

PDA

Displacement:
- **Double integration** of acceleration
- Low-pass filtering before integration
- Susceptible to cumulative drift from low-frequency noise and sensor bias

Velocity:
- Single integration of acceleration
- Residual velocity offset correction
- Susceptible to integration-induced drift

PDA Signal Processing:

Acceleration → Low-pass filtering → Integration → Velocity → Residual velocity offset correction → Integration → Displacement

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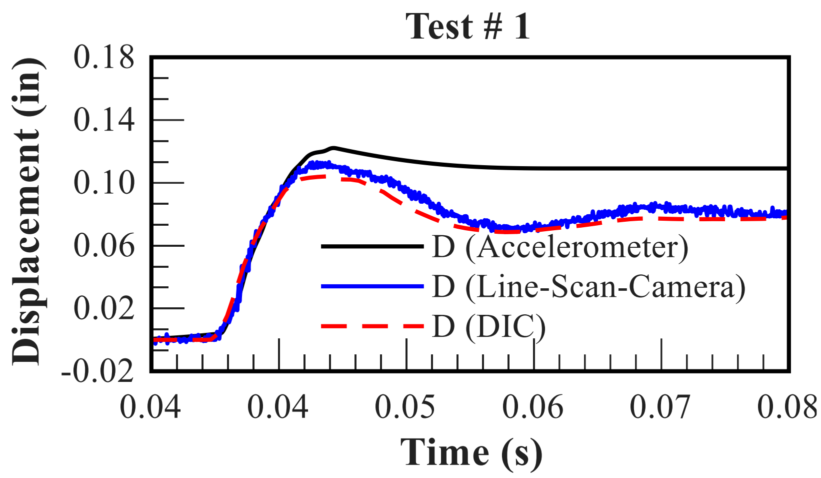
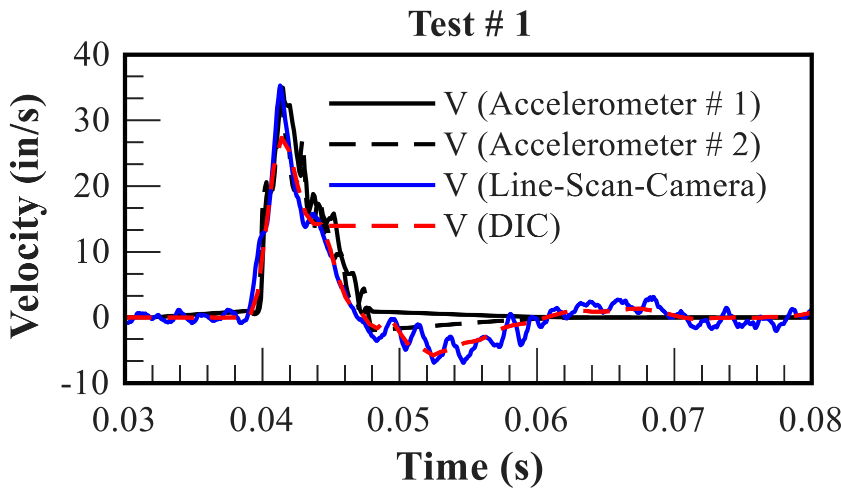
Camera Sampling Rates:

Line-scan camera: 18800 Hz

Area-scan camera: 1722 Hz





Background: Motion Blur Issue (Structural Dynamics)

- **Motion blurs:**
  - Global blur: camera moves (e.g., robotic vision, moving car), blurred background
  - Local blur: blurred target (object) moves in a static background (e.g., shake table)

Global blur

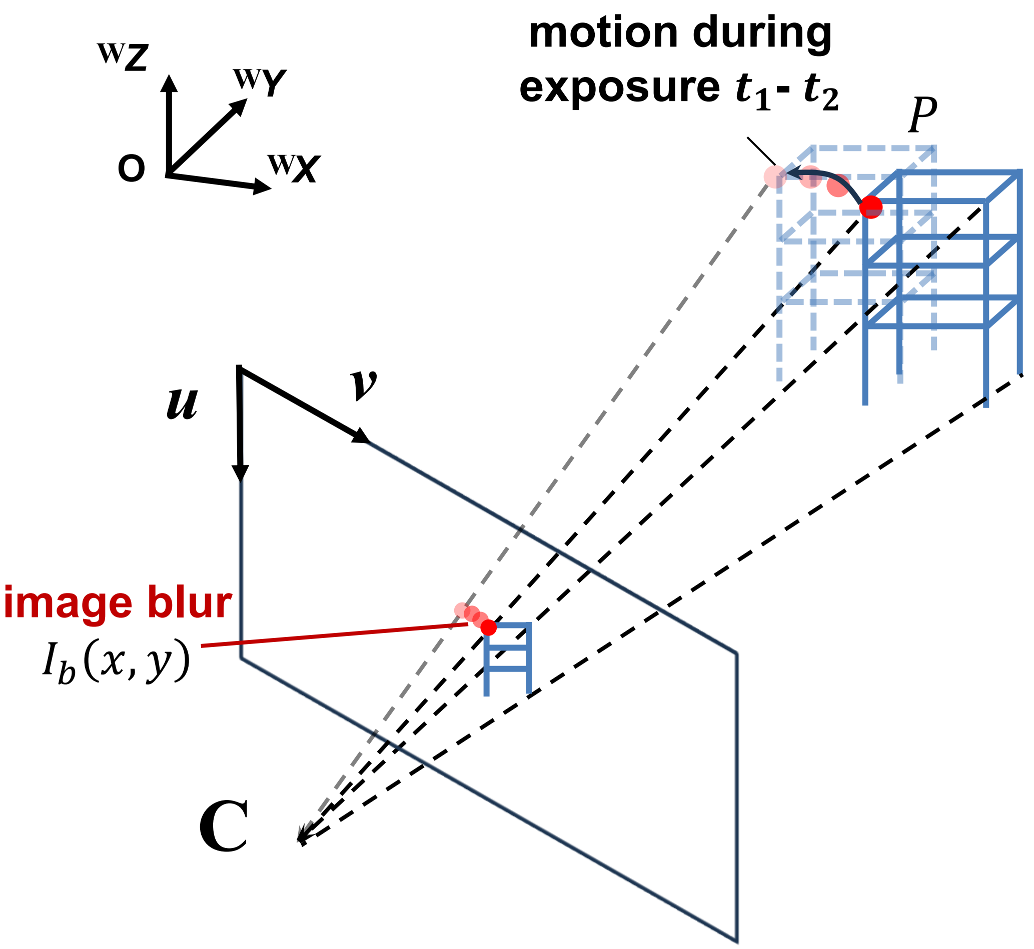
Local blur

- **What factors affect motion blurs?**
  - Shutter speed of camera (affordable -> low shutter speed)
  - Relative movement speeds between cameras and recorded objects

https://expertphotography.com/motion-blur/
https://www.premiumbeat.com/blog/motion-blur-premiere-pro/

Motion Blur Issue in Dynamics

- **Local motion blur in dynamics:**
  - Formulated as the accumulation of photons on camera sensor:
    - $I_b(x,y) = \mathrm{ISP}\left(\int_{t_1}^{t_2} f(t,x,y)\,dt\right)$
      - $\mathrm{ISP}(\cdot)$ - image signal processor operator
- **Potential solution: image deblur**
  - **Spatial**: homogeneous vs heterogeneous?
  - **Setting:** single-frame vs multi-frame?
  - **Manner**: blind (pre-estimated kernel) vs non-blind (realistic but ill-posed)?
  - **Blur kernel:** blur kernel-based vs end-end kernel-free / learning-based?



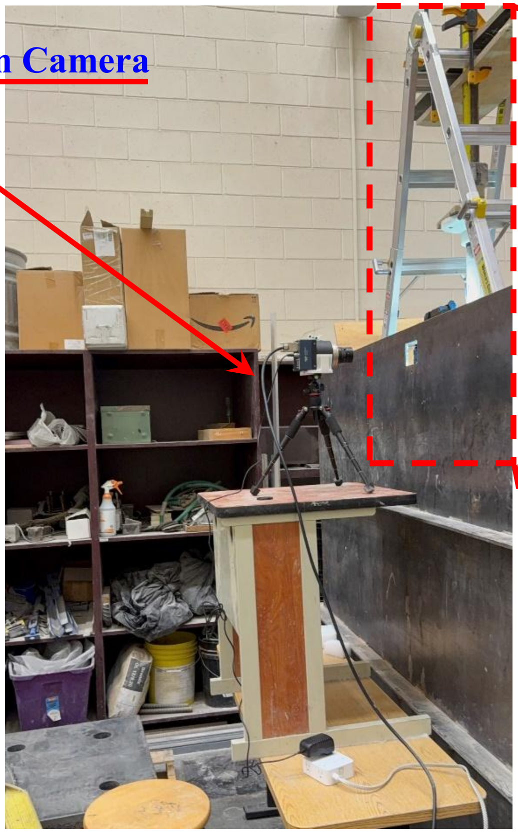
$$^S\mathbf{x}_{p'} \sim \mathbf{M}_{\mathrm{aff}}\,\mathbf{M}_{\mathrm{proj}}[\mathbf{R}|\mathbf{T}]\,^W\mathbf{X}_P$$

Motion blur in structural dynamics

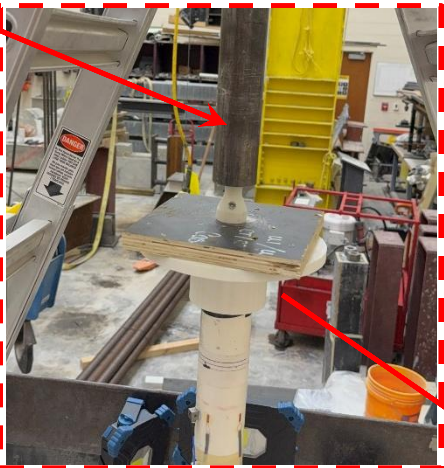
Improvement: Removing Blur (Camera Setting and Darker Pattern)

Test	FPS	Image
1	12804	
2	12804	
3	12804	

Line Scan Camera

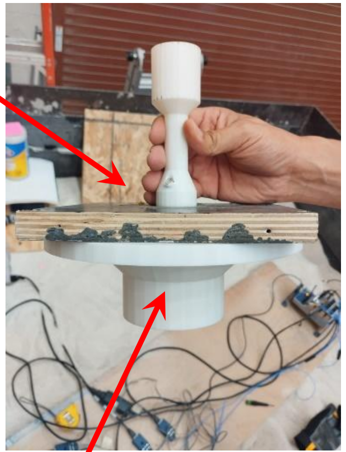


Hammer Guide



=== Recording Details ===
Width=16384 px
Height=1 px
PitchBytes=16384
BytesPerFrame=16384
LinesPerFrame=1
Exposure=75 µs

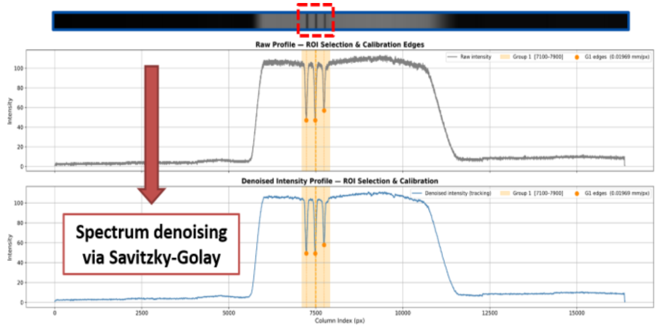
Pencil Line Pattern



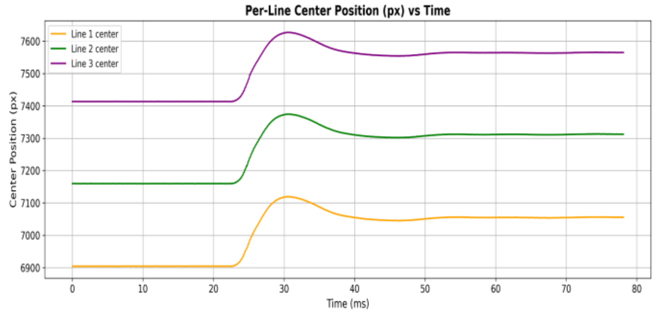
Centralizer

Revised Measurement Pipeline (After Experiments)

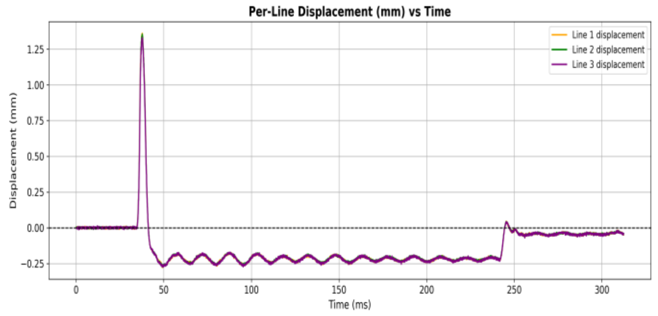
- **Step 1: Initialization (done once, on the reference frame)**
  - Load the image sequence and select the frame range to analyze
  - Define the region of interest (ROI) bracketing the marker lines
  - Calibrate the spatial scale (mm per pixel) from the known line spacing
  - Build the zero-strain reference by averaging line positions over the first frames



- **Step 2: Per-frame data processing (repeated for every frame)**
  - Obtain the 1-D intensity profile (single row, or averaged across rows)
  - Denoise the profile spatially with a Savitzky–Golay filter
  - Locate lines coarsely by ZNSSD template matching
  - Refine to sub-pixel precision with a Gaussian valley fit

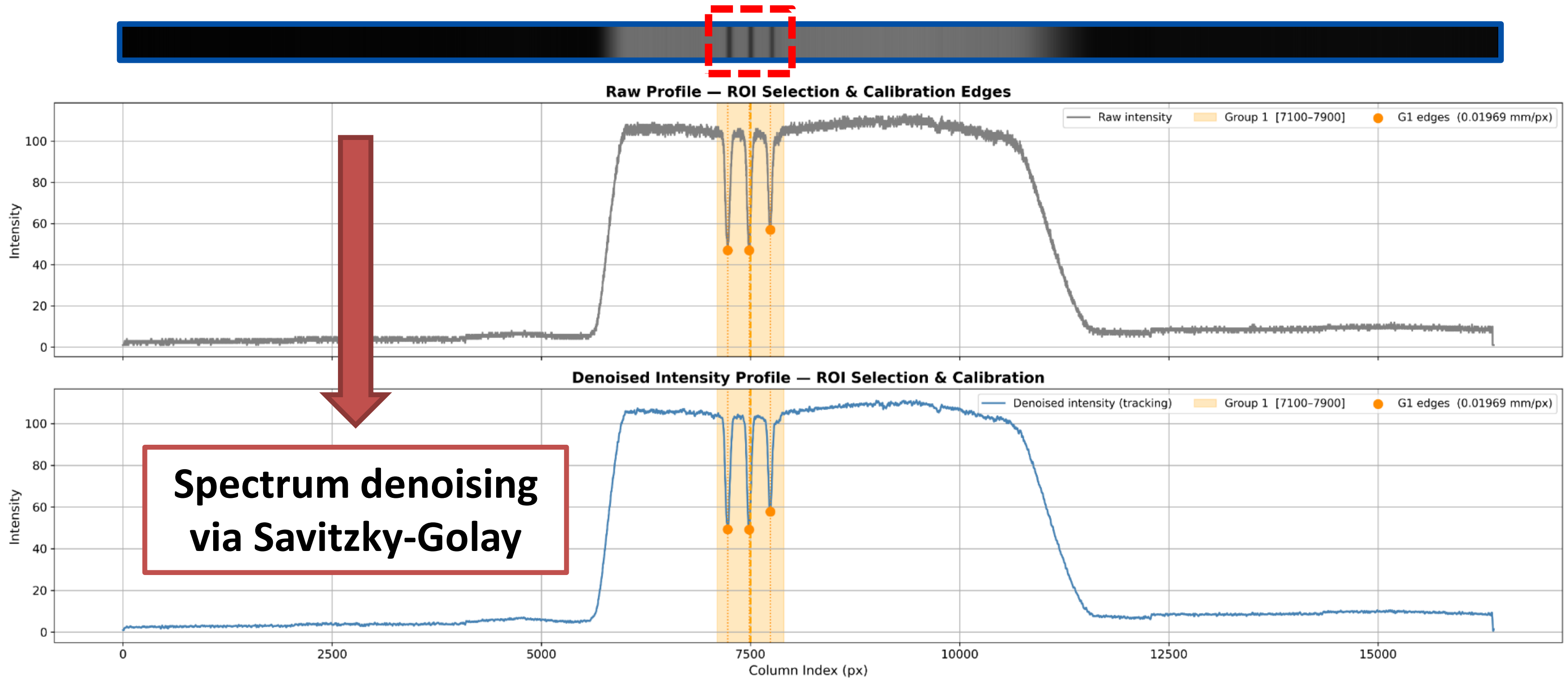


- **Step 3: Post-processing and output**
  - Compute each line's displacement from the reference
  - Compute strain per segment as the fractional change in line spacing
  - Quantify the noise floor from a no-strain window



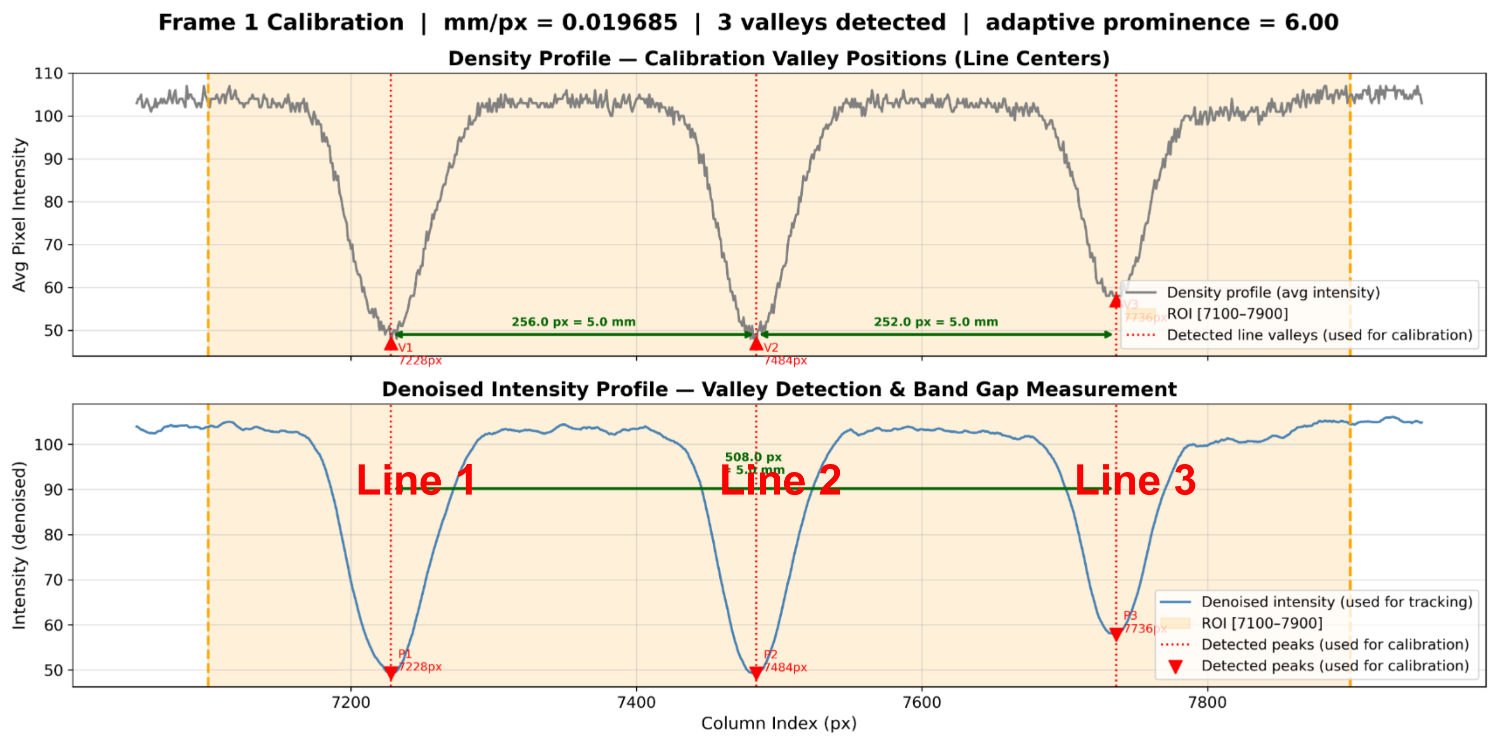
Denoising via Savitzky-Golay Filter (Selected Test)

- **What Savitzky-Golay does:**
  - Fits a low-degree polynomial over a **sliding window** of points
  - Replaces each point with the fitted polynomial value at that position
  - Suppresses high-frequency noise while preserving peak shape and position
  - Unlike a simple moving average, does NOT flatten or shift the spike dips
  - Spike positions (location of line markers) are preserved accurately
- **Parameters**
  - SMOOTH_WINDOW
    - Must be ODD number
  - SMOOTH_POLY
    - Cubic polynomial



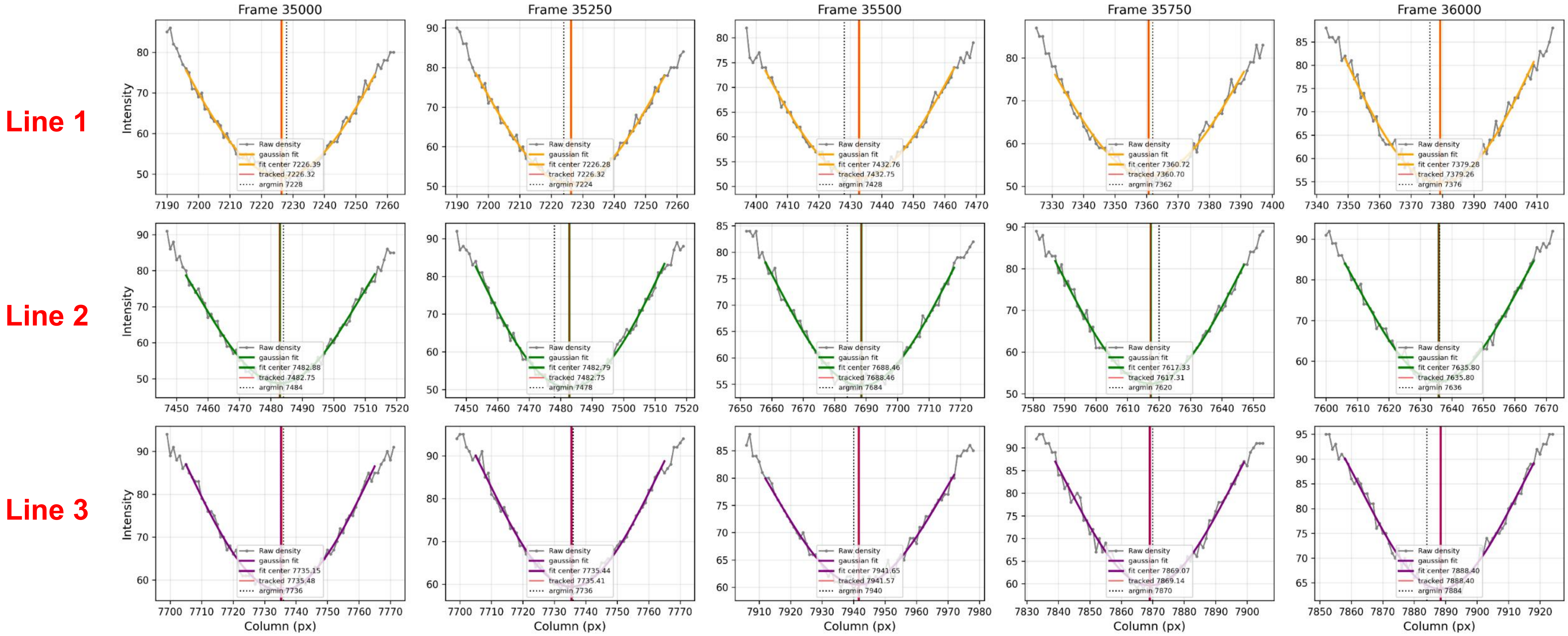
Line Detection and Spatial Calibration (Denoising Effect)

- **Coarse line localization**
  - Dark marker lines appear as local intensity valleys
  - Each line is searched within a predefined local window
  - Template matching (ZNSSD) provides an initial center estimate
  - The estimated center initializes for sub-pixel refinement
- **Line position estimation**
  - $$x_i^{(0)}(t) = \arg\min_{\Delta x \in W_i} C_{ZNSSD}(\Delta x, t)$$
    - W_i : search window for line *i*
    - $x_i^{(0)}(t)$: coarse center estimate



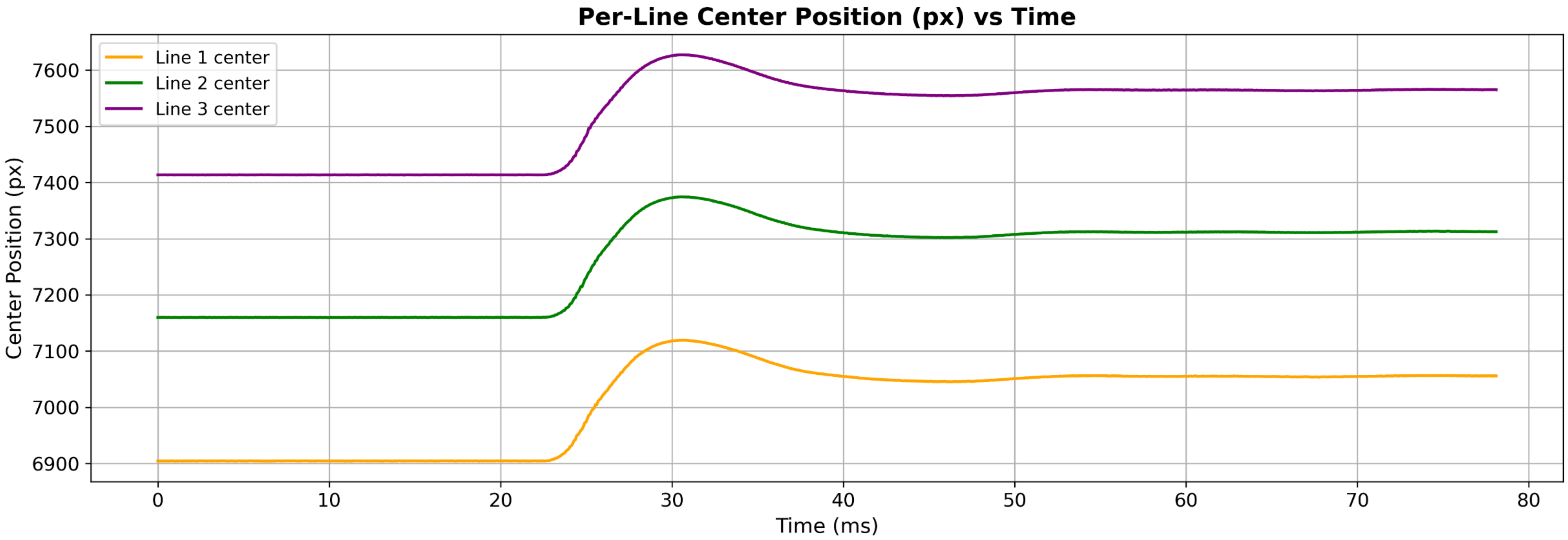
Sub-pixel Line-center Refinement by Gaussian Fitting

- **Line-position refinement**
  - Local fitting window initialized from the coarse estimate
  - Gaussian valley fitted using least-squares minimization
  - Sub-pixel line position obtained from the fitted Gaussian center

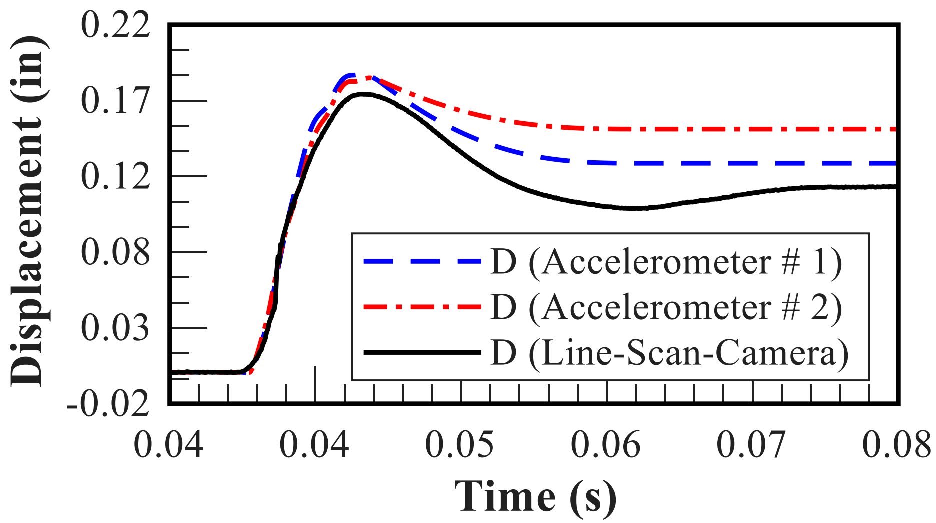


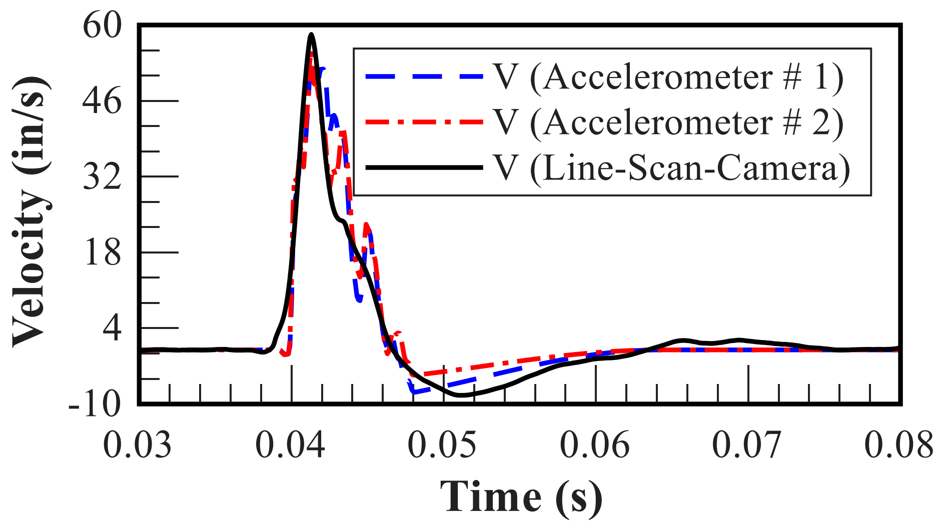
Position Tracking of Line Centers

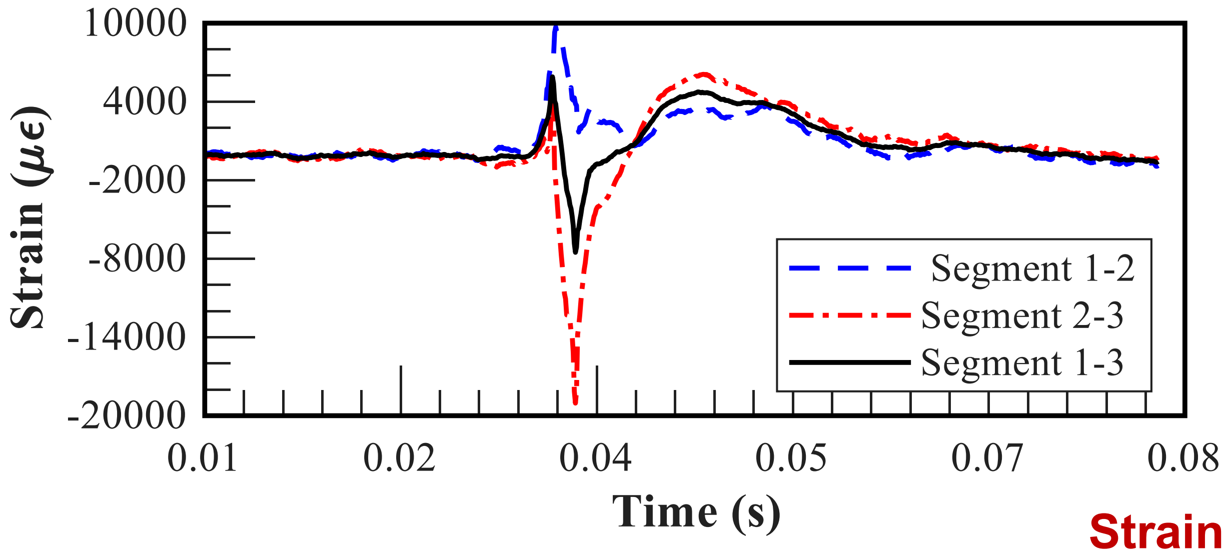
- **Confirms reliable per-line tracking**
  - Continuous frame-to-frame line trajectories
  - Basis for displacement and strain
  - No motion blur disrupting detection
  - No missed detections or line switching

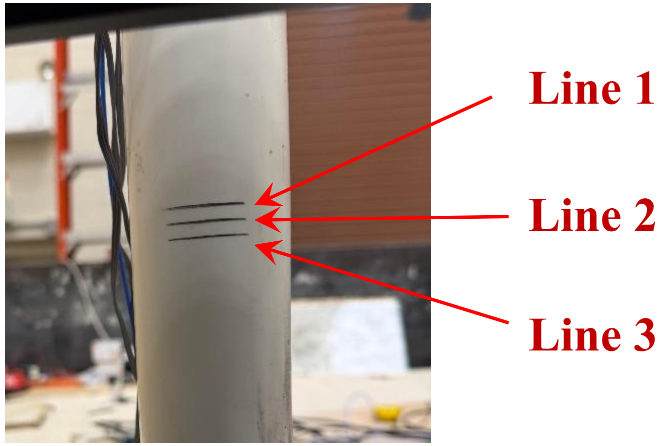


Displacement, Velocity, and Strains (Selected Test)









Strain measurements need more investigation

Presentation Overview

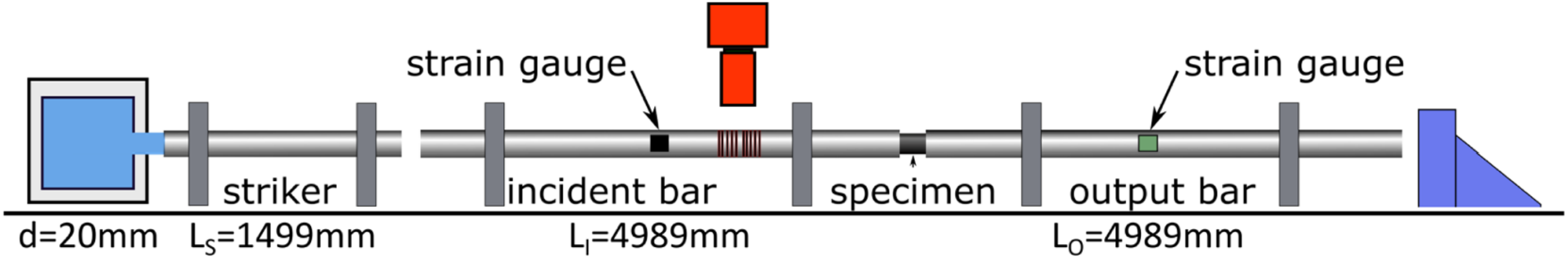
- Project Introduction
- Review of Past Deliverables
- DIC Background and 2D-DIC
- Transformation from 2D-DIC to 1D-DIC
- **Current Work: Medium-Scale Pile Tests**
  - Sandbox Experiment: Displacement, Velocity, and Strains
  - **Improved Experiment: “Hopkinson” Pile Test**
  - Parametric Analysis for Evaluation of Pile Rebound Risk
- **Future Work**
- **Discussion and Comments from FDOT**

Literature: Usage of Line-Camera DIC in Hopkinson Bar

Split Hopkinson Pressure Bar (SHPB)

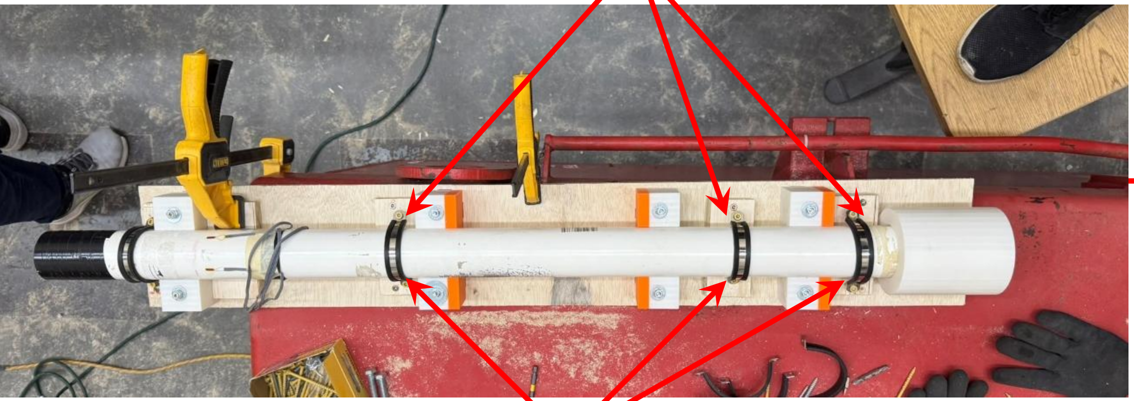
- Named after Bertram Hopkinson (1914) and later refined by Kolsky (1949) into the Split Hopkinson Pressure Bar (SHPB).
- Standard experimental technique for high strain-rate material testing.
- A striker generates a compressive stress wave through the incident bar, specimen, and output bar.
- Strain gauges measure the incident, reflected, and transmitted waves.
- Wave propagation theory is used to determine stress, strain, and strain rate.

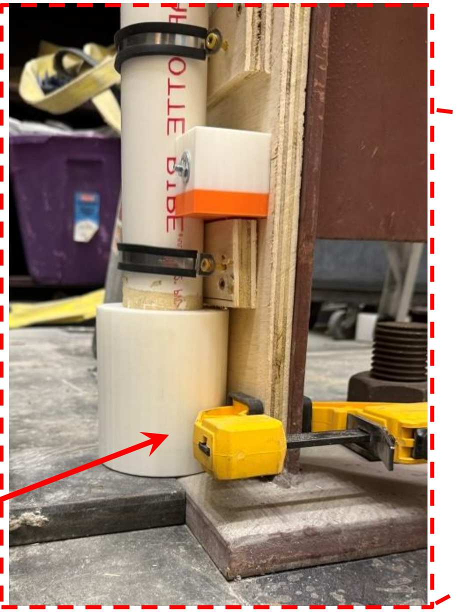
Key Idea: Replace conventional strain gauges with Line-Scan **DIC** to perform non-contact strain measurements while preserving measurement accuracy.

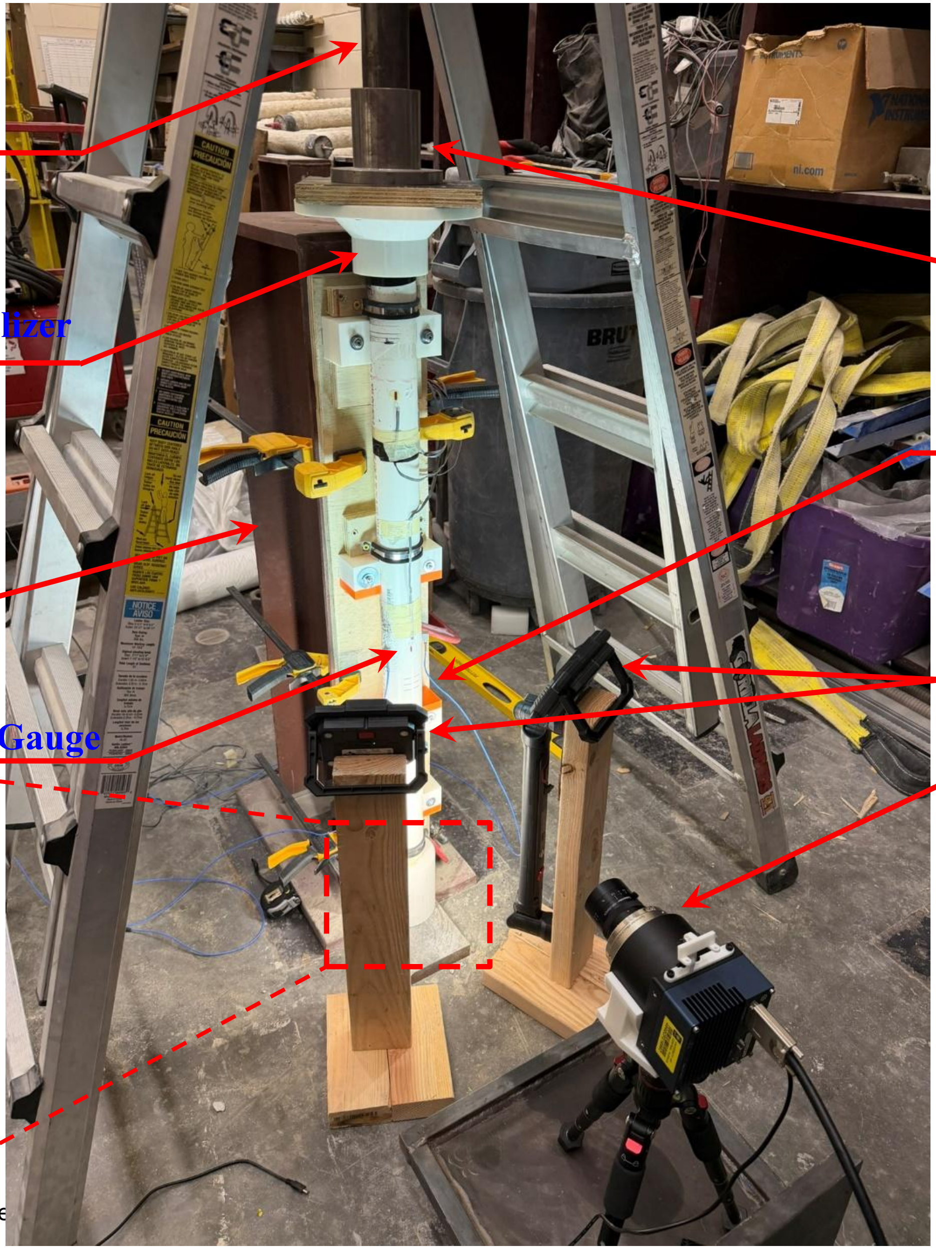


Reference: Roth, Christian C., et al. "Replacing strain gages by line camera DIC in Hopkinson bar experiments." *International Journal of Impact Engineering* (2025): 105620.

Improved Experimental Setup: “Hopkinson” Pile Test





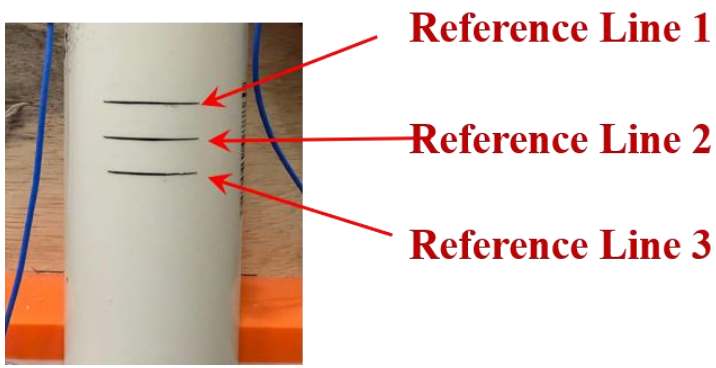


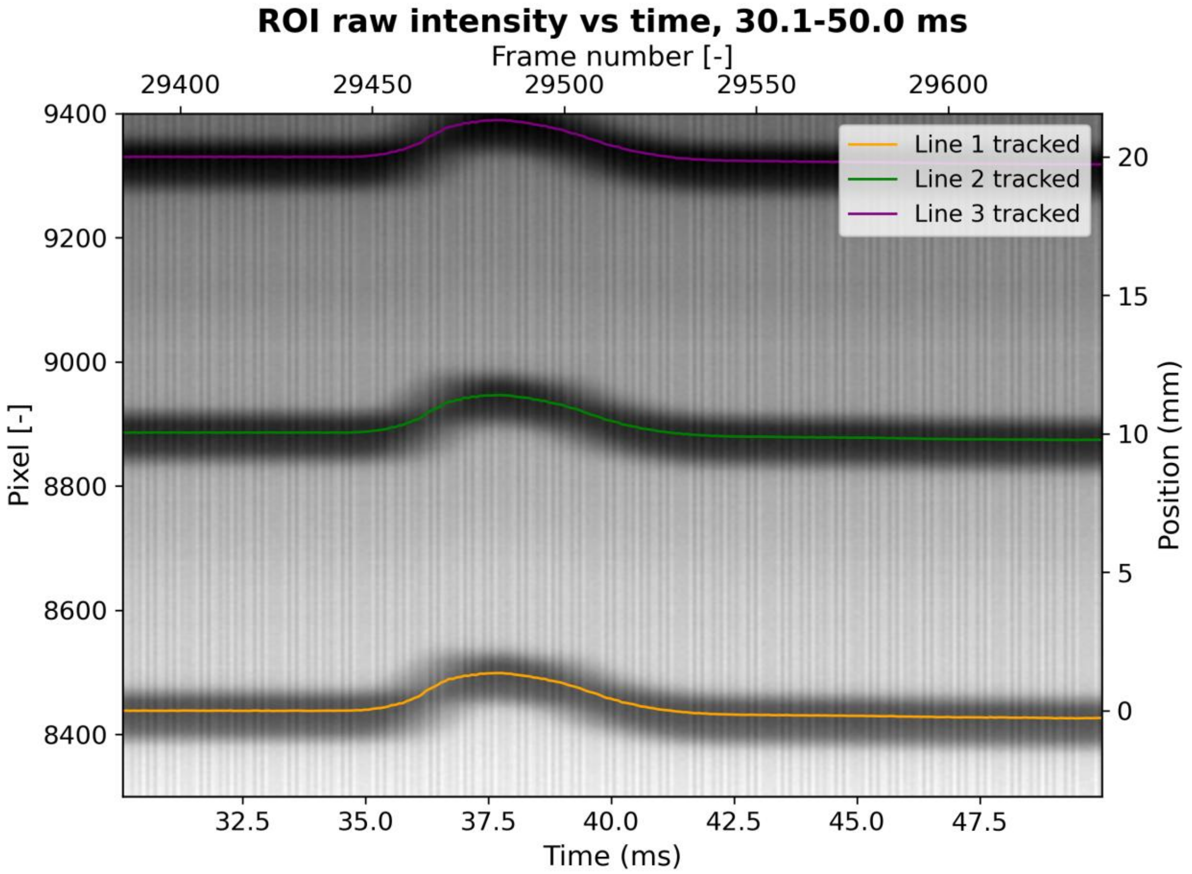
Hopkinson Pile Test: ZNSSD Subset-DIC Method

- **Implement the ZNSSD:**
  - ZNSSD provides an initial center estimate
  - The colored trajectories follow the dark marker during impact
  - Direct proof the tracker follows lines

$$C_{\mathrm{ZNSSD}} = \sum \left[\frac{(f_i - \bar{f})}{\sqrt{\sum (f_i - \bar{f})^2}} - \frac{(g_i - \bar{g})}{\sqrt{\sum (g_i - \bar{g})^2}} \right]^2$$

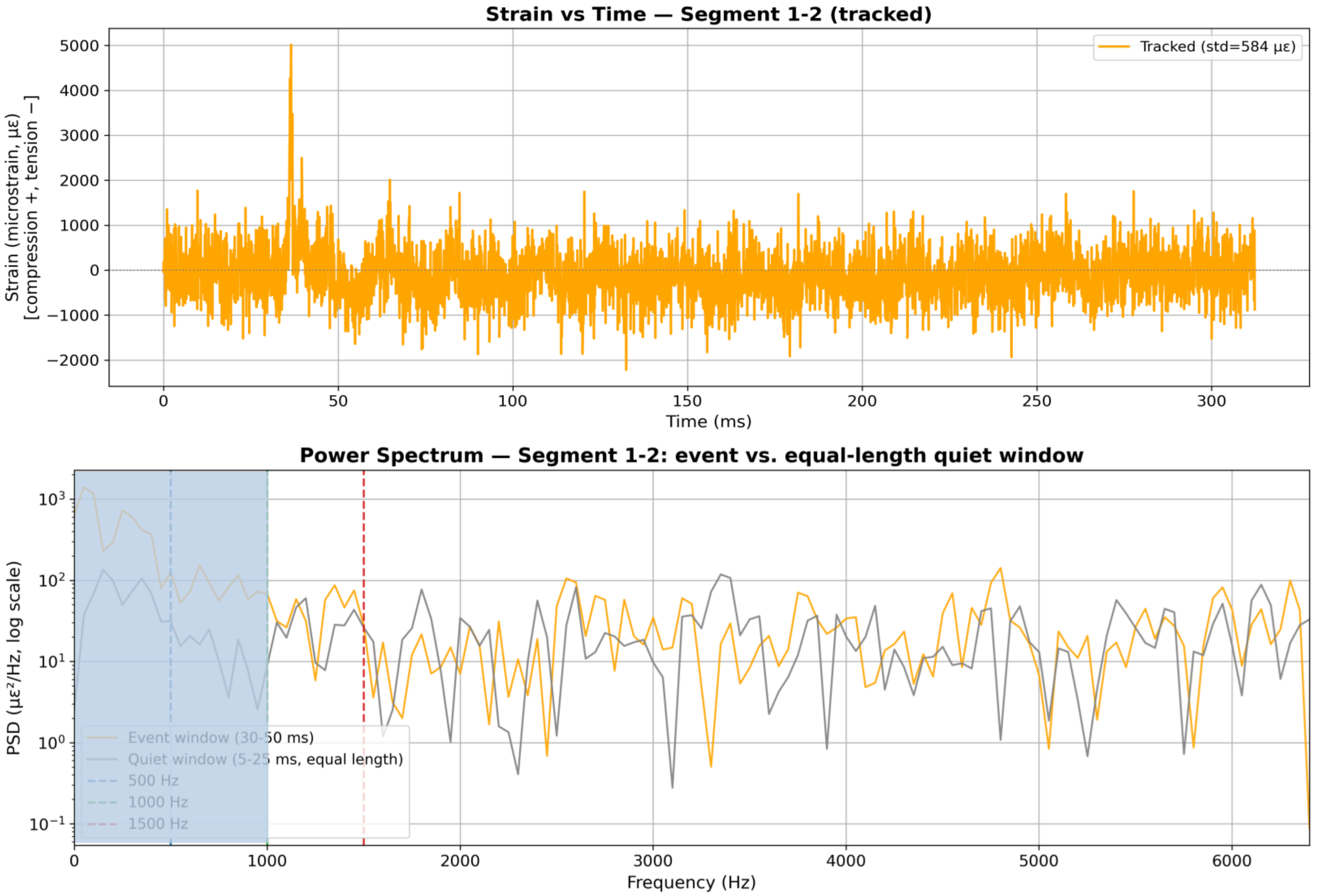
Parameter	Value
ROI width	1100 px
Subset half-width	40 px
Convergence tolerance	0.01 px
Reference frames averaged	200 frames
Valley prominence	6.0
Max per-frame search bound	60 px





Low-Pass Filter Design

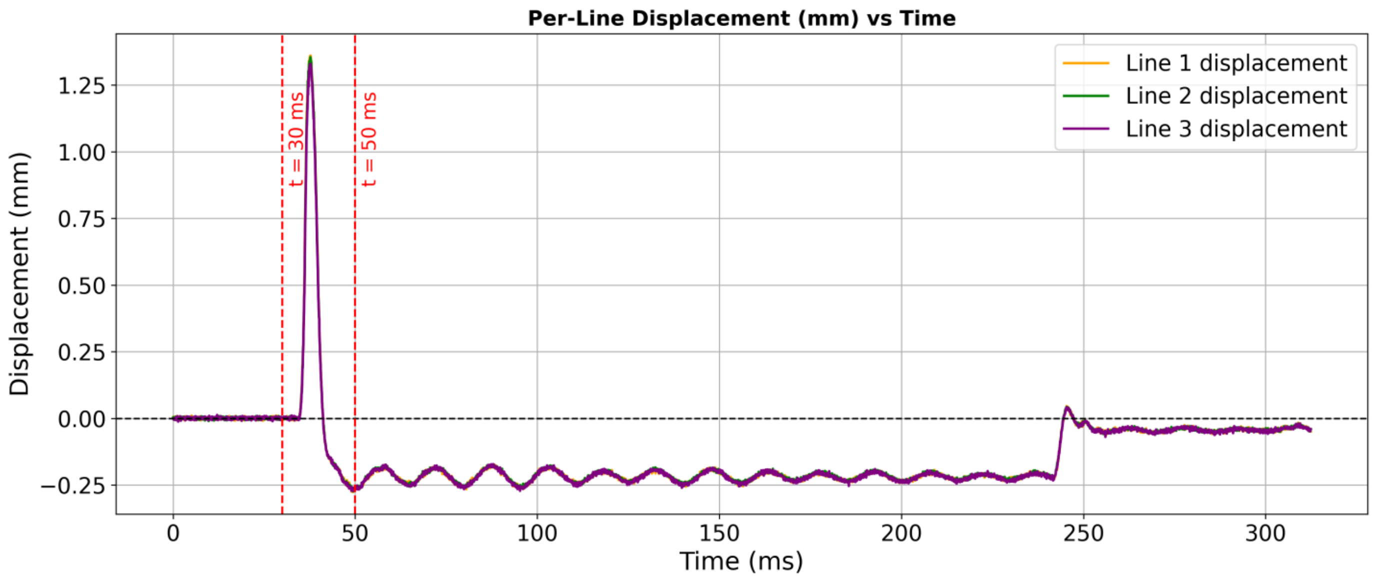
- **Power spectrum compares the impact event to a quiet window:**
  - Quiet window: equal-length slice **before impact** (5–25 ms)
  - Event window: the slice **bracketing the impact** (30–50 ms)
  - Spectrum shown to **Nyquist frequency**: 6400 Hz (half the 12,804 Hz frame rate)
  - <1000 Hz: signal from impact; >1000 Hz: mostly noise
  - Cumulative energy: integrated PSD below each cutoff frequency

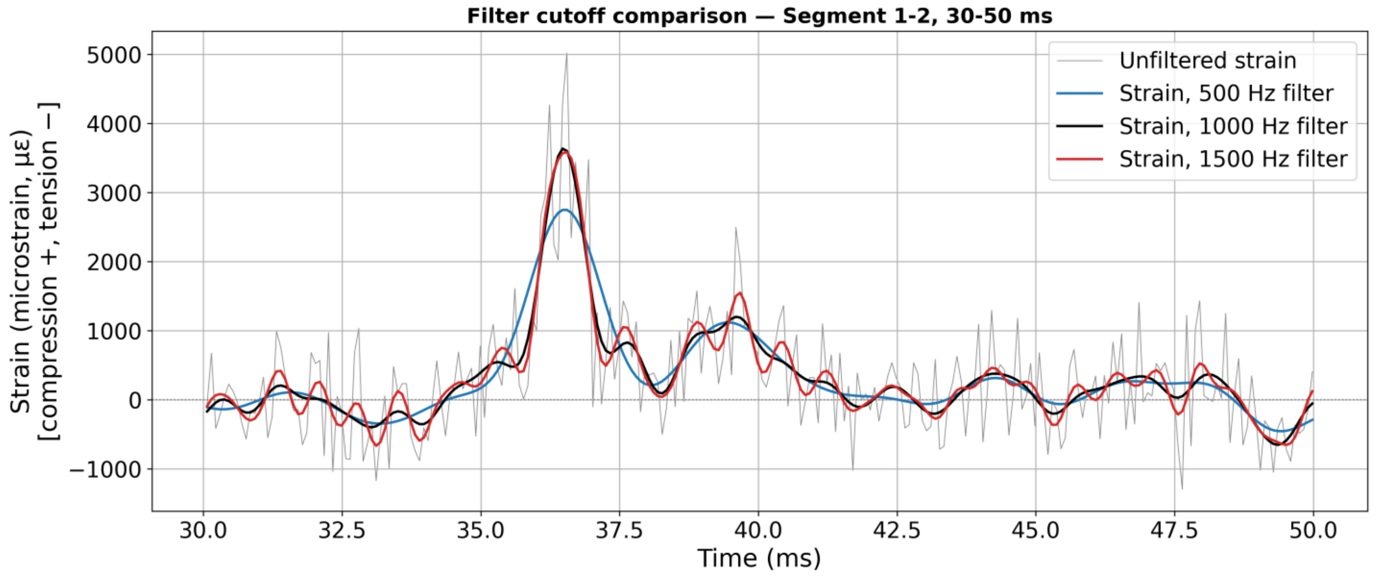


Cumulative Event Energy Below	200 Hz	500 Hz	1000 Hz	1500 Hz	2000 Hz
% of Total Event Energy	34.6%	59.6%	68.4%	73.3%	74.5%

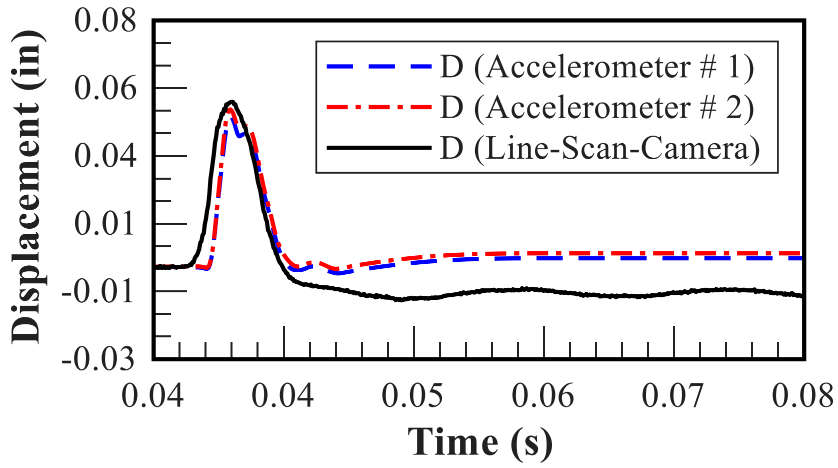
Displacement and Strain Extraction from Tracked Lines

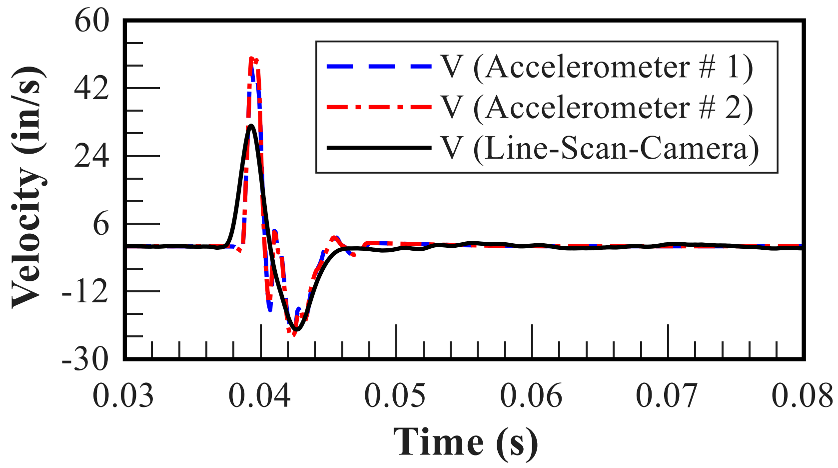
- **Results of the same tracked event:**
  - Displacement: full record and also shows vibration decay after impact
  - Strain: zoomed to **30-50 ms**
  - Raw strain contains substantial high-frequency **noise**, requiring frequency-based filtering
  - All 3 lines track together: same shape, same timing
  - Strain is obtained from inter-line spacing changes

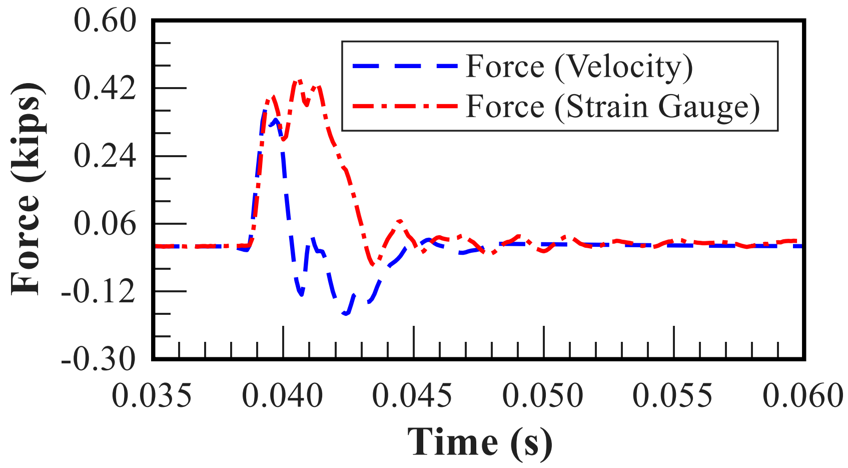


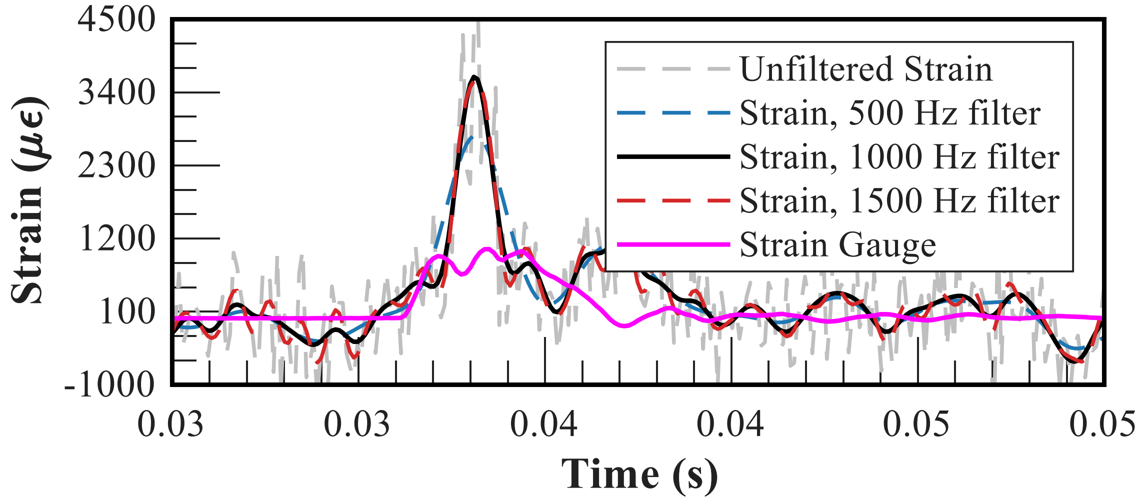


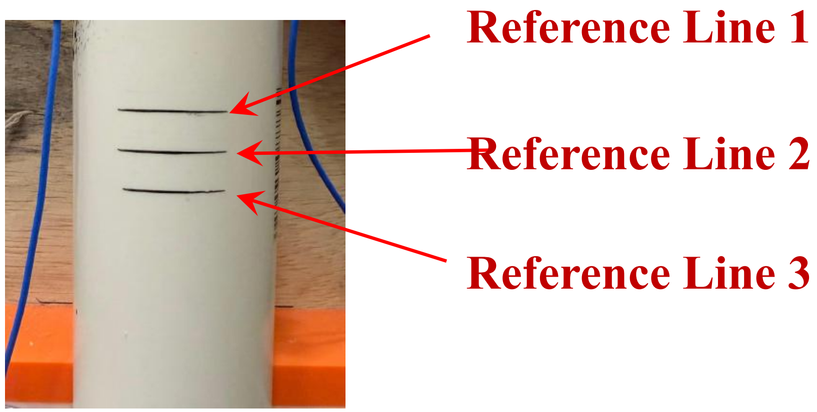
Displacement, Velocity, Forces, and Strains ("Hopkinson" Pile Test)











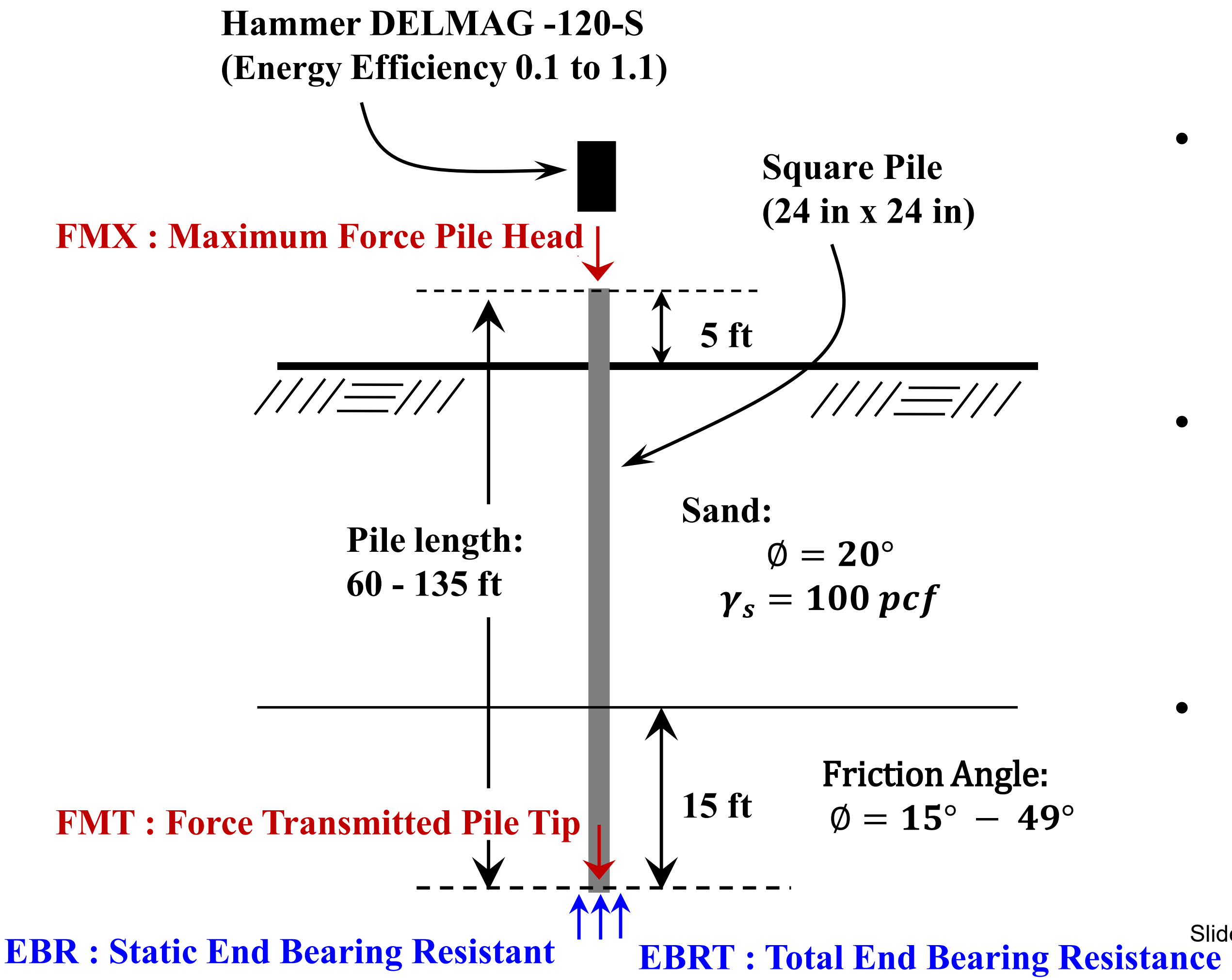
Improved Strain Measurements with the New Setup

Presentation Overview

- **Project Introduction**
- **Review of Past Deliverables**
- **DIC Background and 2D-DIC**
- **Transformation from 2D-DIC to 1D-DIC**
- **Current Work: Medium-Scale Pile Tests**
  - Sandbox Experiment: Displacement, Velocity, and Strains
  - Improved Experiment: “Hopkinson” Pile Test
  - **Parametric Analysis for Evaluation of Pile Rebound Risk**
- **Future Work**
- **Discussion and Comments from FDOT**

Parametric Analysis for Evaluation of Pile Rebound Risk

- **Parametric Analysis using GRLWEAP**
  - ✓ Development of force-based envelopes between pile rebound (%) and key resistance components obtained from wave equation analyses (594 GRLWEAP cases).



Proposed Correlations

- $\boldsymbol{Rebound}\ (\%)\ \boldsymbol{vs}\ \boldsymbol{FMT - EBRT}$

$$\boldsymbol{Rebound}\ (\%) = 130 \cdot \boldsymbol{e}^{-0.0095*(\boldsymbol{FMT-EBRT})}$$

- $\boldsymbol{Rebound}\ (\%)\ \boldsymbol{vs}\ \boldsymbol{FMX - EBRT}$

$$\boldsymbol{Rebound}\ (\%) = -0.0933 \cdot (\boldsymbol{FMX - EBRT}) + 150$$

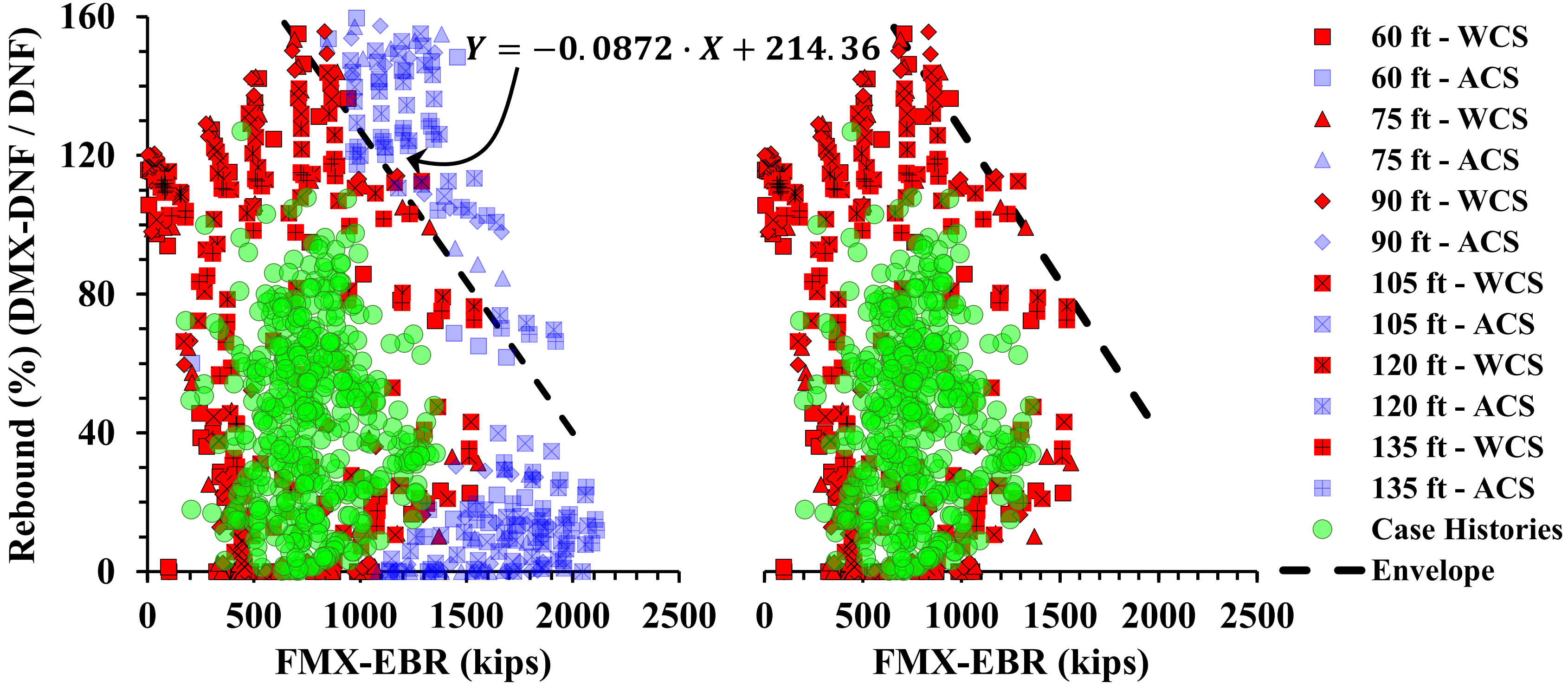
- $\boldsymbol{Rebound}\ (\%)\ \boldsymbol{vs}\ \boldsymbol{FMX - EBR}$

$$Rebound\ (\%) = -0.0872 \cdot (FMX - EBR) + 214.36$$

Validation and Results

- **GRLWEAP Parametric Analysis**
  - ✓ Used 20 case histories to validate the relationship between rebound (%) and FMX-EBR.
  - ✓ Removed points exceeding the FDOT maximum compressive and tensile stress limits.
  - ✓ Removed results for friction angles of 17°, 21°, and 49°.

WCS: Within Compressive and tensile Stress Limits
ACS : Above Compressive and tensile Stress Limits



Future work

- **Illumination**
  - Evaluate different illumination conditions to improve image quality and measurement accuracy.
- **Patterns**
  - We will test different pattern types, materials, printed markers, and tattoos.
- **Pile Material**
  - We will consider concrete or steel piles for the large-scale tests.
- **Sampling Rate**
  - We will determine the most appropriate sampling rate (1KHz-20KHz) to minimize noise while maintaining measurement accuracy.
- **Line Scan Camera**
  - Improve computing code to process the line scan camera signal.

Thank you very much!

Welcome Comments from FDOT

References

- Cosentino, P. J., Bostater Jr, C. R., Franqui, A., Rogulski III, R. J., & Jensen, M. (2020). Quantifying Pile Rebound with Deflection Measuring Systems Best Suited for Florida Soils. FDOT Report.
- M. Nayyerloo et al., "Seismic structural displacement measurement using a line-scan camera: camera-pattern calibration and experimental validation," Journal of Civil Structural Health Monitoring, vol. 1, no. 3, pp. 113-124, 2011.
- J. Blaber, B. Adair, and A. Antoniou, "Ncorr: open-source 2D digital image correlation matlab software," Experimental Mechanics, vol. 55, no. 6, pp. 1105-1122, 2015.
- M. A. Sutton, J. J. Orteu, and H. Schreier, Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications. Springer Science & Business Media, 2009.
- B. Pan, K. Qian, H. Xie, and A. Asundi, "Two-dimensional digital image correlation for in-plane displacement and strain measurement: a review," Measurement science and technology, vol. 20, no. 6, p. 062001, 2009.
- Roth, C. C., Legrelle, F., Tancogne-Dejean, T., Grolleau, V., & Mohr, D. (2025). Replacing strain gages by line camera DIC in Hopkinson bar experiments. International Journal of Impact Engineering, 105620.

Thank you!

RISElab
Sense the Unseen

Resilient Infrastructure Sensing & Evaluation

Contact: Dr. Patrick Sun
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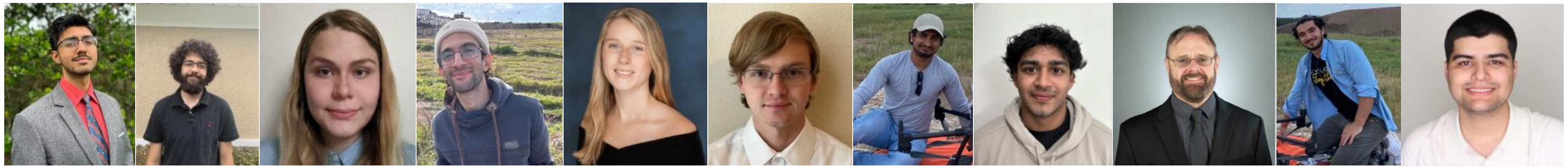
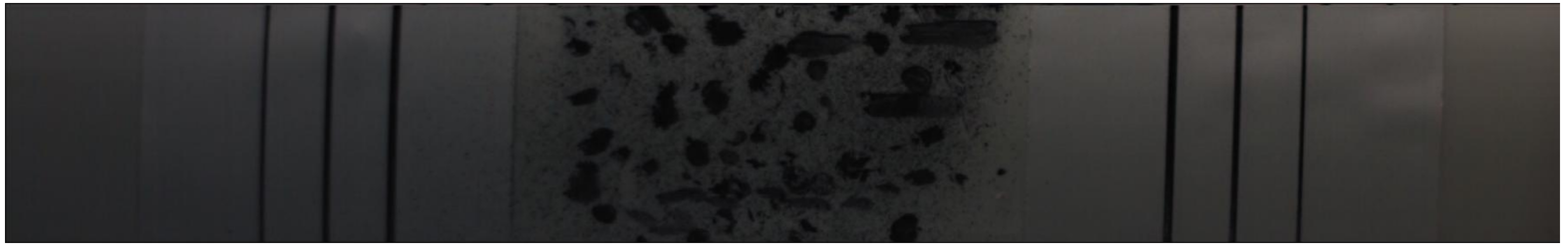
Hinkley Center for Solid and Hazardous Waste Management
Florida Department of Environmental Protection
FDOT
USDA
Florida Department of Agriculture and Consumer Services
Orange County Utilities Department
UCF
NSF
University of Michigan
Detroit Riverfront Conservancy



Supplemental Materials

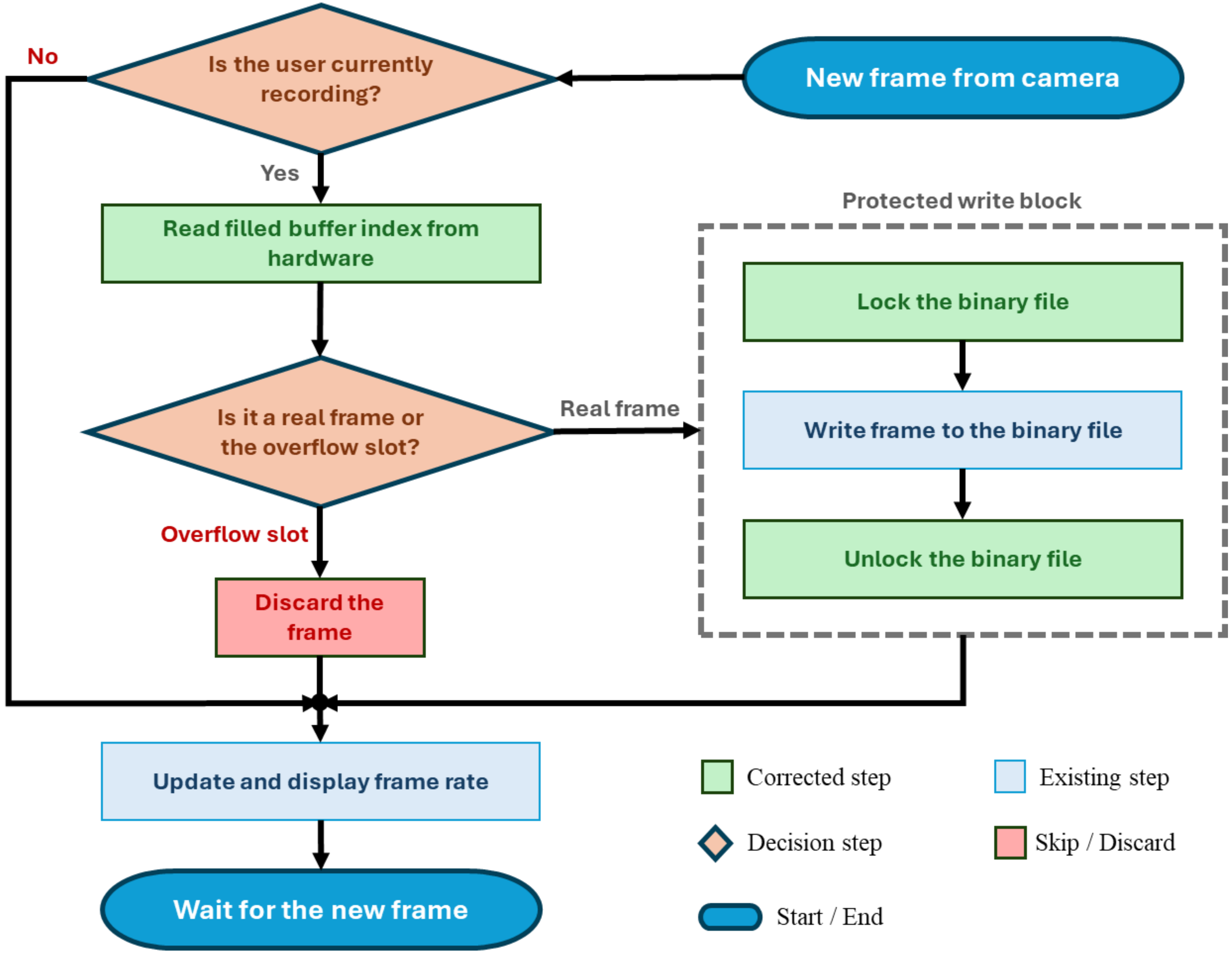
Area-scan Camera

- **Impact test with high-speed area-scan camera**



- **Details:**
  - Dimensions: 4096 x 448
  - FPS: 1954

Process flowchart of the corrected XferCallback() function

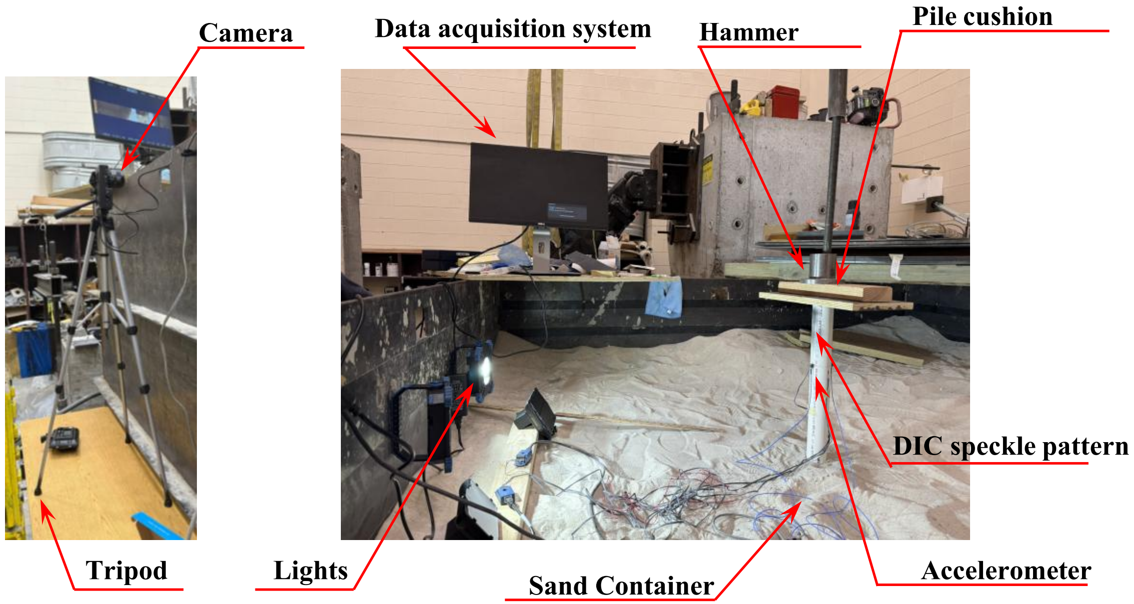


Deliverable 2- Software and Preliminary Results (Option 1)

- **Design of the Hardware System for Image/video Acquisition**
  - ✓ Architecture of the hardware system, area- and line- scan cameras, calibration, data acquisition, data storage, and future developments.
- **Preliminary Experimental Tests – Wave Velocity in Piles**

Wave velocity ↑

Wave velocity ↓



(a) DIC assembly

(b) Sand Container with pile and instrumentation

- **Evaluation of Pile Rebound Risk Based on Pile Resistance Components**