Recent Advances in Measuring Volume Changes of Soil Specimen During Triaxial Testing

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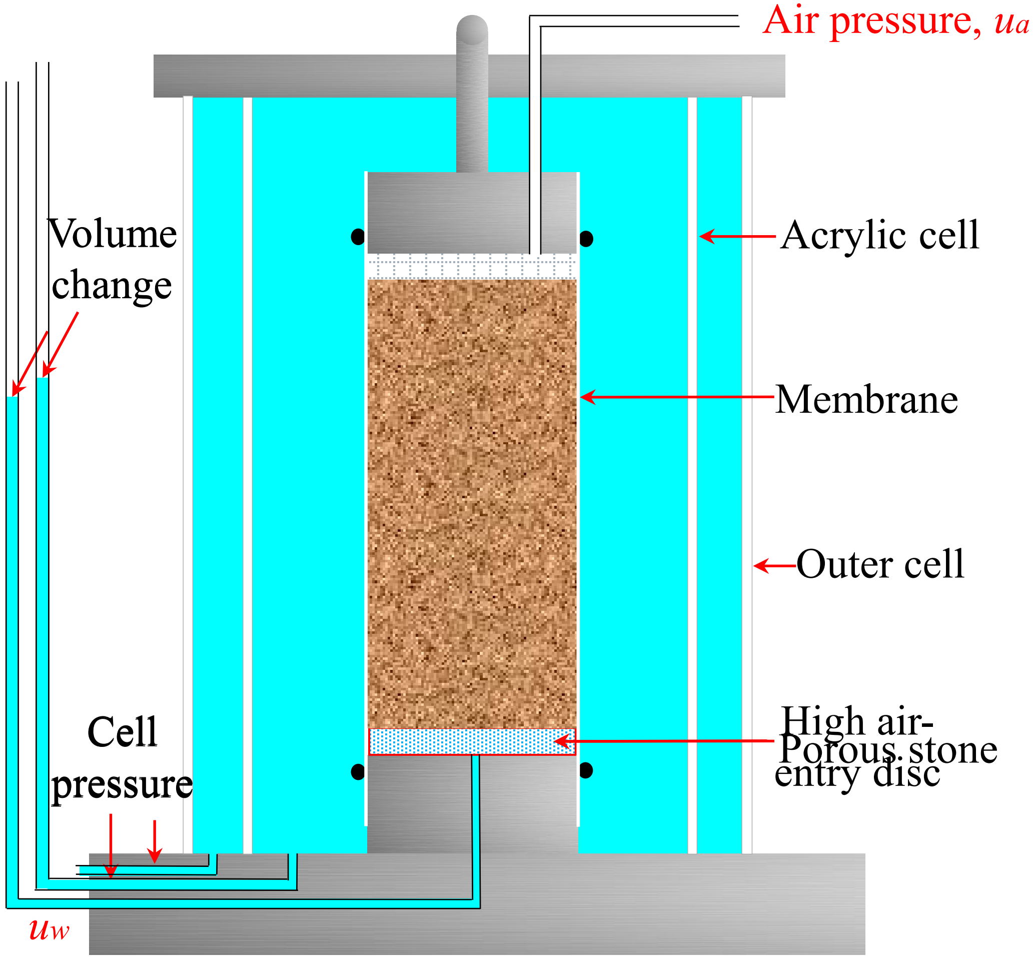
Outline

- Introduction
- Limitations of Existing Methods
- Principle of Photogrammetry-Based Method
- Post-Processing and Validation Tests
- Conclusions

Double-wall Suction-Controlled Triaxial Apparatus



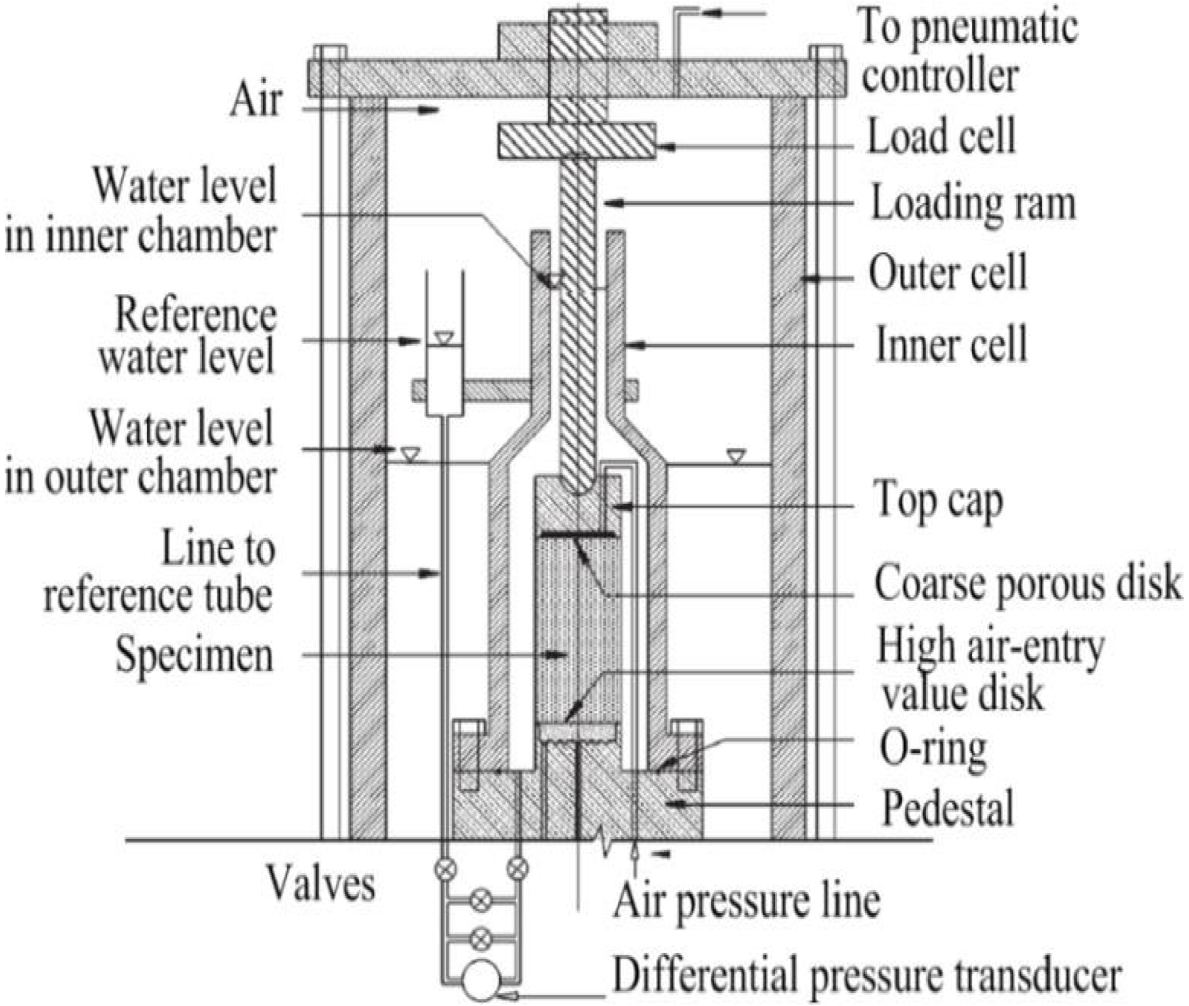
	Saturated	Unsaturated
Phase	Soil solids water	Soil solids, water, air
Volume change	$\Delta V = \Delta V_W$	$\Delta V \neq \Delta V_W$
Water pressure	$u_w \geq 0$	$u_w < 0$

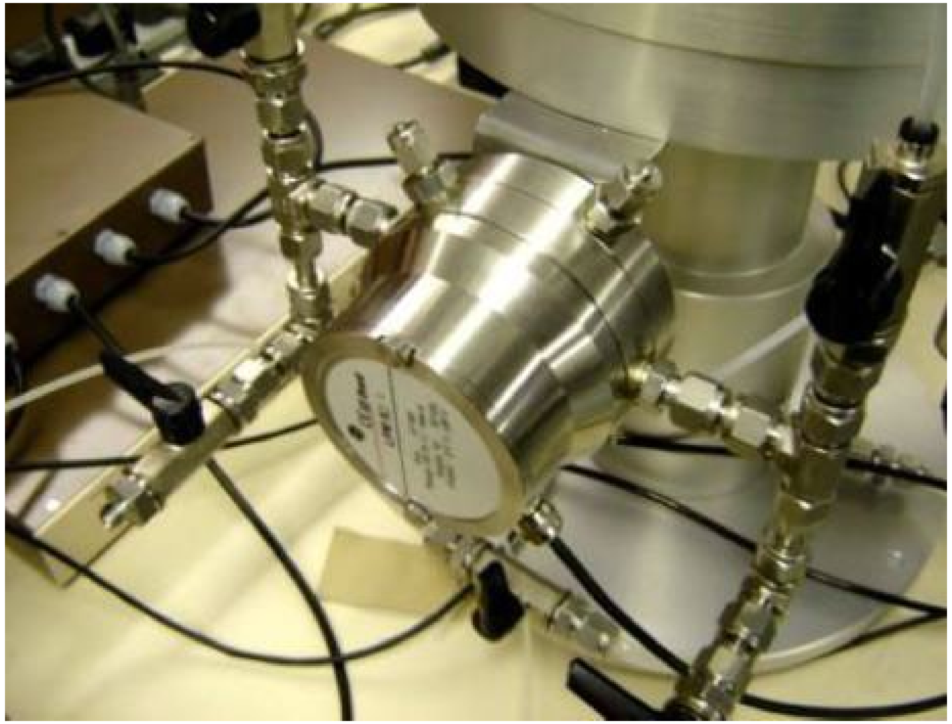
Matric suction, $s = u_a - u_w$

GCTS Triaxial Testing Apparatus for Unsaturated Soils

- Simple and Straightforward Concept;
- Suitable for large Strains;
- Extensively used

Double-wall with Differential Pressure Transducer



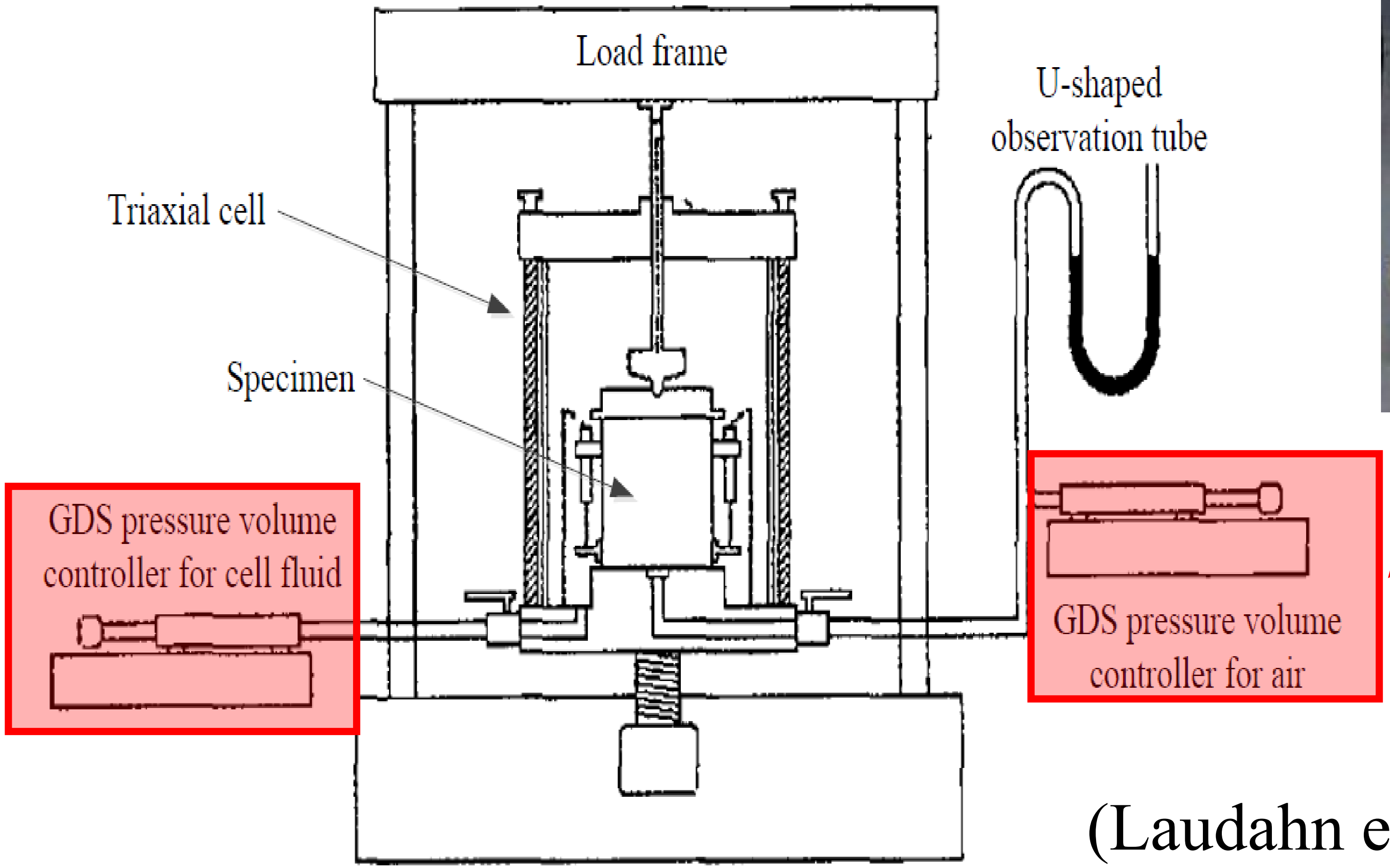


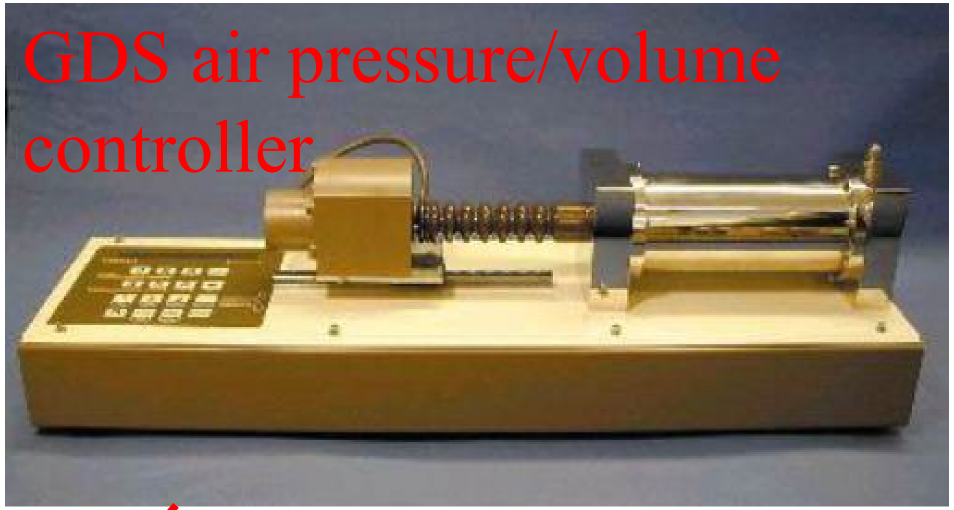
Ng et al. (2002)

Limitations of Double-wall System

- Require Major Equipment Modification (about $80K-$100K)
- Deformations of Top and Base not Considered
- Air Bubble in Cell/Channels Difficult to Remove
- Water Absorption Affected by Temperature, Pressure, and Time
- Creep Makes Calibration Difficult
- Steel Inner Cell Could be an Option, Air Bubble Not Visible

Direct Measurement of Air and Water Volumes



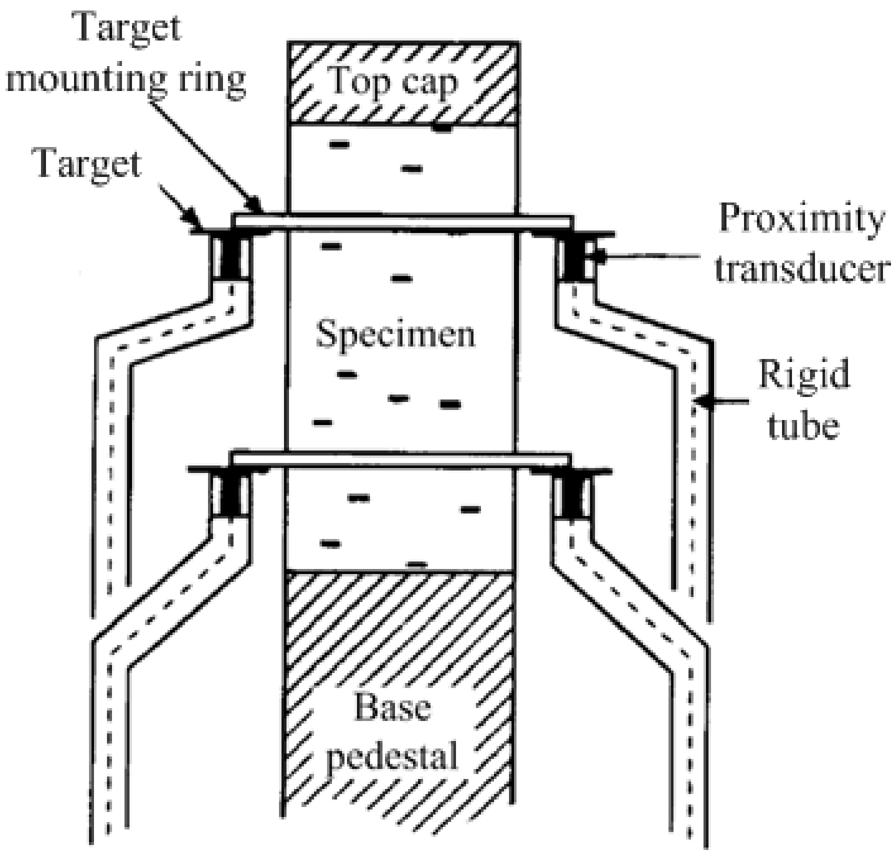


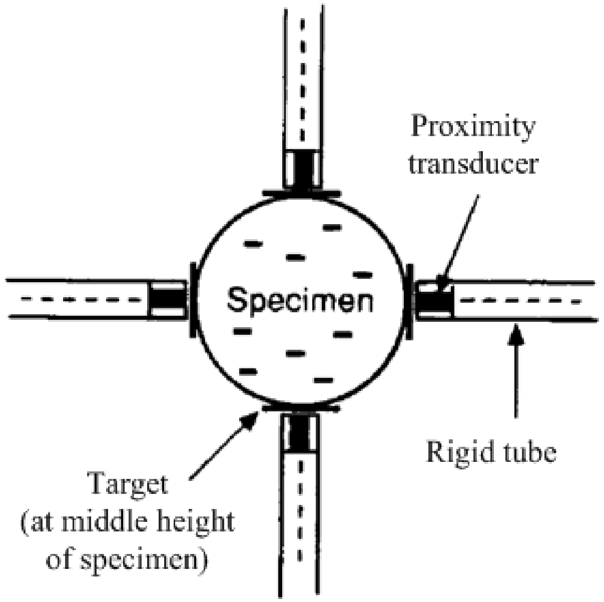
(Laudahn et al. 2005)

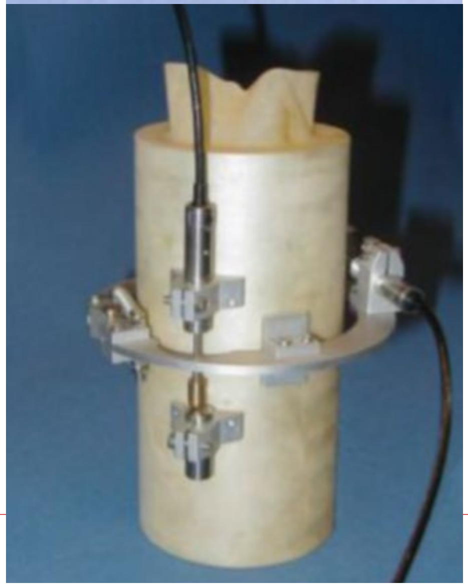
Limitations of Direct Air and Water Measurements

- Require Additional Air-volume Controller
- Air Phase must be Continuous
- Sensitive to Temperature and Atmospheric Pressure Changes
- Air Leakage and Diffusion through Tubes, Connections, and HAE Disk Undetectable
- Not Extensively Used

Miniature LVDT for Lateral Strain





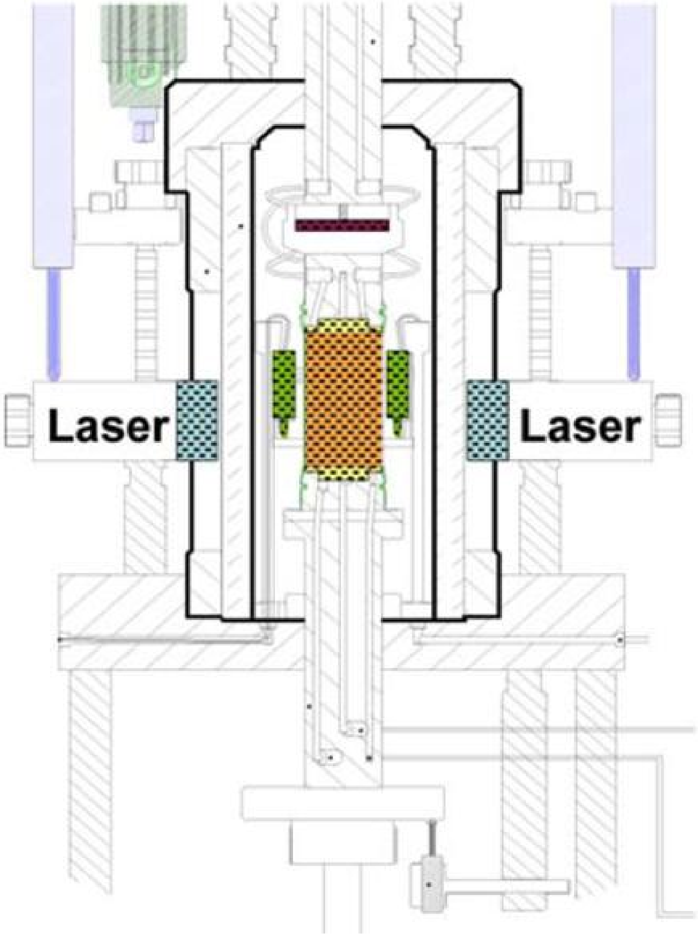


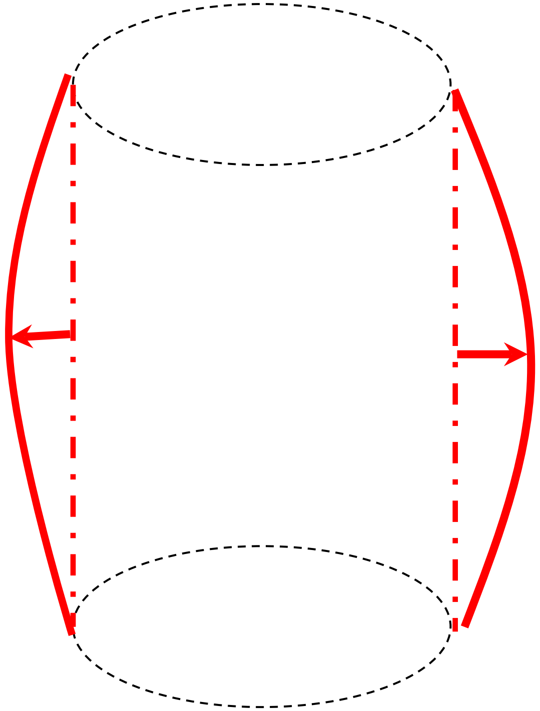
(Hird and Hajj 1995)

Limitations of Miniature LVDT for Lateral Strain

- Specially Designed LVDTs
- Limited Measurement Points: < 3
- Not Suitable for Soft Specimens
- Not Accurate When There is Shearing Plane
- Errors Raised due to Seating, Closing of Gaps, and Alignments

Electro-optical Laser Scanner





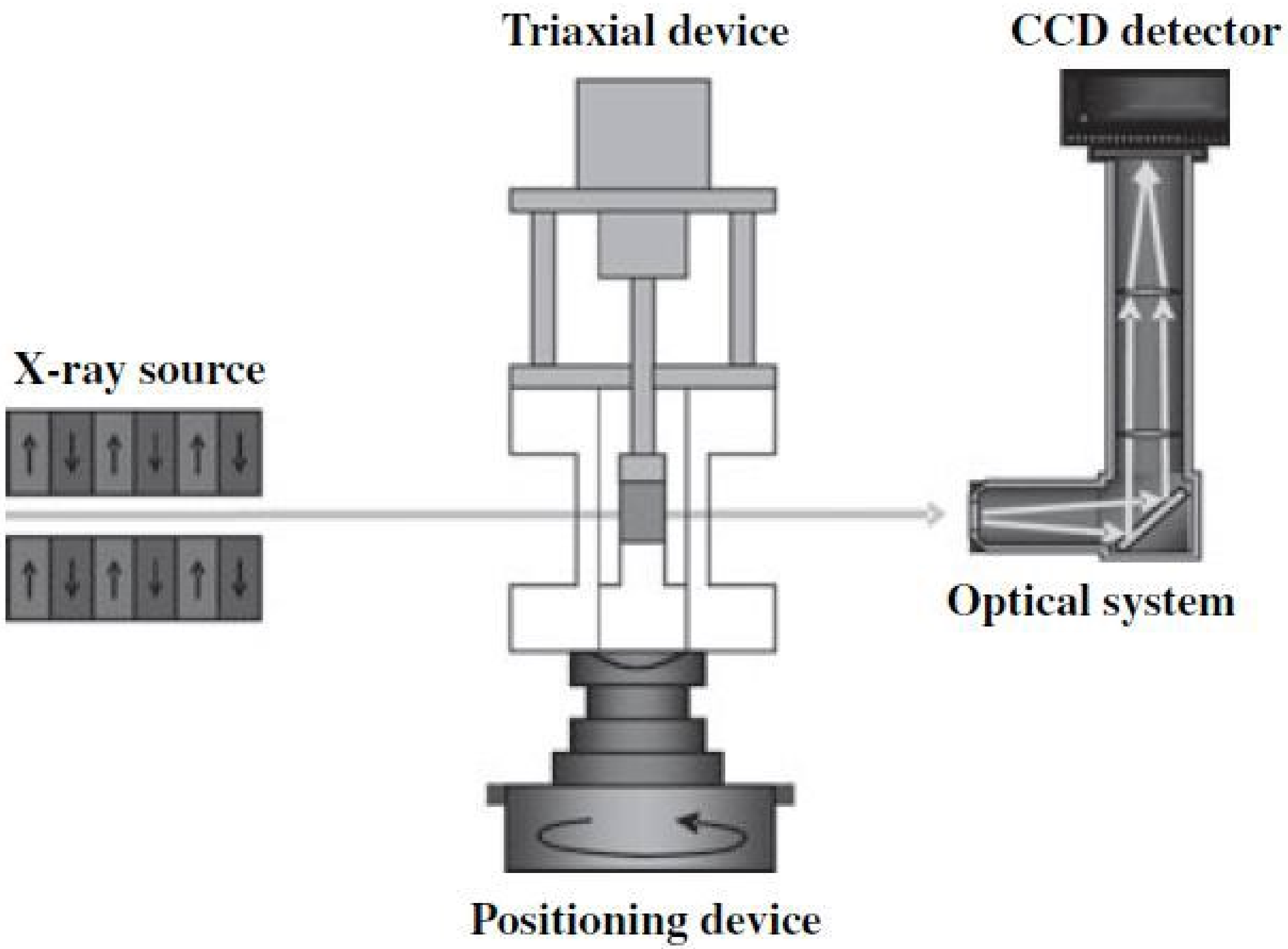
(Romero et al. 1997)

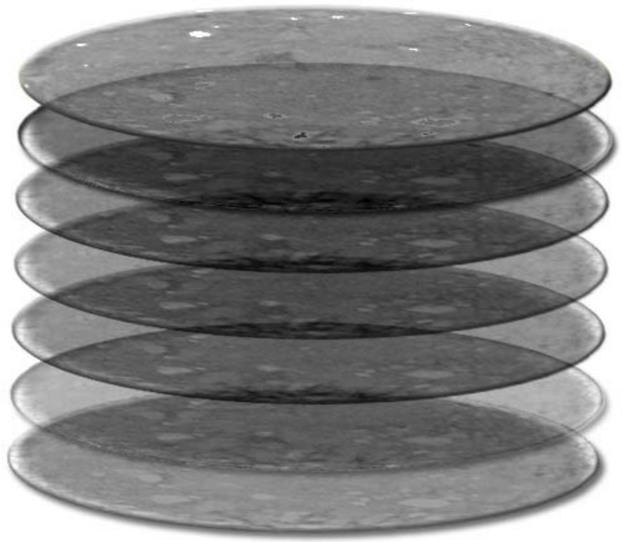
Limitations of Electro-optical Laser Scanner

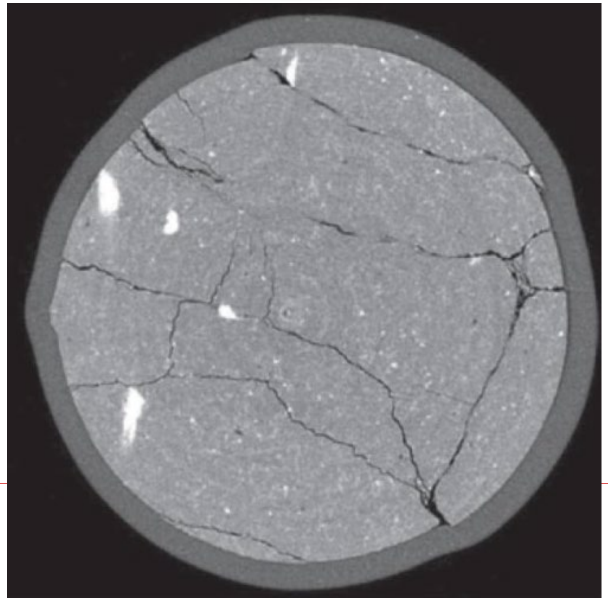
- Require equipment modification;
- Localized displacement along two opposite sides only;
- Refraction not considered.

Effects of Refraction

X-ray Computed Tomography





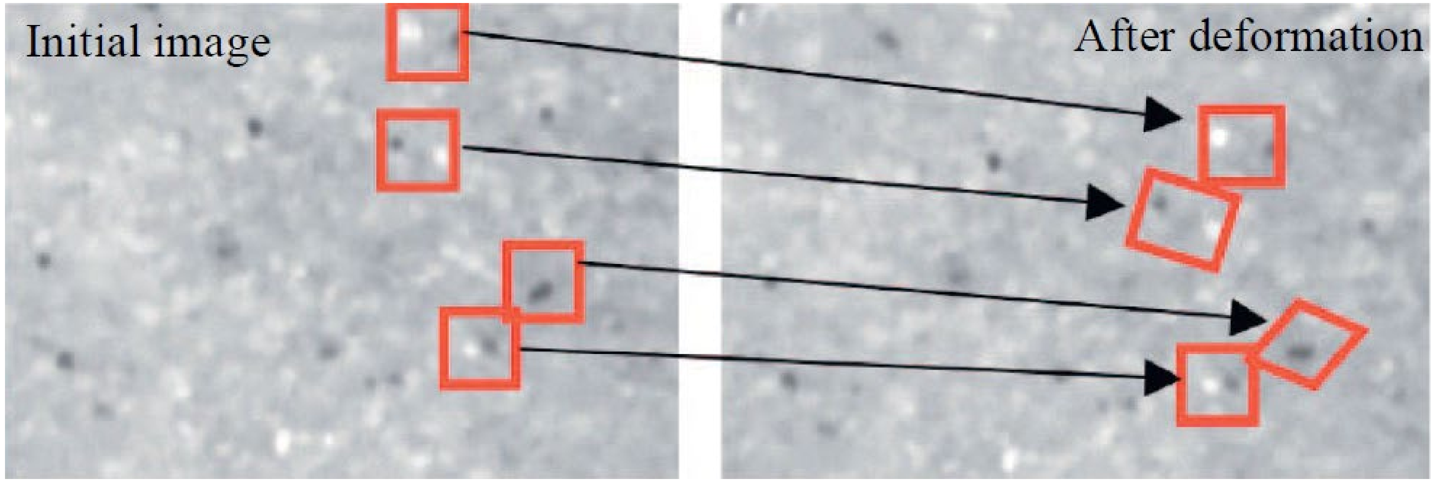


(Lenoir et al. 2007)

Limitations of X-Ray CT

- Much More Expensive;
- Potential Healthy Concerns;
- Special Designed Triaxial Testing System, No Metal;
- Time-consuming for Unsaturated Soils

3D Digital Image Correlation

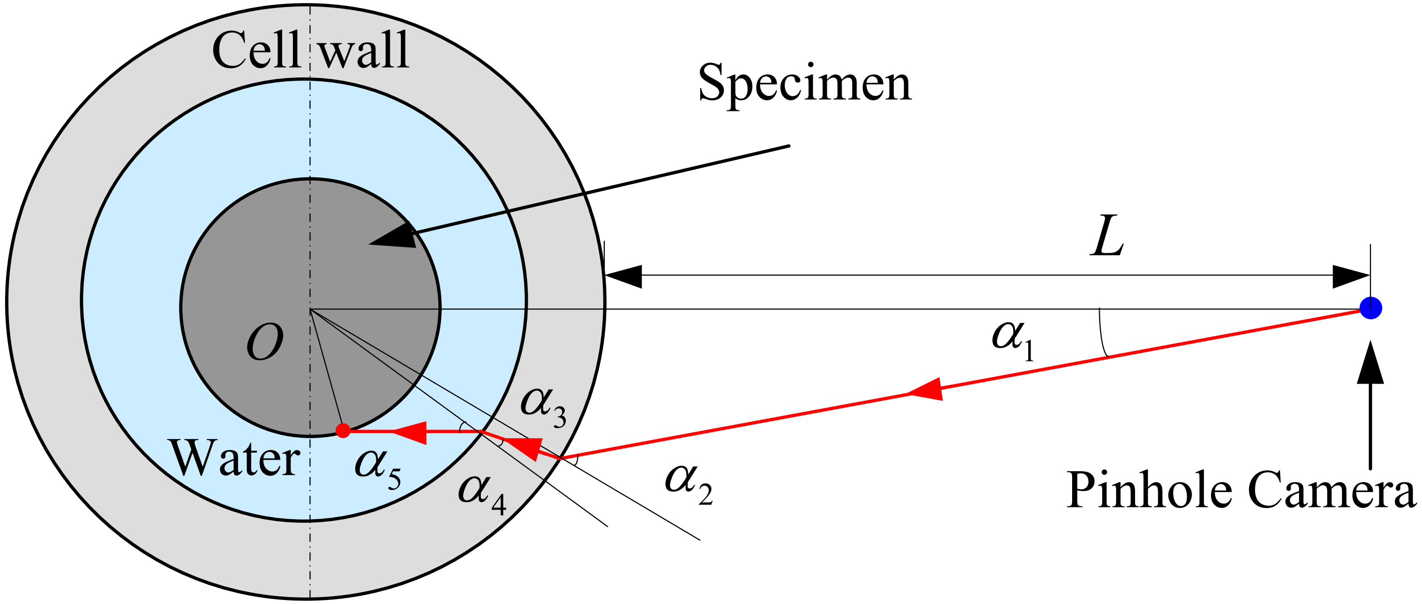


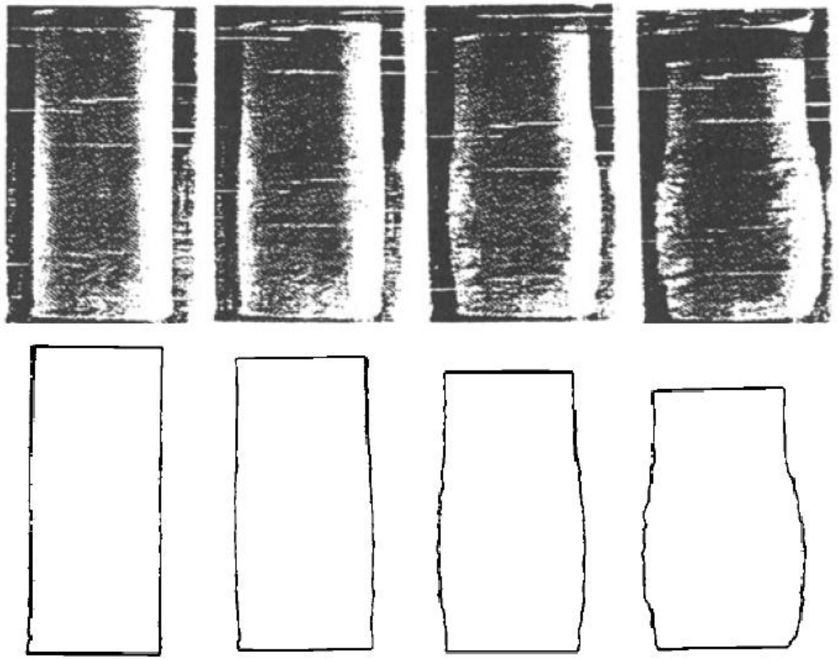
(White et al. 2003)

Limitations of DIA

- Refraction Not Considered
- Camera Position Need Accurately Positioned
- Partial 3D Constructions possible
- Total Volume Change Not Available

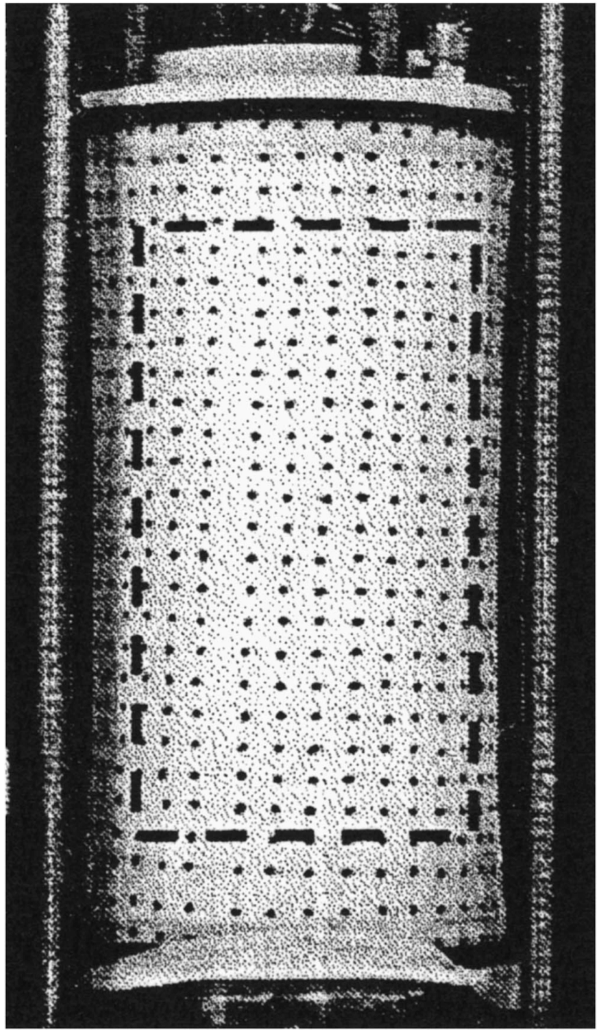
Digital Image Analysis

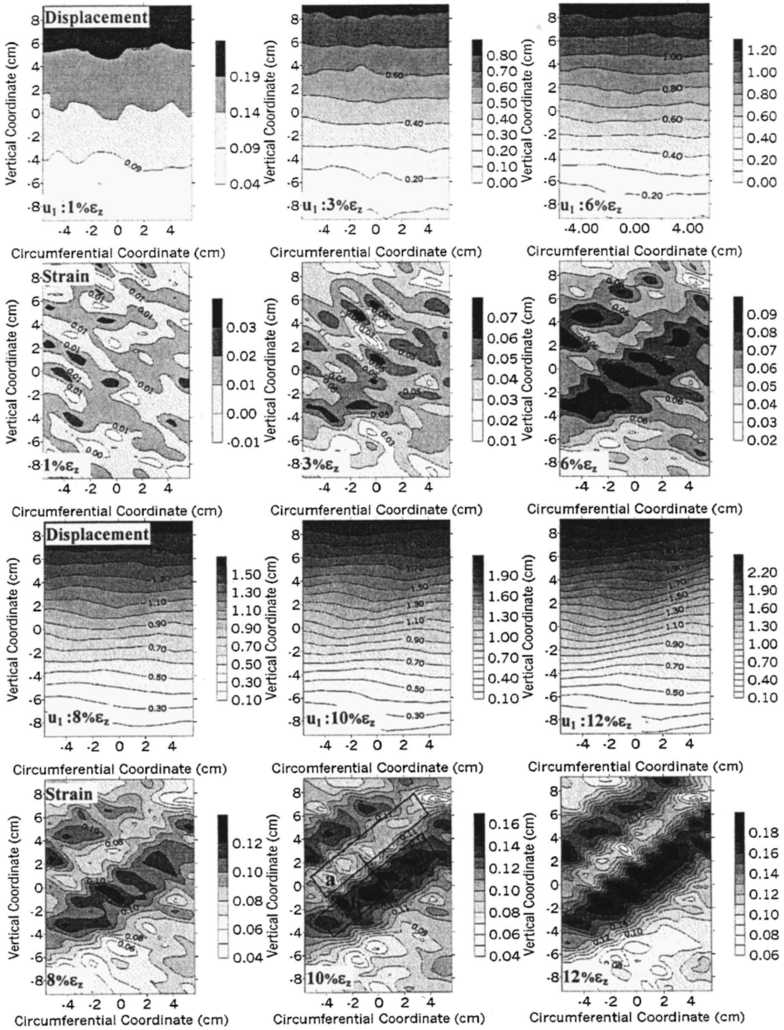




(Macari et al. 1997)

3D Digital Image Analysis





(Lin and Penumadu 2006)

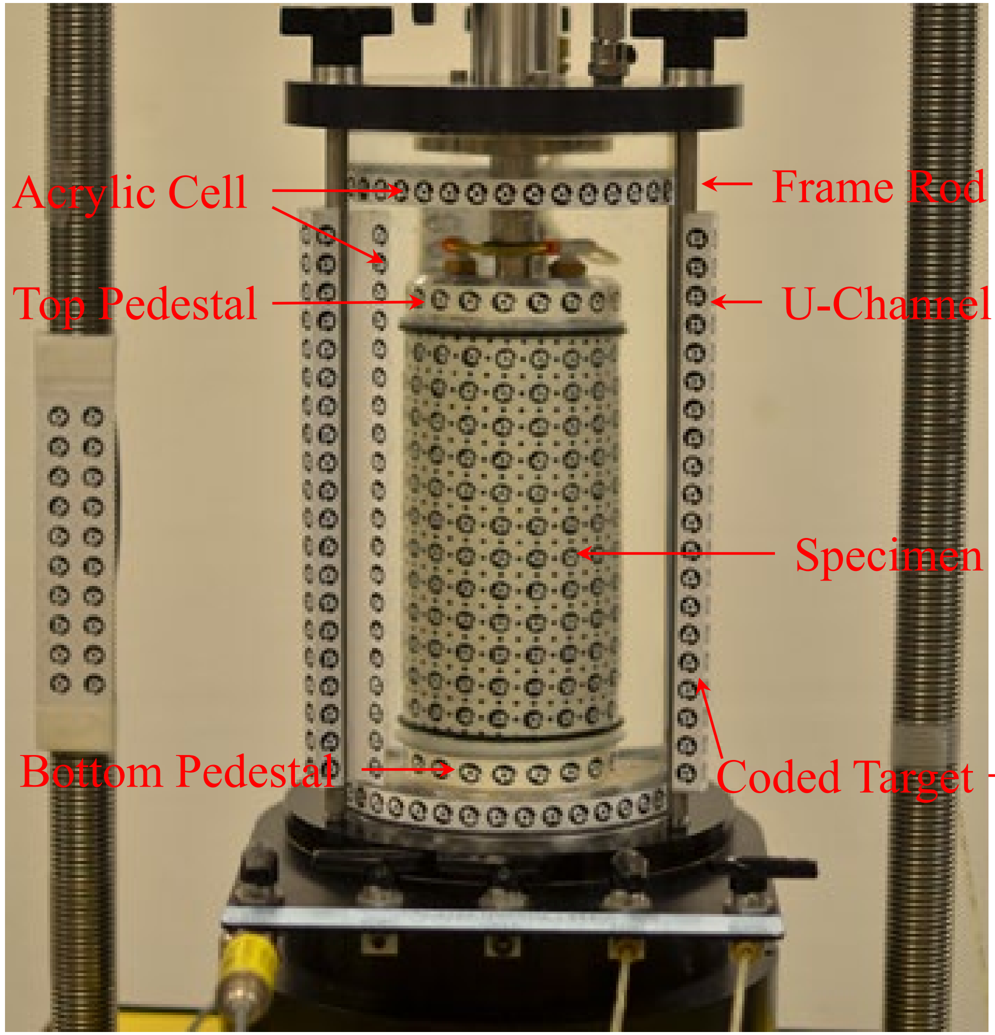
Assumption Used in the DIA

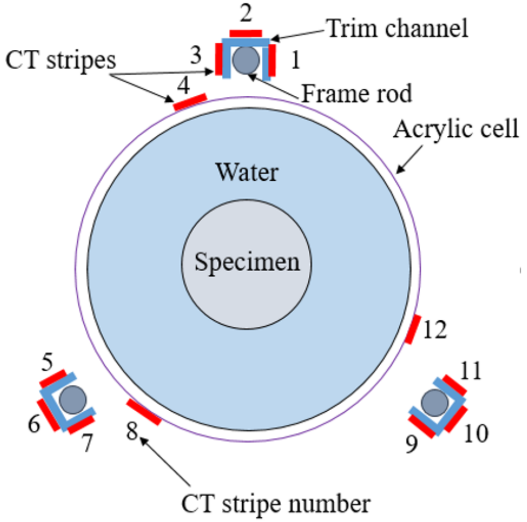
- Soil specimen and acrylic chamber **perfectly** cylindrical and installed vertically;
- Camera placed **perfectly** at the horizontal direction
- Shooting direction **exactly** passes center of the chamber
- Soil specimen installed **exactly** at center of the chamber
- Camera, chamber, and specimen positions **accurately** known;
- Deformation of acrylic cell wall is **negligible**
- Soil deformations occur **homogenously** along the radial directions.

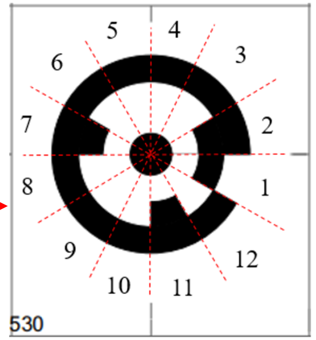
Existing Methods to Measure Volume

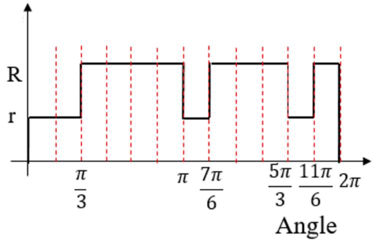
Method	Reference	Equipment Modification	Volume change	Advantages	Disadvantages	Accuracy (%)	Volume change	Price ($)
Double cell GCTS	Bishop and Donald 1961	Yes	Total	Appropriate for large strains, widely used	Difficult to calibrate, water absorption of acrylic wall, air bubble, de-aired water, sensitive to temperature	0.25	Total	about $100,000
Differential Pressure Transducer GDS	Ng, Zhan and Cui 2002	Yes	Total	Stable and not sensitive to temperature, suitable for small strain	Require careful calibration, use high quality de-aired water, remove all air bubbles	0.04	Total	about $100,000
Measurement of Pore Air and Water Pressure	Geiser 1999	Yes	Total	Direct measurement on volume change of air and water	Sensitive to temperature and atmospheric pressure, undetectable leakage	0.25	Total	50,000
LVDT	Blatz and Graham 2000	No	Total	Suitable for small strains	Clamping problems, can only be used for rigid specimens	0.01	Total	<5,000
Laser Scanner	Romero et al. 1997	Yes	Total	Non-contact	High cost setup, sophisticated installation procedures		Total	>20,000
X-ray CT	Desrues et al. 1996	Yes	Total	Non-contact, no refraction, detect internal local densification	High cost setup, sophisticated installation procedures, potential health problem	1	Total	>>200,000
Digital Image Correlation	White et al. 2003	No	local	Non-contact, detect non-uniform deformation	Cannot account for refraction		local	<5,000
2-D Image Boundary Detection	Macari et al. 1997	No	Total	Non-contact	Problematic refraction correction, suitable for small deformation	2	Total	<2,000
This Study	Zhang et al. (2015)	No	Total and local	Non-contact, real 3D	Intensive computation	0.25	Total and local	<2,000

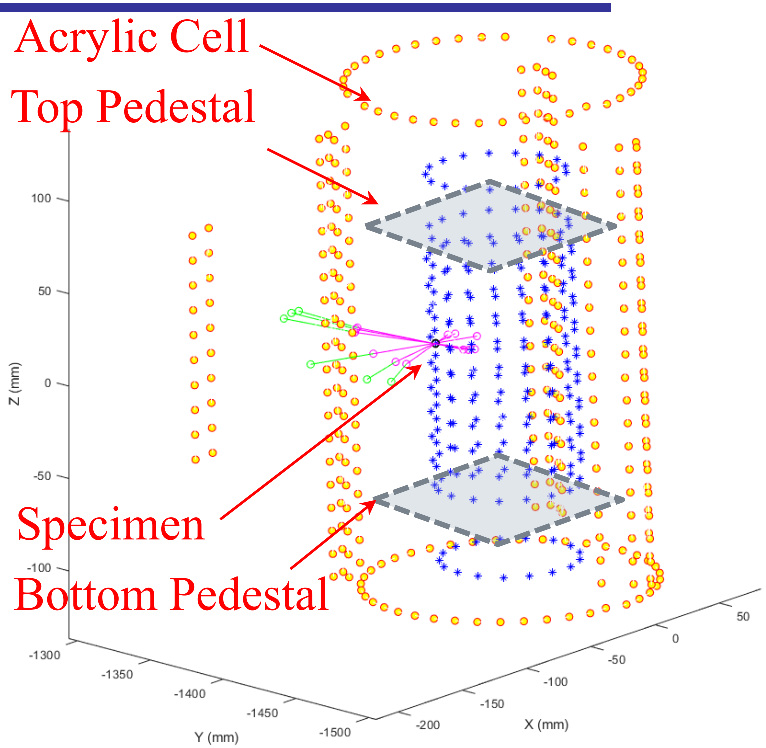
A Photogrammetry-Based Method

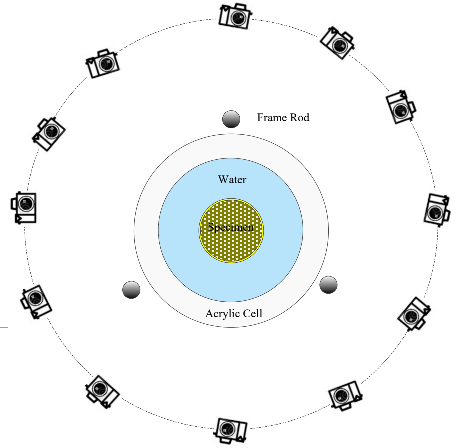


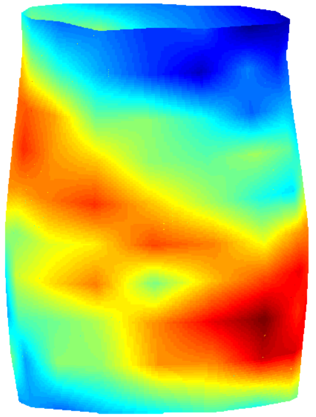




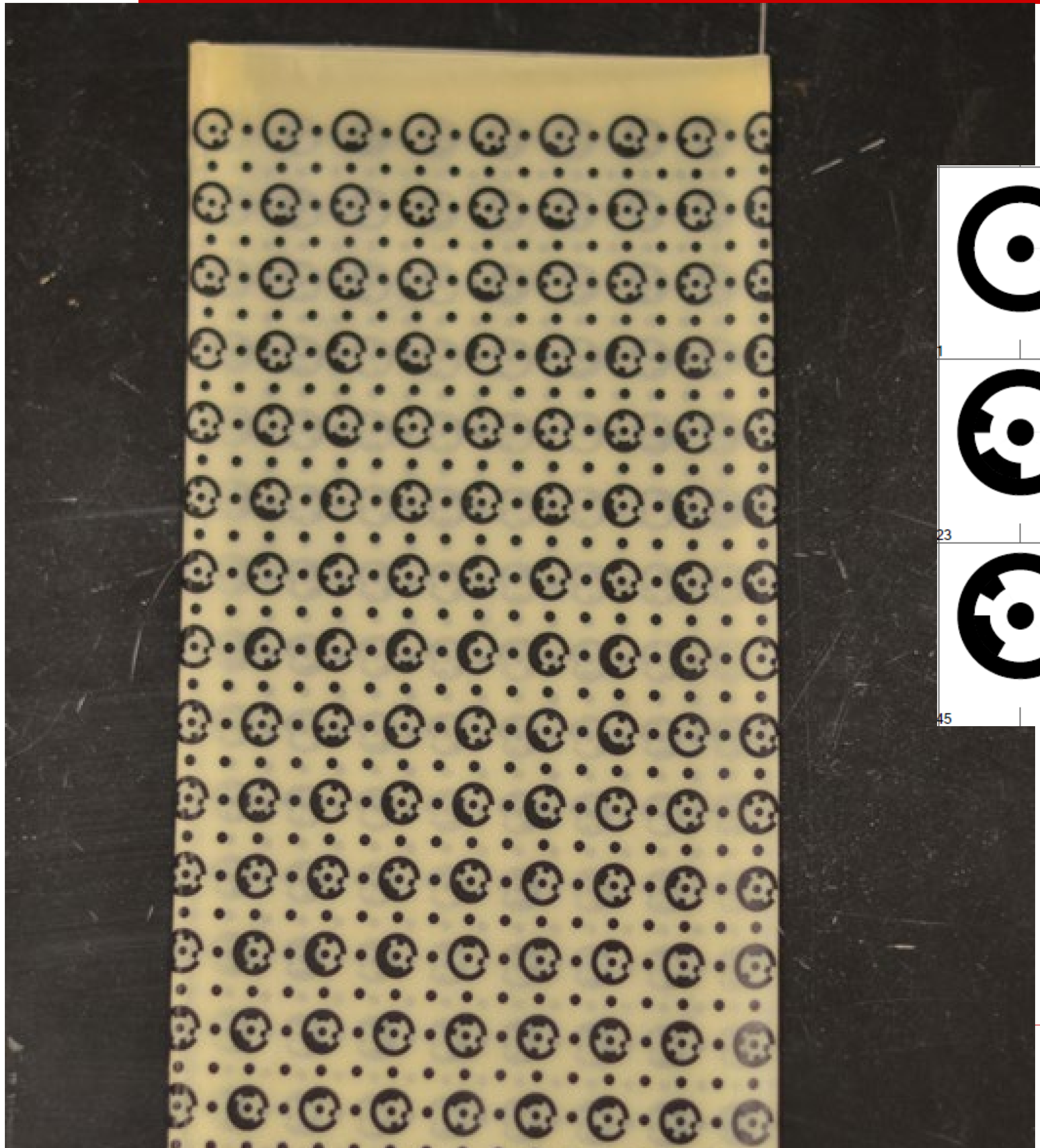


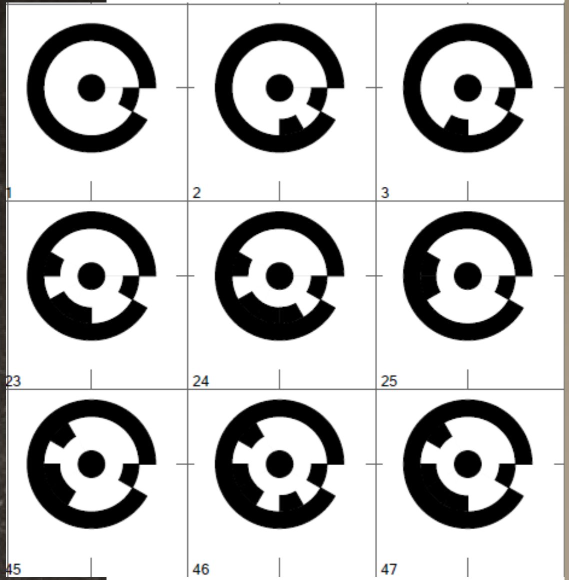


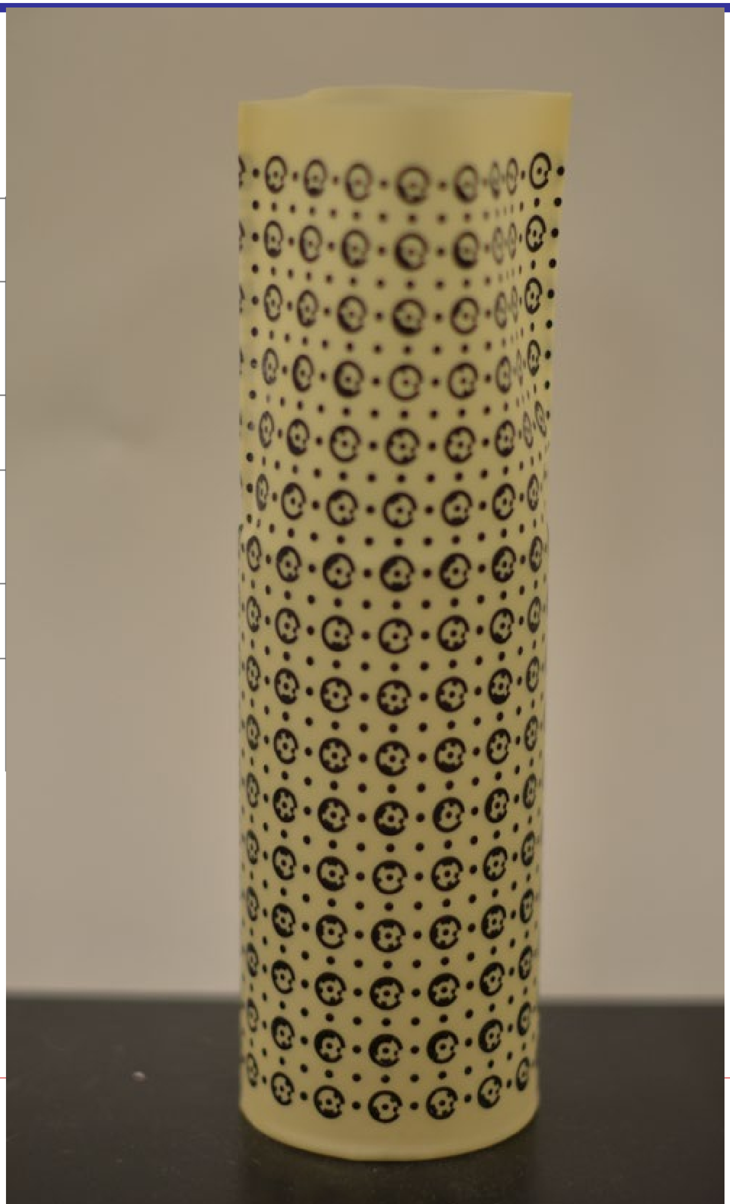




Membrane and Coded Target Design



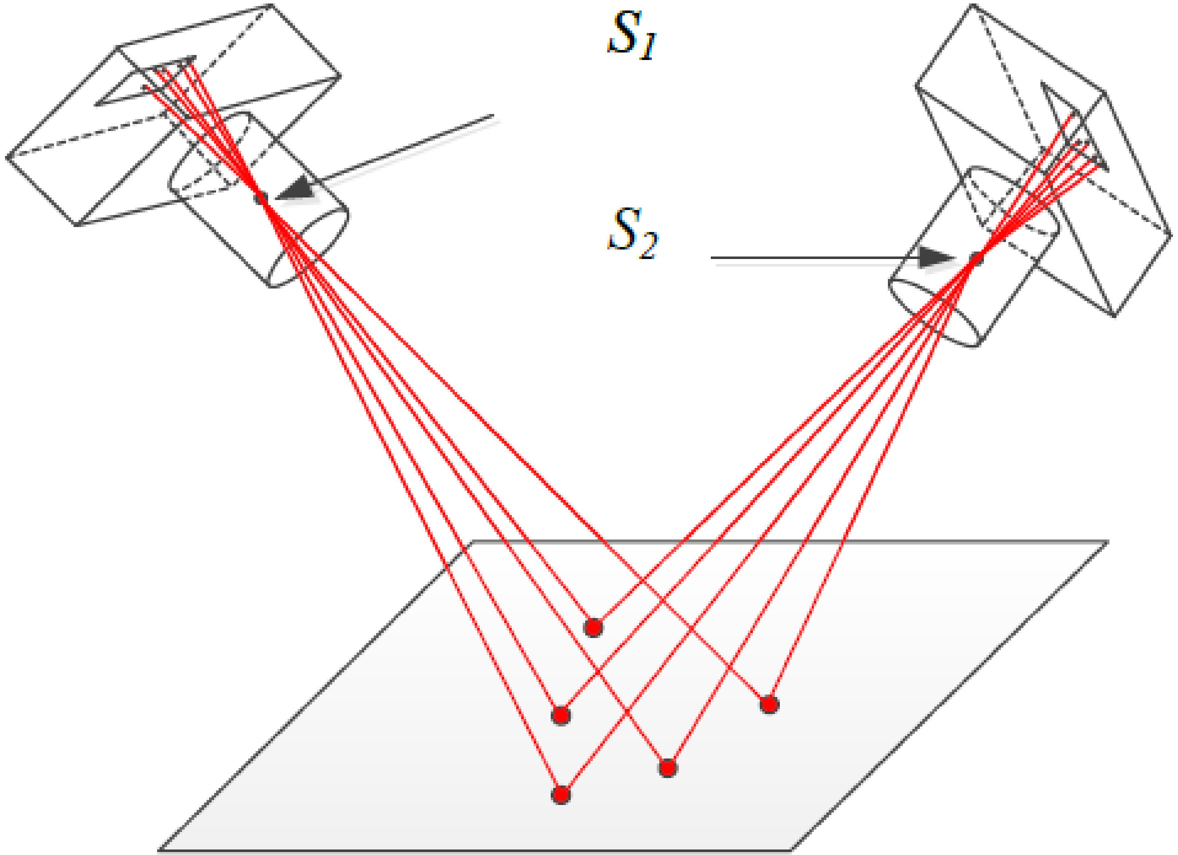




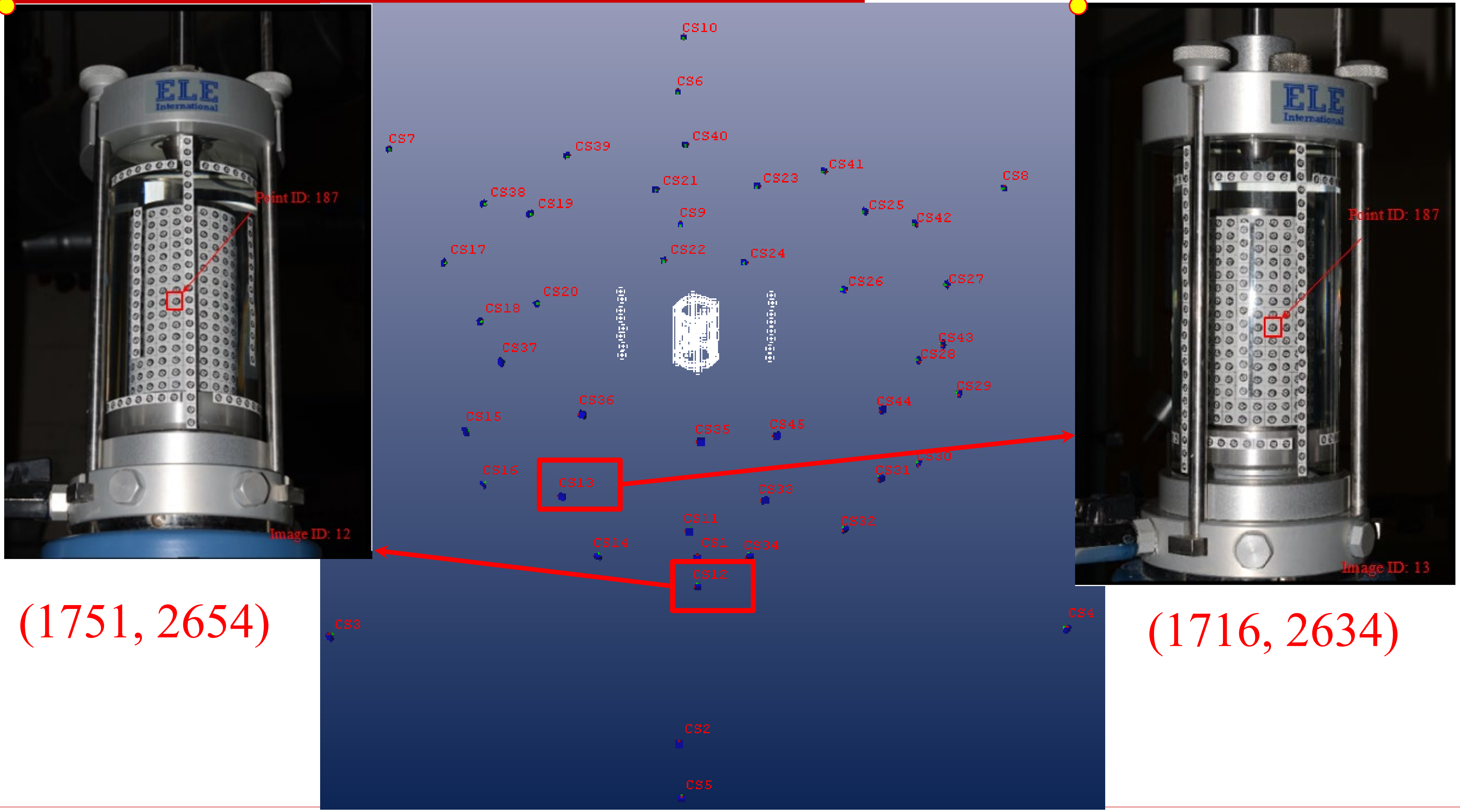
Procedures of the Proposed Method

- Attach Measurement Targets;
- Taking Photos around the Acrylic Cell with Specimens inside;
- Apply the Photogrammetry to Determine Camera and Cell Positions;
- Apply Multiple Ray-tracings to Correct Refraction;
- Least-square Optimization for 3D Coordinates for a Point;
- Repeat the Process for All Targeted Points
- Mesh Generation, Total, and Local Volume Change Calculation.

Principle of Photogrammetry



Camera and Cell Positions from Photogrammetry



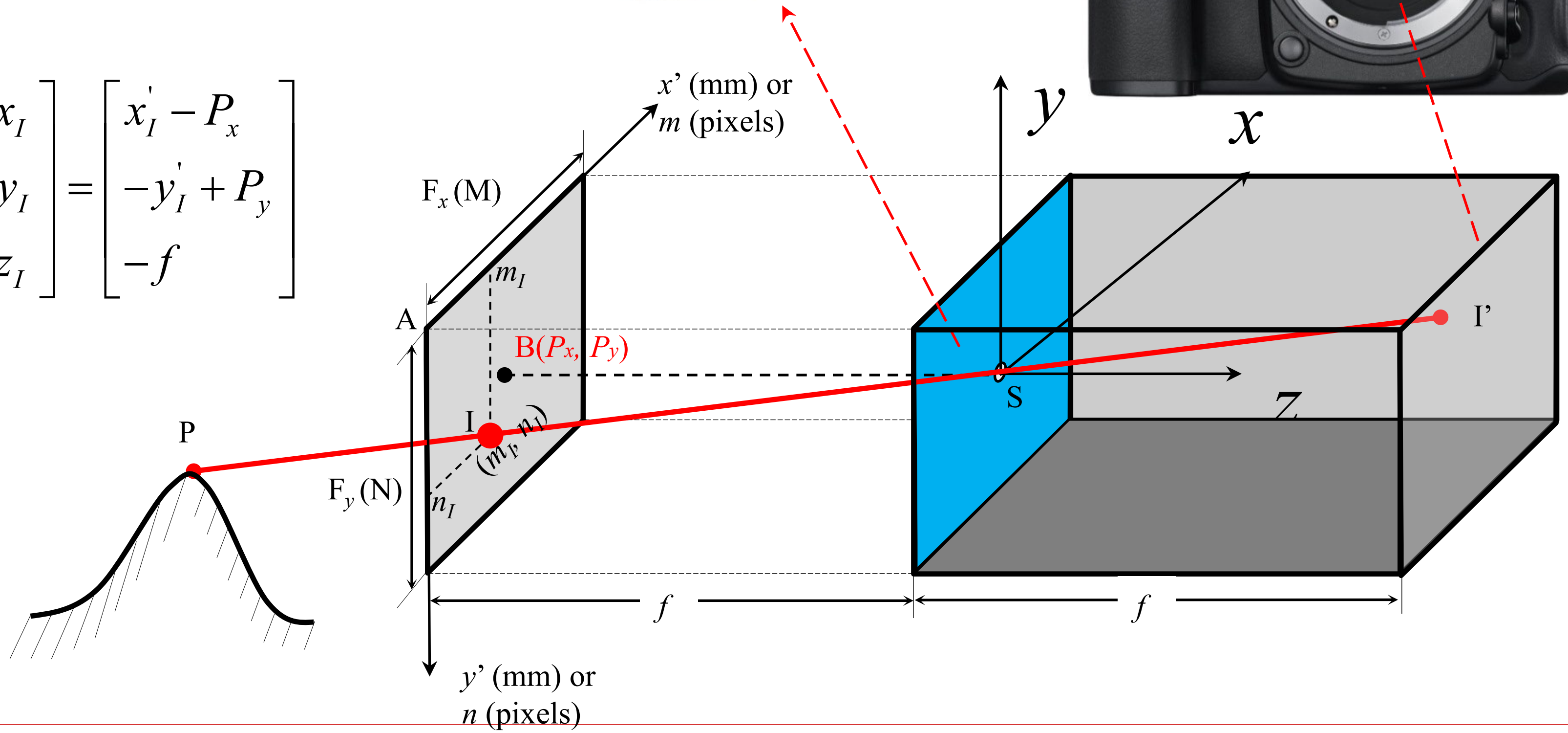
(1751, 2654)

(1716, 2634)

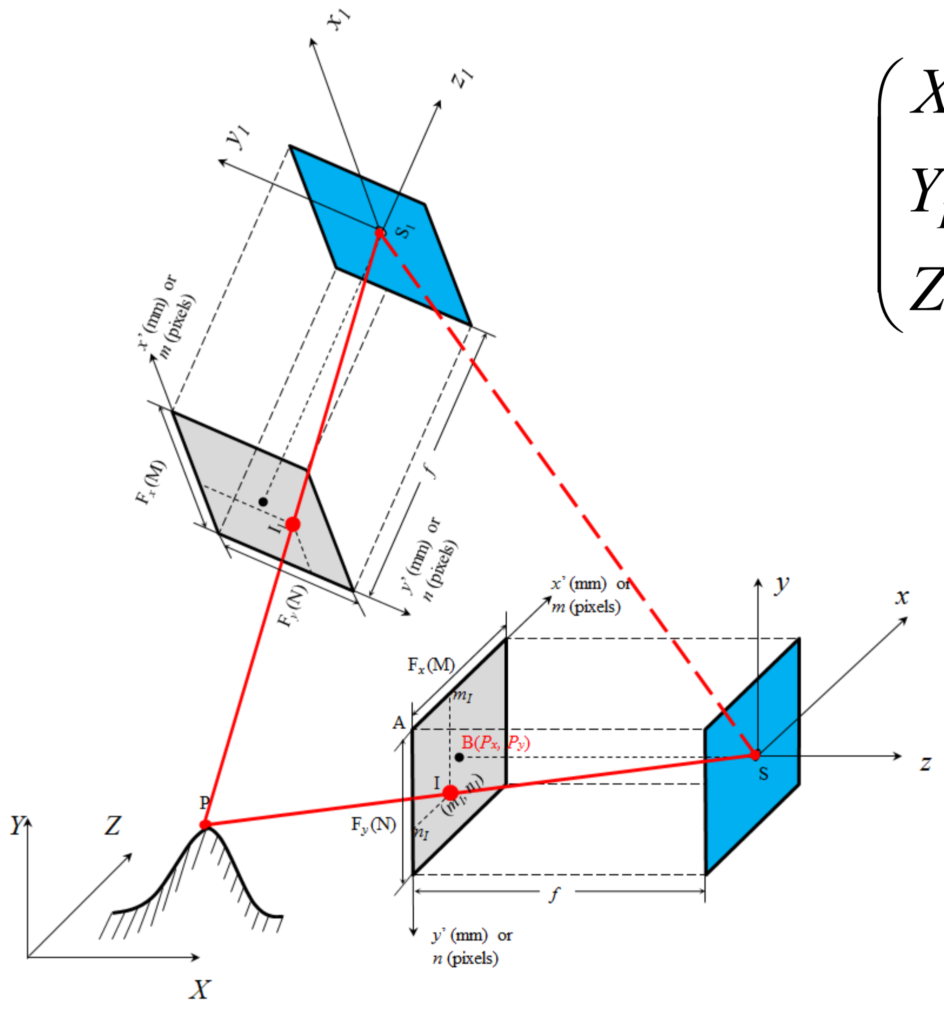
Pinhole Camera Model

$$\begin{bmatrix} x_I' \\ y_I' \end{bmatrix} = \begin{bmatrix} F_x / M & 0 \\ 0 & F_y / N \end{bmatrix} \begin{bmatrix} m_I \\ n_I \end{bmatrix}$$

$$\begin{bmatrix} x_I \\ y_I \\ z_I \end{bmatrix} = \begin{bmatrix} x_I' - P_x \\ -y_I' + P_y \\ -f \end{bmatrix}$$



Principle of Photogrammetry



$$\begin{pmatrix} X_I \\ Y_I \\ Z_I \end{pmatrix} = R(\omega, \varphi, \kappa) \begin{pmatrix} x_I \\ y_I \\ z_I \end{pmatrix} + \begin{pmatrix} X_s \\ Y_s \\ Z_s \end{pmatrix}$$

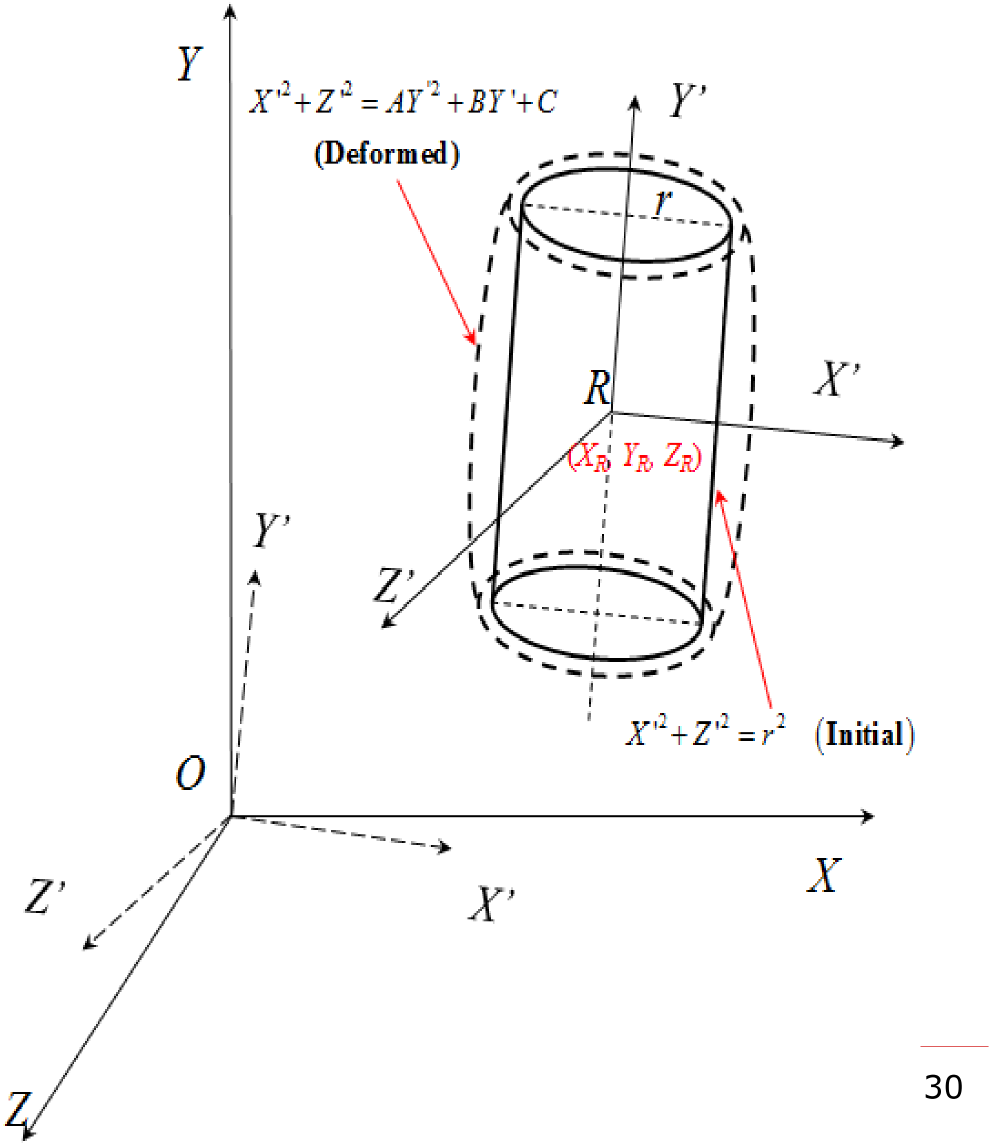
Coplanarity Condition

$$\overrightarrow{SS_1} \bullet \left(\overrightarrow{SI} \times \overrightarrow{S_1 I_1} \right) = 0$$

Changes in Cell Shape under Different Pressures

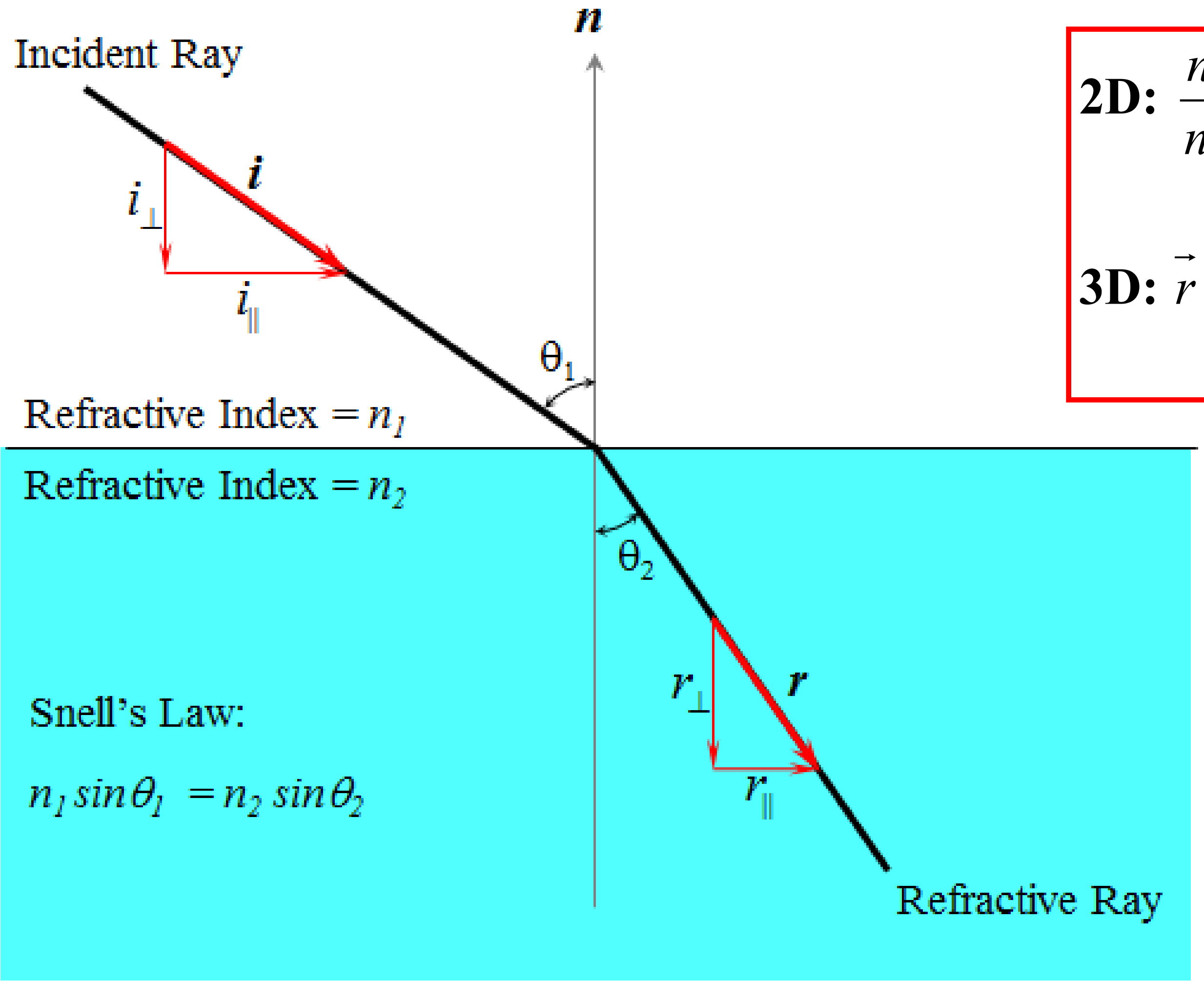
$$X^2 + Z^2 = AY^2 + BY + C$$

$$F(X,Y,Z) = \begin{bmatrix} X - X_R \\ Y - Y_R \\ Z - Z_R \end{bmatrix}^T R_1^T \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mathbf{-A} & 0 \\ 0 & 0 & 1 \end{bmatrix} R_1 \begin{bmatrix} X - X_R \\ Y - Y_R \\ Z - Z_R \end{bmatrix} - \begin{bmatrix} X - X_R \\ Y - Y_R \\ Z - Z_R \end{bmatrix}^T R_1^T \begin{bmatrix} 0 \\ B \\ 0 \end{bmatrix} - C = 0$$



Effects of Refraction

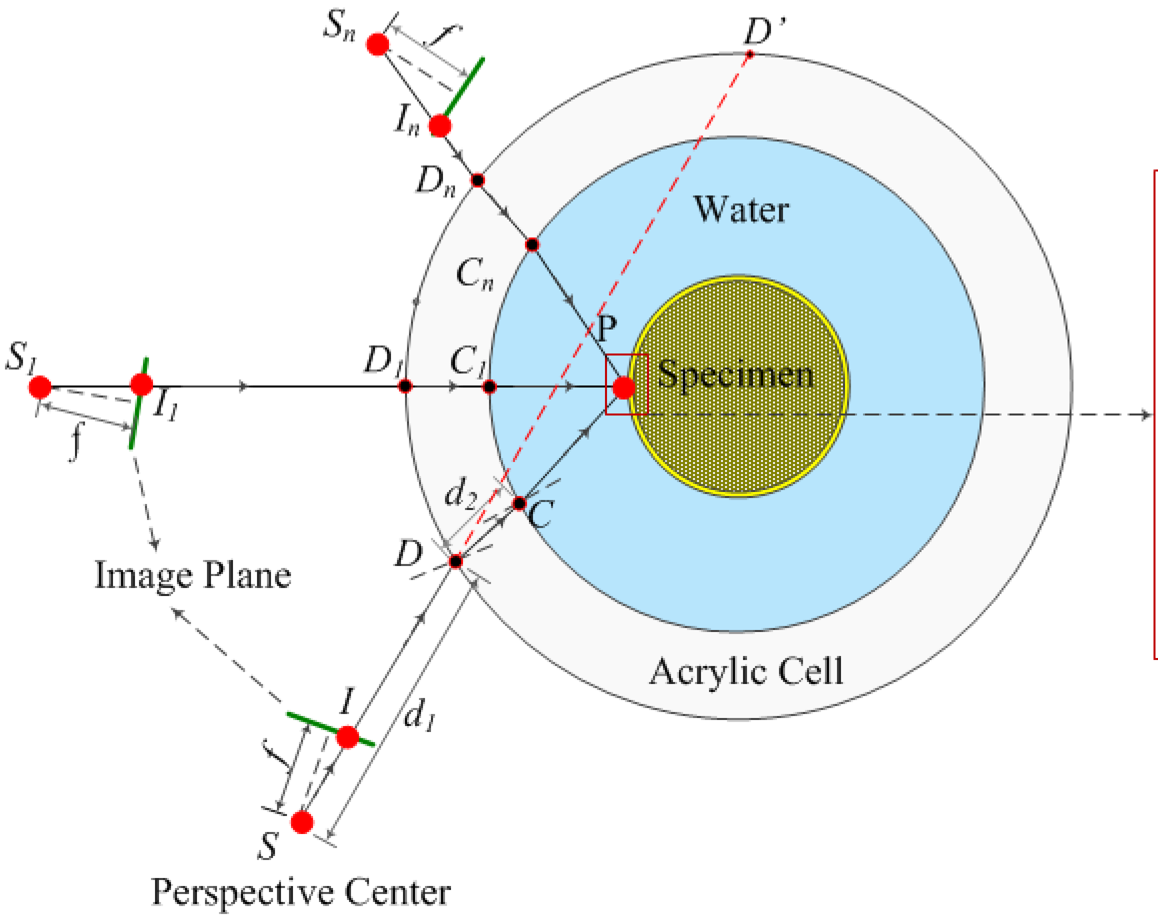
Snell’s Law for Refraction

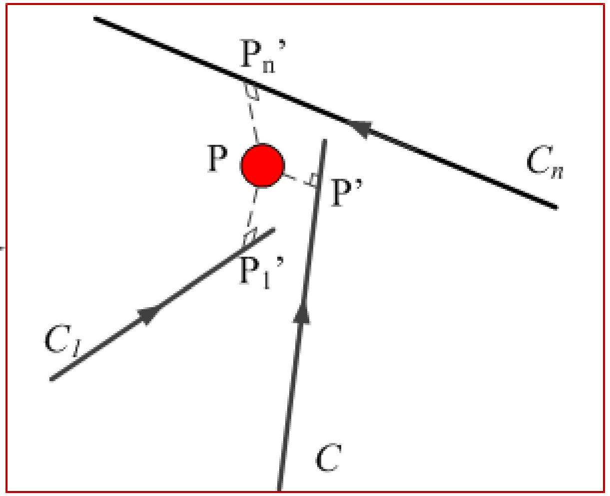


2D: $$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

3D: $$\vec{r} = \frac{n_1}{n_2}\vec{i} - \left(\frac{n_1}{n_2}\left(\vec{i}\bullet\vec{n}\right) + \sqrt{1-\left(\frac{n_1}{n_2}\right)^2\left[1-\left(\vec{i}\bullet\vec{n}\right)^2\right]} \right)\vec{n}$$

Multiple Ray-tracings for Refraction Corrections





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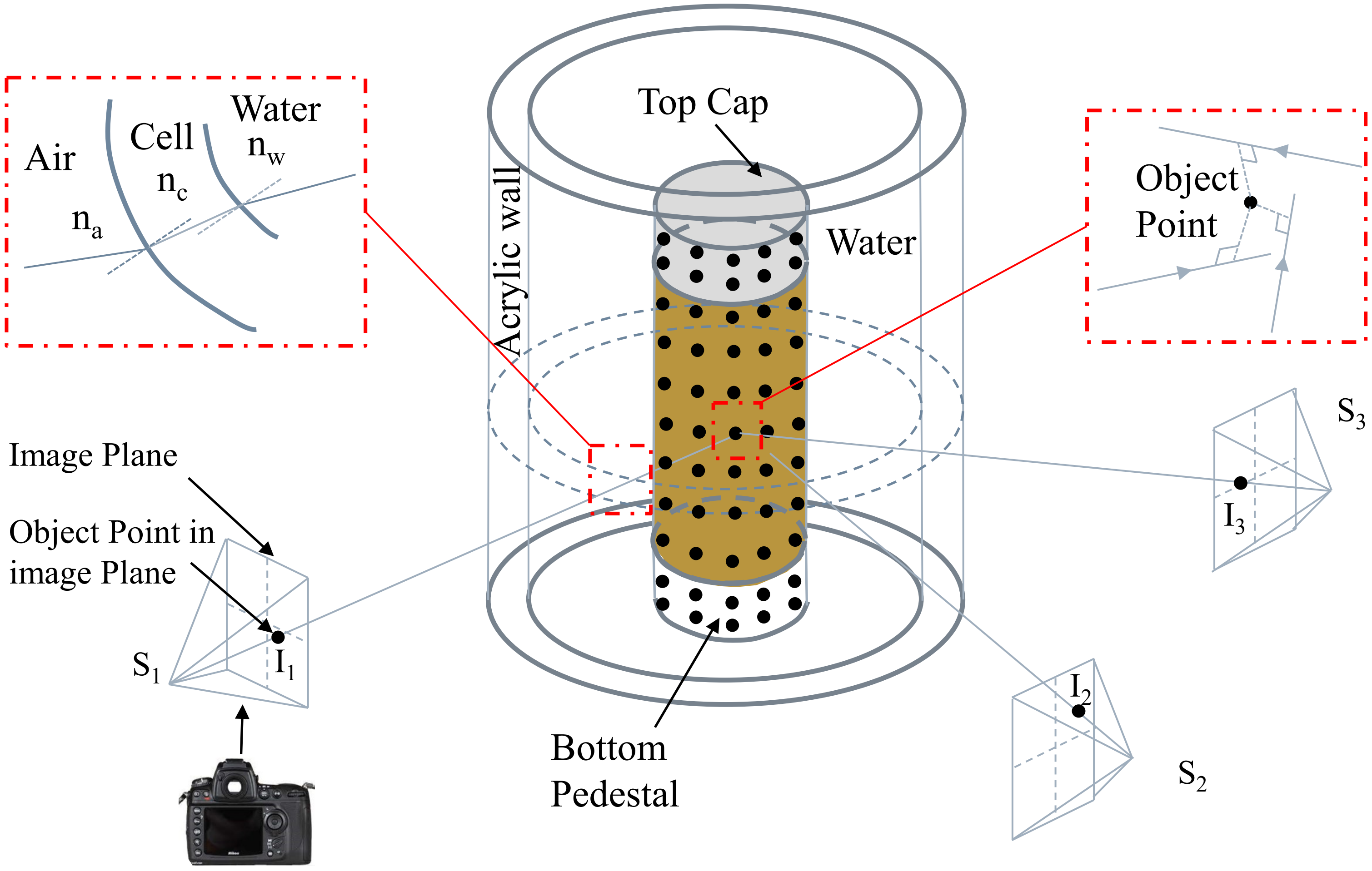
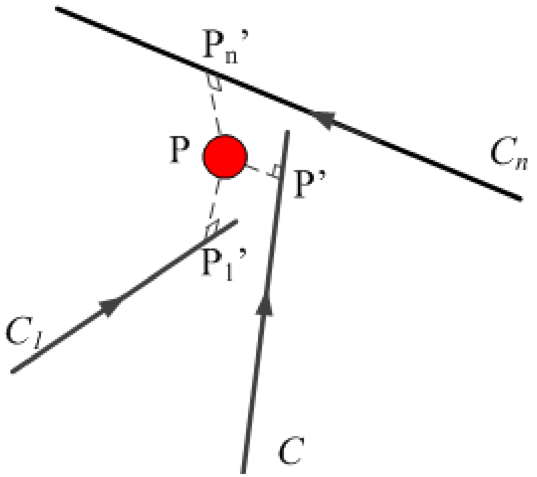


Least-Square Optimization for 3D Coordinates



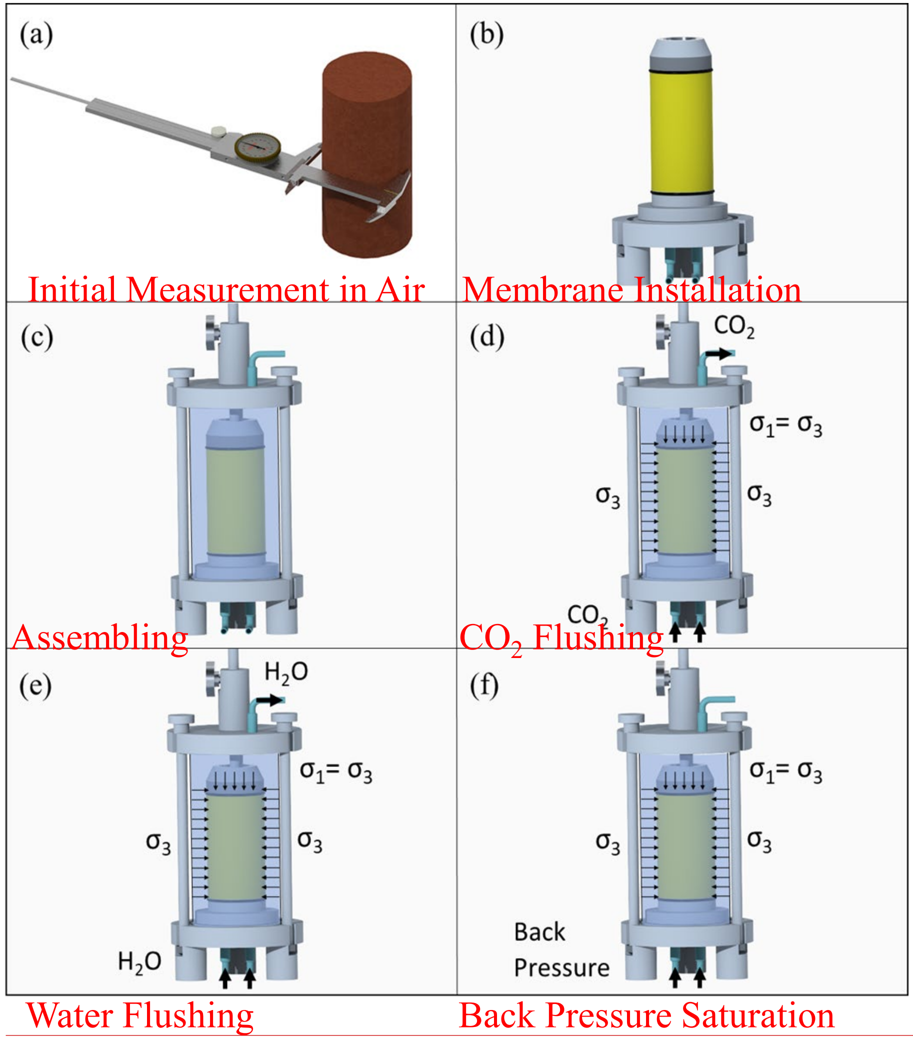
To find [Xp, Yp, Zp], which can minimize:

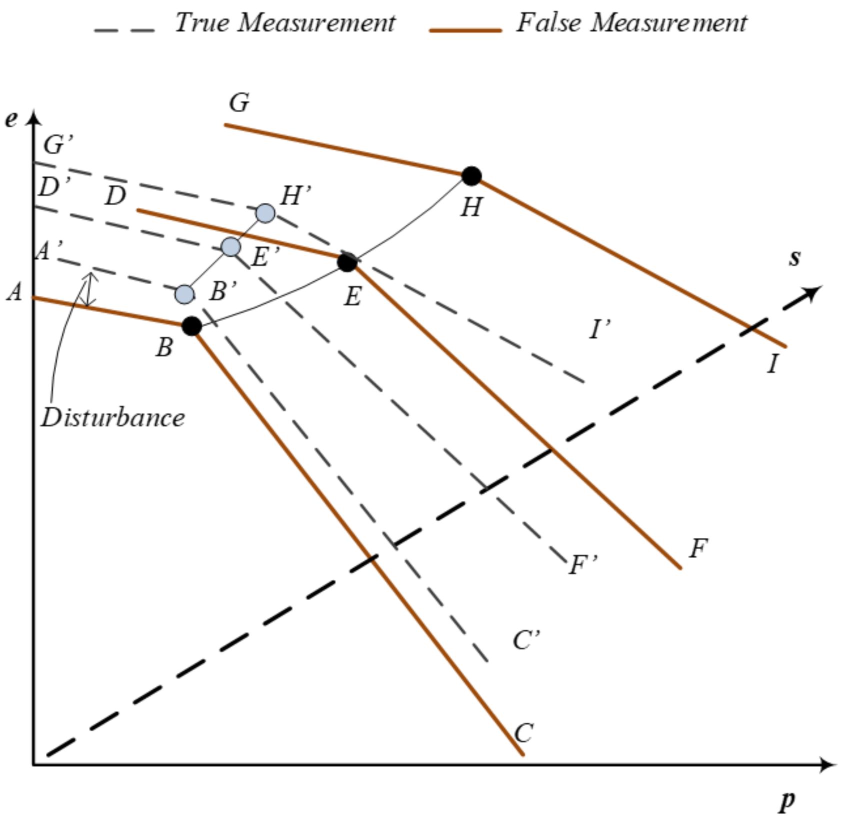
$$\sum_{i=1}^{n} d_i^{\,2} = \sum_{i=1}^{n} \begin{bmatrix} X_P - X_{C_i} \\ Y_P - Y_{C_i} \\ Z_P - Z_{C_i} \end{bmatrix}^T \begin{bmatrix} X_P - X_{C_i} \\ Y_P - Y_{C_i} \\ Z_P - Z_{C_i} \end{bmatrix} - \left\{ \begin{bmatrix} X_P - X_{C_i} \\ Y_P - Y_{C_i} \\ Z_P - Z_{C_i} \end{bmatrix}^T \begin{bmatrix} \alpha_{r2i} \\ \beta_{r2i} \\ \gamma_{r2i} \end{bmatrix} \right\}^2 \quad (n \geq 3)$$

Postprocessing

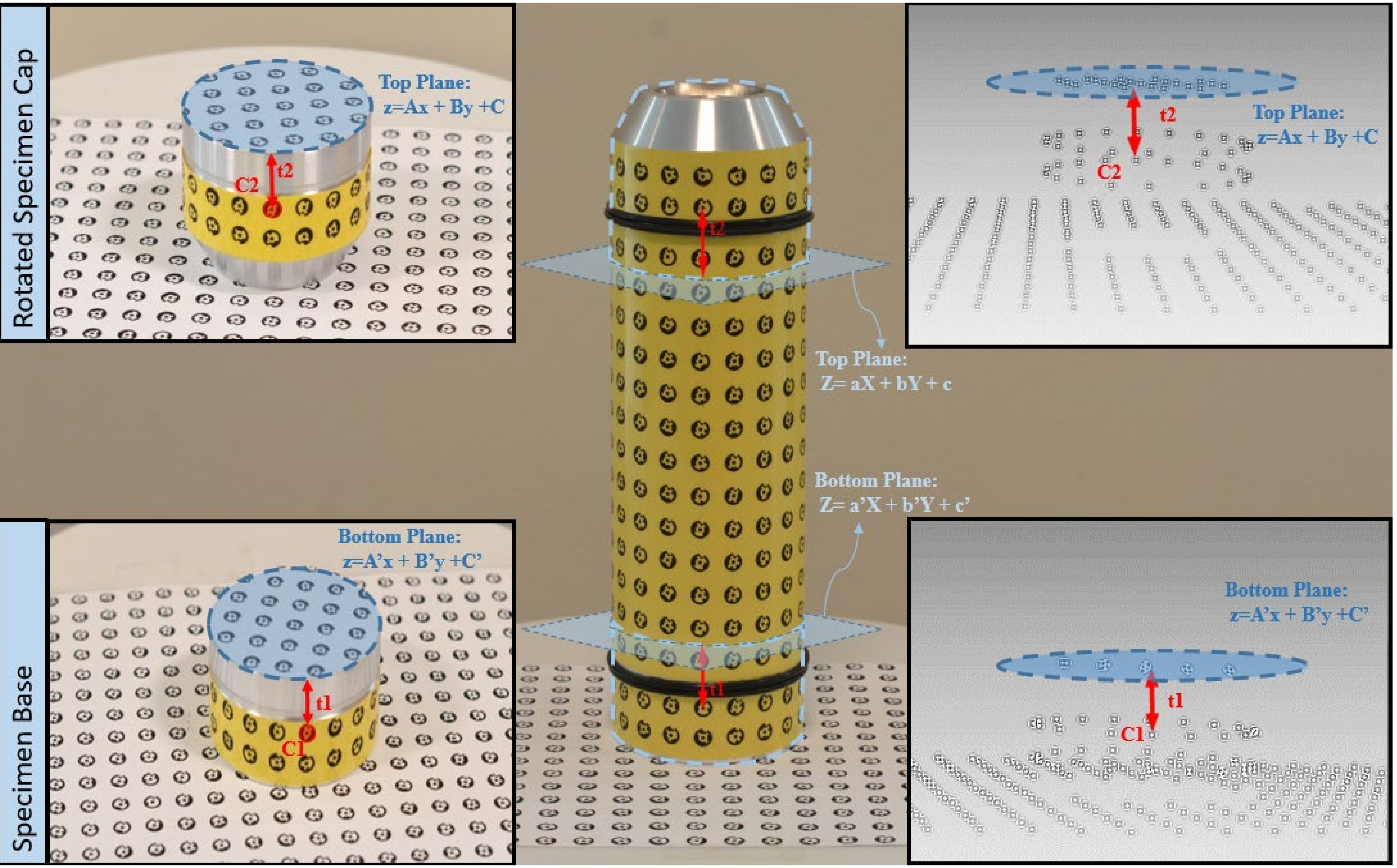
Absolute Volume, Tilting, Eccentricity, and Localized Strains

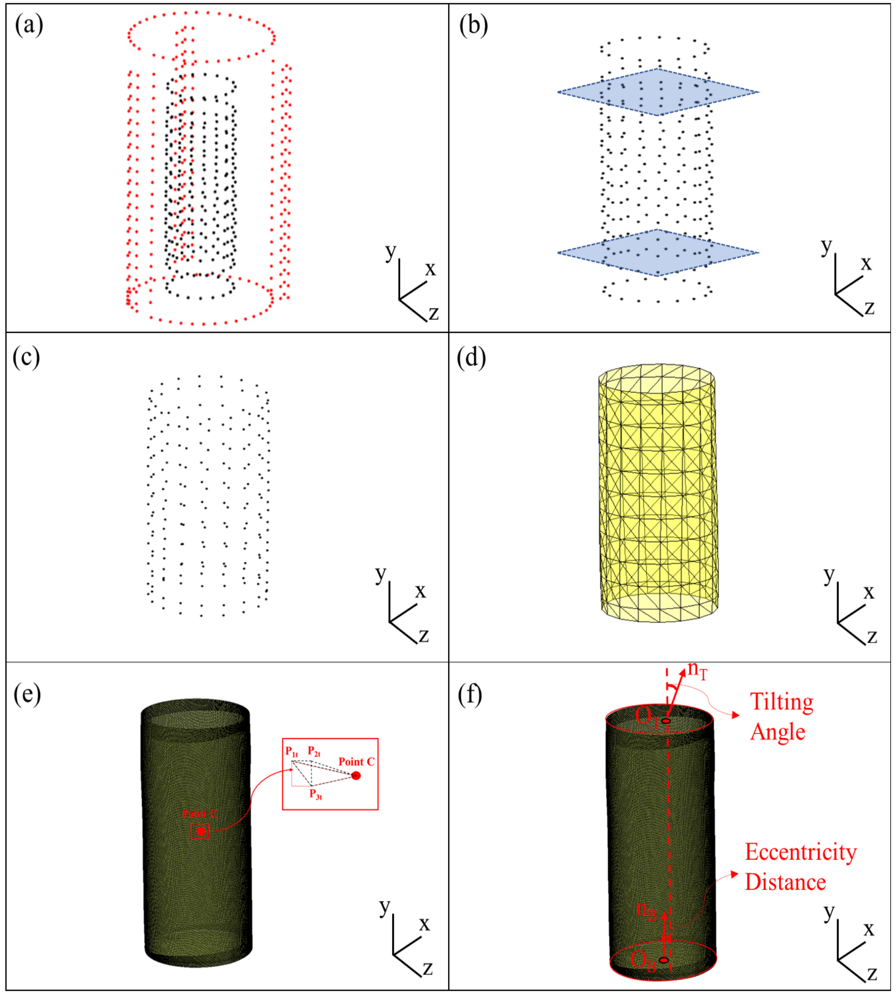
Triaxial Testing Procedures: Relative vs. Absolute Soil Volume



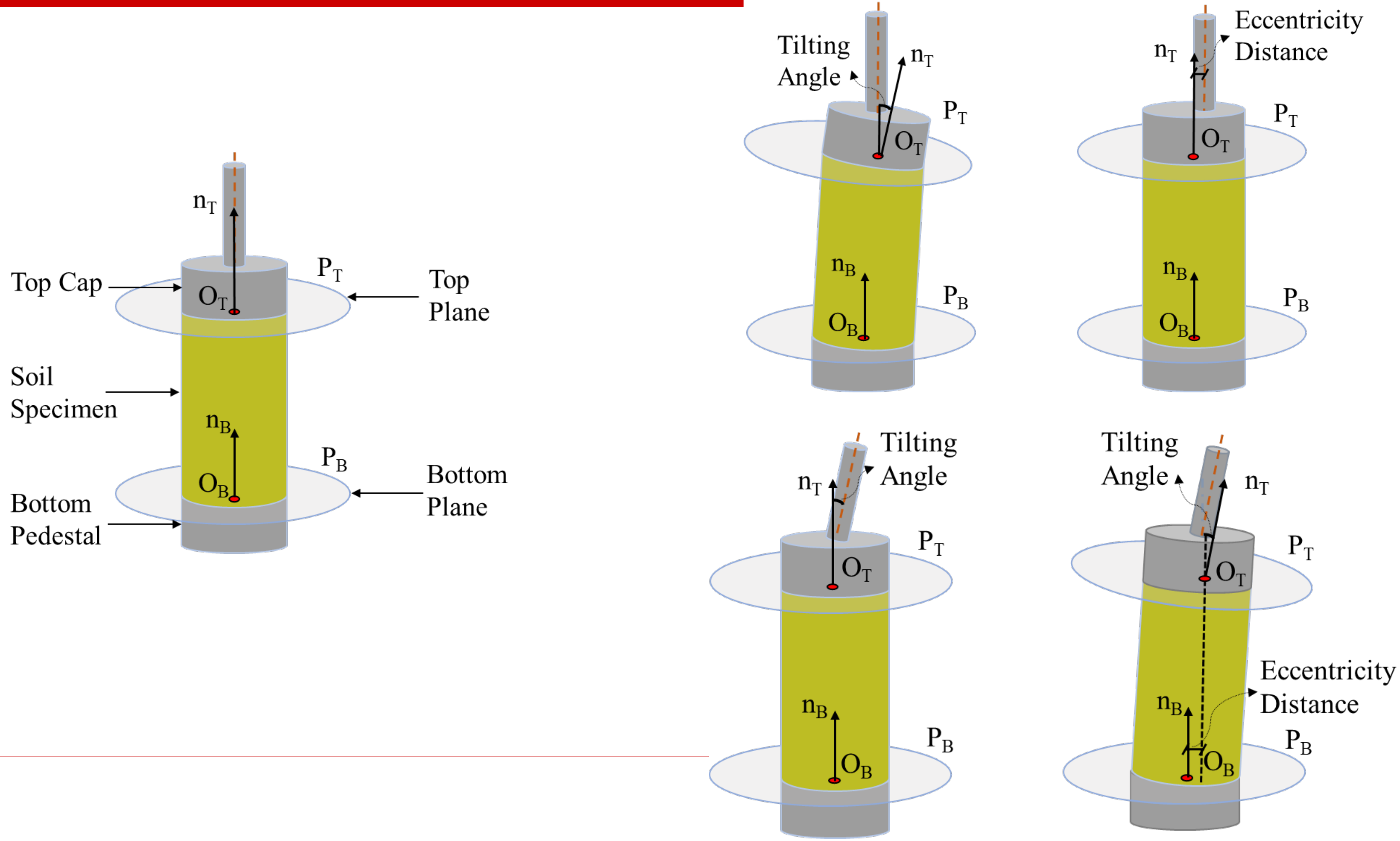


Absolute Soil Volume

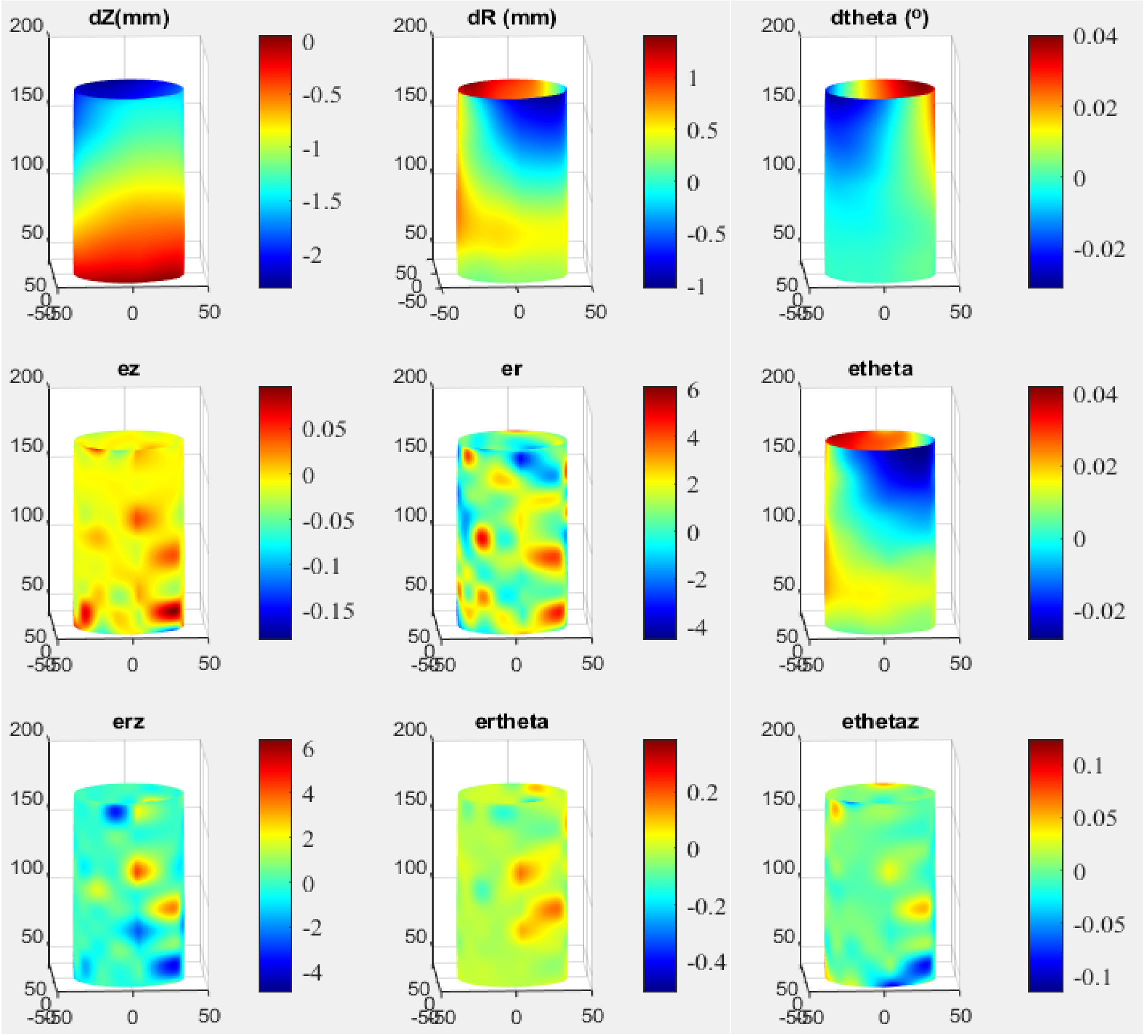




Tilting and Eccentricity



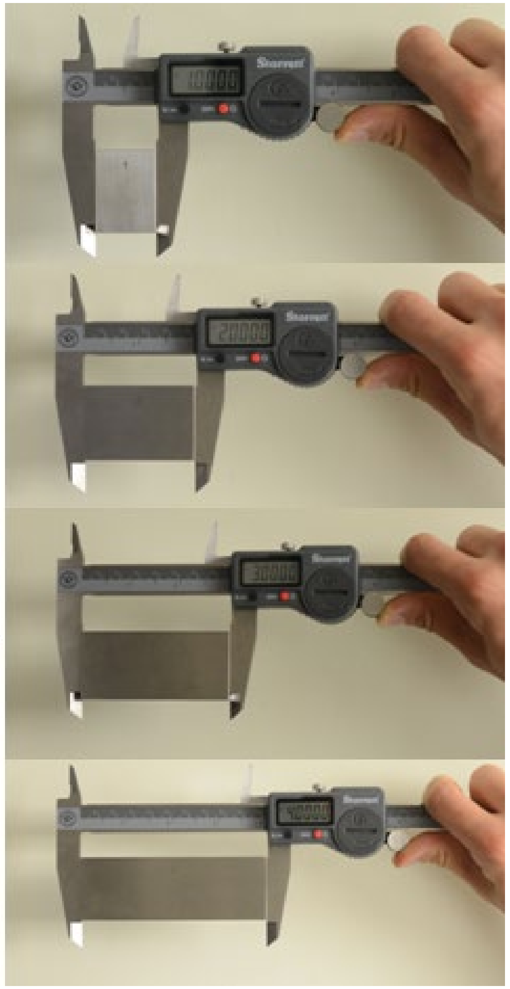
Strain Localizations



Validation 1

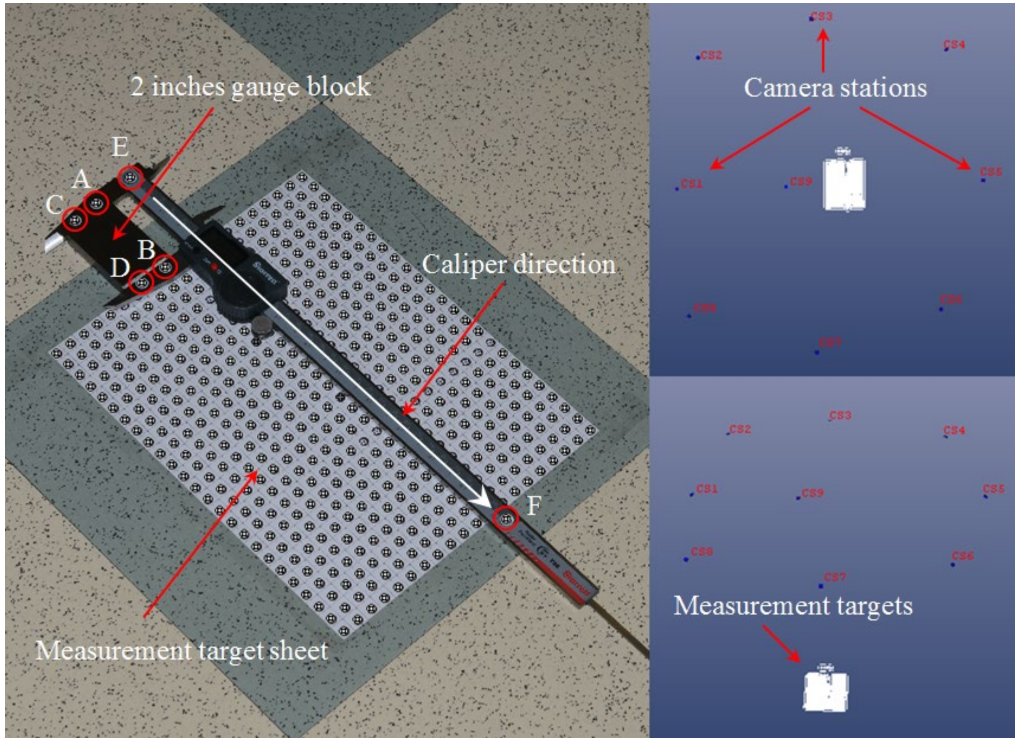
Accuracy in the Air

Certified Gauge Blocks and Digital Caliper



Validation Tests with Gauge Blocks and Digital Caliper

500 Targets



Points used	A and B				C and D				Error average (micron)	Average of absolute error (micron)
Gauge block (mm)	25.4	50.8	76.2	101.6	25.4	50.8	76.2	101.6		
Error (micron)	3.94	3.40	-0.06	0.00	3.19	1.11	-3.91	-0.41	1.04	2.29

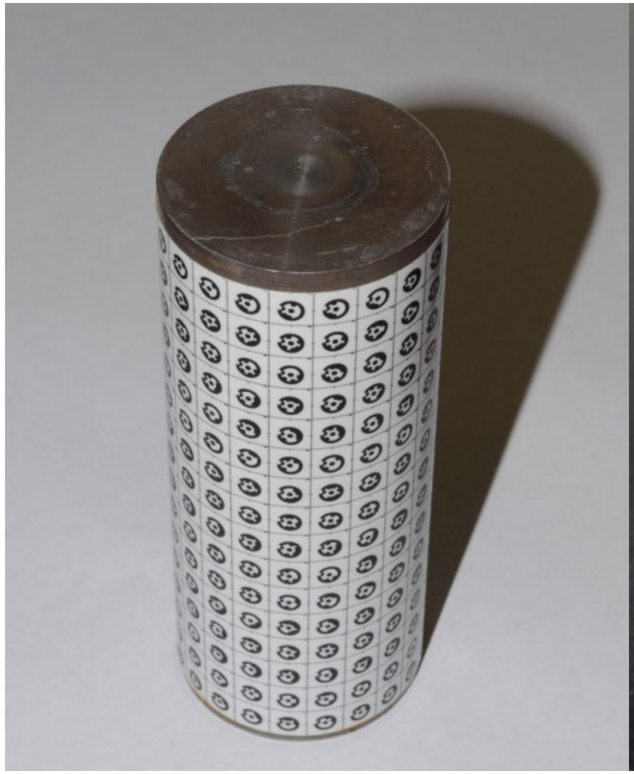
Validation 2

Accuracy of Point Measurements

Validation Tests with Steel Cylinder

21×16=336

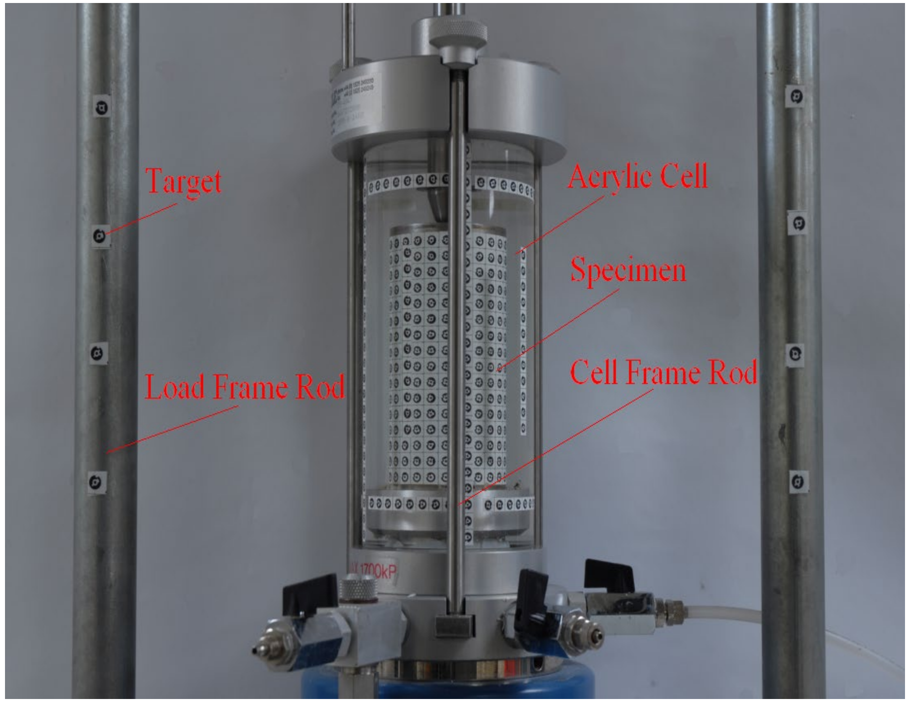
216

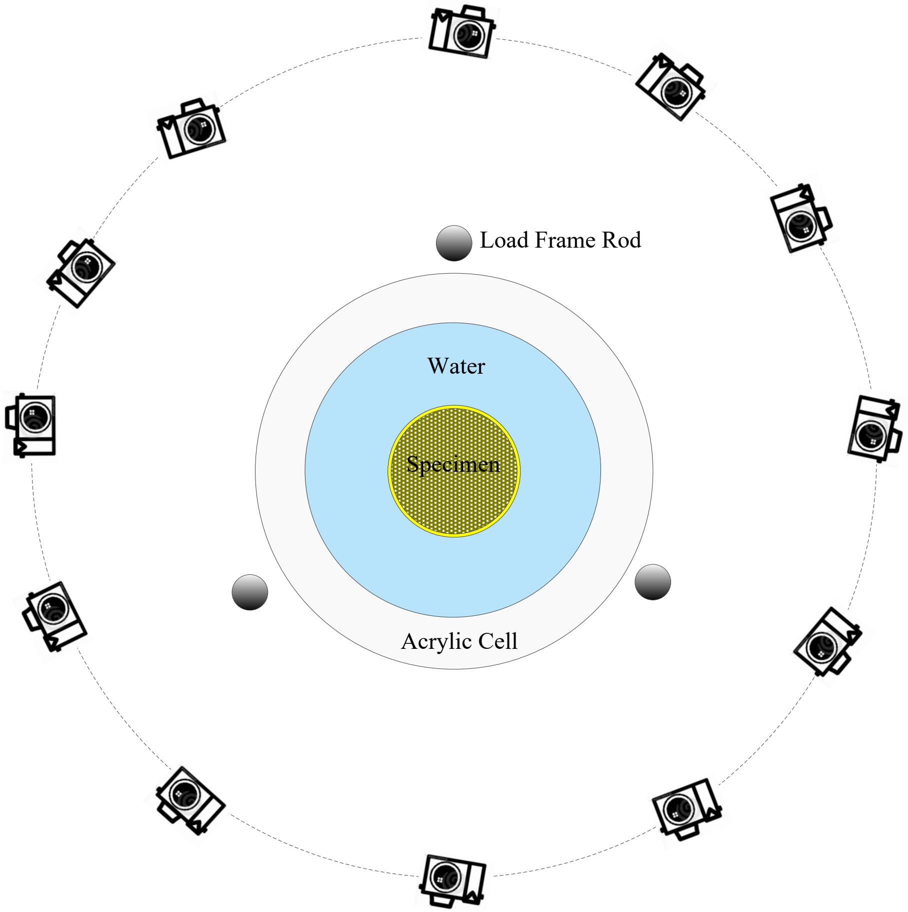


Acrylic cell, 4 × 8 inches

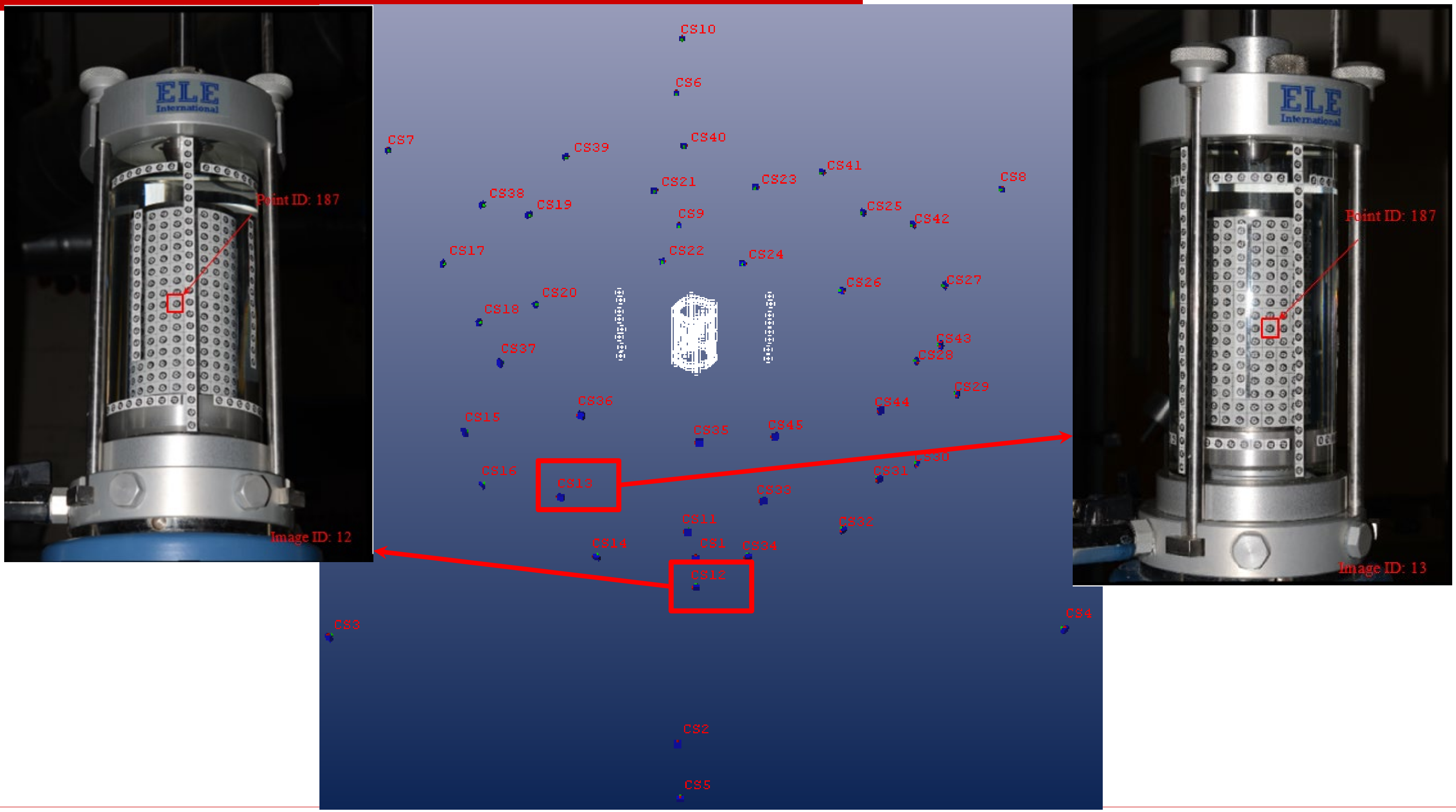
E=200 GPa, μ=0.3, $\varepsilon_v < 10^{-3}$

System Setup for the Proposed Method

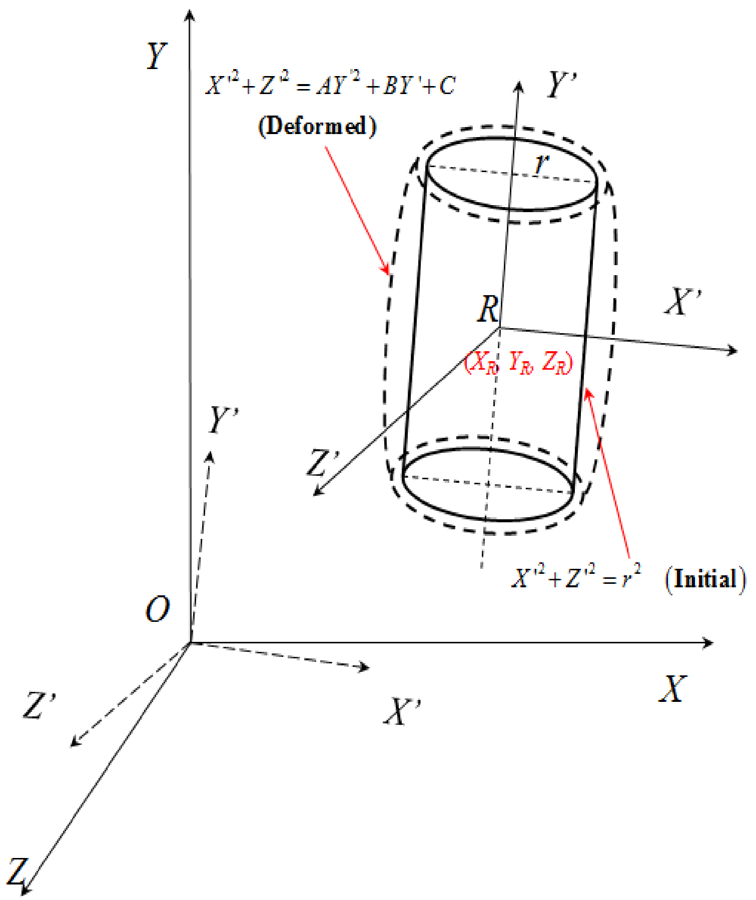


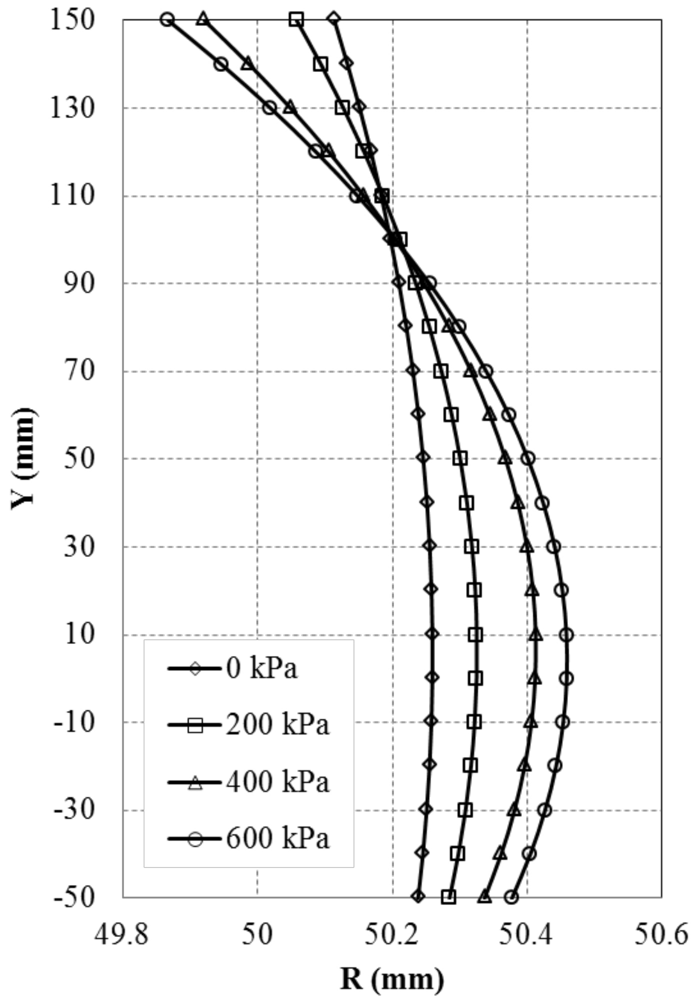


Camera and Cell Positions from Photogrammetry

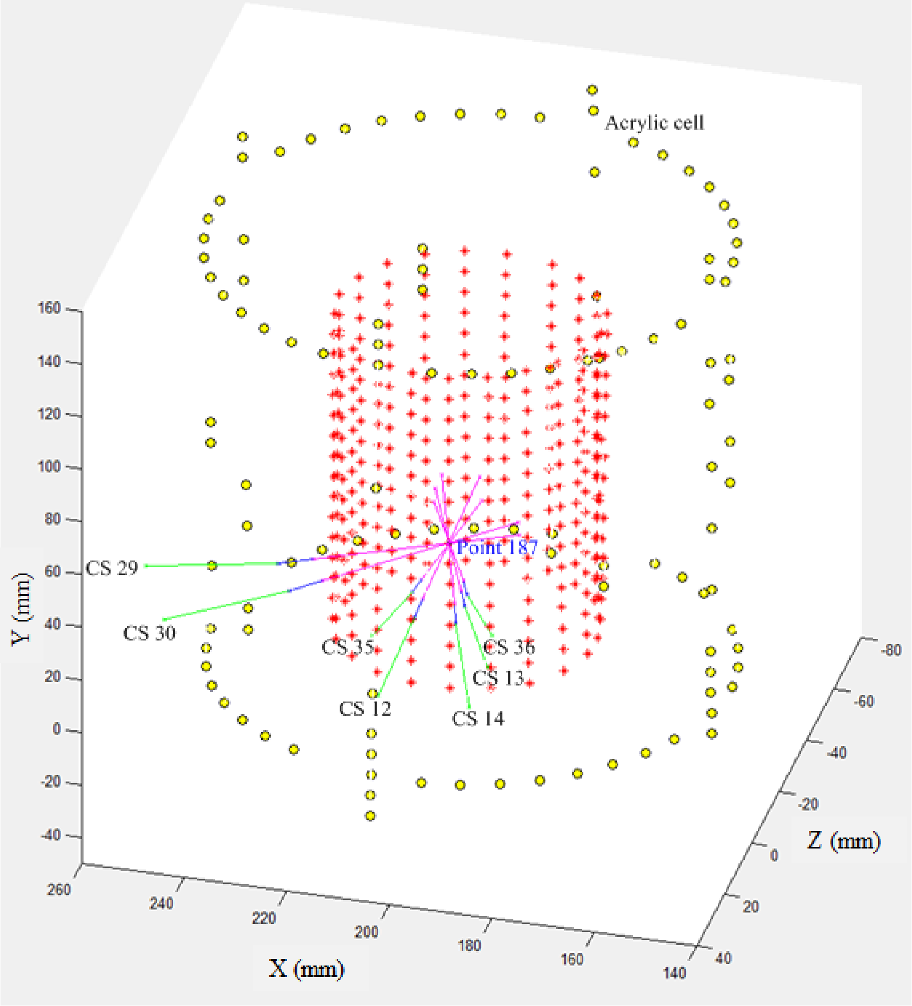


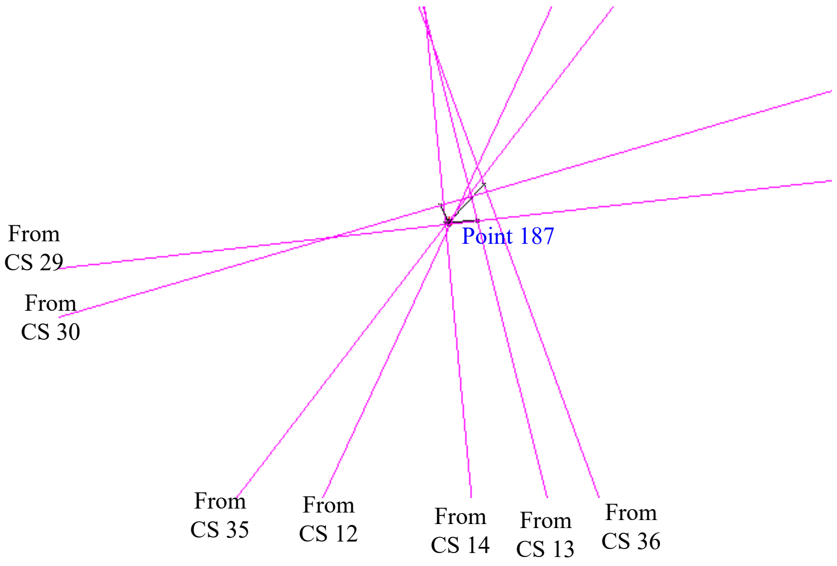
Changes in Cell Shape under Different Pressures



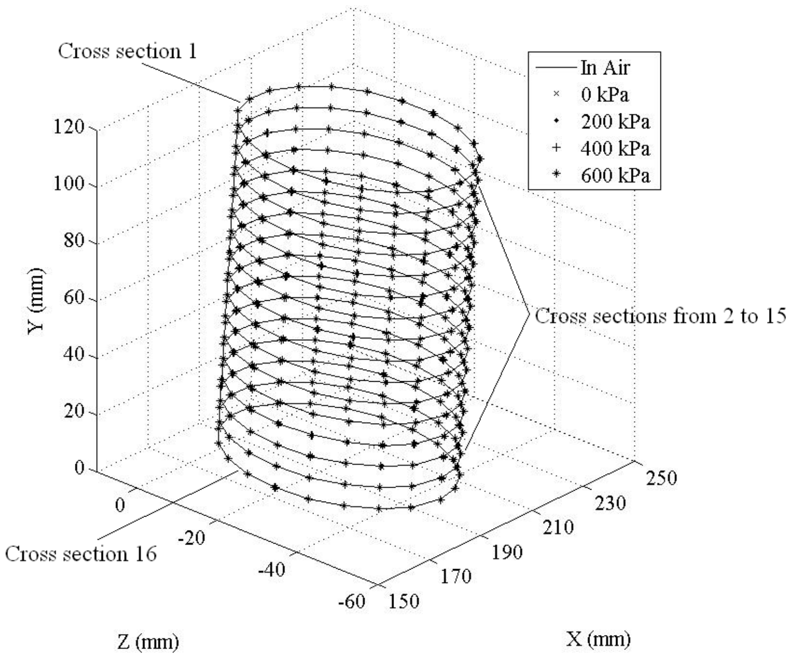


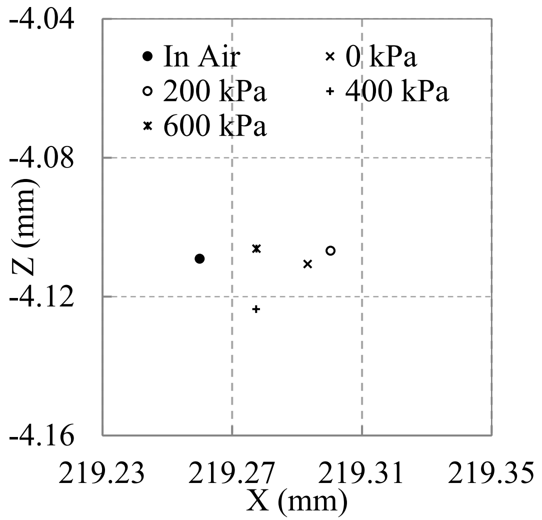
3D Multiple Ray-Tracing Process

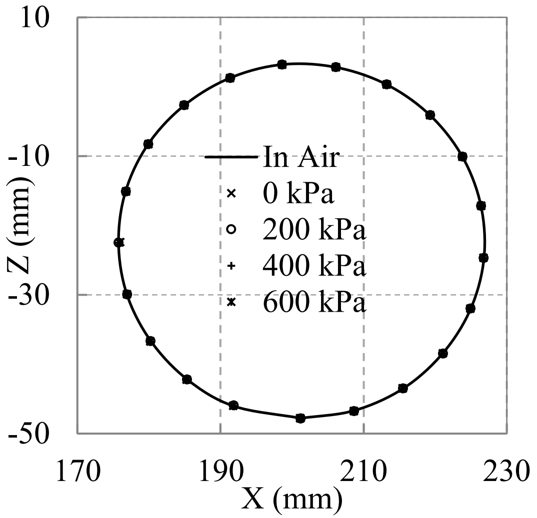




Accuracy of Measurement







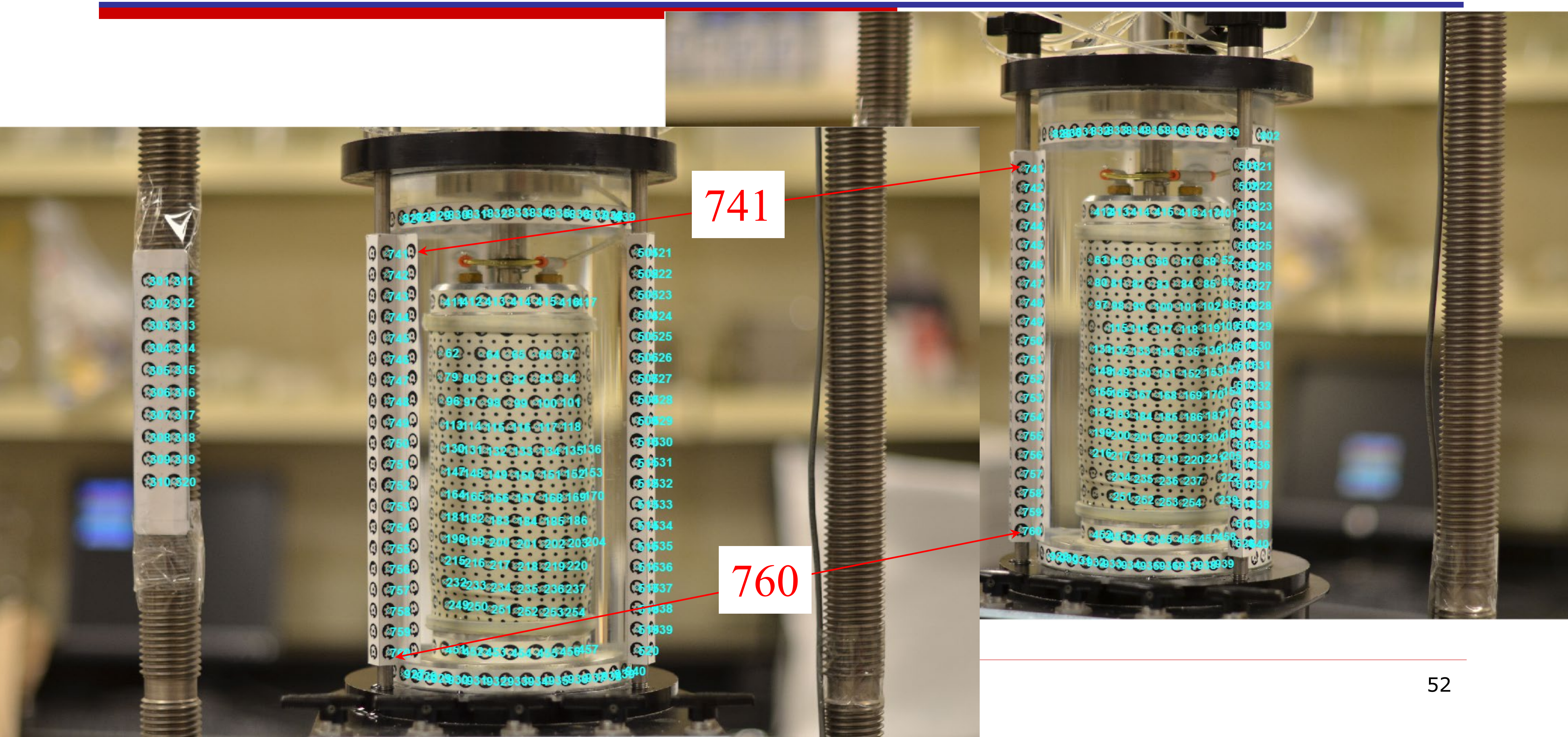
Case	Error (mm)	
	Average	Standard deviation
In air	0	0
0 kPa	0.076	0.061
200 kPa	0.056	0.042
400 kPa	0.063	0.033
600 kPa	0.07	0.049

Validation 3

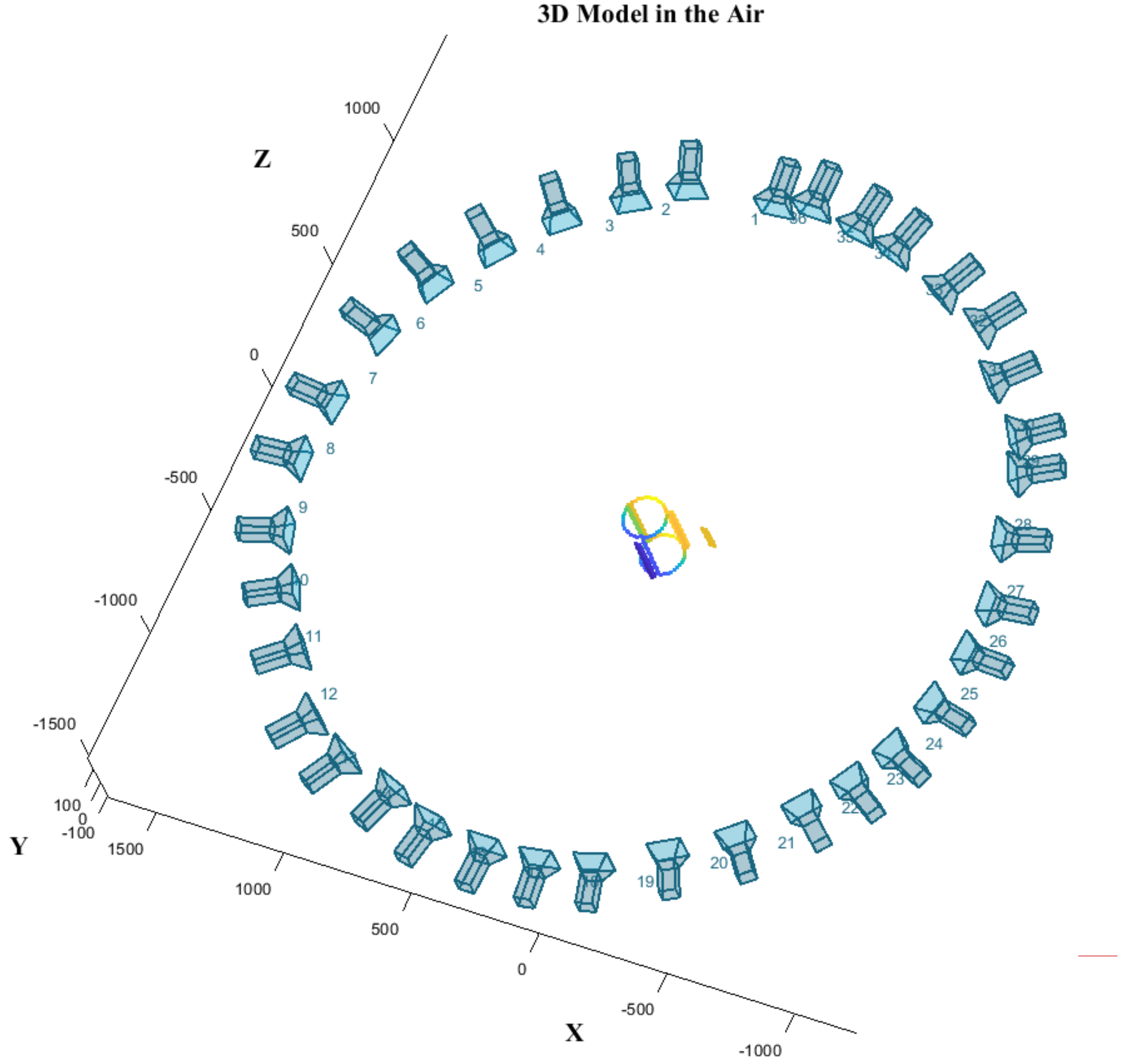
Accuracy of Total Volume Measurements

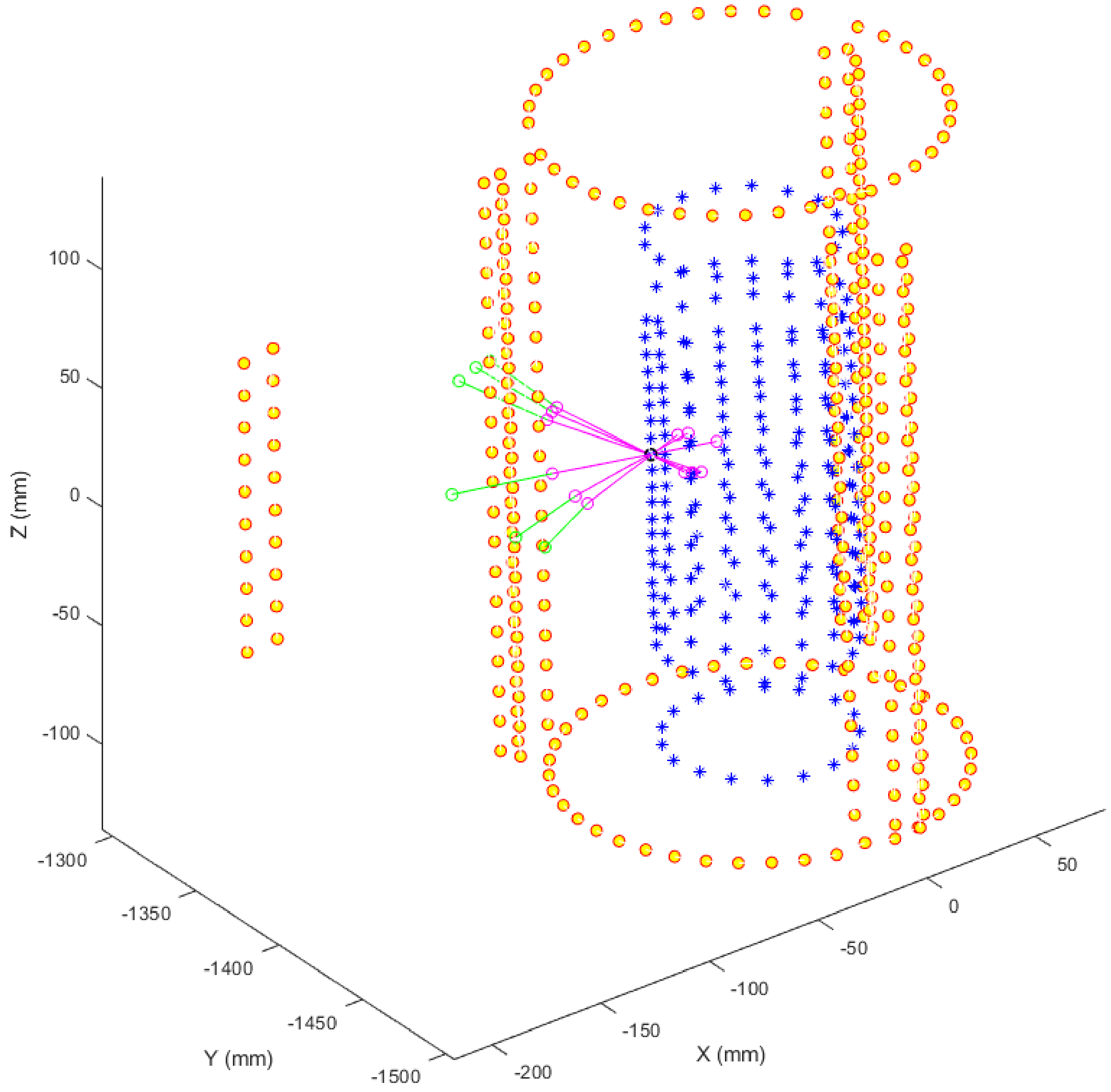
& Strain Localization

Validation Tests with a Saturated Sand Specimen

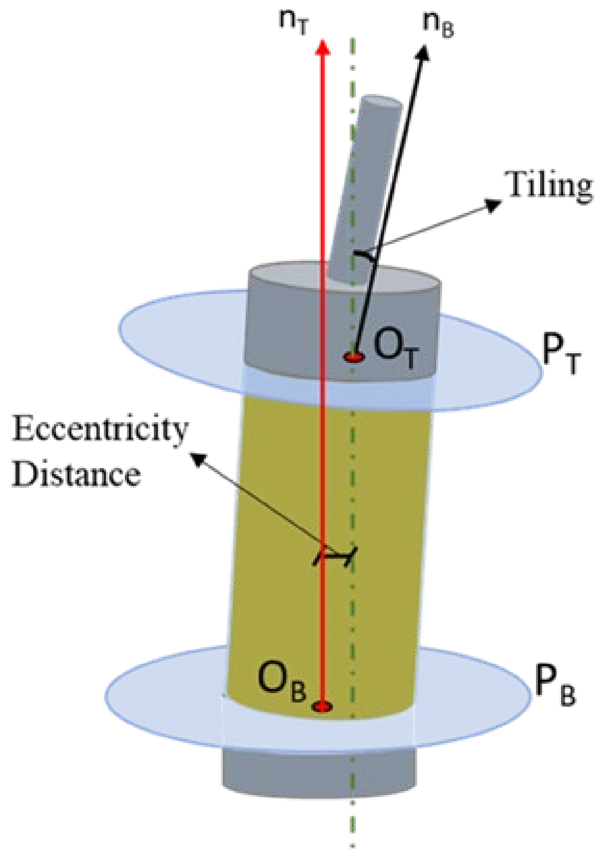


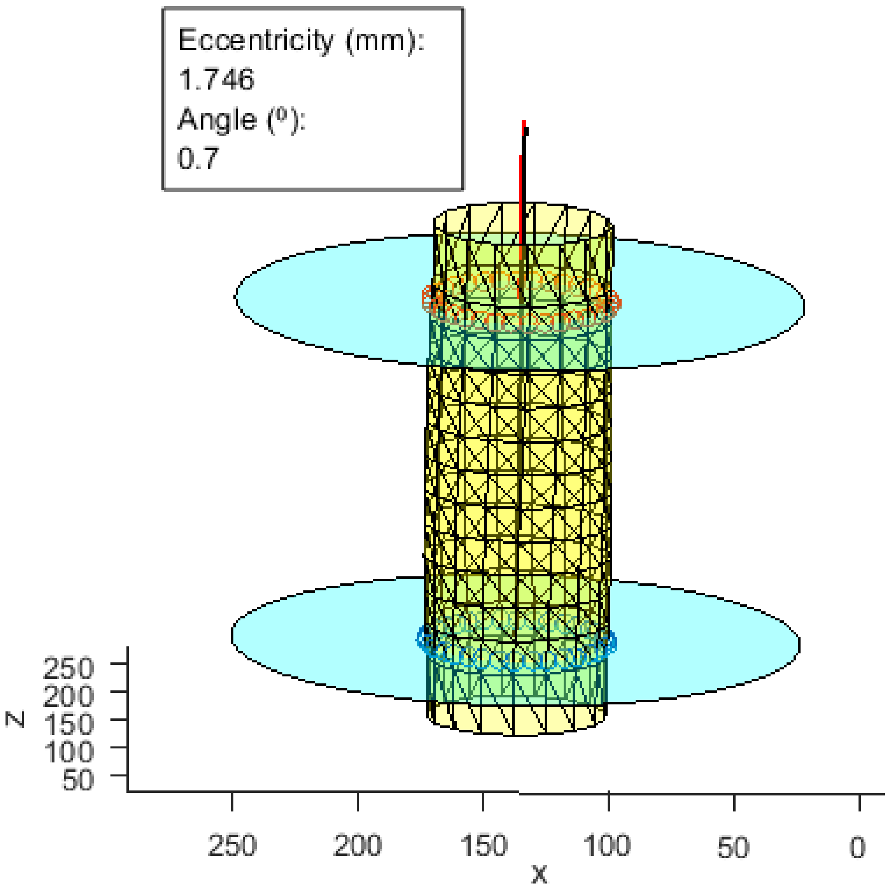
3D Reconstruction and Ray-tracing

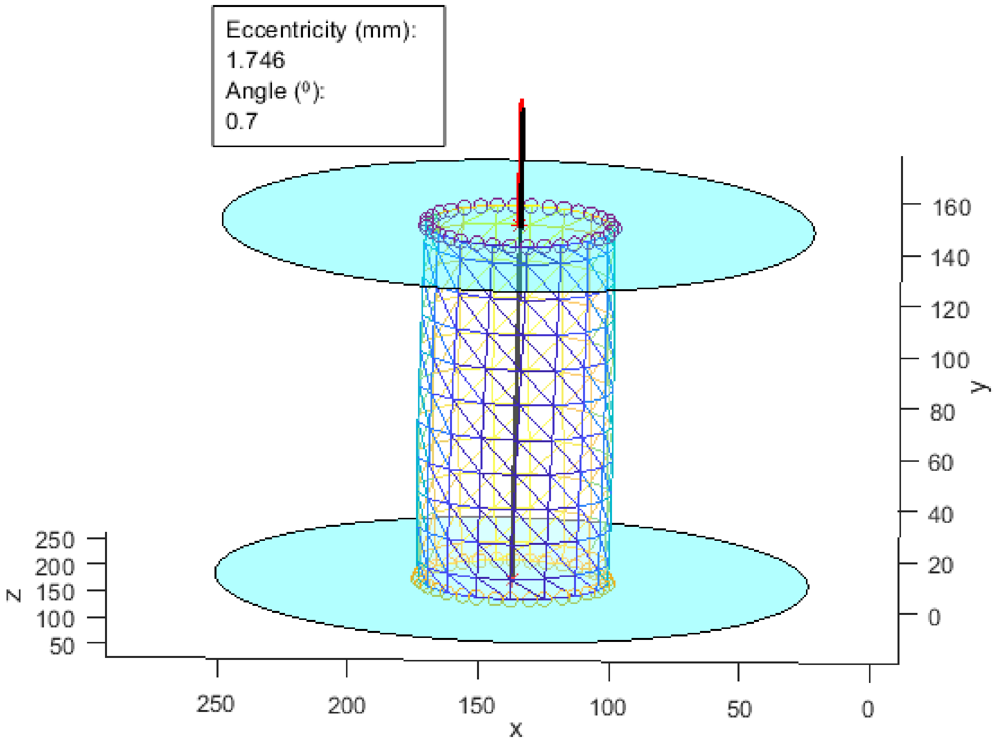




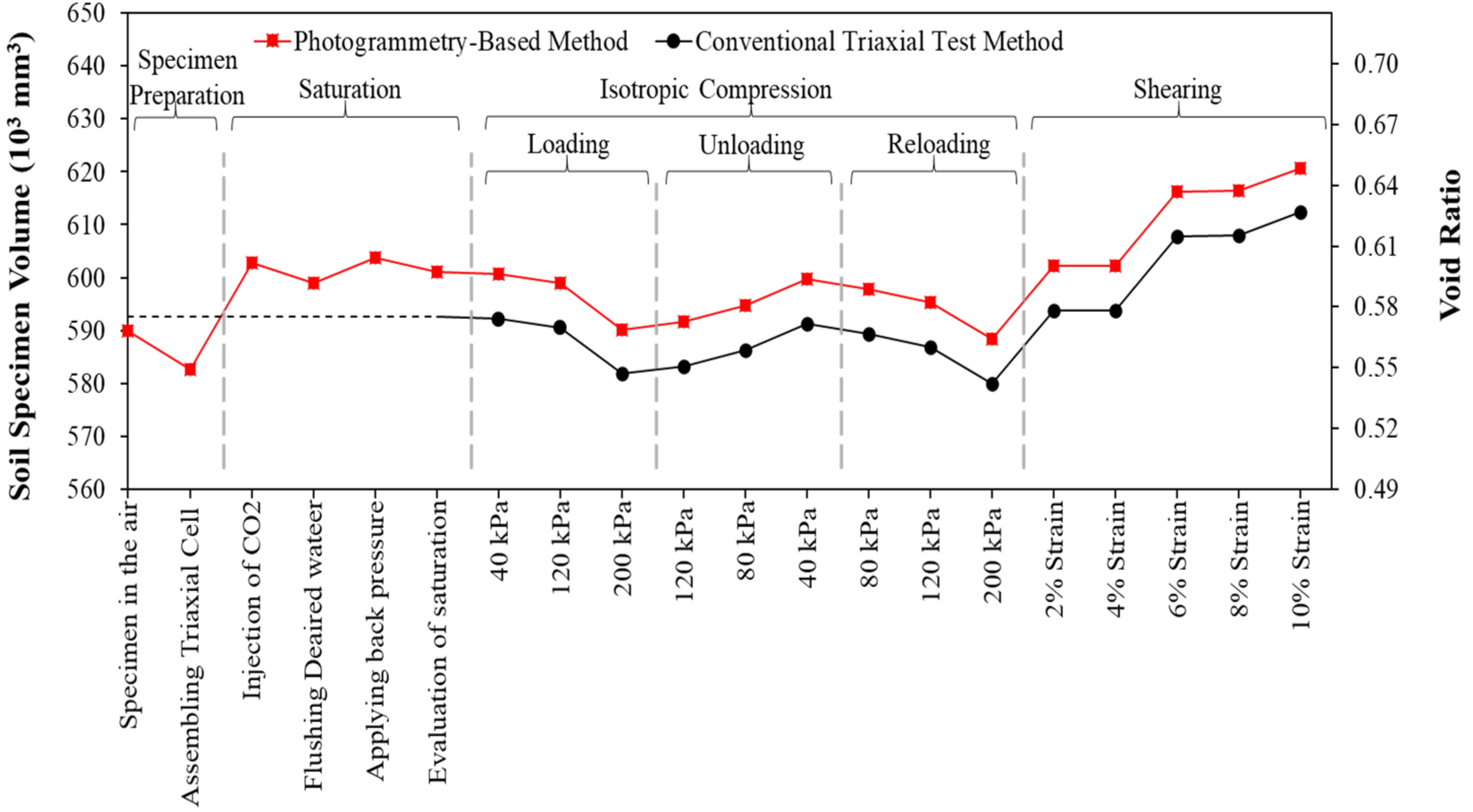
Absolute Volume, Tilting, and Eccentricity



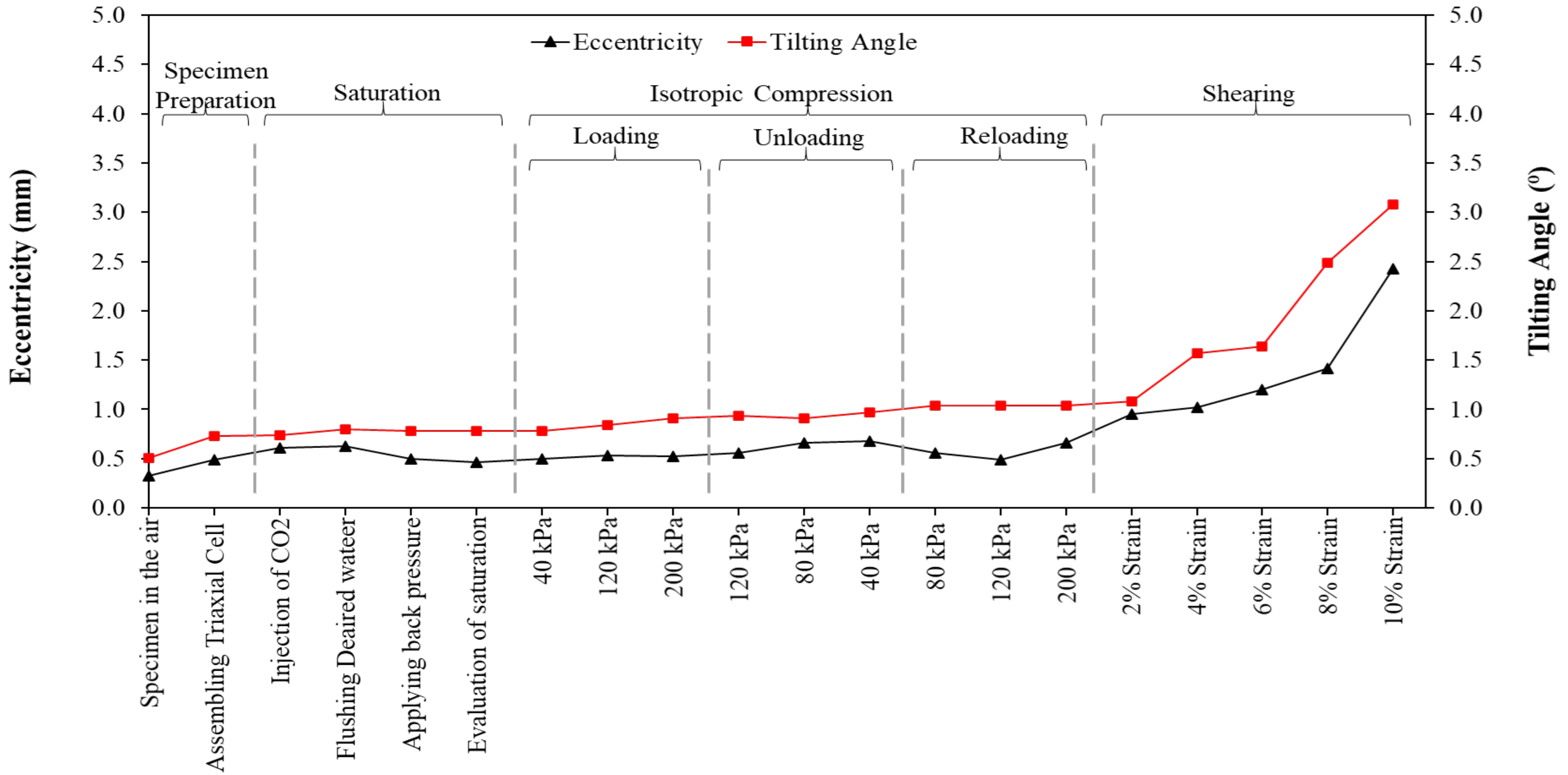




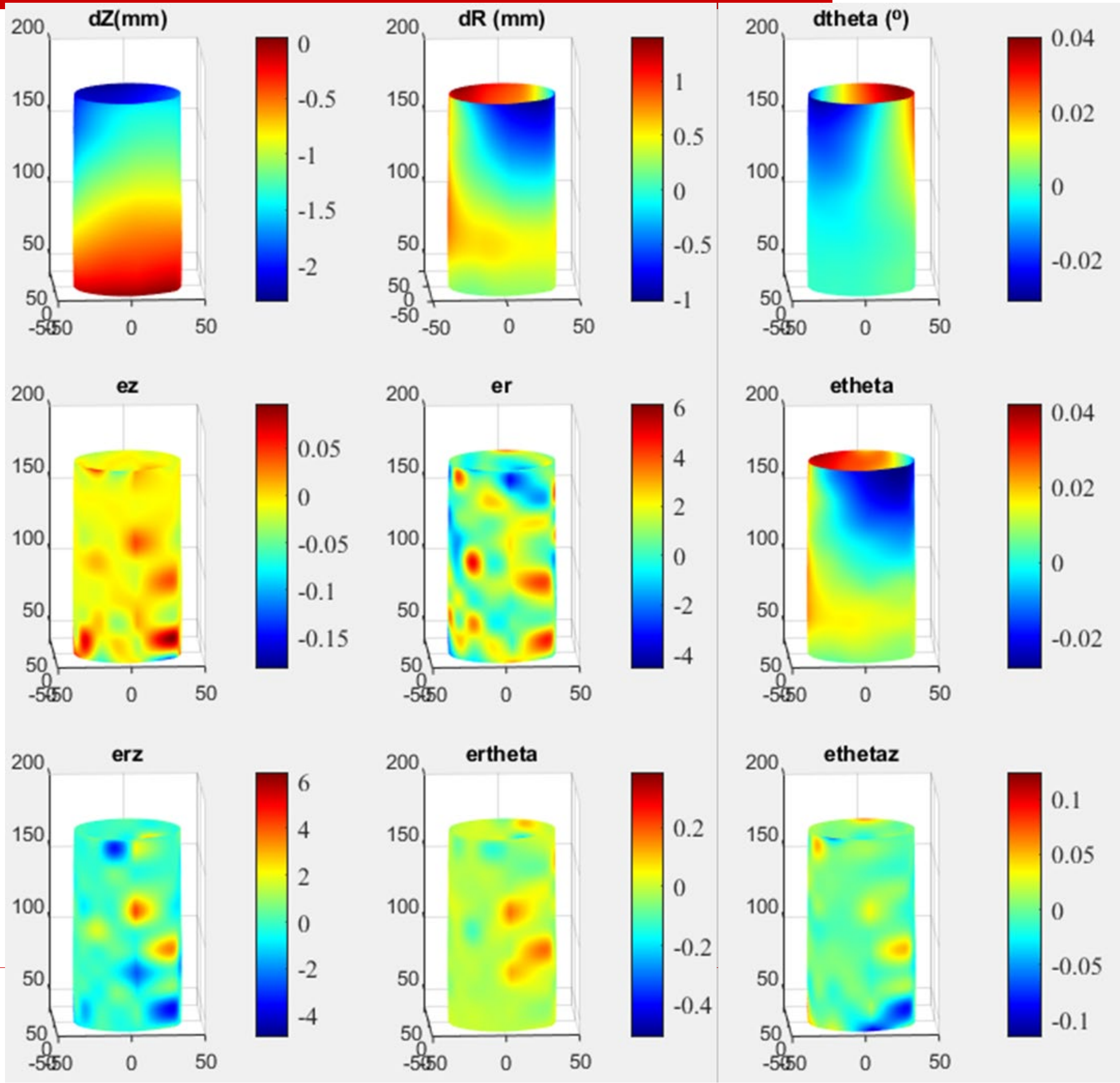
Relative vs. Absolute Soil Volume



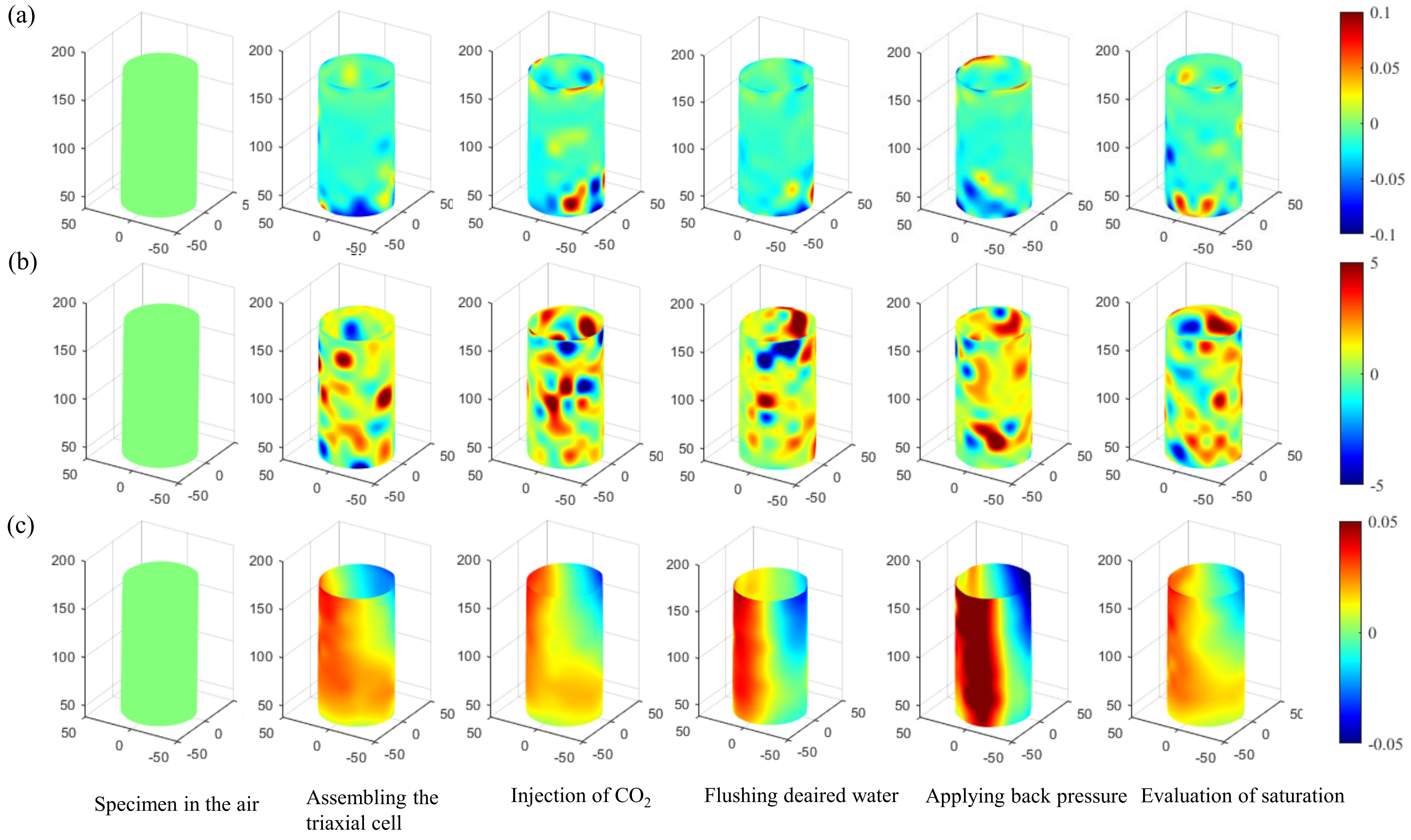
Tilting and Eccentricity



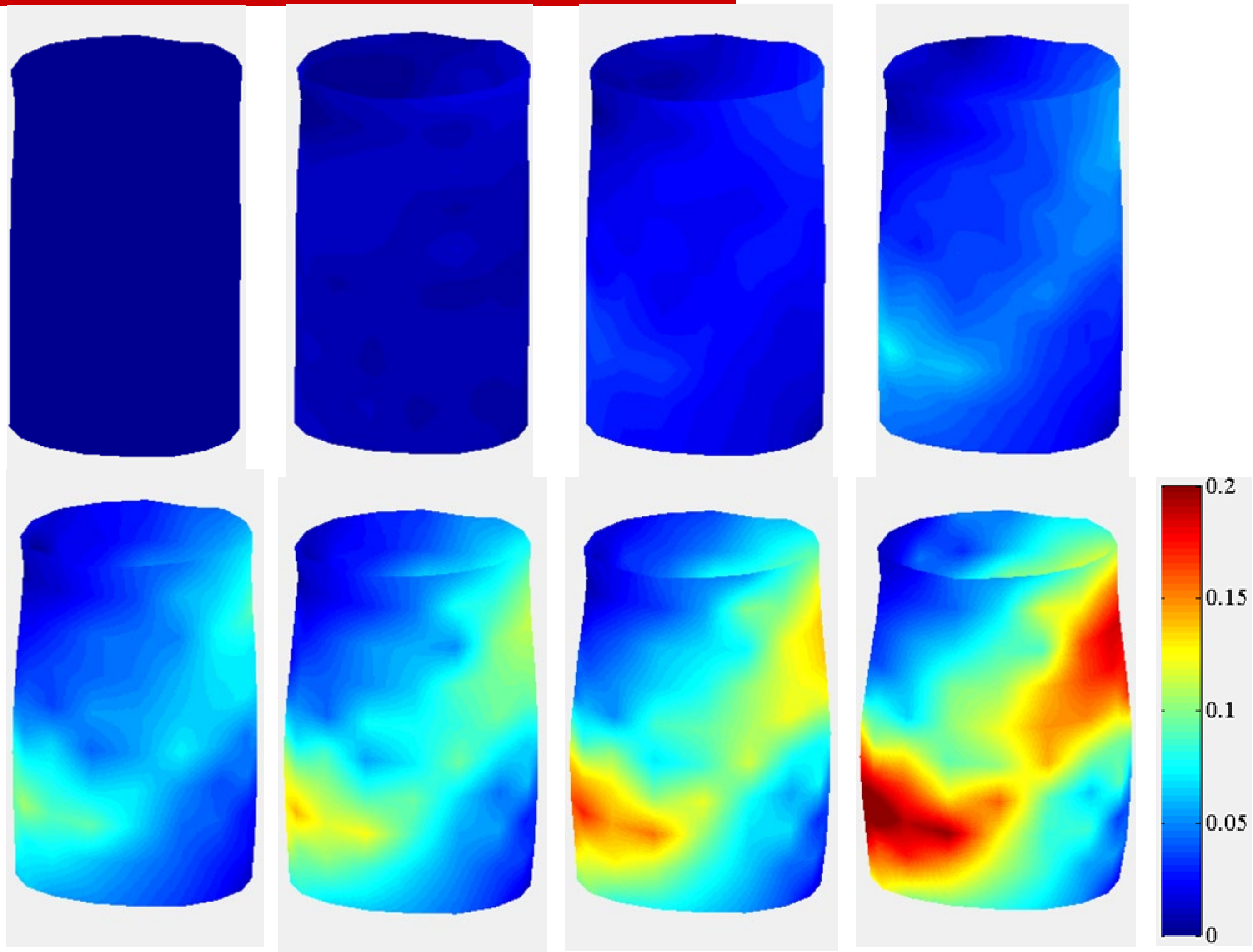
Full Field Displacement and Localized Strains



Disturbance in Assembling and Specimen Saturation



Development of Shear Band



On-Going: Multi-Camera System for Dynamic Tests

Lorex 4K NVR system with 12 security cameras

Conclusions

- An optical method developed which integrated photogrammetry, Multiple ray-tracing, and Least-Square optimization
- Can be used for both Saturated and unsaturated Soils
- Accuracy for point measurement: <5 micron in the air, 76 micron in water
- Accuracy for total volume measurement: <0.25%
- Simple and cost-effective: < $2,000
- Computation intensive: PhotoSoilVolume, 3 minutes/loading step

Questions: zhangxi@mstu.edu

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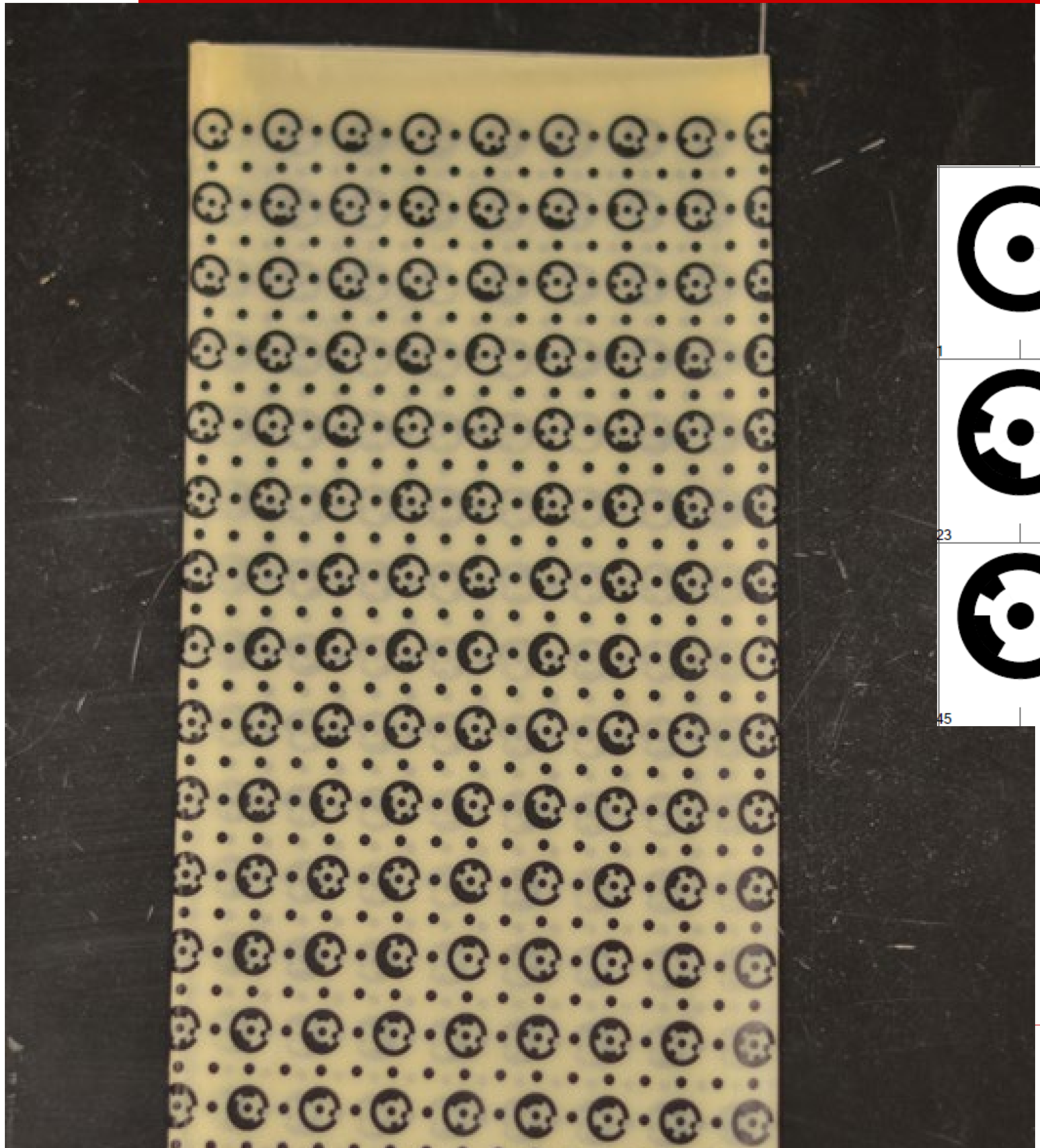
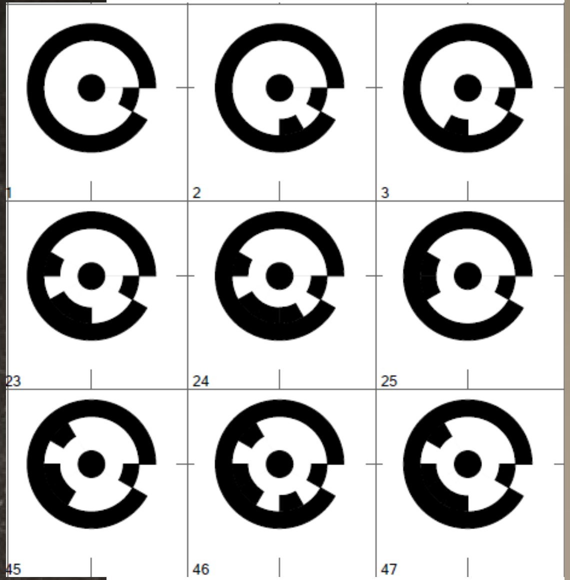
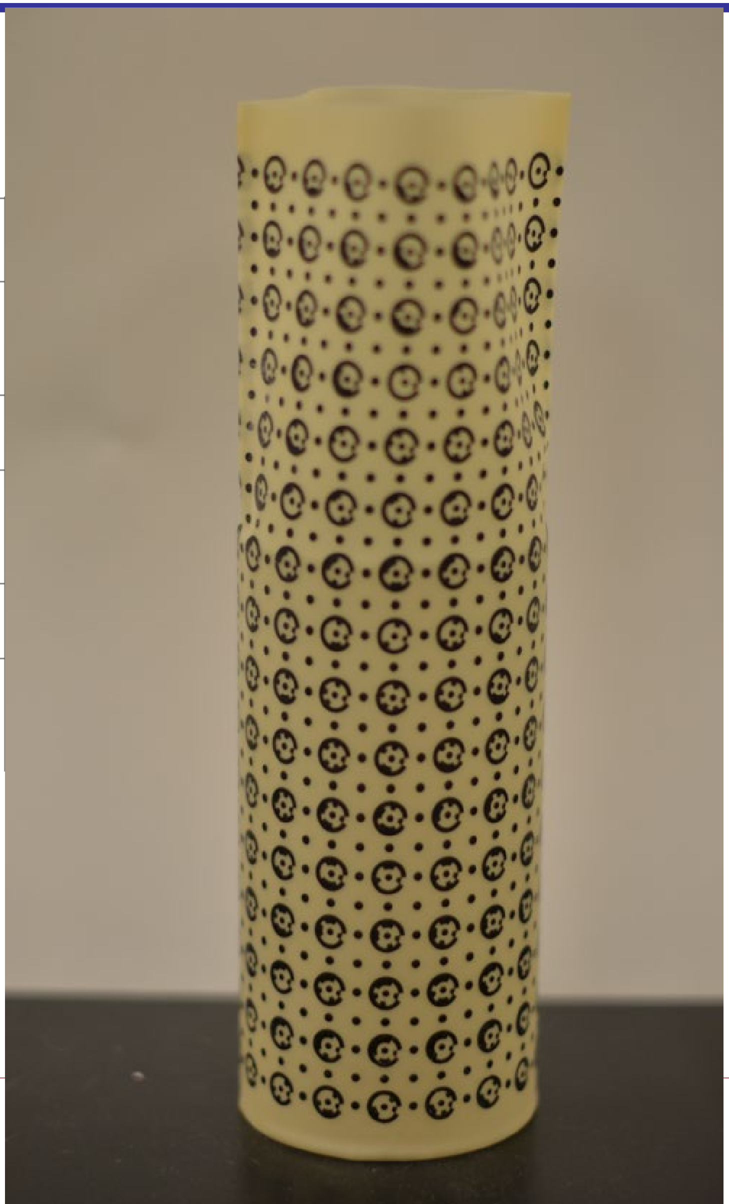
- Students: **Xiaolong Xia, Sara Fayek, Robert Barnett, Richard Gorzel, and Benton Brightwell**
- **PanamUnsat 2021 organizing committee** for give me the opportunity to make this keynote lecture
- **ISSMGE TC106** for the **2016 International Award for Innovation in Unsaturated Soil Mechanics**

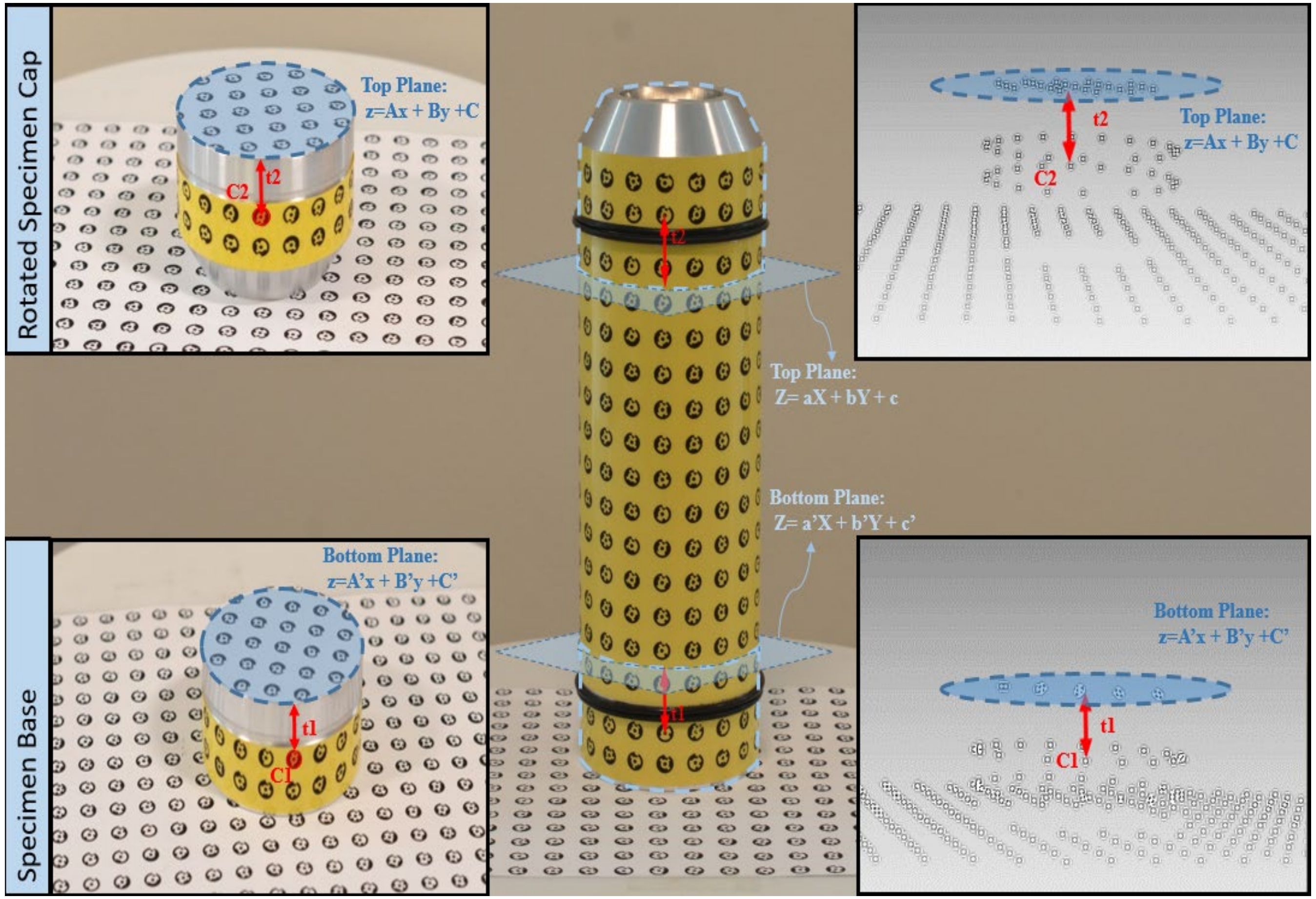
Membrane and Coded Target Design







Determination of Top and Bottom Boundaries



Volume Calculations