Advanced Imaging Techniques for Soil-Structure Interaction Problems

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Presentation Outline

- Motivation
- Advanced Imaging Techniques
- Soil-Structure Interaction Problems
- Conclusions and Recommendations
• Motivation
  • Advanced Imagining Techniques
  • Soil-Structure Interaction Problems
  • Conclusions and Recommendations
• Provide non-contact, non-intrusive, and continuous measurement of soil deformation field
• Detect soil displacement with high precision
• Allow multiscale observations of granular media behavior
• Generate large amount of useful qualitative and quantitative results in studying soil-structure interaction problems to:
  - Confirm hypotheses
  - Verify empirical formulas
  - Validate numerical modeling
• Motivation

• Advanced Imagining Techniques

  Digital Image Correlation (DIC)

  Stereo Digital Image Correlation

  Particle Kinematics Analysis

• Soil-Structure Interaction Problems

• Conclusions and Recommendations
DIC is a widely recognized pattern recognition technique used in surface displacement analysis.

Step 1: Acquire images of undeformed (time $t$) and deformed (time $t+\Delta t$) of the field of view (images A and B, respectively), and subdivide images into interrogation windows.

Step 2: Calculate the frequency domain cross correlation function (Eq. 1) for each interrogation window.

Step 3: For each interrogation window, find the peak of the cross correlation function, corresponding to the displacement of the window between image A and image B.
DIC is not a blackbox, the obtained results can vary significantly depending on how the DIC analysis is carried out. There is lack of standard and guidances on how DIC analysis should be conducted for geotechnical engineering applications.

Look Good ≠ Correct

Main components in carrying out a successful DIC analysis:

1. Preprocess
2. Interrogation window size
3. Correlation methods
4. Evaluation algorithms
5. Vector validation and post processing
Non-uniform lighting

To quantify the lighting condition of a soil image, a method based on the statistical distribution of the average intensity value of subsets of an image is proposed.

LS<0.85 require light correction

**Linear filtering**

\[ g(x,y) = f(x,y) - LPF(f(x,y)) + \text{mean}(LPF(f(x,y))) \]
Image texture

Good Texture

Bad Texture

\[ TN = (1 - \frac{AC}{3.7}) \times 100 \]

\[ AC (m,n) = \frac{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} f(i,j) f(i+m,j+n)}{\sum_{i=0}^{M-1} \sum_{j=0}^{N-1} [f(i,j)]^2} \]

It is important to know TN is affected by soil particle image resolution. It was found for the same soil, images of higher soil particle image resolution would have a greater TN.

Particle image resolution 3.75 px
*Image texture enhancement*

![Image texture enhancement](image.png)

TN=0.41  TN=1.53  TN=2.66  TN=5.63  TN=6.80
Effect of image texture on the accuracy of DIC analysis
Effect of resolution on the accuracy of DIC analysis

- **4M px**
  - $e_{mb} = 0.143^\circ$
  - $e_{rms} = 0.198^\circ$

- **250K px**
  - $e_{mb} = 0.055^\circ$
  - $e_{rms} = 0.085^\circ$

- **16K px**
  - $e_{mb} = 0.335^\circ$
  - $e_{rms} = 0.400^\circ$
Selection of the appropriate interrogation window size is often a trial and error process, because it depends on a large number of factors including image texture, correlation methods, dynamic spatial range, and complexity of the expected deformation pattern.

Small interrogation windows could lead to unreliable analysis due to (1) lack of texture within the window and (2) violation of the dynamic spatial range limit.

Large interrogation windows could also lead to poor results due to violation of the assumption that the deformation within an interrogation window should be uniform.
DIC-Interrogation window size

256×256 px  128×128 px  32×32 px  16×16 px
DIC-Correlation methods

Frequency-based method:

**Advantage:**
computational time

**Disadvantage:**
require the interrogation window size to be at least 2 to 4 times the expected displacement between images.
DIC-Evaluation methods

- **Single Pass** (64×64 px)
- **Multi Pass** (64×64 px, 3 passes)
- **Adaptive** (128×128 to 16×16 px, 4 passes)
- **Multigrid** (128×128 to 16×16 px, 4 passes)
**Hybrid DIC**

*Hybrid* evaluation method takes the same iterative evaluation procedure similar to *multigrid* except the first pass of the *hybrid* evaluation method is implemented in the spatial domain rather than frequency domain.

To improve the computational efficiency of conventional spatial domain correlation, a method called hierarchical block-based matching algorithm (HBMA) is adopted for the first pass of *hybrid* DIC.
HBMA

1. Construct a 3-level pyramid image pairs by down sampling both the original and deformed images using a low pass filter.

2. Perform a standard spatial domain correlation to find the initial estimate of the displacement vectors at the coarse resolution level.

3. The displacement vectors detected at the coarse level are used as estimates for interrogation window offset.

4. Repeat step 2 with a smaller search range to refine the obtained displacement vectors in the finer resolution level.

5. Finally repeat step 3 and 4 at the actual image resolution level to obtain the final displacement vectors, and these vectors are the first pass estimates of the hybrid DIC evaluation procedure.
Advantages of Hybrid DIC

<table>
<thead>
<tr>
<th>Evaluation Methods</th>
<th>$e_{mb}$ (px)</th>
<th>$e_{rms}$ (px)</th>
<th>Computational Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBMA</td>
<td>0</td>
<td>0</td>
<td>61.85</td>
</tr>
<tr>
<td>HBMA</td>
<td>0</td>
<td>0</td>
<td>0.98</td>
</tr>
<tr>
<td>FFT</td>
<td>0.72</td>
<td>0.31</td>
<td>0.20</td>
</tr>
</tbody>
</table>

**Displacement (Pixels)**

- FFT
- HBMA
DIC-Vector Post Processing

(a) high quality DIC analysis

(b) post processed vector map from (a)

(c) poor quality DIC analysis,

(d) over post processed vector map from (c)

The goal is to remove a small amount of spurious vectors not to make poor quality DIC vector map look visually pleasing.
Infinitesimal strain theory – only valid for very small deformation.

For soil-structure interaction problems, it is generally required to implement finite strain theory.
The trajectories of a soil element were often obtained by direct integration of the incremental displacements at each interrogation window. This is so called Eulerian trajectories. This approach is ok for uniform flow problems and falls short for applications where high gradient flow is expected.

We have written an algorithm that allows tracking the soil element (interrogation window) throughout a sequence of images to obtain the so called Lagrangian trajectories.
• Motivation

• Advanced Imagining Techniques
  
  *Digital Image Correlation (DIC)*

  *Stereo Digital Image Correlation*

  *Particle Kinematics Analysis*

• Soil-Structure Interaction Problems

• Conclusions and Recommendations
Step 1: Obtain camera parameters such as focal length, rotation matrix and translation vector of the two cameras through camera calibration.
Step 2: Obtain a series of paired images at the region of interest during test.
Step 3: Calculate the corresponding 2D displacement field from the images using conventional DIC techniques.
Step 4: Construct the out of plane displacement field based on the obtained camera parameters and 2D displacement vector pairs.
Reconstruction

\[
\begin{align*}
\frac{dx_1}{dx} &= \tan \alpha_1 \frac{dz}{dx} \\
\frac{dy_1}{dy} &= \tan \beta_1 \frac{dz}{dy} \\
\frac{dx_2}{dx} &= \tan \alpha_2 \frac{dz}{dx} \\
\frac{dy_2}{dy} &= \tan \beta_2 \frac{dz}{dy}
\end{align*}
\]

\[
\tan \alpha_1 = \frac{y_2 - y_1}{z_2 - z_1} \\
\tan \alpha_2 = \frac{y_2 - y_1}{z_2 - z_1}
\]

\[
\begin{bmatrix}
\frac{dx_1}{dx} \\
\frac{dy_1}{dy} \\
\frac{dx_2}{dx} \\
\frac{dy_2}{dy}
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & -\tan \alpha_1 \\
0 & 1 & -\tan \beta_1 \\
1 & 0 & -\tan \alpha_2 \\
0 & 1 & -\tan \beta_2
\end{bmatrix}
\begin{bmatrix}
\frac{dx}{dz} \\
\frac{dy}{dz}
\end{bmatrix}
\]
**Calibration**

The oblique viewing arrangement of stereo system introduces a strong perspective distortion that leads to a non-uniform magnification across the obtained images. To correct non-uniform magnification, the obtained images need to be dewarped into a common grid so that the image axes are parallel to the axes in physical space. This can be done through either geometric back projection or general mapping function.

**Projection equations (dewarp):**

\[
X_d = \frac{a_{10}X_i + a_{11}Y_i + a_{13} + a_{14}X_i^2 + a_{15}X_iY_i + a_{16}Y_i^2}{a_{30}X_i + a_{31}Y_i + 1 + a_{34}X_i^2 + a_{35}X_iY_i + a_{36}Y_i^2}
\]

\[
Y_d = \frac{a_{20}X_i + a_{21}Y_i + a_{23} + a_{24}X_i^2 + a_{25}X_iY_i + a_{26}Y_i^2}{a_{30}X_i + a_{31}Y_i + 1 + a_{34}X_i^2 + a_{35}X_iY_i + a_{36}Y_i^2}
\]

solved by Levenberg-Marquart method, then linear transformation:

\[
X_o = \frac{X_d}{M} + X_{offx}
\]

\[
Y_o = \frac{Y_d}{M} + Y_{offy}
\]
• Motivation

• Advanced Imagining Techniques
  
  Digital Image Correlation (DIC)
  Stereo Digital Image Correlation
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• Soil-Structure Interaction Problems

• Conclusions and Recommendations
Several methods have been developed in the past to identify circular features in densely structured packing. Peng et al. (2007) has developed an algorithm based on Hough transform to identify circular particle.

a. Schematic of a round particle in a grayscale image
b. Gradient field of round particle
c. Transform gradient field to an accumulation array by assigning higher grayscale intensities to the pixels along the direction of each gradient vector.
d. Actual accumulation array for Silica gel particles
e. We have used the algorithm to identify silica gel particles
Several particle tracking algorithms are available in the literature. The algorithm described below was developed by Crocker et al (1996).

1. A search radius smaller than the default search radius is adopted, in order to identify small particle displacements.

2. Once these particle positions are identified, they are stored in memory, and are removed from the search domain for subsequent passes.

3. The search algorithm is invoked again, with larger search radii, in order to identify remaining particles.

4. The process is repeated, until all particles are identified.

5. If multiple particles are identified within the same search radius, they are ignored. Finally, the positions of the remaining unidentified particles are determined assuming that the correct position is the one resulting in the minimum total particle displacements from successive images.
Non-affinity of particle motion is a measure that quantifies the extent to which the particle deviates from the motion of the neighboring particles within a given radius from its center point, which represents the localization and heterogeneity in granular media.

Non-affine motion = Actual motion – Affine motion

It serves as a bridge to link particle level observations to meso-scale phenomena; it is also a useful qualitative measure of the local deviation of the particle movements from a smooth continuous displacement field.
**Method 1: Particle Level DIC**

1. Perform DIC analysis for a sequence of images, ensuring that each particle contains multiple interrogation windows (preferably more than 3 across)

2. Based on the previously obtained particle tracking results for each image pair,
   a. extract DIC displacement vectors contained within each particle and assign it to the given particle
   b. find the particle centroid translation

(a) DIC displacement vectors, (b) particle centroid translation, (c) particle rotational components
Method 2: Intensity-Based Image Registration

Correlate the two particles using the MATLAB built-in function `imregtform`, which performs image registration between the two images, by means of minimizing the mean square difference between the image intensities of the two images.

\[ Y = RX + T \]

\[ R = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \]

\[ \theta = \text{atan2d}(R(2,1), R(1,1)) = \text{atan2d}(\sin \theta, \cos \theta) \]

where \( X \) and \( Y \) are the displaced and original location of the particle, \( R \) and \( T \) are the rotation and translation components
Method 3: Least Square Points Estimation

Transformation equation:
\[ y_i = R x_i \]

For a set of \( n \) points, \( R \) can be obtained through least-squares estimation.

Covariance matrix \( C \) of \( x_i \) and \( y_i \)
\[
\mu_x = \frac{1}{n} \sum_{i=1}^{n} x_i \quad \mu_y = \frac{1}{n} \sum_{i=1}^{n} y_i
\]

\[
C = \frac{1}{n} \sum_{i=1}^{n} (y_i - \mu_y)(x_i - \mu_x)^T
\]

Singular value decomposition
\[
C = U D V^T
\]

\( D \) is the diagonal matrix containing singular values of \( C \), and \( U \) and \( V \) are the orthogonal matrices.

\( R \) can be determined uniquely as follows:
\[
R = U S V^T
\]

where \( S \) must be chosen as
\[
S = \begin{cases} 
I & \text{if } \det(U) \det(V) = 1 \\
\text{diag}(1,1,\ldots,1,-1) & \text{if } \det(U) \det(V) = -1
\end{cases}
\]
Errors in the Proposed Methods

1. Error increases with decreasing particle resolution.
2. Large error can occur for rotation of less than 1°.
3. Negative errors mean underestimation.
4. Error converges to zero as rotation angle increases beyond 1°.
5. M1 produces large error if rotation angle is greater than 10°.
6. M3 produces large error for small particle rotation (<1°).
### Pros and Cons of the Proposed Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>Texture</th>
<th>Memory (25,000 particles with a resolution of 30px/particle)</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>Not good for large rotation (&gt;10°).</td>
<td>High</td>
<td>Natural sand texture</td>
<td>Low-1.25MB</td>
<td>ImageJ DIC MATLAB</td>
</tr>
<tr>
<td>Method 2</td>
<td>Local maximum</td>
<td>Low</td>
<td>Natural sand texture</td>
<td>Medium-50MB</td>
<td>ImageJ MATLAB</td>
</tr>
<tr>
<td>Method 3</td>
<td>Not good for small rotation (&lt;1°).</td>
<td>Low</td>
<td>Color adhesives</td>
<td>High-200MB</td>
<td>ImageJ MATLAB</td>
</tr>
</tbody>
</table>
Motivation

Advanced Imagining Techniques

**Soil-Structure Interaction Problems**

*Projectile Penetration (High Speed DIC Application)*

*Pile Penetration (DIC and Particle Analysis Application)*

*Earth Retaining Structure (Particle Rotation Application)*

*Tunneling (Stereo DIC application)*

Conclusions and Recommendations
Transparent sands are made by matching the refractive index of fused quartz and a pore fluid made of either mineral oil or sucrose.
Experiment Setup

- Projectile
- Embedded sheet
- Transparent soil

[Diagram of experiment setup with labeled components such as Pressure gage, Reservoir chamber, Line bearings, 500 W tungsten light, Work station, Acrylic box, Trigger, High speed camera, Helium source, etc.]
DIC Analysis

Deformation field of a 60° cone projectile into an embedded sheet transparent soil sample (vi = 13 m/s)

t=1ms  t=2ms  t=3ms  t=4ms  t= 5ms
(a) Eulerian trajectories from $t=1\text{ms}$ to $t=5\text{ms}$,
(b) exploded view of Eulerian trajectories below the cone tip
(c) exploded view of Eulerian trajectories along the cone shaft
Soil elements along the boundary of the cavity are compressed and sheared, where maximum strains are developed directly in front of the cone projectile during penetration and extends outward radially.

From the volumetric strain plot, it is also interesting to see a dilation zone is developed close to the compression zone to accommodate shearing.
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• Advanced Imaging Techniques

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• Conclusions and Recommendations
1-dropweight system,
2-pile,
3-pneumatic bladder,
4-test soil,
5-supporting element
(a) Ottawa Sand; (b) Silica Gel
Vertical contours of displacement vector field for approx. 2mm increment of penetration into Ottawa sand, at a depth of 2D with three testing conditions (a) UOM, (b)COM, (c)COD
Horizontal contours of displacement vector field for approx. 2mm increment of penetration into Ottawa sand, at a depth of 2D with three testing conditions (a) UOM, (b) COM, (c) COD.
Incremental shear strain maps calculated for approx. 2mm penetration into Ottawa sand, at depth of 2D with three testing conditions (a) UOM, (b) COM, (c) COD
Incremental volumetric strain maps calculated for approx. 2mm penetration into Ottawa sand, at depth of 2D with three testing conditions (a) UOM, (b) COM, (c) COD
Particle trajectories for 0.5D of penetration into silica gel, at a depth of 2D (a) unconfined, (b) unconfined close up, (c) confined and (d) confined close up
Non-affine particle motion for an increment of approx. 2mm penetration into confined silica gel with different search radius, at a depth of 2D (a) 5 particles, (b) 10 particles, (c) 15 particles and (d) 20 particles
Non-affine particle motion of a search radius of 15 particles, at a depth of 2D (a) an increment of approx. 2mm penetration, and (c) cumulative penetration of 0.5D penetration into confined silica gel.
• Motivation
• Advanced Imagining Techniques

• **Soil-Structure Interaction Problems**
  
  *Projectile Penetration (High Speed DIC Application)*
  
  *Pile Penetration (DIC and Particle Analysis Application)*
  
  **Earth Retaining Structure (Particle Rotation Application)**
  
  *Tunneling (Stereo DIC application)*

• Conclusions and Recommendations
Image of face treated HDPE
Optical Setup

Note: All units are in mm
Particle Identification

Preprocessed Images

Images of particle identification
Particle trajectories for $\Delta/H = 0.05$: (a) test 1 (active, smooth wall), (b) test 3 (active, rough wall), (c) test 2 (passive, smooth wall), and (d) test 4 (passive, rough wall)
Shear strain map for $\Delta/H = 0.05$: (a) test 1 (active, smooth wall), (b) test 3 (active, rough wall), (c) test 2 (passive, smooth wall), and (d) test 4 (passive, rough wall)
Rigid body rotation map in degrees for $\Delta/H = 0.05$: (a) test 1 (active, smooth wall), (b) test 3 (active, rough wall), (c) test 2 (passive, smooth wall), and (d) test 4 (passive, rough wall)
Particle rotation in degrees for \( \Delta/H = 0.05 \): (a) test 1 (active, smooth wall), (b) test 3 (active, rough wall), (c) test 2 (passive, smooth wall), and (d) test 4 (passive, rough wall). (positive-counterclockwise, negative-clockwise)
• Motivation

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  Projectile Penetration (High Speed DIC Application)

  Pile Penetration (DIC and Particle Analysis Application)

  Earth Retaining Structure (Particle Rotation Application)

  Tunneling (Stereo DIC application)

• Conclusions and Recommendations
Schematic drawing of testing box
Experiment Setup

Schematic drawing of cylindrical tunnel models

Cameras configuration and Scheimpflug condition
1. Calibration error results from out of plane deformation. Dewarping coefficients are commonly calculated based on a calibration grid placed in a single plane, and errors occur when particles/speckles move in the out of plane direction due to non-uniform magnification.

Solution: Multiplane calibration should improve the errors, though difficult to carry out in the actual test.
Stereo DIC Errors

Calibration Error Analysis

Percent Error

In Plane Movement (in)

Out of Plane Movement (in)

single plane
multi plane
2. Reconstruction error results from out of plane motion of seeding particles. The reconstruction theory assumes the seeding particles remain in a plane, but this is not true during an experiment where random out of plane motion is expected.
1. Fused quartz diffuse laser. In a transparent soil sample, the laser sheet quickly diffused into a volume. Therefore, the images captured include motion of speckles within that volume. This is ok if the motion of the speckles within the volume is relatively uniform, but a significant problem if the motion within the volume is complex.

2. For conventional DIC, we can reduce the depth of field by adjusting F-stop of the lens, so that we only focus on a thin plane and the rest become out of focus. However, for stereo DIC we need the depth of field to maintain focus of the field of view. In my opinion, laser sheet is not ideal for this application.
Many have reported that the problem of face stability does not arise for tests performed at 1g with small tunnel diameter. Chambon and Corte (1994) have reported significant size effect in their centrifuge tests, and concluded the minimum support pressure increases directly with the tunnel diameter. We have experienced similar problems. As the supporting pressure inside the tunnel reduces, the soil that directly in front of the tunnel face moves into the tunnel, however very little soil movement were observed above the tunnel, and the stability of the soil is provided by arching effects.

Tunnel Blowout Test

Left view DIC analysis

Right view DIC analysis
Stereo DIC analysis results

Reconstructed 3D displacements vector plot

Reconstructed 3D displacements contour plot
**Possible Reasons:**

1. Fused quartz is very strong and has a reported friction angle of 48° to 55°.

2. The mineral oil used to make transparent soil has a viscosity 10 times that of water which further increases its strength.

3. The tunnel diameter used in the test is about 50mm, which is half of some other scholars have used (100mm) in their centrifuge tests.

**Solutions:**

1. Increase model tunnel diameter.
   - Require larger testing box to avoid boundary effects.

2. Use weaker material.
   - The matching oil used to make weaker transparent material such as silica gel is hazardous.

3. Reduce the strength of fused quartz.
   - The angularity and the hardness of fused quartz particle contributes to its high strength. We could potentially polish the particles to make them less angular. However, more study is needed to see the effectiveness of this approach.
Motivation

Advanced Imagining Techniques

Soil-Structure Interaction Problems

Conclusions and Recommendations
Conclusions

- Imaging techniques are a powerful tool for non-destructive lab measurement of soil response to investigate soil-structure interaction problems.

- Many codes have been developed to allow multiscale observations of the behavior of granular media from micro-scale kinematics to meso-scale phenomenal, which is essential to deepen our understanding of soil-structure interaction problems.
The shape function employed in our code to implement finite strain theory is linear that is valid for small to moderate soil deformation. Higher order formulations such as linear strain triangles with quadratic shape functions may be readily implemented in the algorithm to improve accuracy for applications where large soil deformations are expected.

Stereo DIC allows measurement of 3D soil deformation, but is limited in a given plane. To extend the technique, a scanning stereo DIC system can be developed where the spatial resolution of stereo DIC into the depth component can be obtained by continuously scanning the light sheet through the volume assuming the soil deformations are negligible during each scanning time frame.
• The algorithms used to identify densely packed particles are limited for 2D semi round and round particles. These algorithms combine with other techniques such as watershed analysis could potentially identify densely packed irregulars shape particles in 2D.

• All raw data produced were collected from physical modelling tests. They were somewhat limited due to the cost and time required to perform physical tests, however they can be used as benchmark data to validate numerical models. Numerical modelling such as finite element (FE) analysis and discrete element method (DEM) allows the generation of large amount of data in a cost effective way that can be used for parametric studies.
• For applications where large soil deformations are expected in a short time frame such as projectile penetration, tomographic DIC is commercially available that allows instantaneous measurement of all three deformation component in a 3D measurement volume.

• The particle kinematics analysis package developed does not take into account of the effect of particle crushing. The regions undergoing particle crushing can be identified through post mortem analysis using new technology such as QICPIC.

• All particle kinematics analyses conducted are limited in 2D. The combination of X-ray tomography with volumetric DIC techniques can be used to extend these particle analyses to 3D. However, similar to tomographic DIC system, the techniques are often limited by its high equipment and set-up cost.
Journal Articles:


Journal Articles (under review):


Conference Articles:


Thank You – Questions?