FAA Research on Small Unmanned Aircraft System (sUAS) for Pavement Condition Inspections

Peter-Paul Dzwilewski, P.E.

SWIFT

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Overview

- FAA-funded pavement inspection by sUAS studies
- Two teams performed independent studies
  - sUAS data collected at eight airports
- Data types: Red-green-blue (RGB), thermal, multispectral, Light Detection and Ranging (LiDAR)
- Components of study
  - sUAS data to detect pavement distress
  - Data collection guidelines
  - sUAS integration in traditional pavement inspection
- Current effort to evaluate studies on the use for pavement inspection and consolidate findings into a comprehensive analysis and technical standards

Reports

- Assessment of Small Unmanned Aircraft Systems for Pavement Inspections –DOT/FAA/TC-23/39
- Practical Lessons Learned from Planning, Collecting, Processing, and Analyzing Small Unmanned Aircraft System Data for Airfield Pavement Inspection – DOT/FAA/TC-22/48
- Small Unmanned Aircraft System for Pavement Inspection – DOT/FAA/TC-23/50

Project Team

- Iowa State University (ISU)
  - **Dr. Halil Ceylan, Ph.D., Dist.M.ASCE (PI)**
  - **Sunghwan Kim, Ph.D., P.E., Co-PI**
  - Abdullah Sourav, Ph.D.
- Michigan Tech Research Institute (MTRI)
  - **Colin N. Brooks, Ph.D., Co-PI**
  - Richard Dobson
  - Chris Cook
  - Abby Jenkins
- Applied Pavement Technology, Inc. (APTech)
  - **David G. Peshkin, P.E., Co-PI**

sUAS Platforms and Sensors

Platforms

sUAS platform	Type	Sensor	Claimed Flight Time (minutes)
Bergen Hexacopter	Six rotors, larger	Nikon D850 45.7-mp RGB optical	16
		FLIR Vue Pro R 640x512 thermal	
		Tetracam Micro-MCA6	
Tarot X6	Six rotors, larger	Nikon D850 45.7-mp RGB optical	35
MicroDrones mdMapper1000+	Four rotors, larger	Sony RX1R-II 42.4-mp RGB optical	40
DJI Mavic 2 Pro	Four rotors, small	20-mp RGB optical	31
Mavic 2 Enterprise Advanced	Four rotors, small	48-mp RGB optical Quad Bayer and 640x512 thermal	31
DJI Mavic 2 Enterprise Dual	Four rotors, small	12-mp RGB optical and FLIR 160x120 thermal	31


Tarot X6


Mavic 2 Enterprise Advanced


DJI Matrice 200 Series

RGB Sensors

- Nikon D850 (45.7 mp), DJI X7 (24 mp), Sony RX1R-II (42.4 mp)
- 20 and 48 mp Quad Bayer (**true 12 mp**) on DJI Mavic
    - In Quad Bayer sensors, each pixel is divided into four adjacent sub-pixels

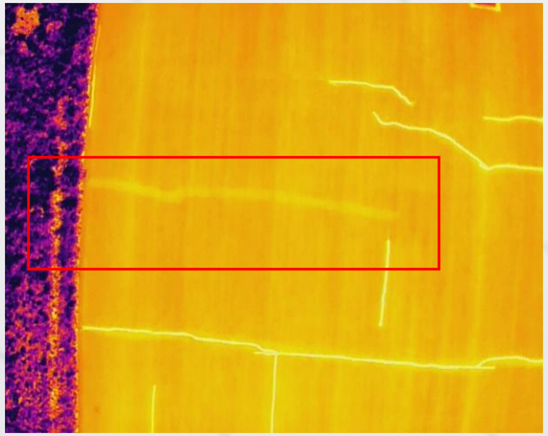
DJI X7

Nikon D850

Thermal Sensors Tested

- 640x512-integrated sensors on DJI
- 640x512 FLIR VUE PRO R
- Only recommended to complement RGB data
- Sealed cracks through pavement marking detection
- Cracks on underlying pavement before a new pavement layer was placed

2.5 mm/pix



31 mm/pix

L&T cracks underneath an asphalt overlay show heat signature in thermal data

Data Resolutions Examined

- RGB – 0.75 to 32 mm
- Digital Elevation Model (DEM) – 3 to 84 mm
- Thermal – 8 to 31 mm
- Resolutions adjusted throughout data collection

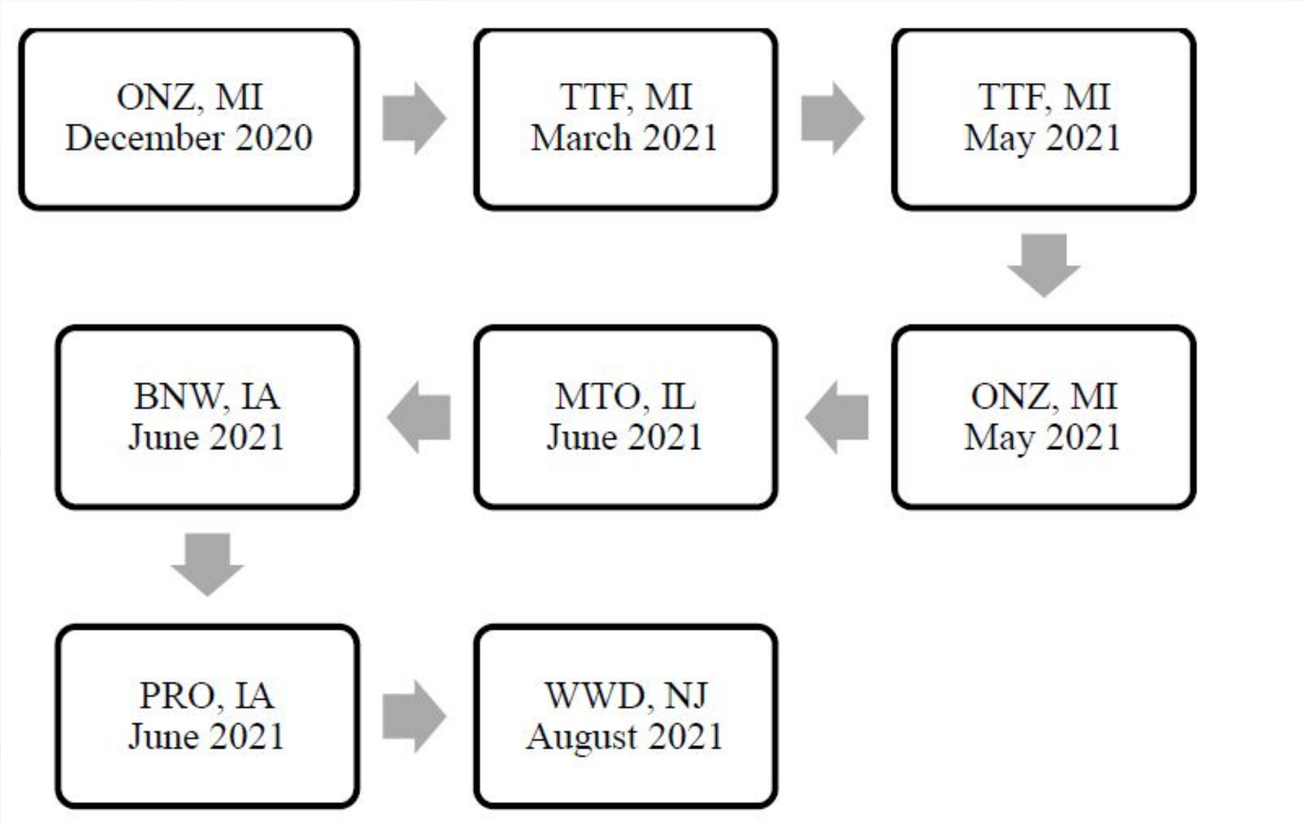
sUAS Platform	Sensors	Flight Altitude (m)	Resolution (mm/pix)	
			Orthophoto	DEM
Tarot X6	45.7-mp optical RGB Nikon D850	18.3	1.5	5.9
Mavic 2 Pro	20-mp optical RGB	15.2	3.5	14
M2EA	512x640 thermal	24.4	31.5	N/A
	48-mp Quad Bayer optical RGB	24.4	4.1	16.2
mdMapper1000+	42.4-mp optical RGB Sony RX1R-II	18.3*	2.2	8.5
		9.1*	1.3	5.4
Tarot X6	45.7-mp optical RGB Nikon D850	9.1	0.8	3

*Collected over limited areas due to unexpected bug flight control software

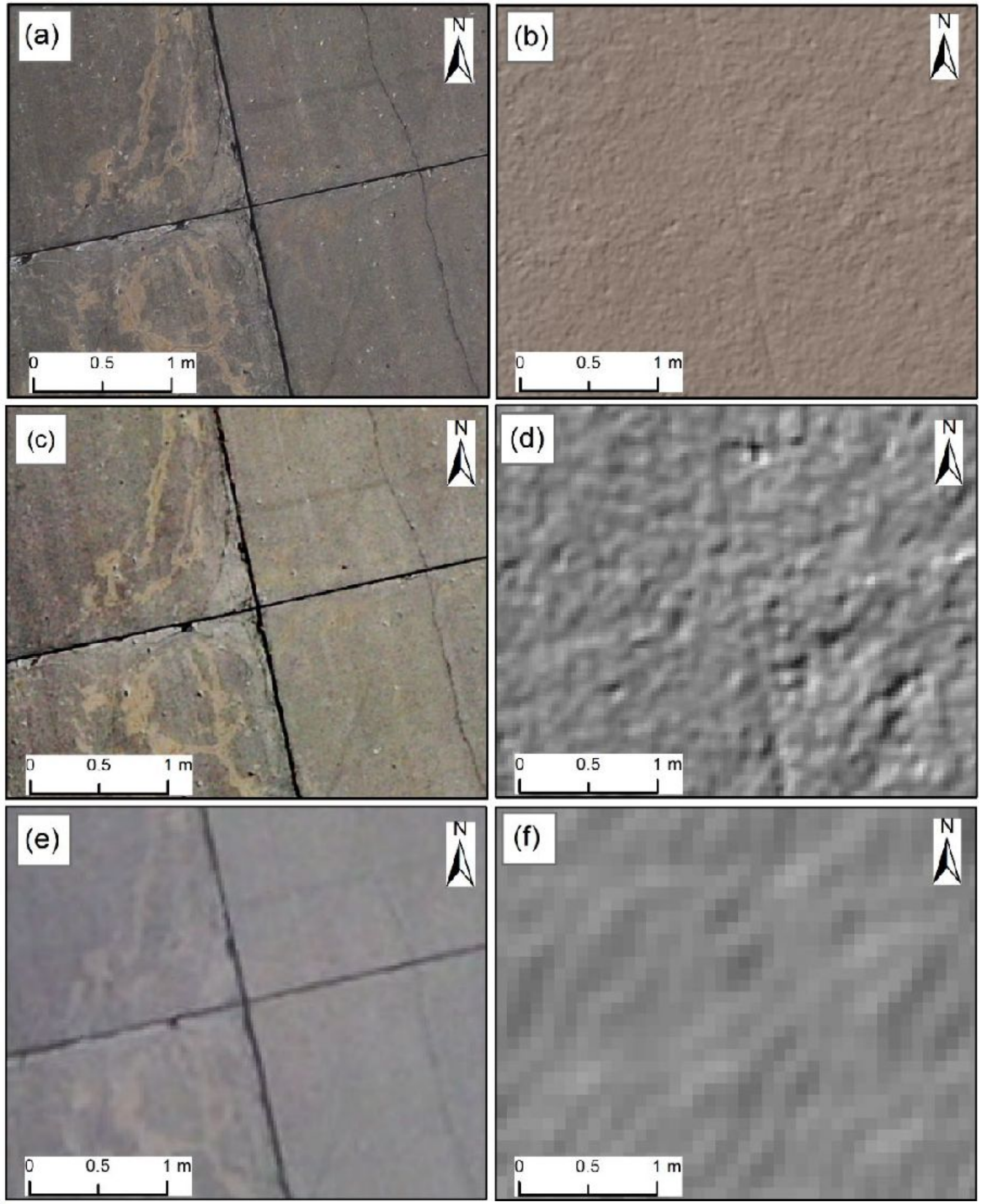
Field Demonstration Airports

ISU-MT-APTech Airports Included

- Grosse Ile Municipal Airport
- Custer Airport
- Coles County Memorial Airport
- Boone Municipal Airport
- Perry Municipal Airport
- Cape May County Airport

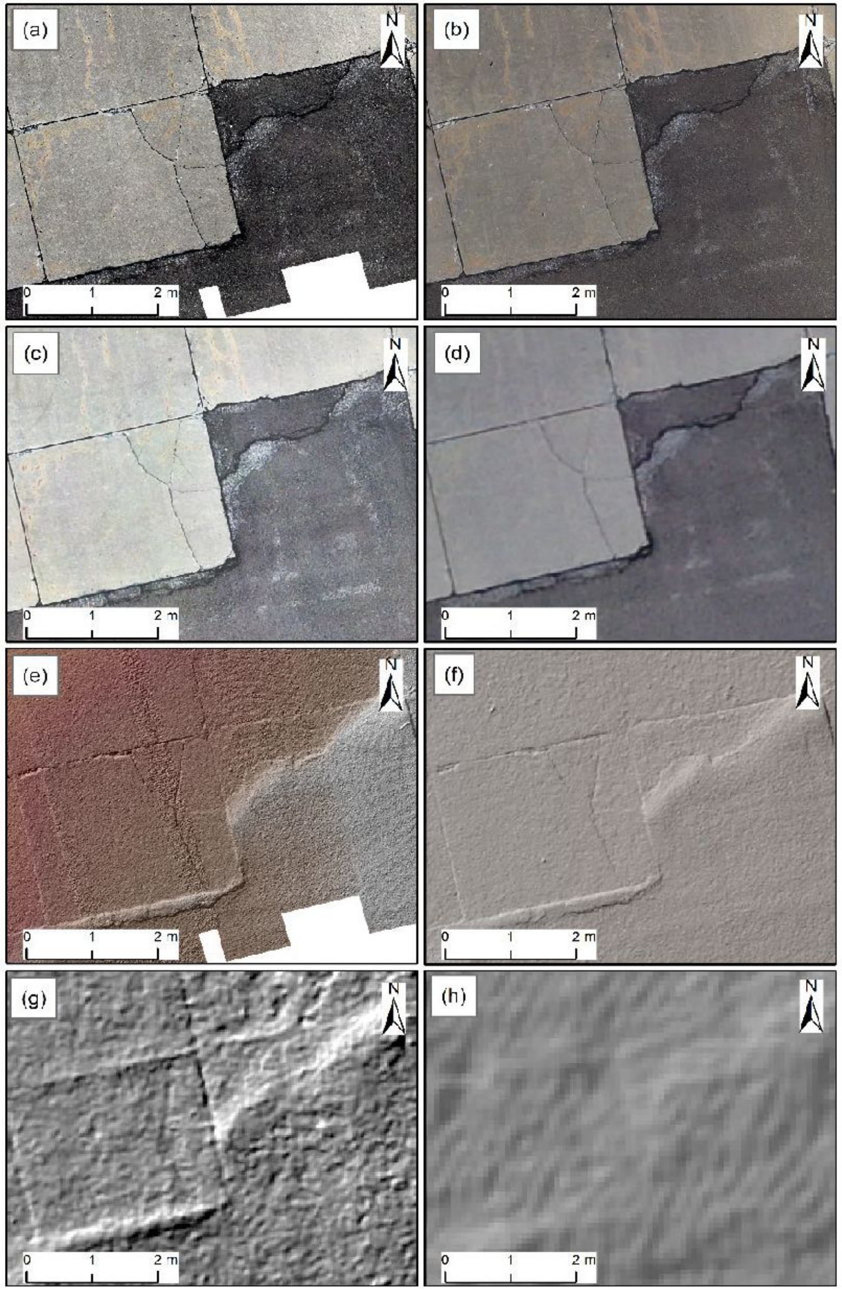


Michigan Examples



- **ONZ (May)**
- Durability Cracking (L), ASR (L), and ASR (M)
- (a) 2.5-mm/pix Orthophoto
- (b) 10-mm/pix DEM
- (c) 7.3-mm/pix Orthophoto
- (d) 29.1-mm/pix DEM
- (e) 21-mm/pix Orthophoto
- (f) 84-mm/pix DEM

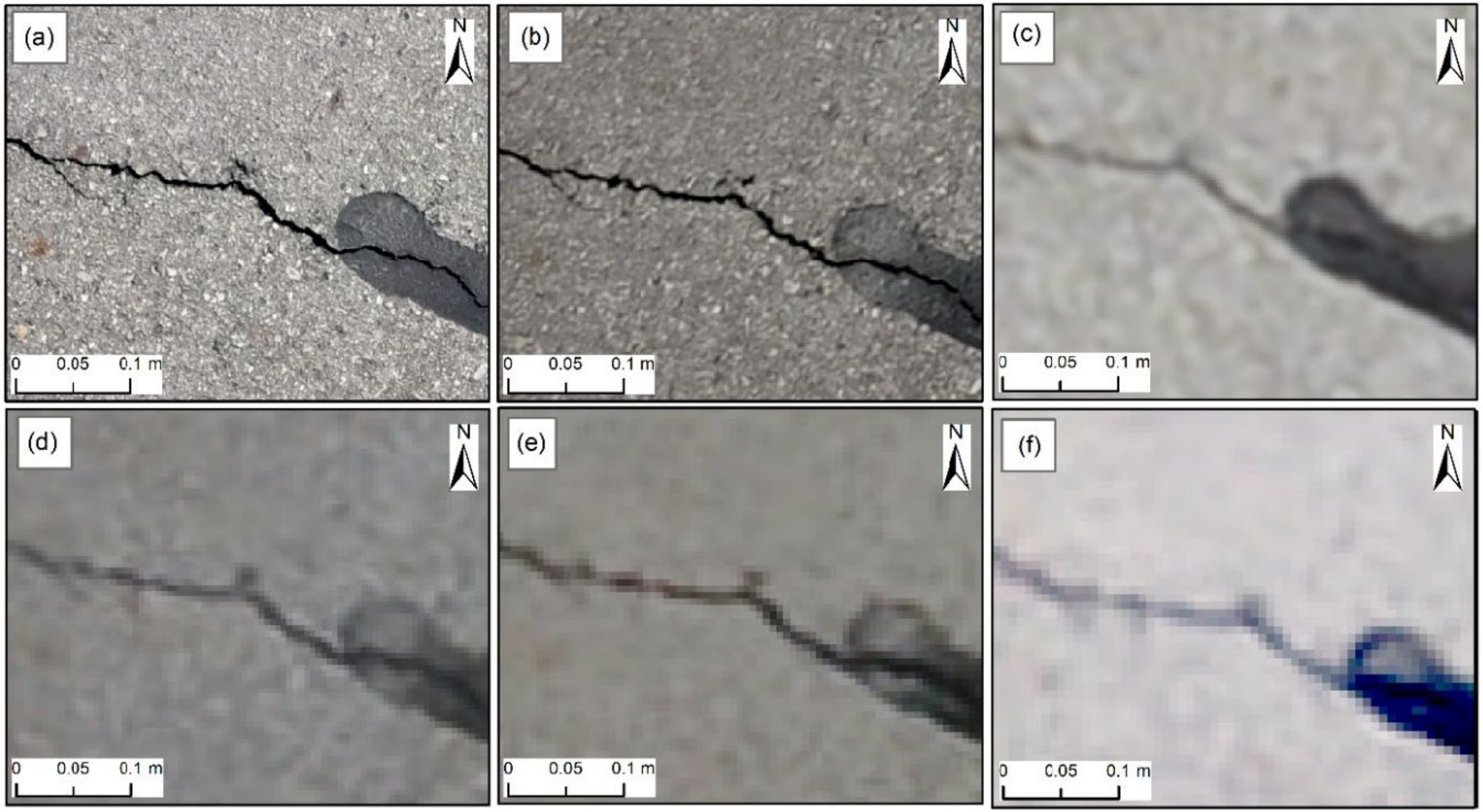
Michigan Examples



- **ONZ (May)**
- Shattered Slab (M), Large Patching (H), and ASR (L)
- (a) 0.8-mm/pix Orthophoto
- (b) 2.5-mm/pix Orthophoto
- (c) 7.3-mm/pix Orthophoto
- (d) 21-mm/pix Orthophoto
- (e) 3-mm/pix DEM
- (f) 10-mm/pix DEM
- (g) 29.1-mm/pix DEM
- (h) 84-mm/pix DEM

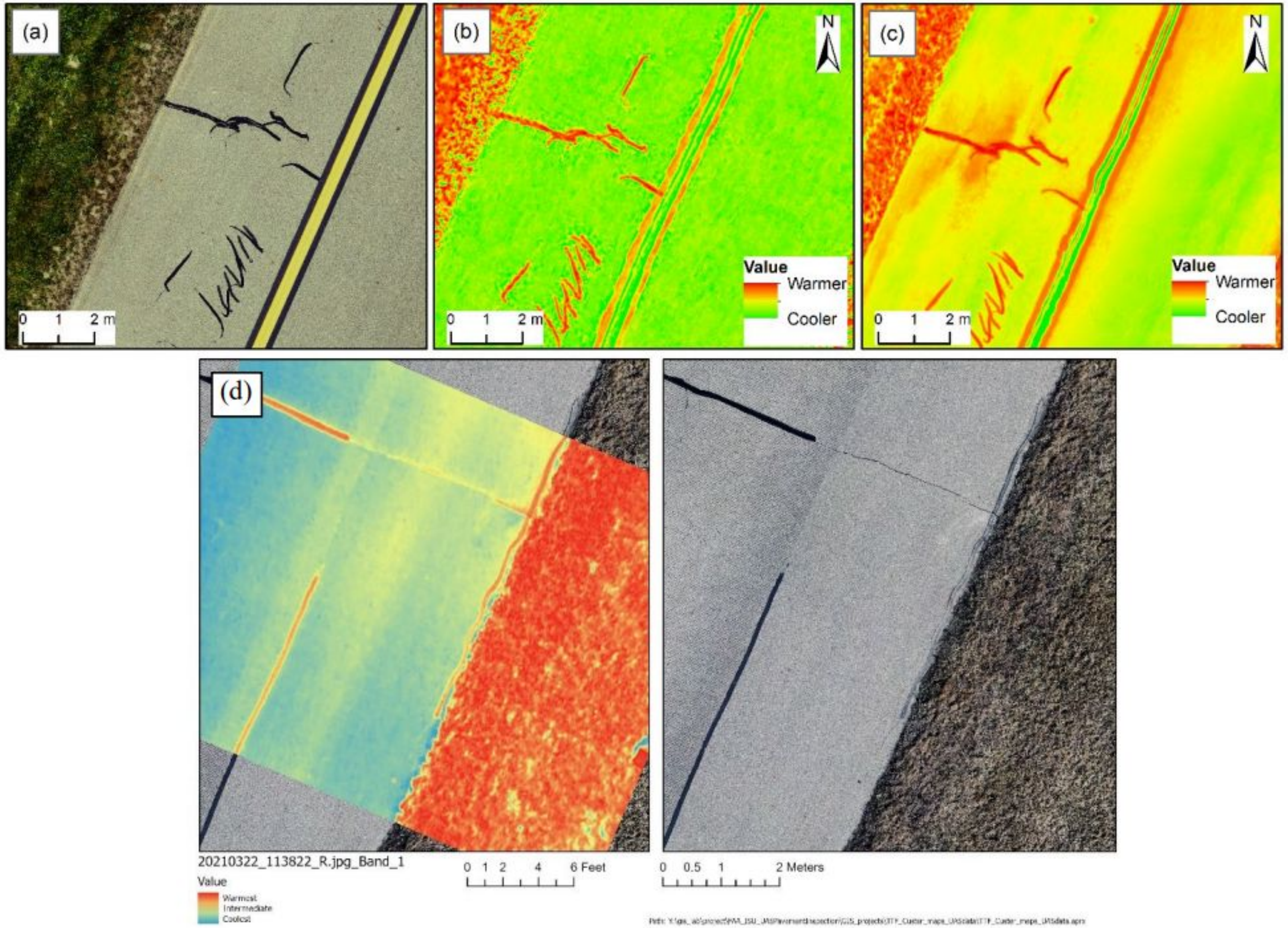
Michigan Examples

- **TTF**
- Unsealed L&T Cracks (M) and Weathering (L)
- (a) 0.8-mm/pix Orthophoto
- (b) 1.5-mm/pix Orthophoto
- (c) 2.4-mm/pix Orthophoto
- (d) 4.9-mm/pix Orthophoto
- (e) 5.6-mm/pix Orthophoto
- (f) 7.2-mm/pix Orthophoto



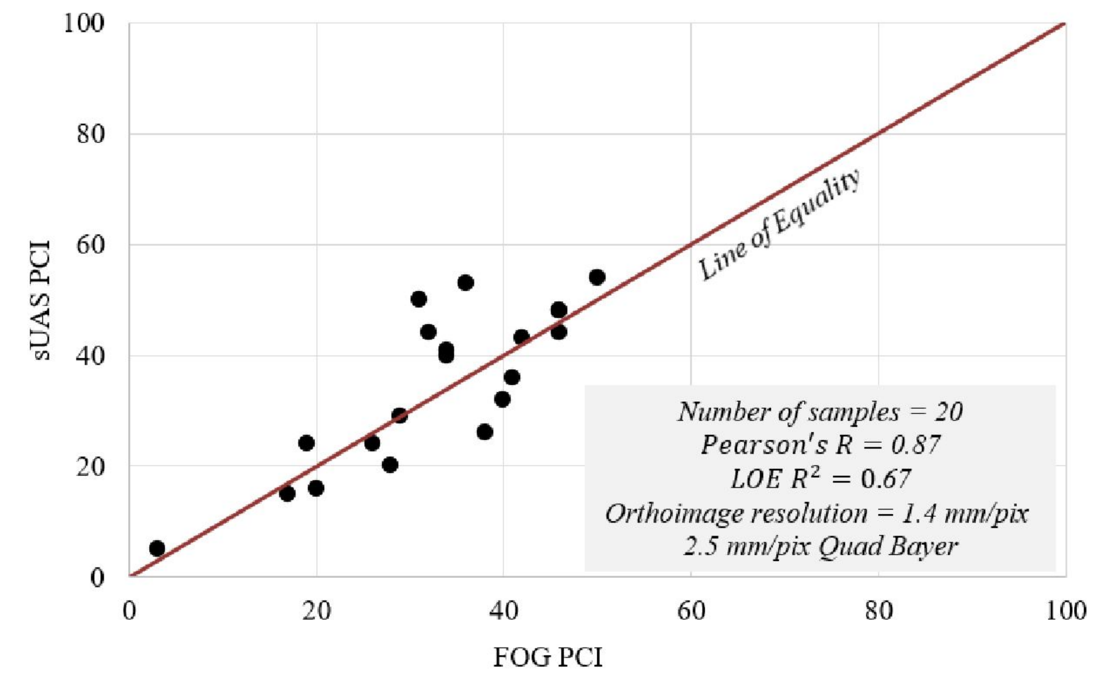
Michigan Examples

- **TTF**
- Sealed L&T Cracks
- (a) 1.5-mm/pix Orthophoto
- (b) 31-mm/pix Stereo Thermal
- (c) 14-mm/pix Stereo Thermal
- (d) Cracks in the 14-mm/pix Stereo-Thermal Results compared to Orthophoto of same area



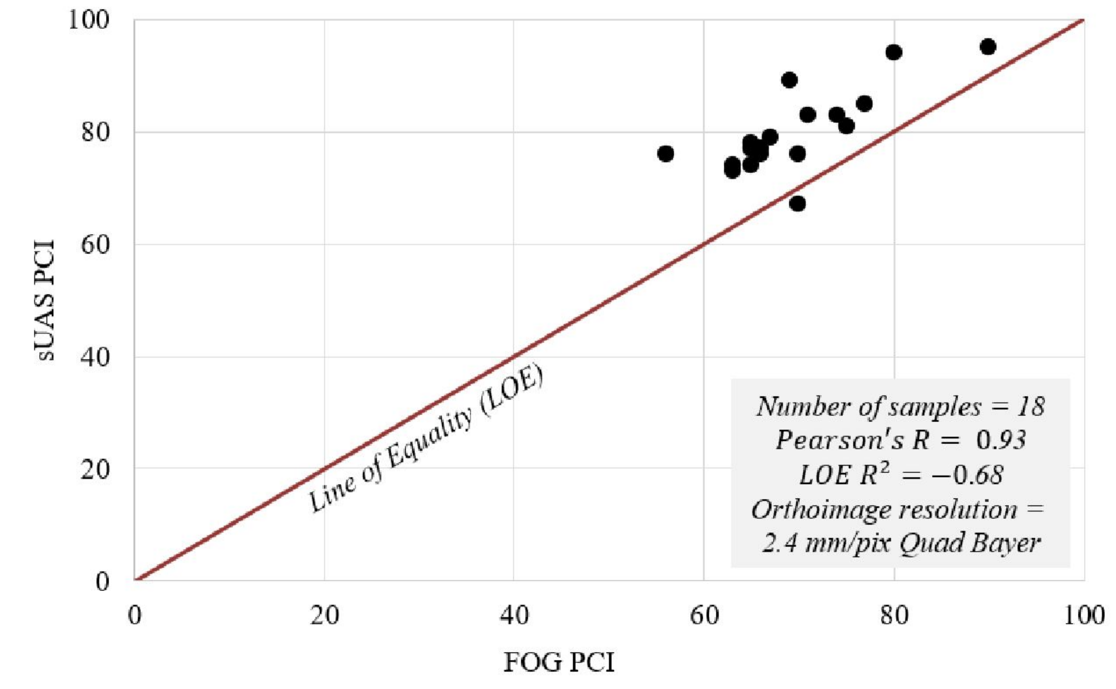
Michigan Foot On Ground (FOG) and sUAS Comparisons

ONZ



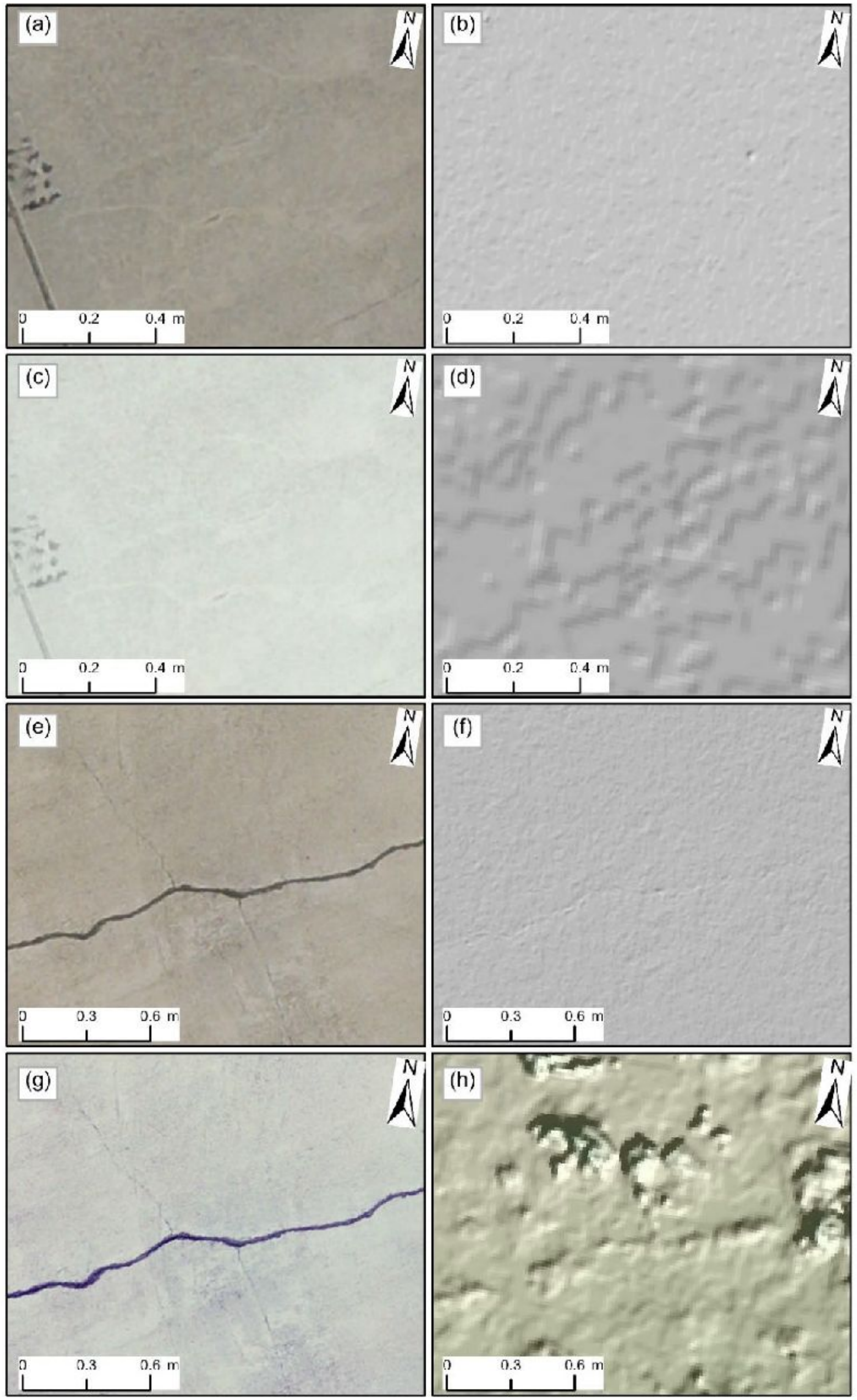
Comparison Between FOG PCI and sUAS PCI Calculated Using 1.4-mm/pix and 2.5-mm/pix Data from ONZ

TTF



Comparison Between FOG PCI and sUAS PCI Calculated Using 2.4-mm/pix Data from TTF

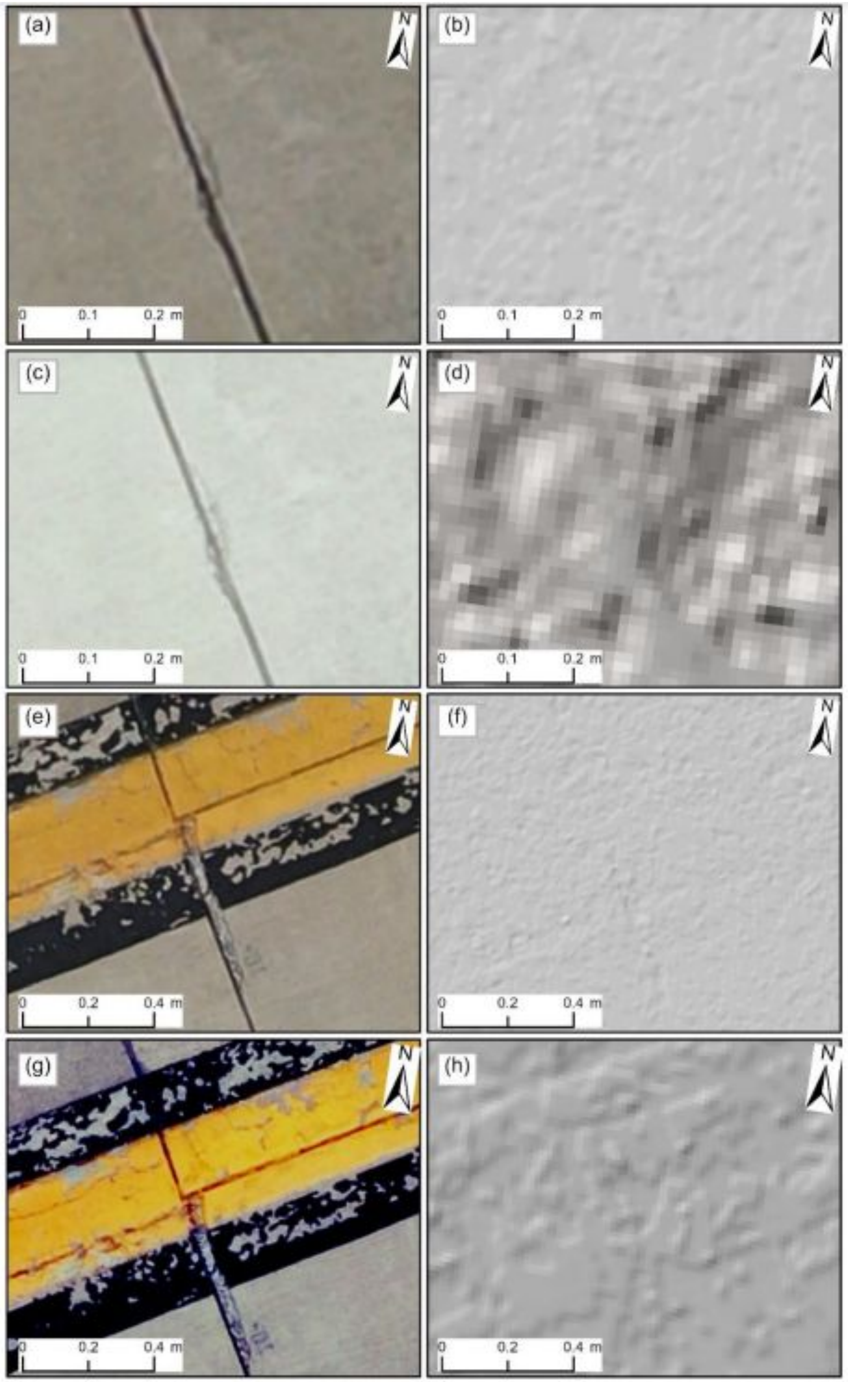
Illinois Examples



- **MTO**
- Shrinkage Cracks (L)
- (a) 2.5-mm/pix Orthophoto
- (b) 5-mm/pix DEM
- (c) 3.6-mm/pix Orthophoto
- (d) 14.3-mm/pix DEM

- Shattered Slab (M)
- (e) 2.5-mm/pix Orthophoto
- (f) 5-mm/pix DEM
- (g) 2.5-mm/pix Orthophoto
- (h) 5-mm/pix DEM

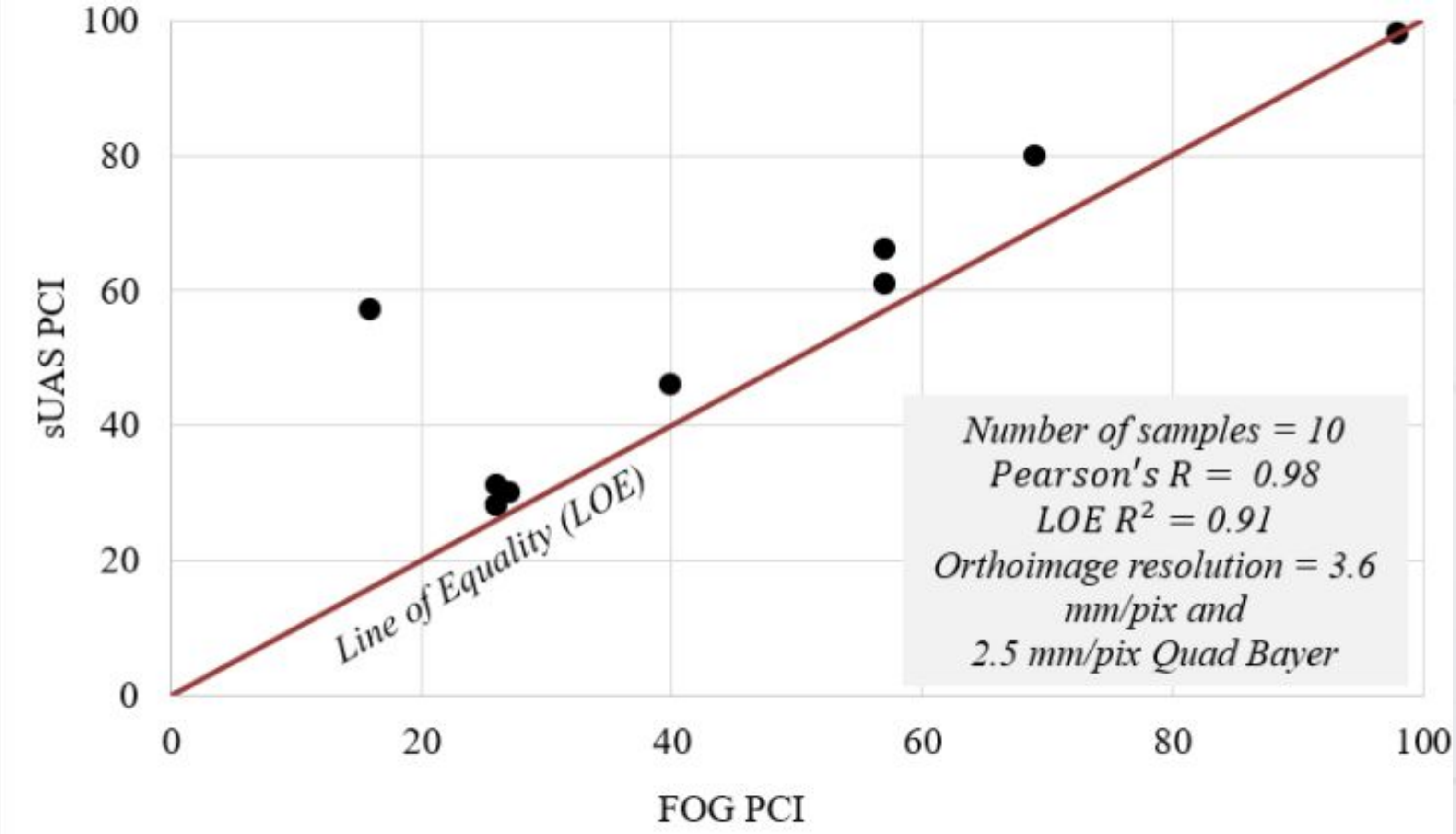
Illinois Examples



- **MTO**
- Joint Spalling (L)
- (a) 2.5-mm/pix Orthophoto
- (b) 5-mm/pix DEM
- (c) 3.6-mm/pix Orthophoto
- (d) 14.3-mm/pix DEM

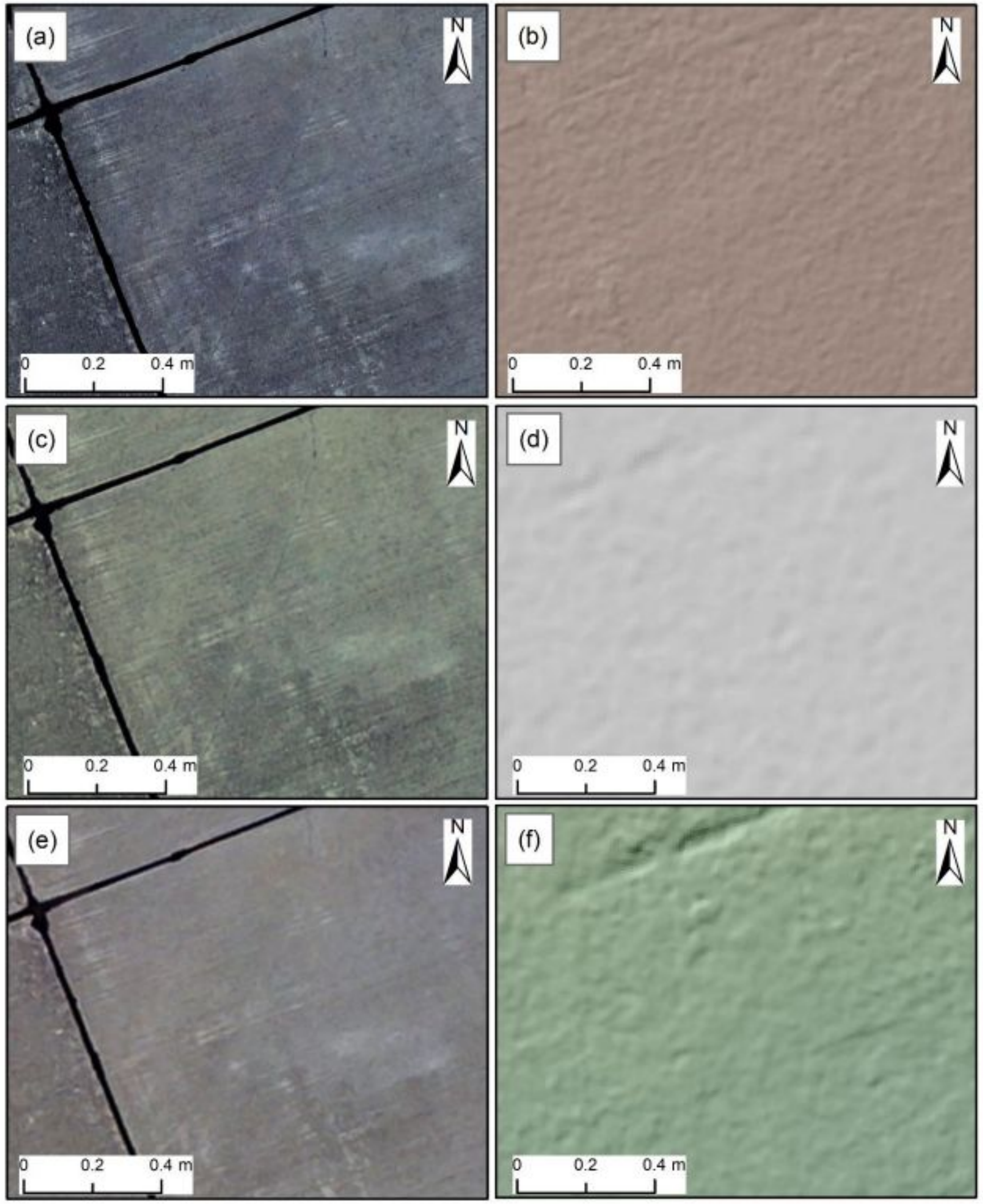
- Joint Spalling (M)
- (e) 2.5-mm/pix Orthophoto
- (f) 5-mm/pix DEM
- (g) 2.5-mm/pix Orthophoto
- (h) 5-mm/pix DEM Derived

Illinois (MTO) FOG and sUAS Comparisons



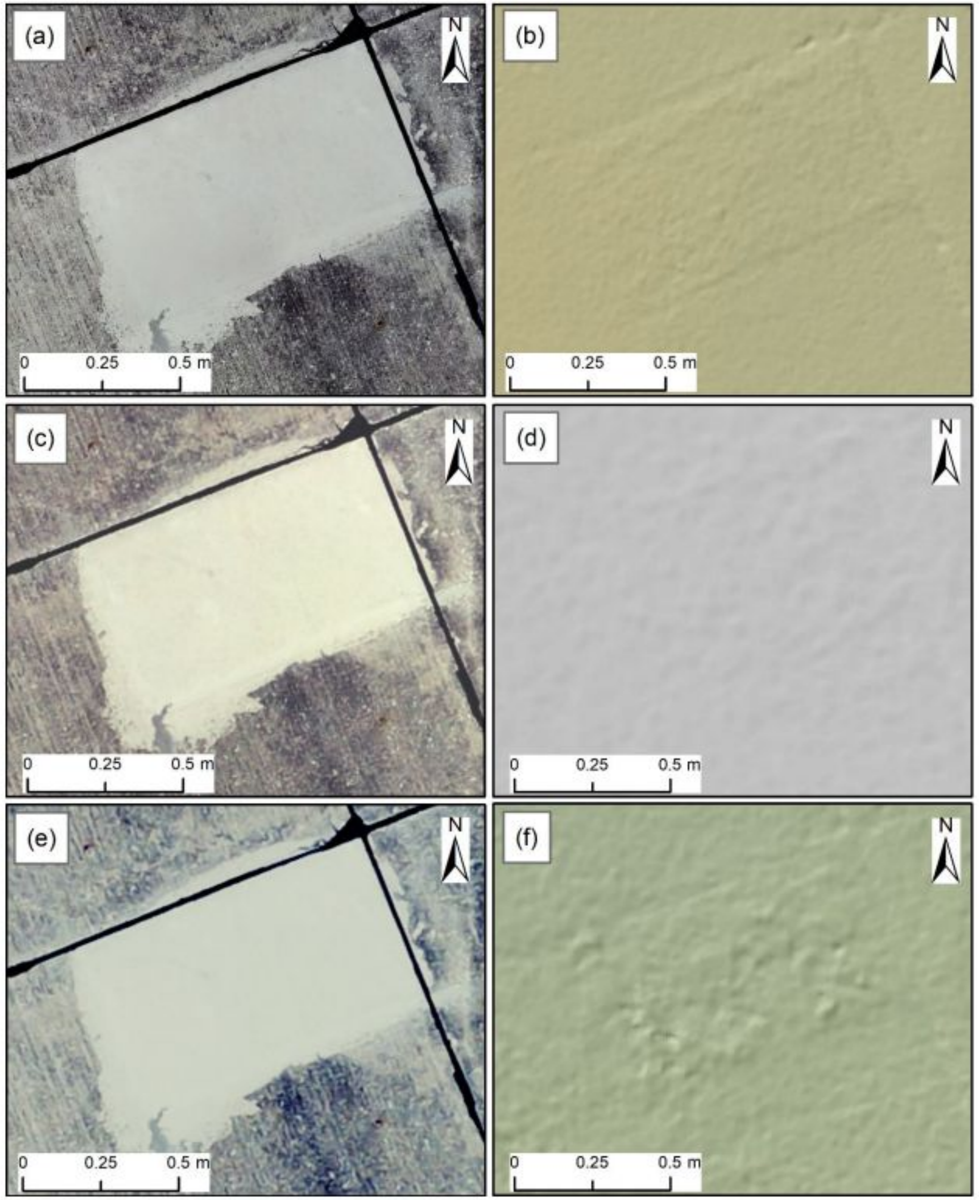
Comparison Between FOG PCI and sUAS PCI Calculated Using 2.5-mm/pix and 3.6-mm/pix Data from MTO

Iowa Examples



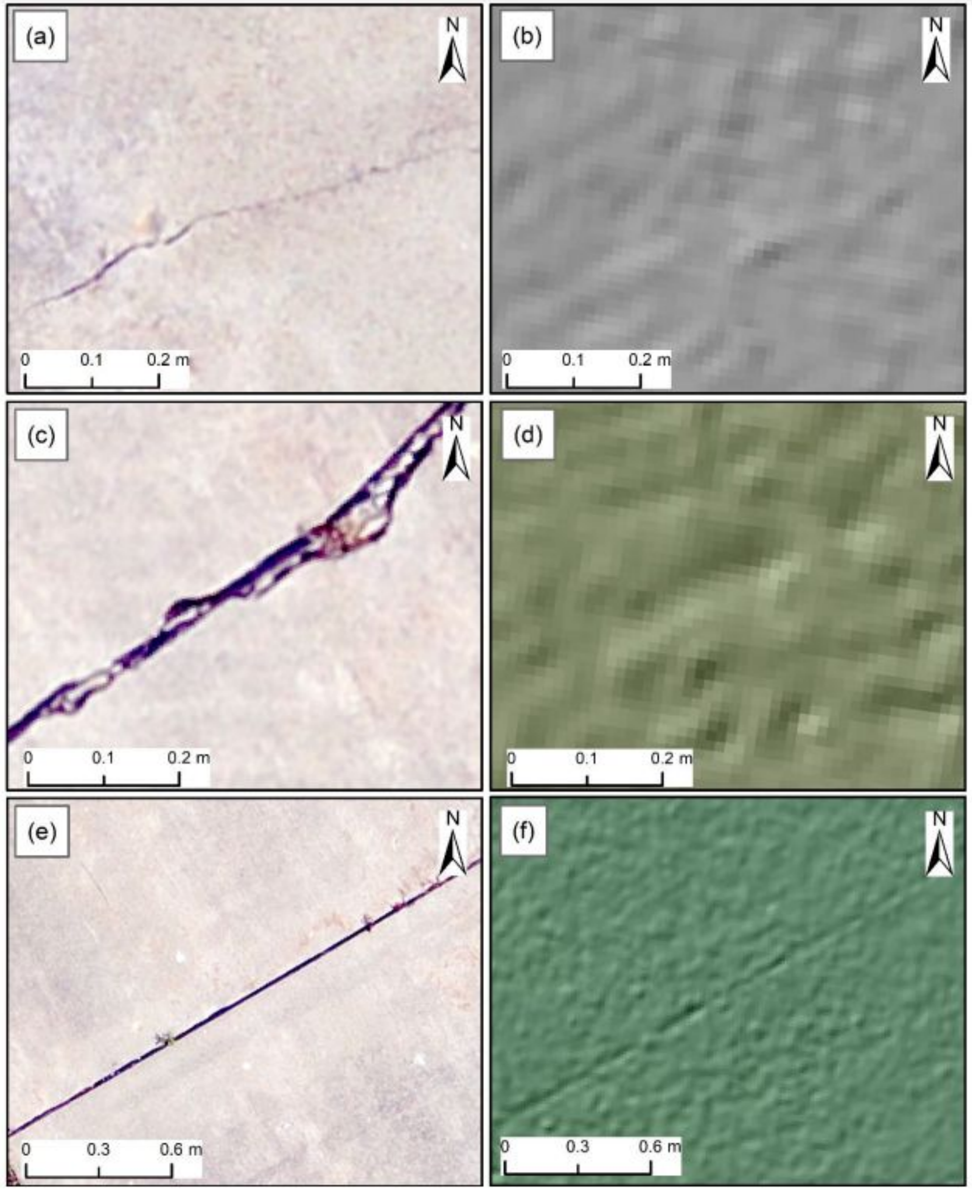
- **BNW**
- Corner Break (L)
- (a) 1.5-mm/pix Orthophoto
- (b) 6-mm/pix DEM
- (c) 3.3-mm/pix Orthophoto
- (d) 13.5-mm/pix DEM
- (e) 2.1-mm/pix Orthophoto
- (f) 8.6-mm/pix DEM

Iowa Examples



- **BNW**
- Large Patching (L)
- (a) 1.5-mm/pix Orthophoto
- (b) 6-mm/pix DEM
- (c) 3.3-mm/pix Orthophoto
- (d) 13.5-mm/pix DEM
- (e) 2.1-mm/pix Orthophoto
- (f) 8.6-mm/pix DEM

Iowa Examples



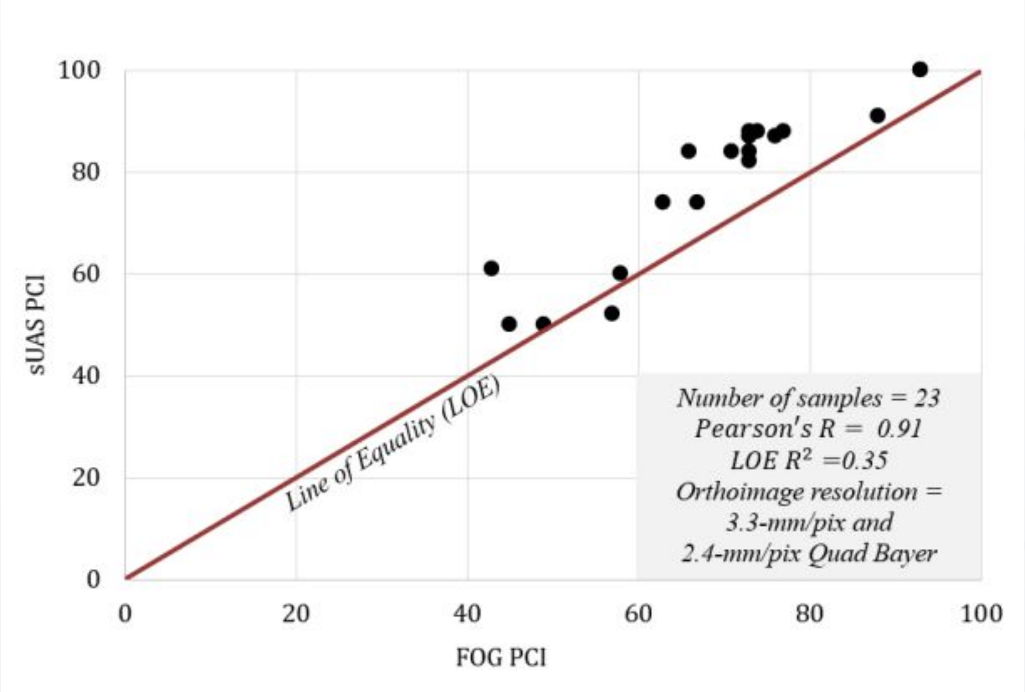
- **PRO**
- Longitudinal, Transverse, and Diagonal (LTD) Cracks (L)
- (a) 3.2-mm/pix Orthophoto
- (b) 12.9-mm/pix DEM

- LTD Cracks (M)
- (c) 3.2-mm/pix Orthophoto
- (d) 12.9-mm/pix DEM

- Joint Seal Damage (H)
- (e) 3.2-mm/pix Orthophoto
- (f) 12.9-mm/pix DEM

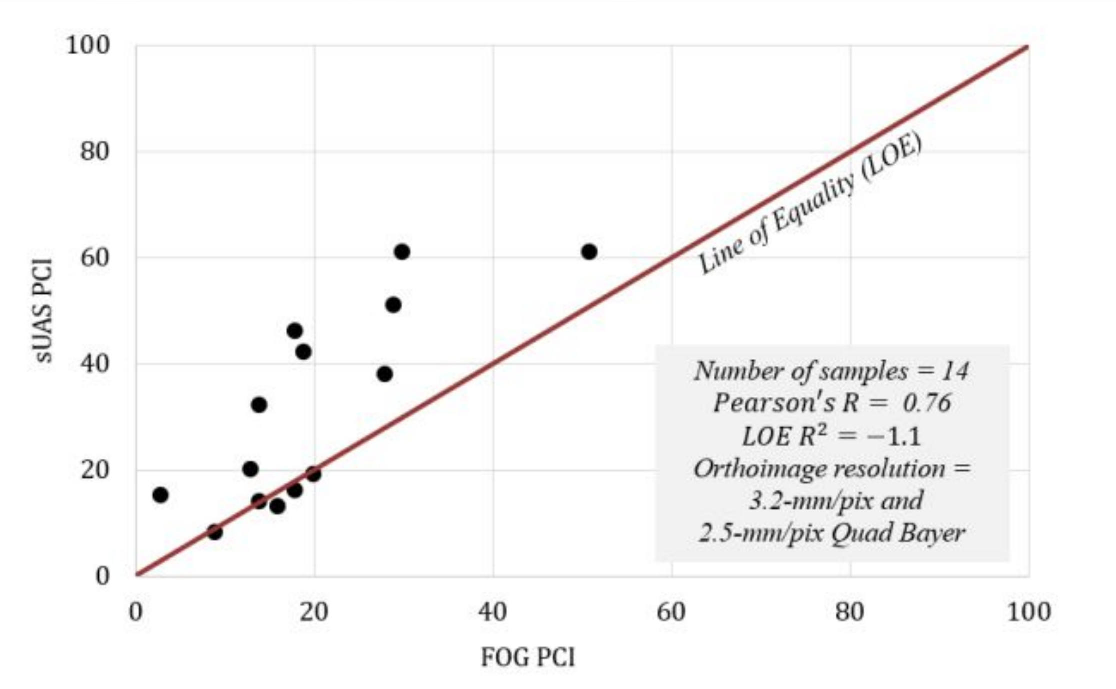
Iowa FOG and sUAS Comparisons

BNW



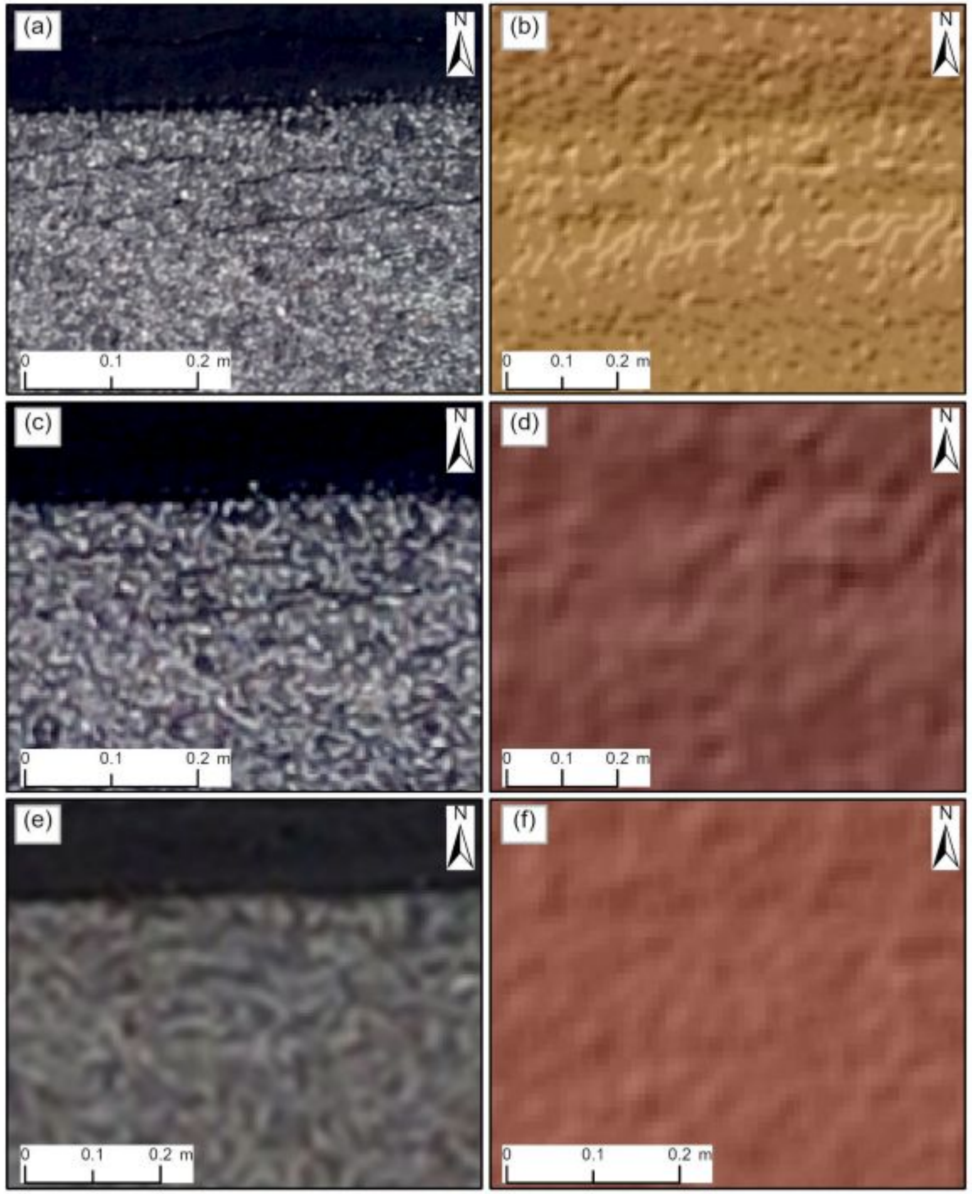
Comparison Between FOG PCI and sUAS PCI Calculated Using 2.4-mm/pix and 3.3-mm/pix Data from BNW

PRO



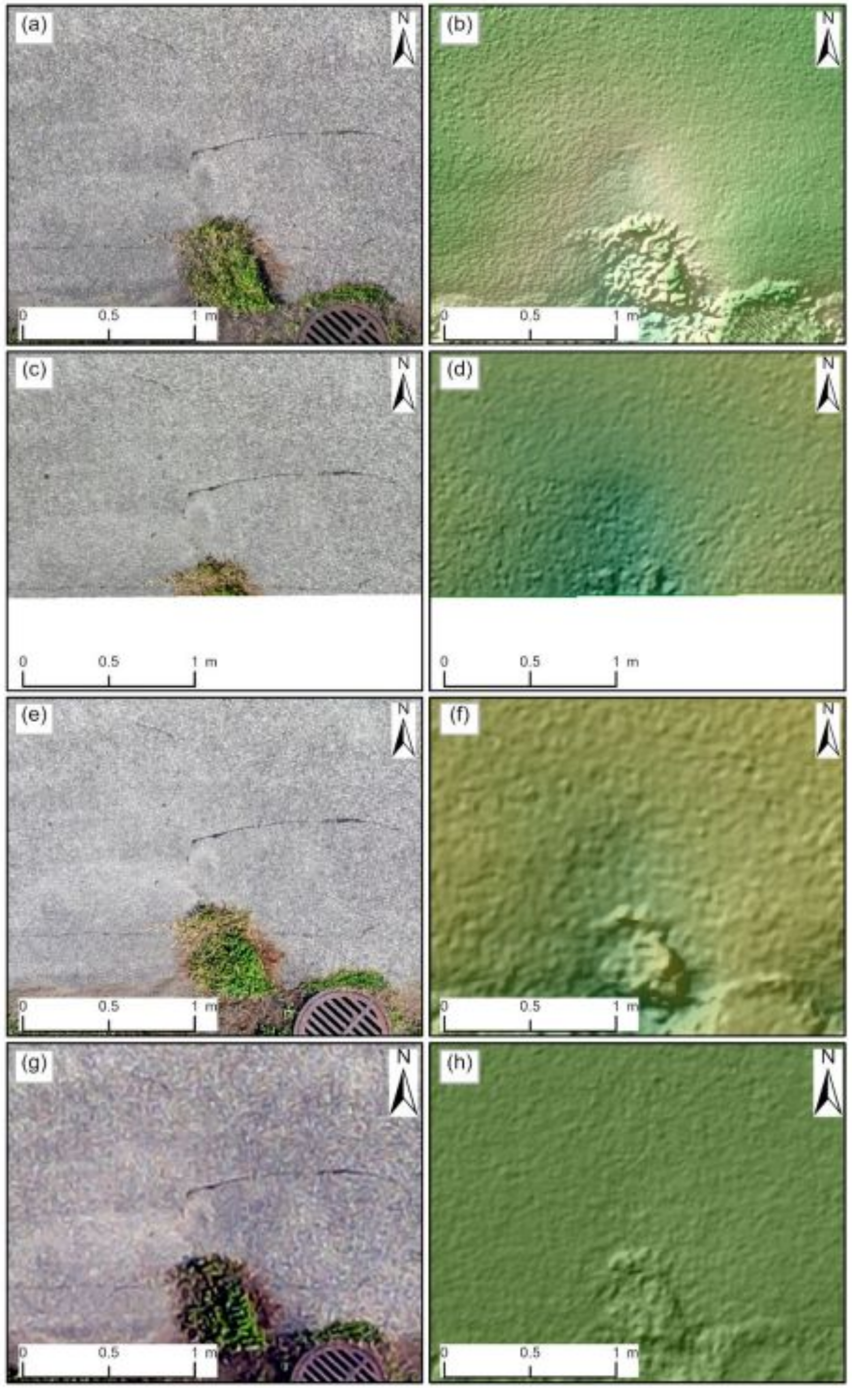
Comparison Between FOG PCI and sUAS PCI Calculated Using 2.5-mm/pix and 3.2-mm/pix Data from PRO

New Jersey Examples



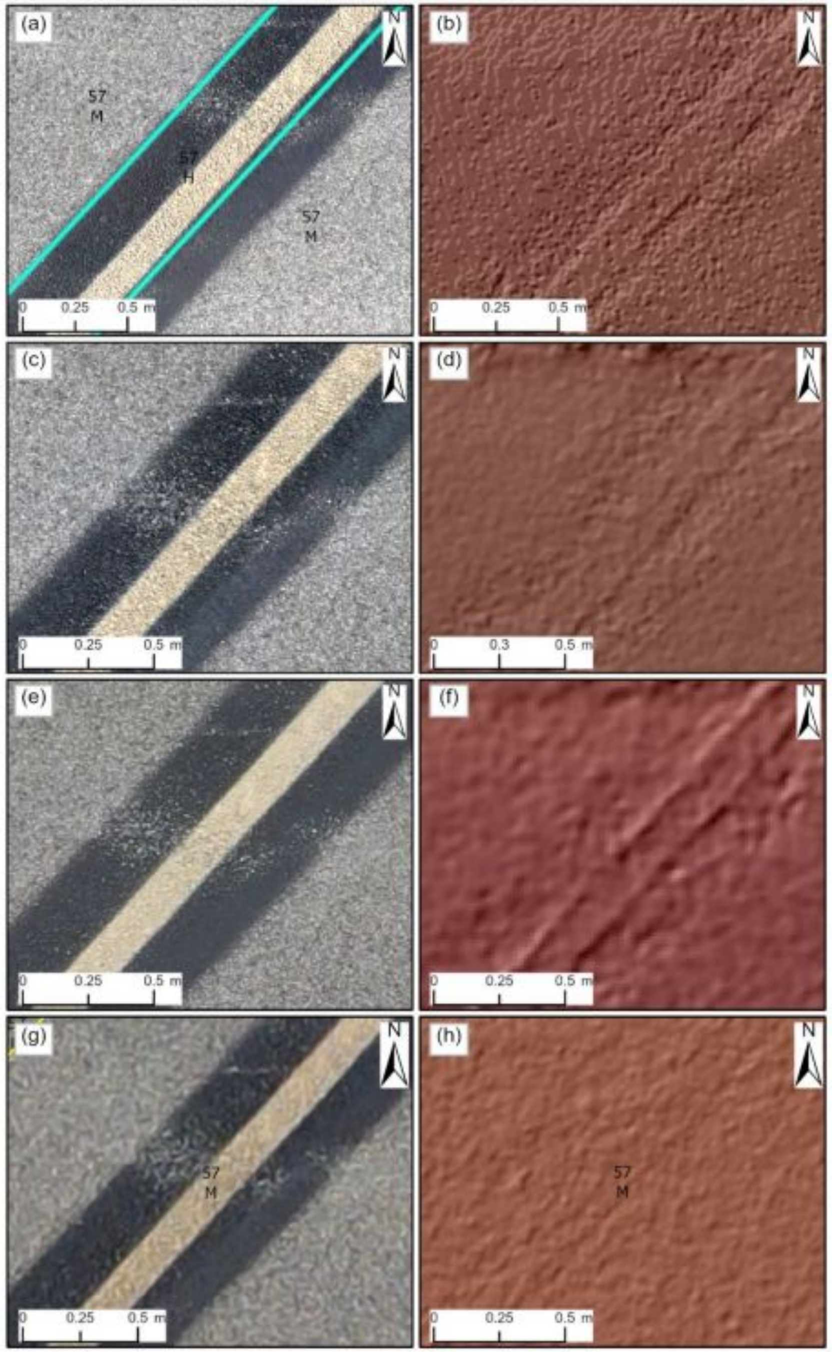
- **WWD**
- Alligator Cracking (L)
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 3.5-mm/pix Orthophoto
- (d) 14-mm/pix DEM
- (e) 4.1-mm/pix Orthophoto
- (f) 16.2-mm/pix DEM

New Jersey Examples



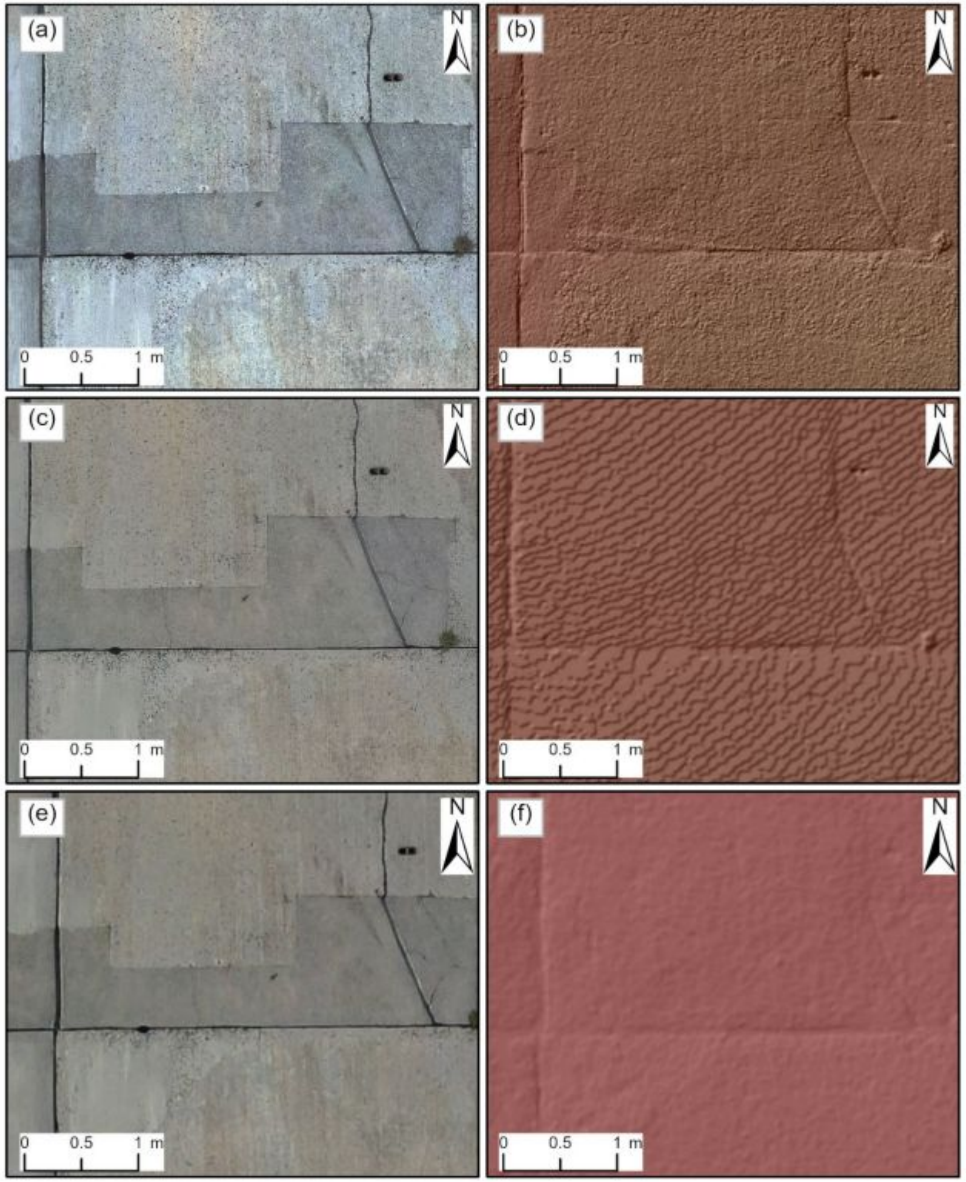
- **WWD**
- Depression
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 2.2-mm/pix Orthophoto
- (d) 8.9-mm/pix DEM
- (e) 3.5-mm/pix Orthophoto
- (f) 14-mm/pix DEM
- (g) 4.1-mm/pix Orthophoto
- (h) 16.2-mm/pix DEM

New Jersey Examples



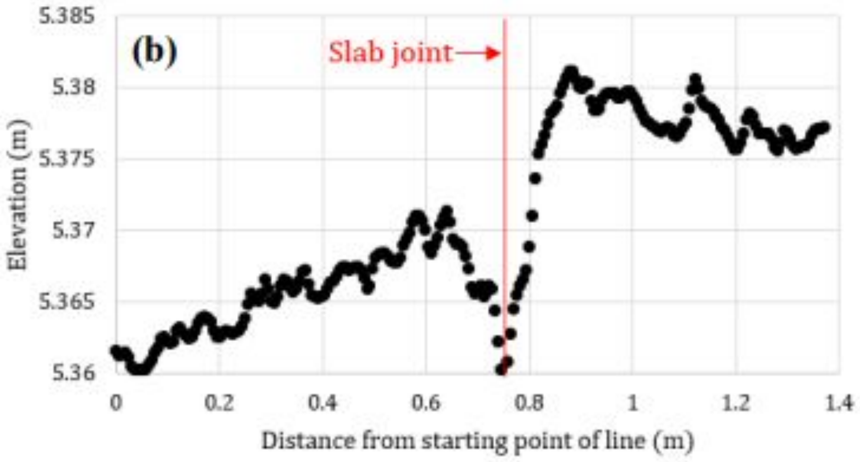
- **WWD**
- Weathering (H)
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 2.2-mm/pix Orthophoto
- (d) 8.9-mm/pix DEM
- (e) 3.5-mm/pix Orthophoto
- (f) 14-mm/pix DEM
- (g) 4.1-mm/pix Orthophoto
- (h) 16.2-mm/pix DEM

New Jersey Examples

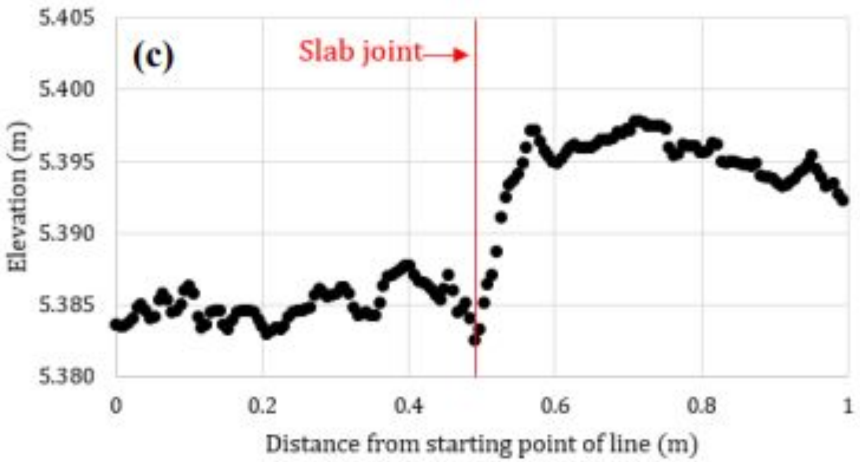


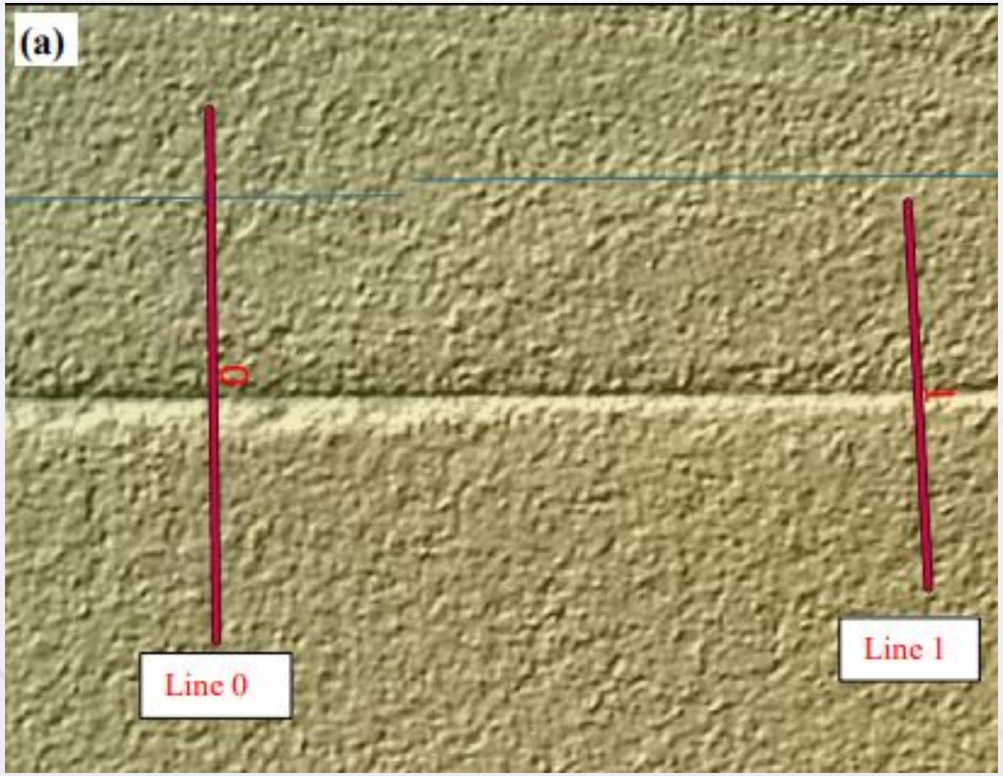
- **WWD**
- Large Patching (M)
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 3.5-mm/pix Orthophoto
- (d) 14-mm/pix DEM
- (e) 4.1-mm/pix Orthophoto,
- (f) 16.2-mm/pix DEM

Examples (WWD)



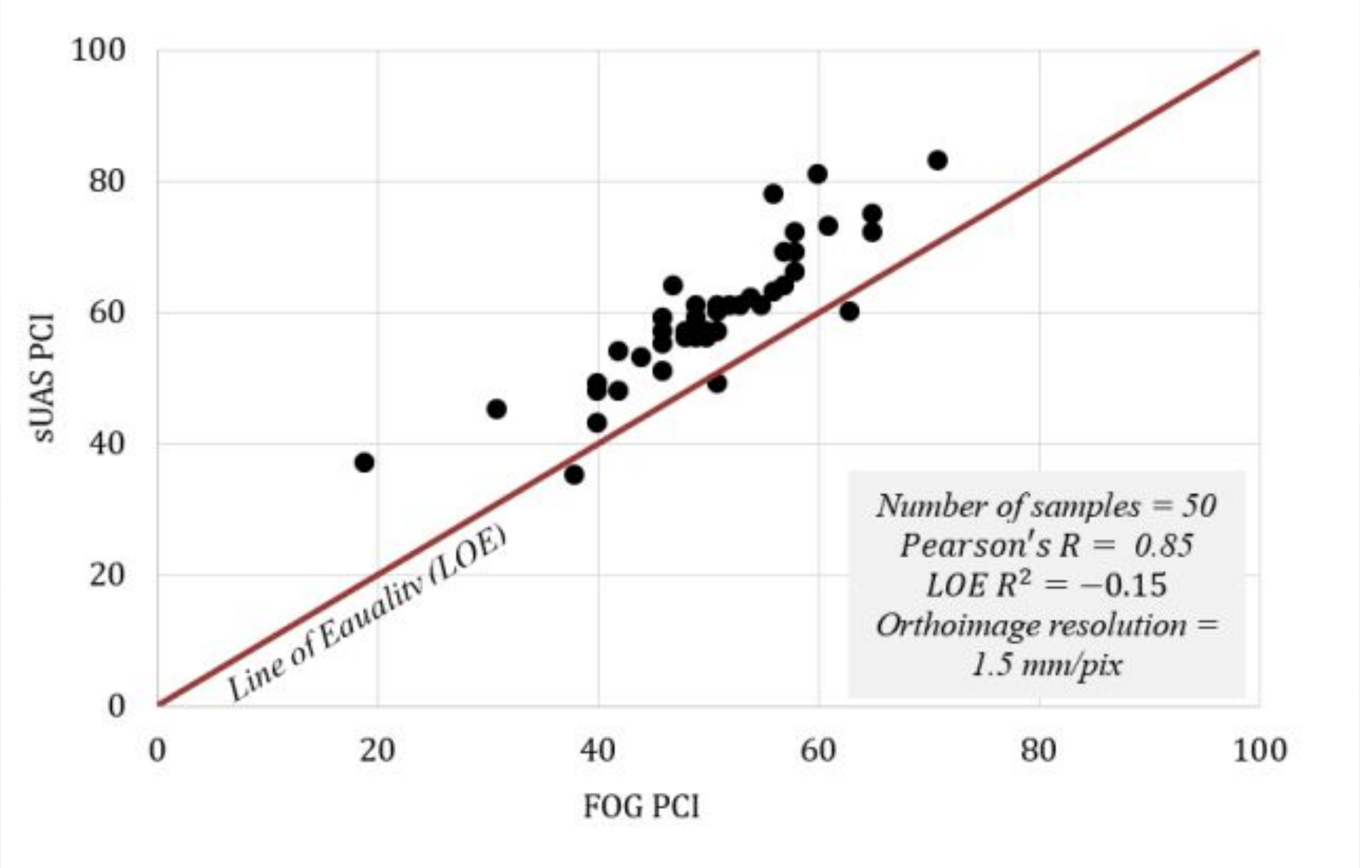
3D profile of pavement with Faulting (M)





- Faulting (M)
- (a) 5.9-mm/pix DEM
- (b) Elevation Difference of the DEM on Line 0
- (c) Elevation Difference of the DEM on Line 1

New Jersey (WWD) FOG and sUAS Comparisons



Comparison Between FOG PCI and sUAS PCI Calculated Using 1.5-mm/pix Data from WWD

Lessons Learned

Light Platforms

- Practical battery life of more than 20 minutes after keeping reserve for the safe return
- Ability to fly at a wind speed of up to 25 km/h with occasional wind gusts of up to 40 km/h
- Continuous data collection with flight assistance software with automated supervised data collection capabilities
- Small and agile sUAS platforms with integrated sensors are recommended for effective and rapid data collection

Heavy Platforms

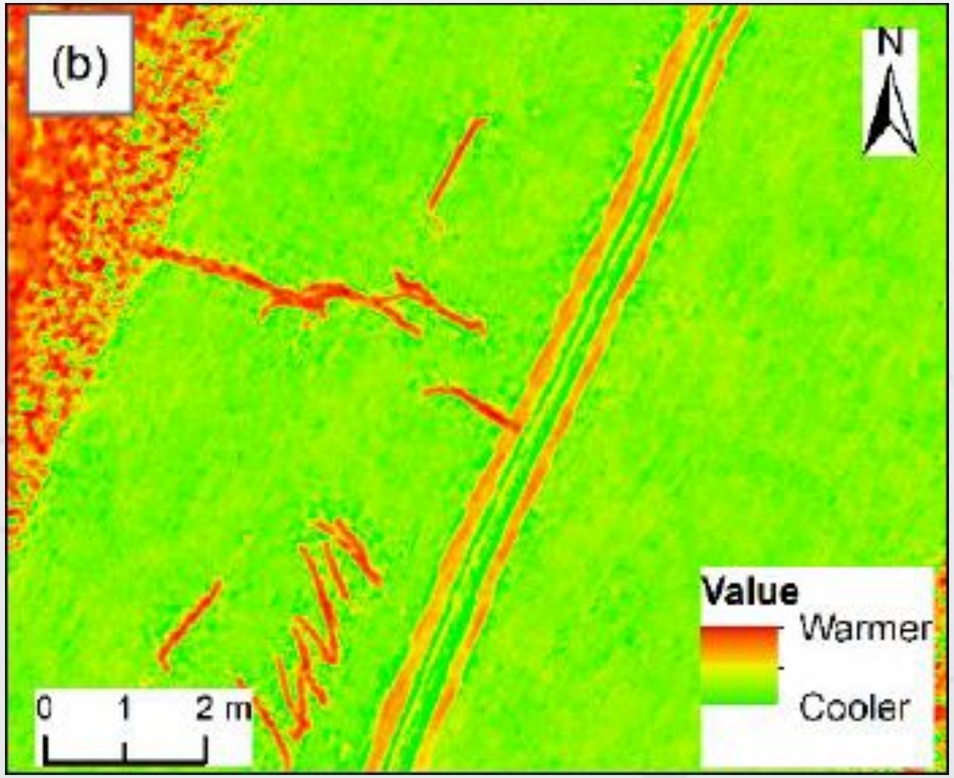
- Ability to carry additional payloads such as cameras that can weigh up to 1 kg
- The supported payload should include the ability to carry multiple sensors, with a focus on optical and thermal imaging
- Support of automated flight plans with flight assistance software
- Recommended for high-resolution and specific types of data collection that require special sensors

Lessons on Sensors (1 of 2)

- Full-frame RGB camera sensors (42+ mp) provide better visual details
  - Not directly integrated with platforms and additional knowledge are required to use them for data collection
- The light sensitivity, aperture, and shutter speed (exposure triangle) need to be adjusted on the non-integrated RGB full-frame cameras to capture the best quality images under different light conditions, flight altitudes, and flight speeds
  - Additional equipment and processing steps are required to capture position information and geotag the collected imagery

Lessons on Sensors (2 of 2)

- Quad Bayer sensors do not provide the same visual details as regular sensors with similar resolution
  - The 20-mp integrated RGB sensor provided better details compared to 48-mp Quad Bayer RGB camera
- The field of view of the thermal sensor is narrow
  - Extra difficulty in orthophoto generation
  - Greatly increases the required image overlap (total flight time)
- The multispectral sensor did not provide additional distress detection in the limited testing



31-mm/pix Stereo Thermal

Practical Data Collection

MINIMUM CREW REQUIREMENT

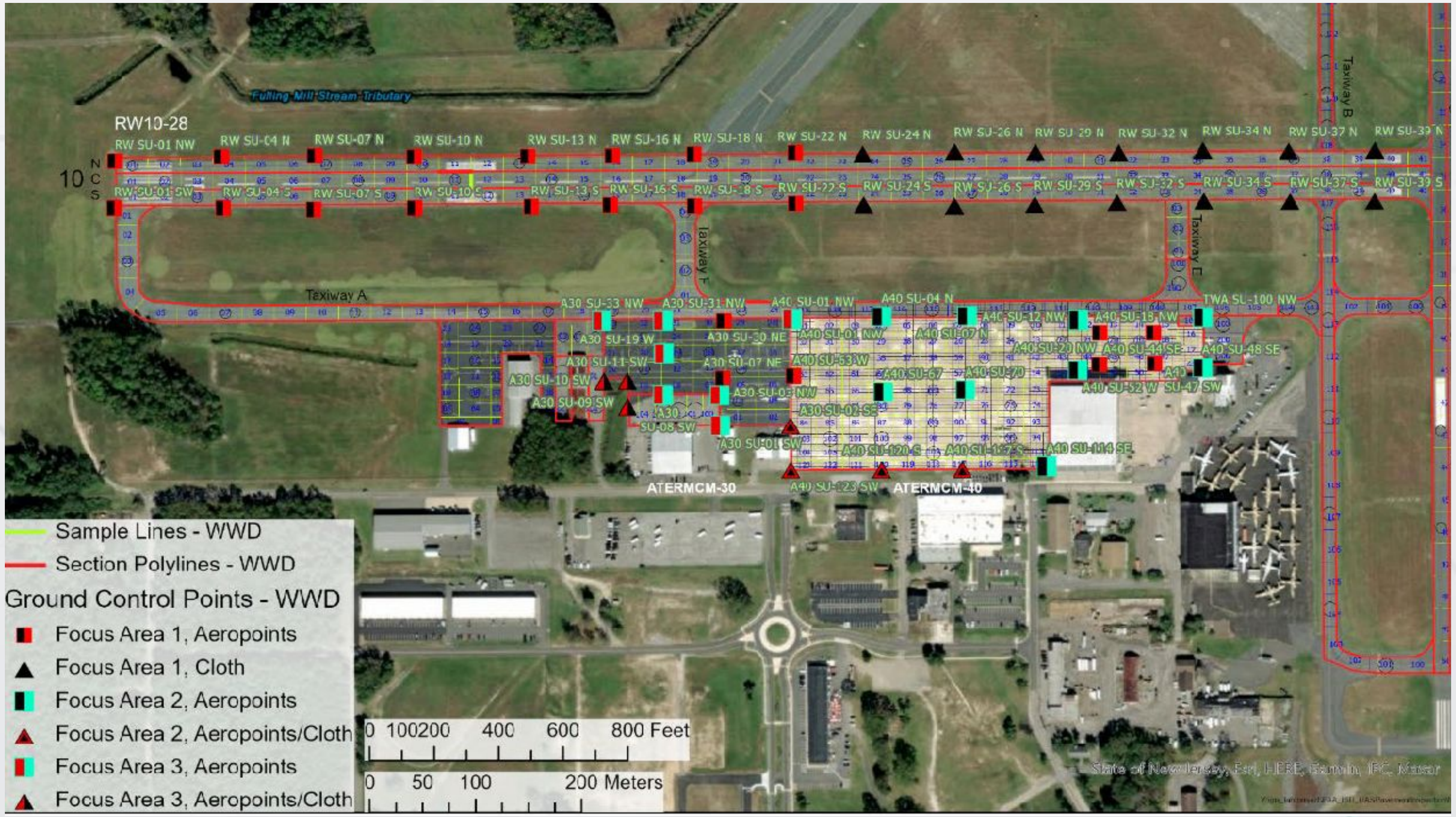
- Three-member sUAS crew could successfully collect sUAS data at an airport with low air traffic
  - One remote pilot, one visual observer, and one person responsible for logistics activities
- Logistics activities can include:
  - Charging sUAS batteries
  - Taking location-tagged field photos
  - Taking measurements of distresses for comparison
  - Placing and removing ground control points (GCPs)
- Can include one additional sUAS pilot with an additional observer to enable simultaneous data collection

High-resolution sUAS data collection with mdMapper1000+ and Bergen Hexacopter sUAS platforms

Practical Data Collection

NUMBER AND OPTIMAL LOCATION OF GCP

- The number and location of GCPs are important to meet data collection and processing needs
- Six or fewer GCPs on a long and narrow runway or taxiway can cause distortion of the orthophoto shape



Ground Control Point locations planned at WWD spaced at 100-m intervals

Practical Data Collection

IMPACT OF WEATHER ON DATA COLLECTION

- sUAS data collection generally requires favorable weather for efficient data collection, with no precipitation and reasonably low wind speeds
- Most sUAS cannot collect usable imagery during precipitation
- Rapid changes in ambient light during an sUAS flight can make the photogrammetric data results inconsistent

Practical Data Collection

SOFTWARE UPDATES AND ISSUES WITH sUAS PLATFORM

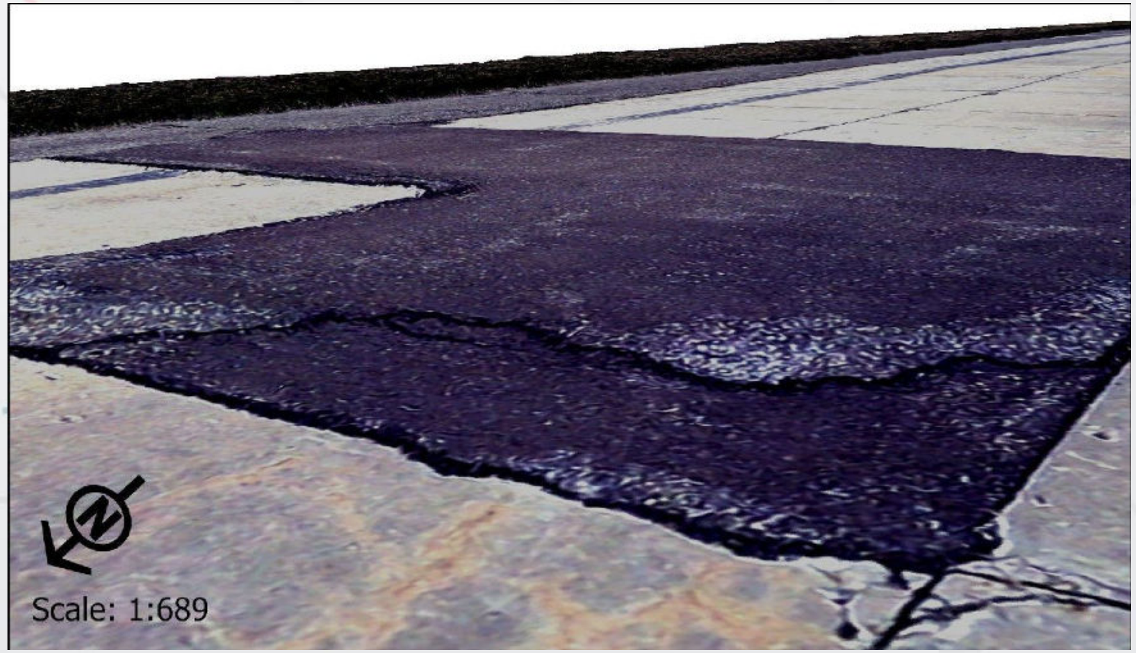
- sUAS are composed of complex technology
  - Many hardware and software components that need to operate properly for safe, efficient, and high-quality data collection
- Strongly recommended to verify all intended flight control applications work the day before flights occur and to keep the settings consistent until after completing data collection
- “Unlocking geozones” may need to be completed
  - Two temporarily restricted zones at untowered airports encountered

General Lessons on Data Processing

- The data processing time for a complete data collection varies based on:
  - Resolution of the data
  - Number of photos
  - Required resolution of the output
- Geospatial data should align accurately to make data easier to compare between different data creators and to compare results over time
- Refer to FAA DOT/FAA/TC-23/50 for Agisoft Metashape data processing lessons

Lessons Learned on Data Types and Resolutions (1)

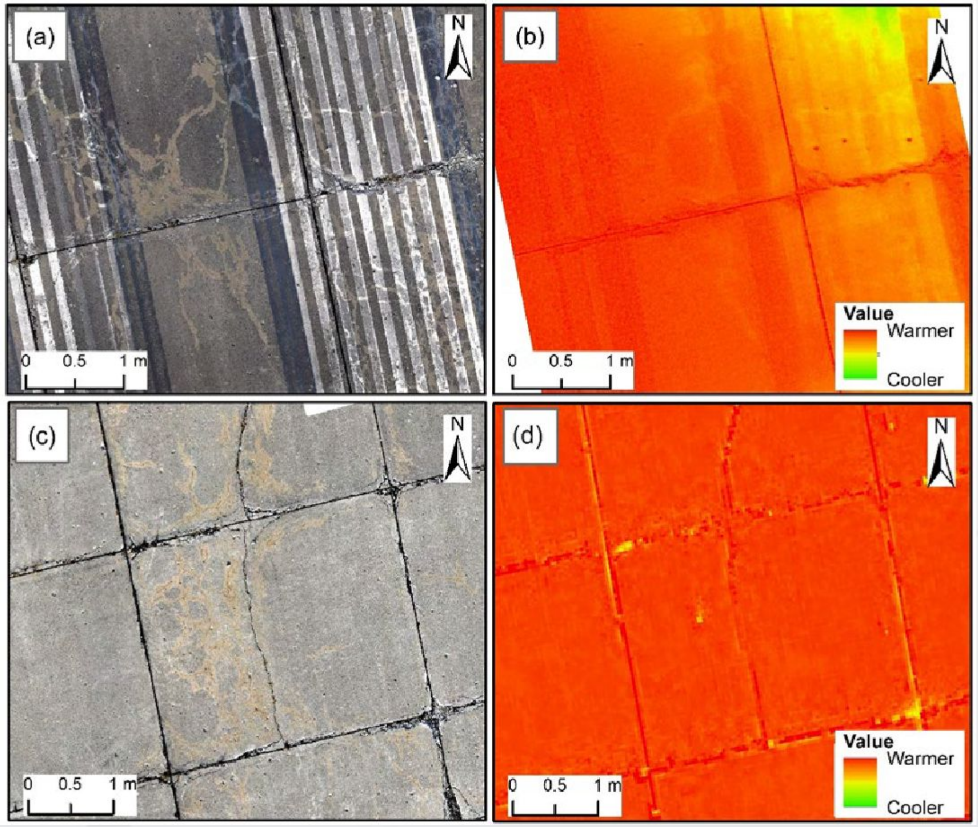
- RGB sensor recommended if only a single sensor is possible
- RGB and DEM data are adequate to detect most distresses
  - If budget and time permit, other sensors could be added for specific needs
- RGB optical orthophoto with resolutions ≤ 5 mm/pix can detect and rate at least some distresses
  - Resolutions ≤ 2 mm/pix produce the best data



Example of draping an sUAS-derived Orthophoto over a DEM showing elevation differences for patching on airport runway

Lessons Learned on Data Types and Resolutions (2)

- DEM with resolution ≤ 20 mm/pix likely to be useful
- Thermal orthophoto with resolution ≤ 30 mm/pix likely to be useful
- Combination of ≤ 1.5-mm/pix RGB optical orthophoto and ≤ 6.0-mm/pix EM are highly recommended



LTD Cracks and D-cracks in PCC Pavement on Runway 17/35 at ONZ

Categories of Distresses

Concrete Distress Minimum Resolutions

Distress Name (PAVER™ Distress Number)	Severity	Distress Detected and Severity Rating (mm/pix)		Airport(s) with Distress
		Orthophoto	DEM	
Blowup (61)				Data not available
Corner breaks (62)	L	2.5	ND	ONZ, BNW, PRO, MTO, WWD
	M, H	21	ND	
LTD cracks (63)	L	7.3	ND	ONZ, BNW, PRO, MTO, WWD
	M	21	ND	
	H*	21		
Durability cracking (64)	L	7.3	ND	ONZ
	M	21	10	
	H	21	29.1	
Joint seal damage (65)	L	ND	ND	BNW, PRO, MTO, WWD
	M	2.5	ND	BNW, PRO, WWD
	H	7.3	6	ONZ, BNW, PRO
Small patching (66)	L	3.3	ND	BNW, PRO, WWD
	M	4.5	6	BNW, PRO, WWD
	H*	4.5	6	PRO
Large patching (67)	L	21	ND	ONZ, BNW, PRO, WWD
	M, H	21	29	ONZ, WWD
Pop-outs (68)	N/A	3.3	6	BNW
Pumping (69)	N/A			Data not available
Scaling (70)	L			Data not available
	M, H*	21	10	ONZ
Settlement or faulting (71)	L	ND	ND	ONZ, PRO, WWD
	M, H*	ND	3	ONZ, PRO, WWD
Shattered slab (72)	L	ND	ND	
	M, H	21	10	ONZ, PRO
Shrinkage cracks (73)	N/A**	2.5	ND	MTO, WWD
Joints spalling (74)	L**	2.5	ND	MTO, BNW, PRO, WWD
	M**, H	2.5	6	
Corner spalling (75)	L**, M**	3.3	ND	MTO, BNW, PRO, WWD
	H	3.3	10	PRO
Alkali-Silica Reaction (76)	L**	7.3	ND	ONZ, BNW, PRO, WWD
	M**, H	7.3	6	ONZ, BNW, PRO, WWD

L = Low, M = Medium, H = High
N/A = Not applicable
ND = Not detected
*Based on the detection of lower severity
**Detection not always possible or misidentified as other distresses

Asphalt Distress Minimum Resolutions

Distress Name (PAVER™ Distress Number)	Severity	Distress Detected and Severity Rating (mm/pix)		Distresses Available
		Orthophoto	DEM	
Alligator cracking (41)	L	3.5	5.9	WWD
	M, H			Data not available
Block cracking (43)	L	7.3	9.2	MTO, WWD
	M, H	7.3	19.6	
Corrugation (44)	N/A			Data not available
Depression (45)	L	ND	ND	WWD
	M	ND	6	TTF, WWD
	H	4.1	16	WWD
Jet blast erosion (46)	N/A			Data not available
Joint reflection cracking (47)	N/A			Data not available
L&T cracking (48)	L	7.3	9.2	TTF, MTO, WWD
	M, H	7.3	19.6	
Oil spillage (49)				Data not available
Patching (50)	L, M, H	4.1	16.2	WWD
Polish aggregate (51)				Data not available
Raveling (52)	L, M, H*	1.5	ND	TTF, WWD
Rutting (53)	N/A			Data not available
Shoving (54)	L	ND	5.9	WWD
	M	2.5	10	MTO, WWD
Slippage cracking (55)				Data not available
Swell (56)	L, M	ND	ND	TTF, WWD
	H			Data not available
Weathering (57)	L, M, H	ND	ND	TTF, MTO, WWD

L = Low, M = Medium, H = High
N/A = Not applicable
ND = Not detected
Data not available means that distress or a particular severity rating was not present.
*Based on the detection of lower severity

Detectable Distresses

Type	PCC Pavement Distresses	AC Pavement Distresses
Detectable	Corner breaks (LMH), LTD cracks (LMH), Durability cracking (LMH), Joint seal damage (MH), Small patching (LMH), Large patching (LMH), Pop-outs, Scaling (MH), Shattered slab (LMH), Shrinkage cracks, Joints spalling (MH), Corner spalling (MH), Alkali-silica reaction (MH)	Alligator cracking (LMH), L&T cracking (LMH), Block cracking (LMH), Patching (LMH), Raveling (H)
Detectable with previous PCI data	Faulting (LMH), Joints spalling (LM), Corner spalling (LM), Alkali-silica reaction (LM)	Raveling (MH), Depression (LMH), Shoving (LMH)
Undetectable	Joint seal damage (L), Alkali-silica reaction (L)	Swell (LM), Weathering (LMH)

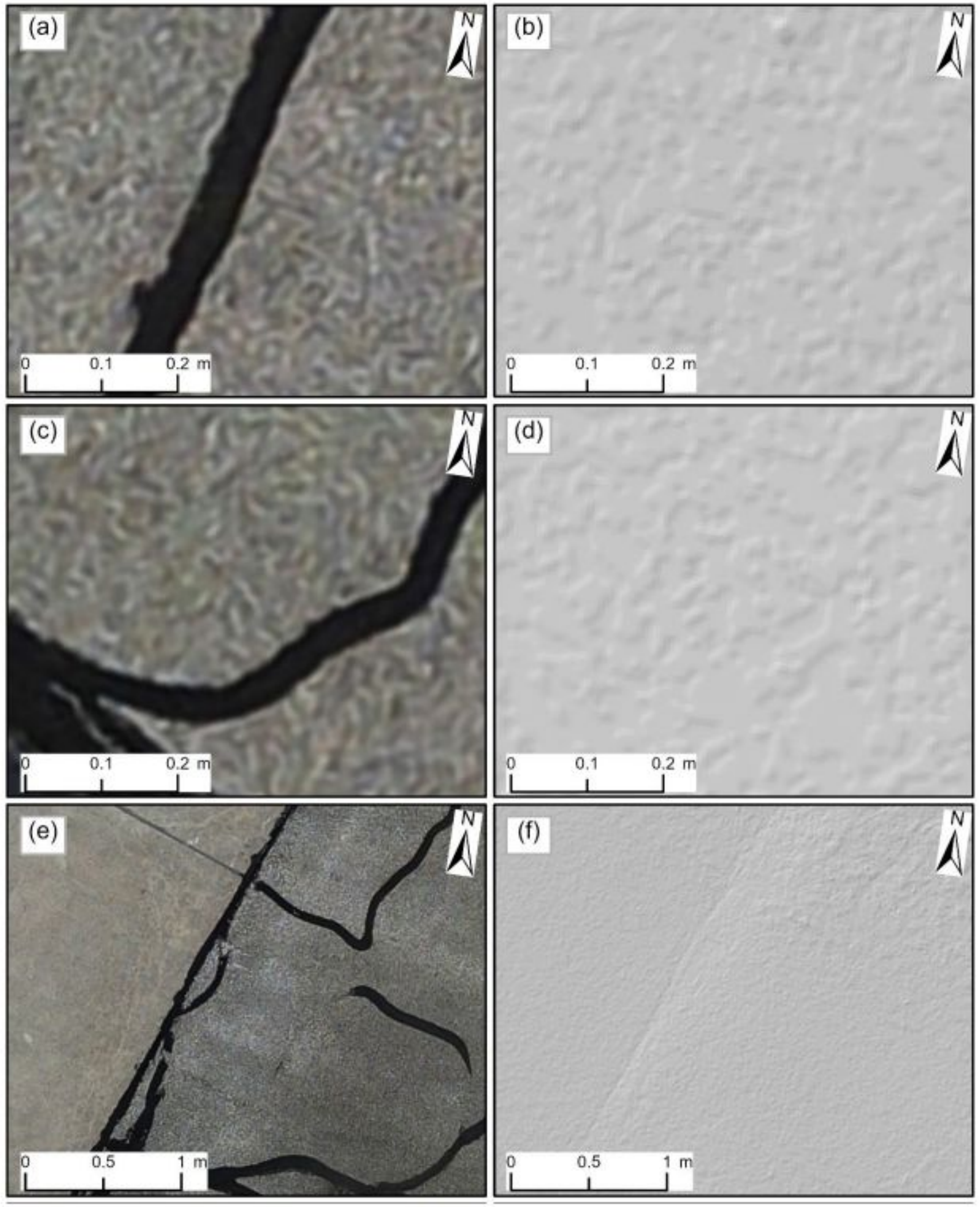
L = Low, M = Medium, H = High

Thank you!

PETER-PAUL DZWILEWSKI, P.E.
PDZWILEWSKI@APPLIEDPAVEMENT.COM

Additional Backup Slides

Illinois Examples

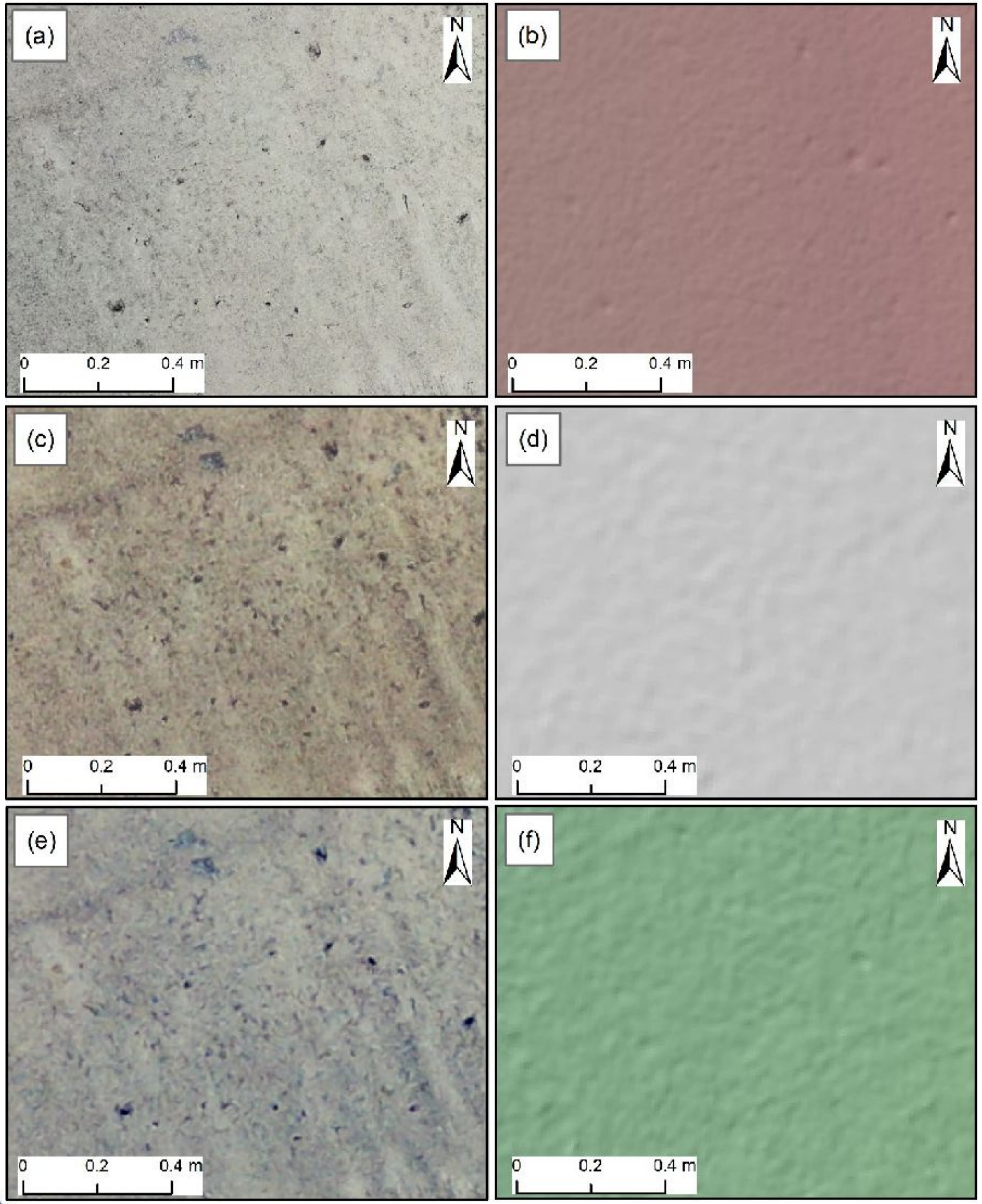


- **MTO**
- L&T Cracks (L)
- (a) 2.5-mm/pix Orthophoto
- (b) 5-mm/pix DEM

- L&T Cracks (M)
- (c) 2.5-mm/pix Orthophoto
- (d) 5-mm/pix DEM

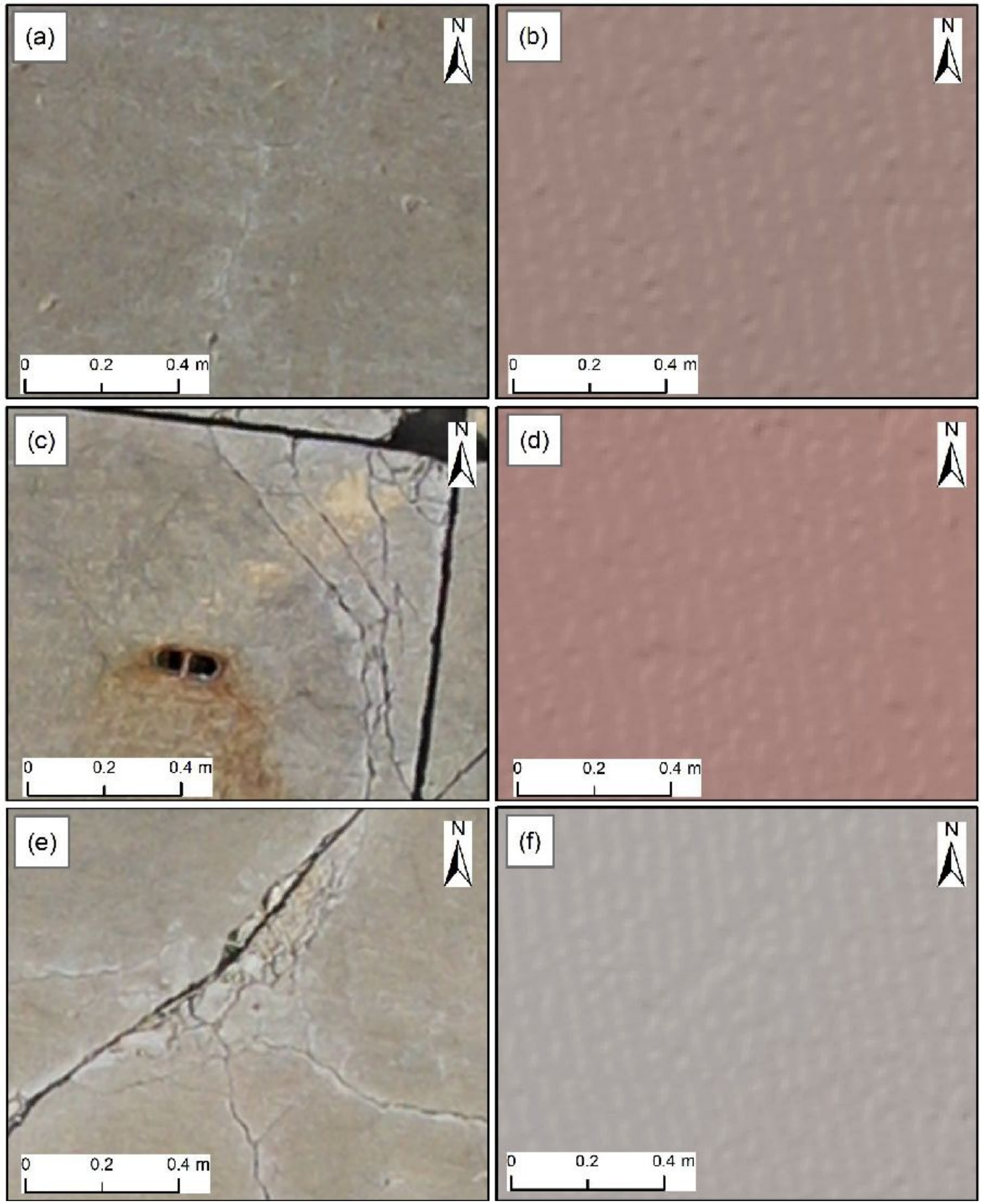
- Shoving (L)
- (e) 2.5-mm/pix Orthophoto
- (f) 5-mm/pix DEM

Iowa Examples



- **BNW**
- Pop-outs
- (a) 1.5-mm/pix Orthophoto
- (b) 6-mm/pix DEM
- (c) 3.3-mm/pix Orthophoto
- (d) 13.5-mm/pix DEM
- (e) 2.1-mm/pix Orthophoto
- (f) 8.6-mm/pix DEM

Iowa Examples

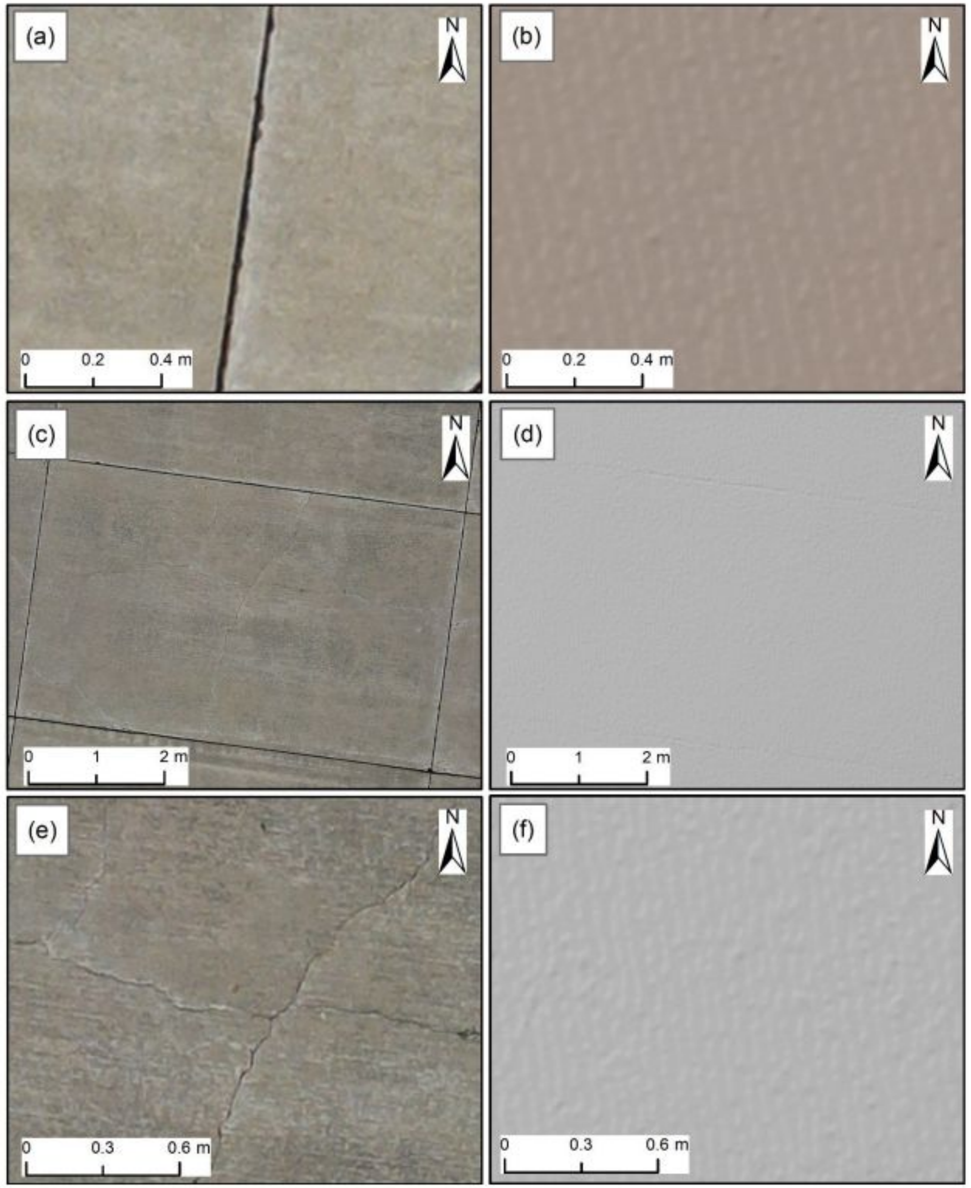


- **PRO**
- Alkali-Silica Reaction (ASR) (L)
- (a) 2.5-mm/pix Orthophoto
- (b) 10-mm/pix DEM

- ASR (M)
- (c) 2.5-mm/pix Orthophoto
- (d) 10-mm/pix DEM

- ASR (H)
- (e) 2.5-mm/pix Orthophoto
- (f) 10-mm/pix DEM

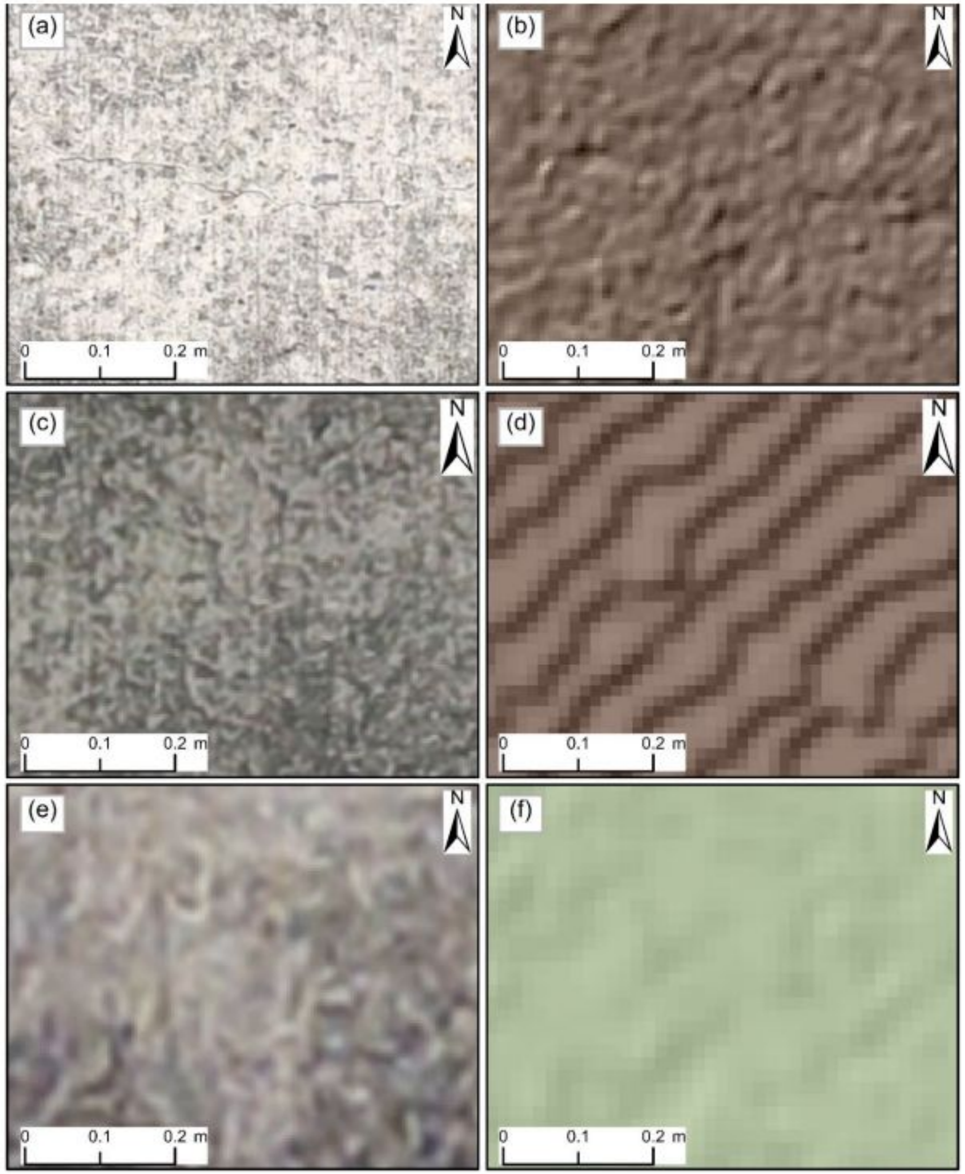
Iowa Examples



- **PRO**
- Faulting (L)
- (a) 2.5-mm/pix Orthophoto
- (b) 10-mm/pix DEM

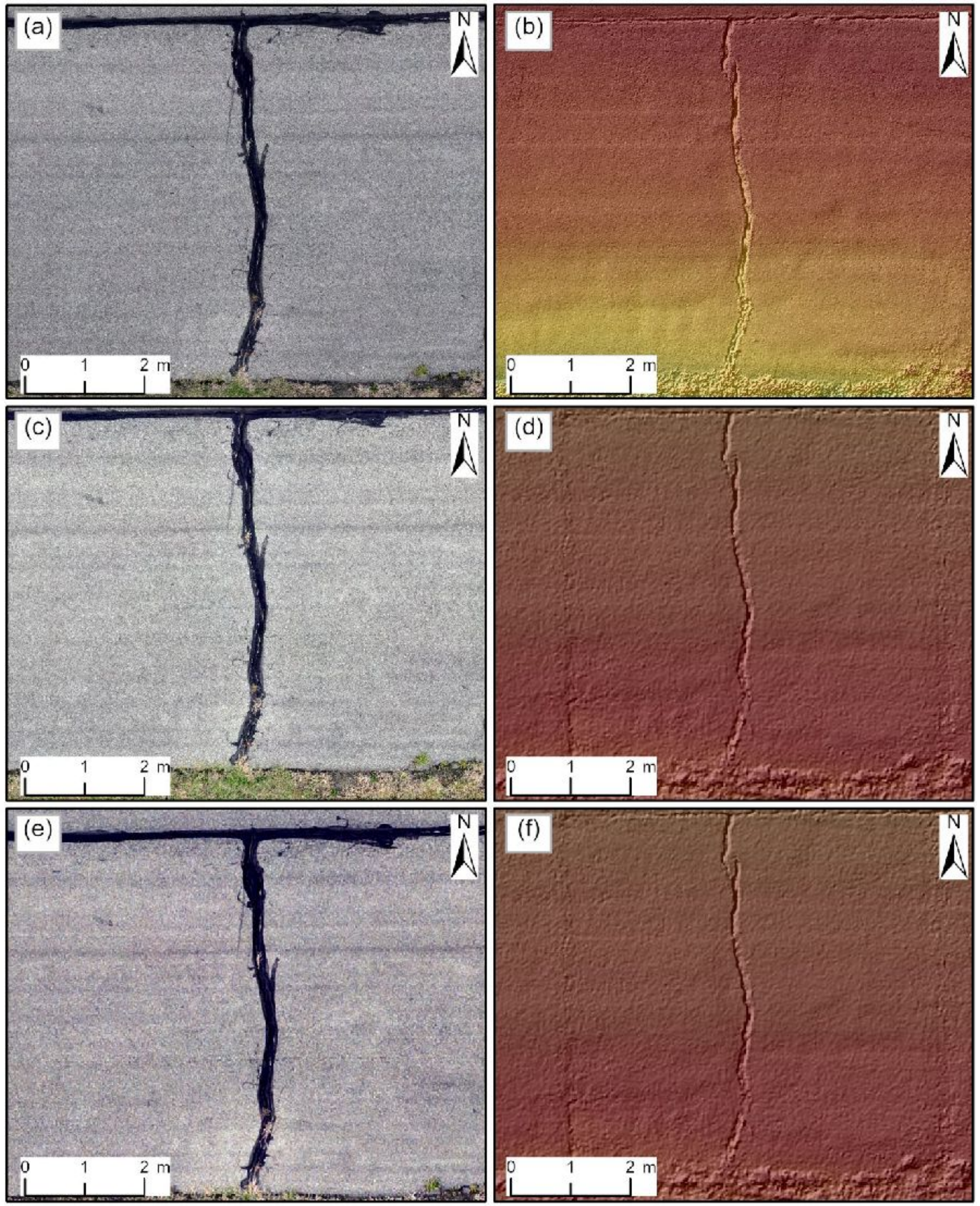
- Shattered Slabs (M)
- (c, e) 2.5-mm/pix Orthophoto
- (d, f) 10-mm/pix DEM

New Jersey Examples



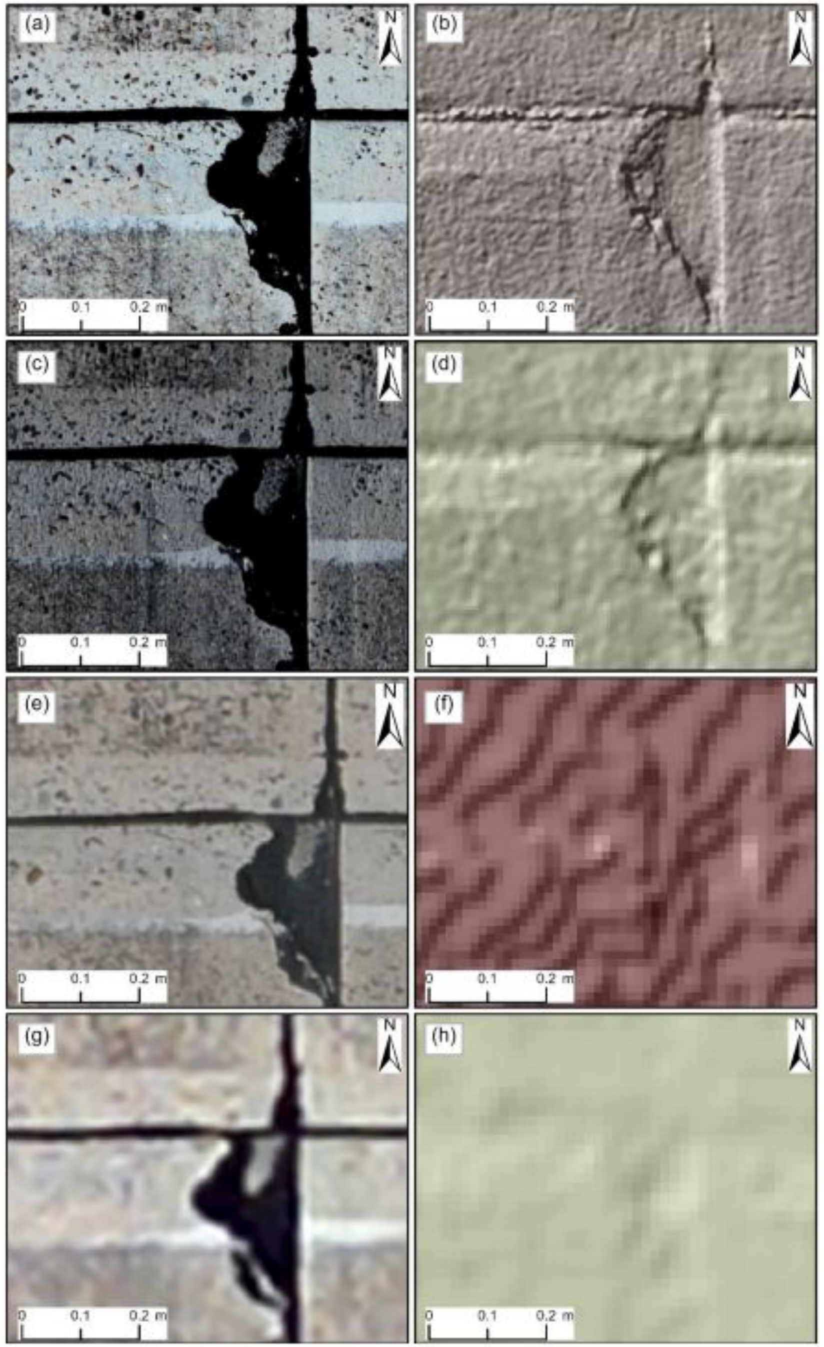
- **WWD**
- Shrinkage Cracks
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 3.5-mm/pix Orthophoto
- (d) 14-mm/pix DEM
- (e) 4.1-mm/pix Orthophoto
- (f) 16.2-mm/pix DEM

New Jersey Examples



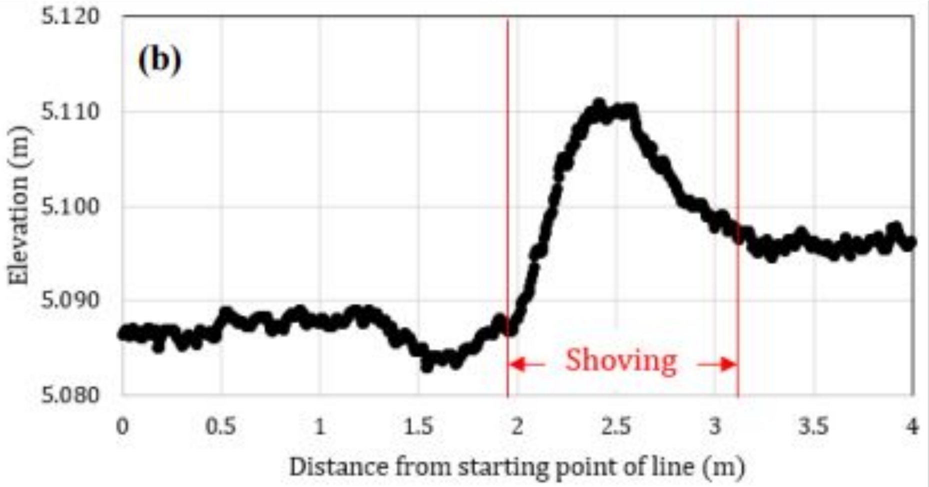
- **WWD**
- LTD Cracks (H)
- (a) 1.5-mm/pix Orthophoto
- (b) 5.9-mm/pix DEM
- (c) 3.5-mm/pix Orthophoto
- (d) 14-mm/pix DEM
- (e) 4.1-mm/pix Orthophoto
- (f) 16.2-mm/pix DEM

New Jersey Examples

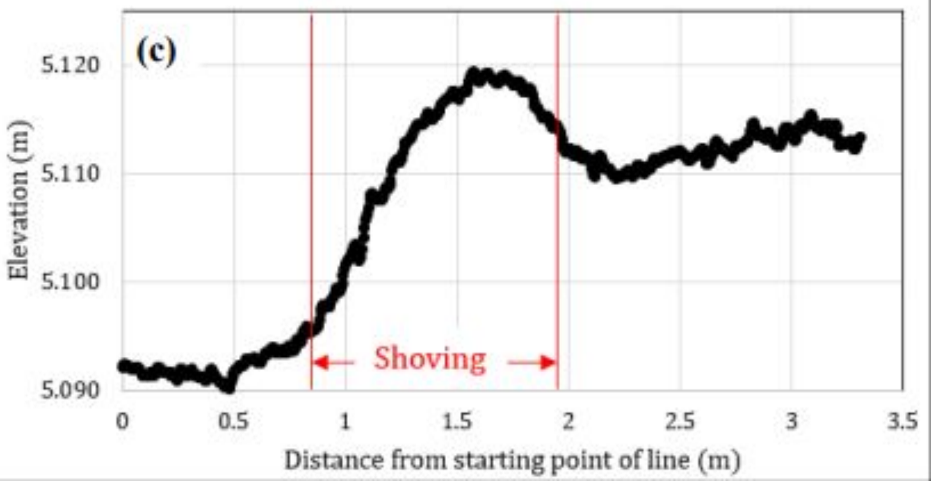


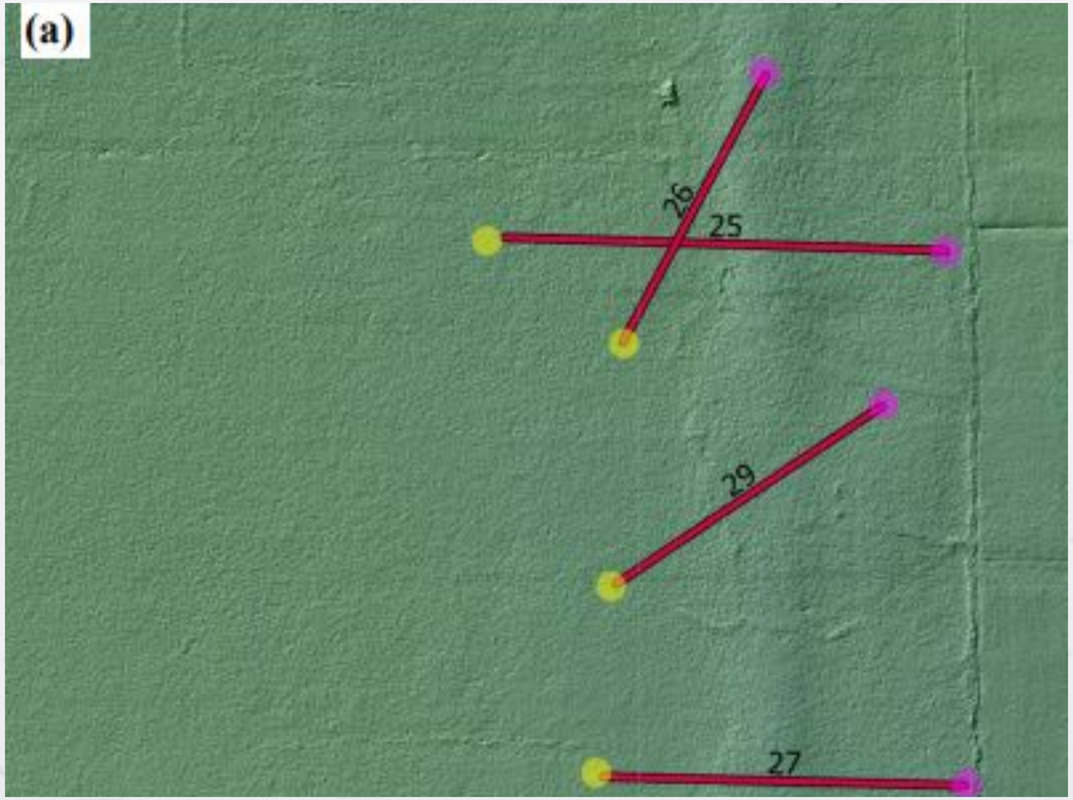
- **WWD**
- ASR (M)
- (a) 0.7-mm/pix Orthophoto
- (b) 2.7-mm/pix DEM
- (c) 1.5-mm/pix Orthophoto
- (d) 5.9-mm/pix DEM
- (e) 3.5-mm/pix Orthophoto
- (f) 14-mm/pix DEM
- (g) 4.1-mm/pix Orthophoto
- (h) 16.2-mm/pix DEM

EXAMPLES (WWD)



3D profile of pavement with Shoving (L)





- Shoving (L)
- (a) 5.9-mm/pix DEM
- (b) Elevation Difference of the DEM on Line 25
- (c) Elevation Difference of the DEM on Line 27

Lessons on Agisoft Metashape Data Processing

- Location information of the GCP, if available, must be used
- Medium or high setting for image alignment is recommended
  - A medium setting for dense cloud generation is recommended
  - The high or very high options can be used based on the resolution requirements
- The DEM and orthophoto output must have a projected coordinate system;
- Each processing parameter should be selected based on:
  - Number of images to be processed
  - Resolution of the data
  - Estimated time required to complete the processing
  - Configuration of the computer or cloud-based services being used