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Visualization of failure and the associated grain-scale mechanical behavior of granular soils under shear using synchrotron X-ray micro-tomography

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Dear Editor,

Thanks for inviting me to submit our work to ***Journal of Visualized Experiments.*** I would like to submit the manuscript entitled "*Visualization of failure and the associated grain-scale mechanical behavior of granular soils under shear using synchrotron X-ray micro-tomography*" authored by Z. Cheng and J. F. Wang to the journal for possible publication.

The paper presents the use of X-ray in-situ scanning test (i.e., X-ray CT scanning conducted at the same time as loading) and image processing techniques to investigate the grain-scale mechanical behavior of granular soils under triaxial compression. The method has the advantage of being able to acquire grain-scale observations (e.g., particle kinematics, strain localization and inter-particle contact evolution, etc.) of soils when it is compared to conventional triaxial testing. The paper shares the details of how an X-ray in-situ scanning test of a soil sample can be carried out, how CT images are acquired, and how image processing and analysis are implemented for the acquisition of grain-scale observations.

I hereby confirm that this manuscript describes original work and currently is not under consideration by any other journal. All previously published work cited in the manuscript has been fully acknowledged. Both authors have contributed substantially to the manuscript and approved the final submission.

We would like to suggest the following colleagues to review this manuscript.

1. Dr. Erdin Ibraim, University of Bristol (Email: erdin.ibraim@bristol.ac.uk)
Dr Ibraim is recommended because he is an expert in studying soil mechanics using conventional triaxial testing techniques.

2. Dr. Kevin J. Hanley, School of Engineering, University of Edinburgh (Email: k.hanley@ed.ac.uk)
He has very rich experience in studying the mechanical response of granular materials under loading using discrete element method (DEM). He has published a lot of journal papers in this field.

3. Prof. Marte Gutierrez of Colorado School of Mines, USA (mgutierr@mines.edu)
Prof. Gutierrez is recommended because he has very rich experience in studying the grain-scale mechanical behavior of granular materials.

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Thank you very much for your attention and we look forward to hearing from you.

Yours Sincerely,
Jianfeng Wang

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TITLE:
Visualization of Failure and the Associated Grain-Scale Mechanical Behavior of Granular Soils under Shear Using Synchrotron X-Ray Micro-Tomography

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KEYWORDS:
granular soils, particle translation, particle rotation, strain localization, contact loss, contact gain, contact movement, triaxial compression, synchrotron X-ray micro-tomography

SUMMARY:
The protocol describes procedures to acquire high-spatial resolution computed tomography (CT) images of a granular soil during triaxial compression, and to apply image processing techniques to these CT images to explore the grain-scale mechanical behavior of the soil under loading.

ABSTRACT:
The rapid development of X-ray imaging techniques with image processing and analysis skills has enabled the acquisition of CT images of granular soils with high-spatial resolutions. Based on such CT images, grain-scale mechanical behavior such as particle kinematics (i.e., particle translations and particle rotations), strain localization and inter-particle contact evolution of granular soils can be quantitatively investigated. However, this is inaccessible using conventional experimental methods. This study demonstrates the exploration of the grain-scale mechanical behavior of a granular soil sample under triaxial compression using synchrotron X-ray micro-tomography (μCT). With this method, a specially fabricated miniature loading apparatus is used to apply confining and axial stresses to the sample during the triaxial test. The apparatus is fitted into a synchrotron X-ray tomography setup so that high-spatial resolution CT images of the sample can be collected at different loading stages of the test without any disturbance to the sample. With the capability of extracting information at the macro scale (e.g., sample boundary stresses and strains from the triaxial apparatus setup) and the grain scale (e.g., grain movements and contact interactions from the CT images), this procedure provides an effective methodology to investigate the multi-scale mechanics of granular soils.

INTRODUCTION:
It is widely recognized that the macro-scale mechanical properties of granular soil, such as stiffness, shear strength and permeability, are critical to many geotechnical structures, for

example, foundations, slopes and rock-fill dams. For many years, on-site tests and conventional laboratory tests (e.g., one-dimensional compression tests, triaxial compression tests and permeability tests) have been used to evaluate these properties in different soils. Codes and standards for testing soil mechanical properties have also been developed for engineering purposes. While these macro-scale mechanical properties have been intensively studied, the grain-scale mechanical behavior (e.g., particle kinematics, contact interaction and strain localization) that governs these properties has attracted much less attention from engineers and researchers. One reason is the lack of effective experimental methods available to explore the grain-scale mechanical behavior of soils.

Until now, most of the understanding of the grain-scale mechanical behavior of granular soils has come from discrete element modeling[1] (DEM), because of its ability to extract particle-scale information (e.g., particle kinematics and particle contact forces). In earlier studies of using DEM techniques to model granular soil mechanical behaviors, each individual particle was simply represented by a single circle or sphere in the model. The use of such over-simplified particle shapes has led to the over-rotation of particles and thereby a lower peak strength behavior[2]. To achieve a better modeling performance, many investigators have used a rolling resistance model[3-6] or irregular particle shapes[7-12] in their DEM simulations. As a result, a more realistic understanding of particle kinematic behavior has been acquired. Aside from particle kinematics, DEM has been increasingly used to investigate grain contact interaction and to develop theoretical models. However, because of the requirement to reproduce real particle shapes and the use of sophisticated contact models, DEM requires extremely high computational capability in the modeling of granular soils with irregular shapes.

Recently, the development of optical equipment and imaging techniques (e.g., the microscope, laser-aided tomography, X-ray computed tomography (CT) and X-ray micro-tomography (μCT)) has provided many opportunities for experimental examination of the grain-scale mechanical behavior of granular soils. Via acquisition and analysis of soil sample images before and after triaxial testing, such equipment and techniques have been utilized in the investigation of soil microstructures[13-19]. More recently, in situ tests with X-ray CT or μCT have been increasingly used to investigate the evolution of void ratio[20], strain distribution[21-24], particle movement[25-28], inter-particle contact[29-31] and particle crushing[32] of granular soils. Here, “in situ” implies X-ray scanning conducted at the same time as loading. In contrast to general X-ray scanning, in situ X-ray scanning tests require a specially fabricated loading apparatus to deliver stresses to soil samples. With the combined use of the loading apparatus and X-ray CT or μCT device, CT images of the samples at different loading stages of the tests can be acquired non-destructively. Based on these CT images, particle-scale observations of granular soil behavior can be acquired. These CT image-based particle-level observations are extremely helpful to verify numerical findings and to gain novel insights into the grain-scale mechanical behavior of granular soils.

This article aims to share the details of how an X-ray in situ scanning test of a soil sample can be carried out, using an exemplary experiment that observes particle kinematics, strain localization and inter-particle contact evolution within a soil sample. The results show that X-ray in situ scanning tests have a great potential to explore the grain-level behavior of granular soils. The protocol covers the choice of X-ray µCT device and the preparation of a miniature triaxial loading apparatus, and detailed procedures to carry out the test are provided. In addition, the technical steps for using image processing and analysis to quantify the particle kinematics (i.e., particle translation and particle rotation), strain localization, and inter-particle contact evolution (i.e., contact gain, contact loss and contact movement) of the soil are described.

PROTOCOL:

1. Designing the experiment well in advance

1.1. Determine test material, particle size, sample size and sample initial porosity.

NOTE: Leighton Buzzard sand with a diameter of 0.15~0.30 mm and a sample size of 8 x 16 mm (Diameter x Height) is used as an example to demonstrate the protocol of this study. Other sands such as Fujian sand, Houston Sand, Ottawa sand and Caicos ooids, etc. and similar sample sizes can also be used.

1.2. Choose an appropriate detector (**Figure 1A**) according to the required spatial resolution and scanning area, which are determined according to the predetermined particle size and sample size. For example, a detector with a spatial resolution of 6.5 µm is used in this study. It has an effective scanning area of 2048 x 860 pixels (i.e.,13.3 × 5.6 mm).

NOTE: During a triaxial compression test, the deformed sample should remain in the scanning region of the detector. A high-spatial resolution detector should be used so that individual particles contain sufficient voxels for the appropriate extraction of particle properties.

1.3. Determine the required energy of the X-ray source (**Figure 1A**) and exposure time according to the test material and sample size. Generally, a higher energy should be used for a larger sample composed of a denser material. Use an X-ray energy of 25 keV and an exposure time of 0.05 s for the sand samples in this study.

NOTE: The required X-ray energy and exposure time can be determined by trial and error using a scanned projection of the sample. The ratio of the minimum grey-scale intensity of the projection to its maximum value should not be lower than 0.2. Otherwise, a higher X-ray energy or longer exposure time should be used.

1.4. Determine the required rotation speed ω (degrees per second) for the rotation stage (**Figure 1A**) of the X-ray device. The rotation speed ω is calculated according to the required number of projections N (e.g., N = 1,080) for CT slice reconstruction.

NOTE: $\omega=180\ V_s/N$. Here, V_s is the scanning speed of the X-ray device, i.e., the number of radiographs scanned and recorded per second. V_s is mainly affected by the performance of the detector and the hardware associated with the detector such as the computer.

1.5. Fabricate a triaxial loading apparatus (**Figures 1B,C**, see also reference 33) to be used in conjunction with the X-ray µCT device. The apparatus should have the same main functions as a conventional triaxial compression apparatus. The design should consider the requirement of sample size, the range of confining stresses and loading rates.

NOTE: The apparatus should be able to fit into the X-ray µCT device and be light to facilitate its rotation using the rotation stage. The triaxial cell should be transparent to X-rays. Considering the transparency requirement, acrylic and polycarbonate might be used to fabricate the triaxial cell.

1.6. Carry out a test with the same confining pressure, loading speed and sample properties (i.e., material, sample size and initial porosity) outside of the X-ray CT scanner to plan when to pause the loading for CT scanning.

2. Carrying out in situ triaxial compression testing

2.1. Place the triaxial loading equipment and the test material on site.

NOTE: The loading apparatus and confining pressure offering device (see the **Table of Materials**) are placed in the X-ray CT scanning room, while the data acquisition and controlling devices are located outside. Triaxial loading and CT scanning of the sample are then operated outside the scanning room.

2.2. Fix a lifting stage on the board of the X-ray micro CT device (**Figure 1B**). Fix a tilting stage on the lifting stage and a rotation stage on the tilting stage, respectively (**Figure 1B**).

NOTE: The lifting stage and tilting stage should have sufficient loading capacity to move the relevant equipment placed on them.

2.3. Adjust the position and orientation of the rotation stage via the tilting stage such that any single X-ray passes through the same points within the sample when it is rotated across 180 degrees around the axis of the rotation stage.

NOTE: Steps 2.2 to 2.3 are applicable to the X-ray micro CT device at Shanghai Synchrotron Radiation Center (SSRF). For X-ray micro CT devices specifically used for in situ triaxial testing, these steps can be omitted after the careful positioning and fixation of the rotation stage.

2.4. Prepare a soil sample on the board according to the following procedures.

2.4.1. Add a small amount of silicone grease around the lateral surface of the top end of the base plate and place a porous stone on its upper surface. Put a membrane around the lateral surface of the top end (**Figure 2A**).

2.4.2. Add a small amount of silicone grease on the contact surfaces between the two parts of the sample maker and lock it. Place the sample maker on the base plate and allow the membrane to pass through it (**Figure 2B**).

2.4.3. Create suction (e.g., 25 kPa) inside the sample maker through its nozzle using a vacuum pump. Fix the membrane to the lateral surface of its upper end. Ensure that the membrane is attached to the inner surface of the sample maker (**Figure 2C**).

2.4.4. Drop the test granular material from a certain height into the sample maker using a funnel until it is completely filled. The upper surface of the soil sample should be the same level as the upper edge of the sample maker (**Figure 2D**).

2.4.5. Place another porous stone on top of the soil sample, and a stainless-steel cushion plate on top of the porous stone. Apply some silicone grease around the lateral surface of the cushion plate. Remove the top side of the membrane from the sample maker and fix it to the cushion plate (**Figure 2E**).

2.4.6. Remove the suction inside the sample maker nozzle and create suction inside the valve on the base plate. Finally, remove the sample maker. A miniature dry sample is produced, as seen in **Figure 2F**.

NOTE: This step demonstrates the procedure of producing a miniature soil sample using the air pluviation method. The traditional dry compaction method can also be used to produce the sample.

2.5. Fix the confining cell on the base plate and fix the chamber top plate on the top of the confining cell (**Figure 1C**).

2.6. Fix the piston shaft of the cell on the chamber top plate (**Figure 1C**).

2.7. Position the base plate together with the confining cell and chamber top plate on the rotation stage. A frame is used to adjust the height of the sample for CT scanning (**Figure 1B**).

NOTE: This frame is used due to the limited movement range of the lifting stage at SSRF. There is no need to use a frame if a lifting stage with a large movement range is used.

2.8. Affix the rest of the loading apparatus on the chamber top plate.

2.9. Install the linear variable differential transformer (LVDT), load cell and stepping motor and activate them (**Figure 1C**).

2.10. Fill the cell with de-aired water through the cell pressure (CP) valve (see **Figure 1C**) using the water supplied from a confining pressure offering device (see **Table of Materials**). Close the water exit (WE) valve (see **Figure 1C**) when the water starts to flow out of the valve.

NOTE: Set the confining pressure offering device to the constant pressure mode with a very low constant pressure value (e.g., 10 kPa).

2.11. Add a constant confining pressure of 25 kPa to the sample and remove the suction inside the sample.

2.12. Gradually increase the confining pressure to a pre-determined value using the confining pressure offering device.

2.13. Carry out the first scan of the sample. For a high-spatial resolution CT scanner (e.g., with a pixel size of 6.5 µm), a full scan of the sample (e.g., with a height of 16 mm) usually requires the sample to be scanned at several different heights (i.e., the scan is divided into several sections).

NOTE: If a low spatial resolution detector and a small size sample are used, the scanning area might be sufficient to acquire a full-field scan of the sample using a single section.

2.13.1. Scan a section of the sample. Set the CT scanner to **Image capture** mode and then start the rotation stage to rotate the entire apparatus across 180 degrees at a pre-determined constant rotation rate (e.g., 3.33 degrees/s) to capture CT projections of the sample at different angles.

NOTE: It is suggested that the sample is scanned from its bottom upwards (i.e., the first section contains all the particles located at the bottom of the sample).

2.13.2. Turn off the **Image capture** mode when the rotation is finished. Rotate the apparatus back to the initial position.

2.13.3. Lift the sample together with the entire apparatus up using the lifting stage (**Figure 1B**) by a certain height (e.g., 4 mm) for scanning the next section of the sample.

NOTE: The lifting should ensure that there is an overlap between the current section and the last section (i.e., there is an overlap between any two consecutive sections). The overlap should be at least 10 pixels to facilitate the stitching of them.

2.13.4. Repeat steps 2.13.1-2.13.3 until the last section of the sample is scanned.

2.14. Apply an axial load on the sample with a constant loading rate. Here, a loading rate of 0.2%/min is used in this study. Users can set a different loading rate according to the experiment requirement.

2.15. Pause the axial loading at a pre-determined axial strain. Wait until the measured axial force reaches a steady value (generally within 2 min) and carry out the next scan. The scan procedures are the same as demonstrated in step 2.13.

2.16. Repeat steps 2.14 and 2.15 until the end of loading.

2.17. Unload the test and remove the sample from the triaxial apparatus.

2.18. Install the base plate and the confining cell on the rotation stage to acquire several flat projections (generally 10 projections) from the detector. Shut down the X-ray source to acquire the same number of dark projections from the detector.

NOTE: Flat and dark projections are used for the phase retrieval of raw CT projections. The implementation of flat and dark correction enhances the contrast between the sample and the surrounding background in the reconstructed CT slices. It also helps to alleviate the ring artifacts resulting from defective pixels of the detector.

3. Image processing and analysis

3.1. Image processing

3.1.1. Implement phase retrieval (**Figure 3B**) of raw CT projections (**Figure 3A**) of the sample using the free software PITRE[34]. Load projections (including the flat and dark projections) into PITRE from the menu **Load image**. Click the icon **PPCI**. Enter the relevant scanning parameters and click **Single** to implement the phase retrieval.

NOTE: The implementation of phase retrieval provides enhancement of interfaces between different phases (i.e., the void phase and the solid phase) in the reconstructed CT slices, which is of significant importance to the subsequent image-based analysis of inter-particle contacts.

3.1.2. Reconstruct CT slices of the sample using PITRE based on the CT projections after phase retrieval (**Figure 3C**). Load the projections into PITRE from the menu **Load image**. Click the icon **ProjSino**. Enter relevant parameters in the appeared window and click **Single** to reconstruct a CT slice.

NOTE: Check horizontal slices to ensure that there are no heavy beam hardening artefacts or ring artefacts. Otherwise change of the current scanning parameters and rescan of the sample are required. Check vertical slices. If the sample is severely tilted prior to the shear, the test is considered unsuccessful.

3.1.3. Implement image filtering on the CT slices. An anisotropic diffusion filter is used to perform image filtering (**Figure 3D**).

3.1.4. Perform image binarization on the filtered CT slices. Implement the image binarization (**Figure 3E**) by applying an intensity value threshold to the CT slices, which is determined according to the intensity histogram of the CT slices using Otsu's method[35].

NOTE: For CT slices with a grey-scale intensity histogram exhibiting a significant overlap of intensities between the solid phase and the void phase, a validation of the image binarization is required using the mass of the solid phase[36].

3.1.5. Separate individual particles from the binarized CT slices using a marker-based watershed algorithm and store the results in a 3D labelled image (**Figure 3F**). Validate the results by comparing the calculated particle size distribution from the CT image to those from a mechanical sieving test.

NOTE: The module **Separate Objects** of the software Avizo Fire can be used to implement this algorithm. Remove the porous stones from the binarized CT slices using the module **Border Kill** of Avizo Fire. To acquire a reliable particle separation results, readers are suggested to try different particle segmentation algorithms[37-39].

3.2. Image analysis

3.2.1. Extract particle properties from the labelled image. A MATLAB script is used to extract particle properties including particle volume, particle surface area, particle orientation and particle centroid coordinates.

NOTE: The intrinsic MATLAB functions *regionprops*, *bwprim* and *pca* are used to acquire these properties of each particle. A more detailed description of these procedures can be found in the work of Cheng and Wang[28].

3.2.2. Extract contact voxels from the binarized CT slices by implementation of a logical operation **AND** between the binary image of the CT slices (**Figure 4**) and a binary image of watershed lines acquired from the implementation of the marker-based watershed algorithm[31].

NOTE: Over-detection of contact voxels could occur due to the partial volume effect and the random noise of CT images[40, 41]. However, a slight over-detection of inter-particle contacts would not have significant effects on the overall trend of inter-particle contact evolution behavior[42].

4. CT image-based exploration of grain-scale mechanical behavior of soils

NOTE: The following image-based analysis is not applicable to idealistically spherical particles or samples with very narrow grading ranges (i.e., monodisperse samples). However, for particles with high roundness and poor grading (e.g., 0.3～0.6 mm glass beads), the methodology yields good results (see Cheng and Wang[31]).

4.1. Quantify particle kinematics of the sample. Use a particle tracking method to track individual particles within the sample at different scans based on either particle volume or particle surface area. A detailed description of this method is given in Cheng and Wang[28].

4.1.1. Calculate the translation of each particle during any two consecutive scans. It is calculated as the difference in the particle centroid coordinates between the two scans.

4.1.2. Determine the rotation angle of each particle according to the difference in its major principal axis orientations between the two scans.

4.2. Quantify the strain field of the sample. Use a grid-based method to calculate the strain field during any two consecutive scans based on the particle translation and particle rotation.

NOTE: The method requires the labeled images of the sample from both scans and the particle kinematics results. Readers are referred to a previous work[24] for a detailed description.

4.3. Analyze inter-particle contact evolution of the sample. Based on the extracted contact voxels, the labeled images of particles and the particle tracking results, analyze the branch vector orientation of the lost contacts and the gained contacts within the sample during each shear increment.

NOTE: A full description of this method is given in Cheng and Wang[31].

REPRESENTATIVE RESULTS:

Figure 5 depicts the particle kinematics results of a Leighton Buzzard sand (LBS) sample at a 2D slice during two typical shear increments, I and II. Most of the particles are successfully tracked and their translations and rotations are quantified following the above protocol. During the first shear increment, neither particle displacements nor particle rotations show clear localization. However, a localized band is developed in both the particle displacement map and particle rotation map during the second shear increment. **Figure 6** shows the octahedral and volumetric strain maps of the sample during the two shear increments. A clear localization zone is observed in the strain maps at the second shear increment, demonstrating the capability of the method to visualize sand failure under triaxial shearing. **Figure 7** depicts the normalized orientation frequency of branch vectors of gained contacts and lost contacts in the sample during the two shear increments. The lost contacts exhibit a clear directional preference towards the minor principal stress direction (i.e., the horizontal direction) during both shear increments.

FIGURE AND TABLE LEGENDS:

Figure 1: X-ray micro CT setup and triaxial loading device. (**A**) A triaxial apparatus used in conjunction with an X-ray micro CT setup. (**B**) An enlarged view of the installation of the triaxial apparatus during triaxial testing. (**C**) Triaxial apparatus from a different angle. This figure has been modified from Cheng and Wang[28].

Figure 2: The process of making a sample. (**A**) Installation of a porous stone and a membrane on the base plate, (**B**) installation of a sample maker, (**C**) creation of suction inside the sample maker, (**D**) dropping sand particles into the sample maker, (**E**) installation of another porous stone and a cushion plate on top of the sand sample, and (**F**) removal of sample maker from the base plate.

Figure 3: Image processing of CT images. (**A**) Raw CT projection, (**B**) the CT projection after phase

retrieval, (**C**) a reconstructed horizontal CT slice, (**D**) the CT slice after image filtering, (**E**) the CT slice after image binarization, and (**F**) the CT slice after particle separation.

Figure 4: Illustration of the extraction of inter-particle contacts of LBS in 2D slices. (**A**) Implementation of a logical operation **AND** between the binary image of a CT slice and the binary image of watershed lines, and (**B**) a typical contact of two LBS particles in 3D space (particles are shown in green and blue and contact is shown in red).

Figure 5: Typical particle kinematics results of an LBS sample during two shear increments. (**A**) Stress–strain curve of the sample under triaxial compression, (**B**) particle displacements and particle rotations of the sample during shear increment I, and (**C**) particle displacements and particle rotations of the sample during shear increment II. This figure has been modified from Cheng and Wang[24].

Figure 6: Typical strain fields of LBS during two shear increments. (**A**) Octahedral shear strain and volumetric strain of the sample during shear increment I. (**B**) Octahedral shear strain and volumetric strain of the sample during shear increment II. This figure has been modified from Cheng and Wang[24].

Figure 7: Typical inter-particle contact evolution results of LBS during two shear increments. (**A**) Normalized orientation frequency of branch vectors of gained contacts and lost contacts of LBS during shear increment I. (**B**) Normalized orientation frequency of branch vectors of gained contacts and lost contacts of LBS during shear increment II.

DISCUSSION:

High-spatial resolution X-ray micro-CT and advanced image processing and analysis techniques have enabled the experimental investigation of the mechanical behavior of granular soils under shear at multi-scale levels (i.e., at macro-scale, meso-scale and grain-scale levels). However, CT image-based meso- and grain-scale investigations require the acquisition of high-spatial resolution CT images of soil samples during loading. The most challenging aspect of this process is perhaps the fabrication of a miniature triaxial loading apparatus that can be used in conjunction with an X-ray micro CT device. One should make an overall consideration of the required sample size, loading stresses and rates, in addition to the restrictions of X-ray micro CT devices such as the spatial resolution, scanning area and the load capacity of the rotation stage.

The determination of optimum X-ray energy and exposure time can be time-consuming but is crucial to the acquisition of high-quality CT images. It is recommended that users try different energies and exposure times during their first scan and determine an appropriate energy and exposure time according to the quality of the reconstructed slices. Besides, samples with different initial porosities can be produced during sample preparation by dropping sand particles into the sample mold from different heights. However, because of the small sample size, producing a sample with a specific initial porosity is more difficult in comparison to conventional triaxial tests. To produce a sample with an initial porosity that is close to a specific value for triaxial testing with CT scanning, users are recommended to practice producing samples in advance.

Compared to conventional triaxial testing, miniature in situ triaxial testing has the advantage of being able to explore the grain-scale mechanical behavior of granular soils, including grain kinematics, strain localization and inter-particle contact interaction, etc. Currently, a popular alternative method to investigate the grain-scale mechanical behavior of granular soils is DEM. Although this technique enables the modeling of sand mechanical behavior under complex loading conditions, grain shapes and contact models are generally over-simplified to achieve high computing efficiency in most DEM studies. In this situation, the grain-scale information extracted from real sand using this protocol is needed for improved validation of DEM models at multi-scale levels. Another advantage of the introduced method for CT image-based strain calculation is the incorporation of particle rotation in the strain calculation. The strain calculation method was shown to produce more reliable strain results than a mesh-base method without considering the effects of particle rotations[24].

Even with its many advantages, using X-ray micro CT to study the inter-particle contact evolution of granular soils may suffer from over-detection of inter-particle contacts. The accuracy of inter-particle detection results relies strongly on the spatial resolution of the X-ray micro-CT. This is due to the partial volume effect of the X-ray micro-CT, in which two isolated particles having a distance smaller than the size of a voxel may be identified as two contacting particles. Fortunately, the general trend of inter-particle contact evolution within granular soils was found to be unaffected by the over-detection of inter-particle contacts. Meanwhile, the inability to extract inter-particle contact forces within granular soils is another disadvantage of X-ray micro-CT compared to DEM studies[43-47] and photo-elastic studies[48,49]. Furthermore, because of the above-mentioned CT image-based grain-scale investigation required to correctly identify and extract individual particles from CT images, the application of this method to soils with highly irregular particle shapes or highly crushable soils containing irregular intra-particle voids is very challenging.

In the future, in situ triaxial testing providing ample data on grain shape and grain kinematics will facilitate the incorporation of real particle shapes in DEM modeling. Subsequently, CT image-based DEM modeling will provide a better understanding of the grain-scale mechanical behavior of granular soils under loading. Meanwhile, given the ability to extract inter-particle contact forces[50], a combination of X-ray diffraction with X-ray micro-CT for in situ triaxial testing will be helpful for the extraction of full grain-scale information (i.e., both grain kinematics and grain contact forces) from granular soils under shearing.

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DISCLOSURES:

The authors have nothing to disclose.

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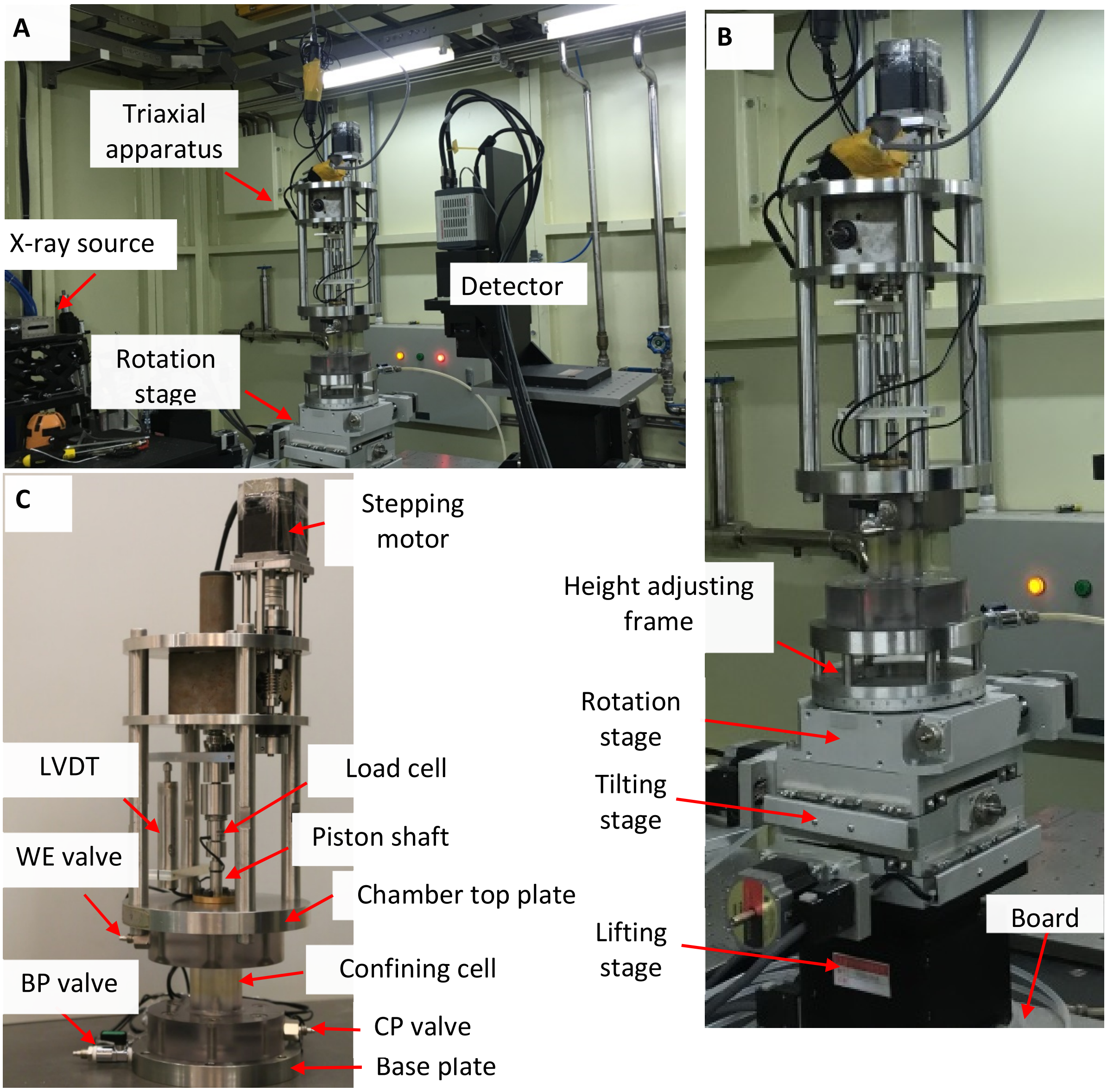

A
Triaxial apparatus
X-ray source
Detector
Rotation stage
B
Height adjusting frame
Rotation stage
Tilting stage
Lifting stage
Board
C
Stepping motor
LVDT
Load cell
Piston shaft
WE valve
Chamber top plate
BP valve
Confining cell
CP valve
Base plate

Figure 1

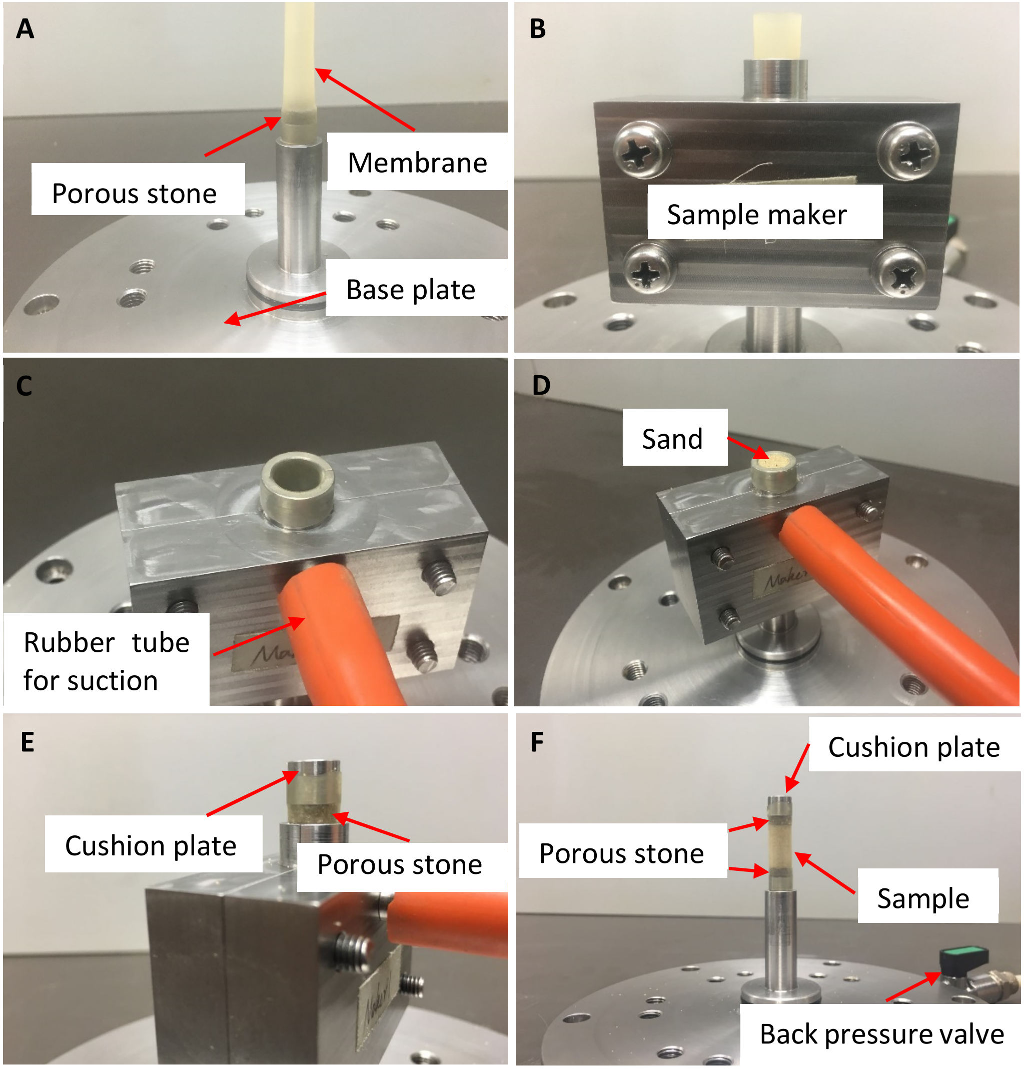

A
Membrane
Porous stone
Base plate
B
Sample maker
C
Rubber tube
for suction
D
Sand
E
Cushion plate
Porous stone
F
Cushion plate
Porous stone
Sample
Back pressure valve

Figure 2

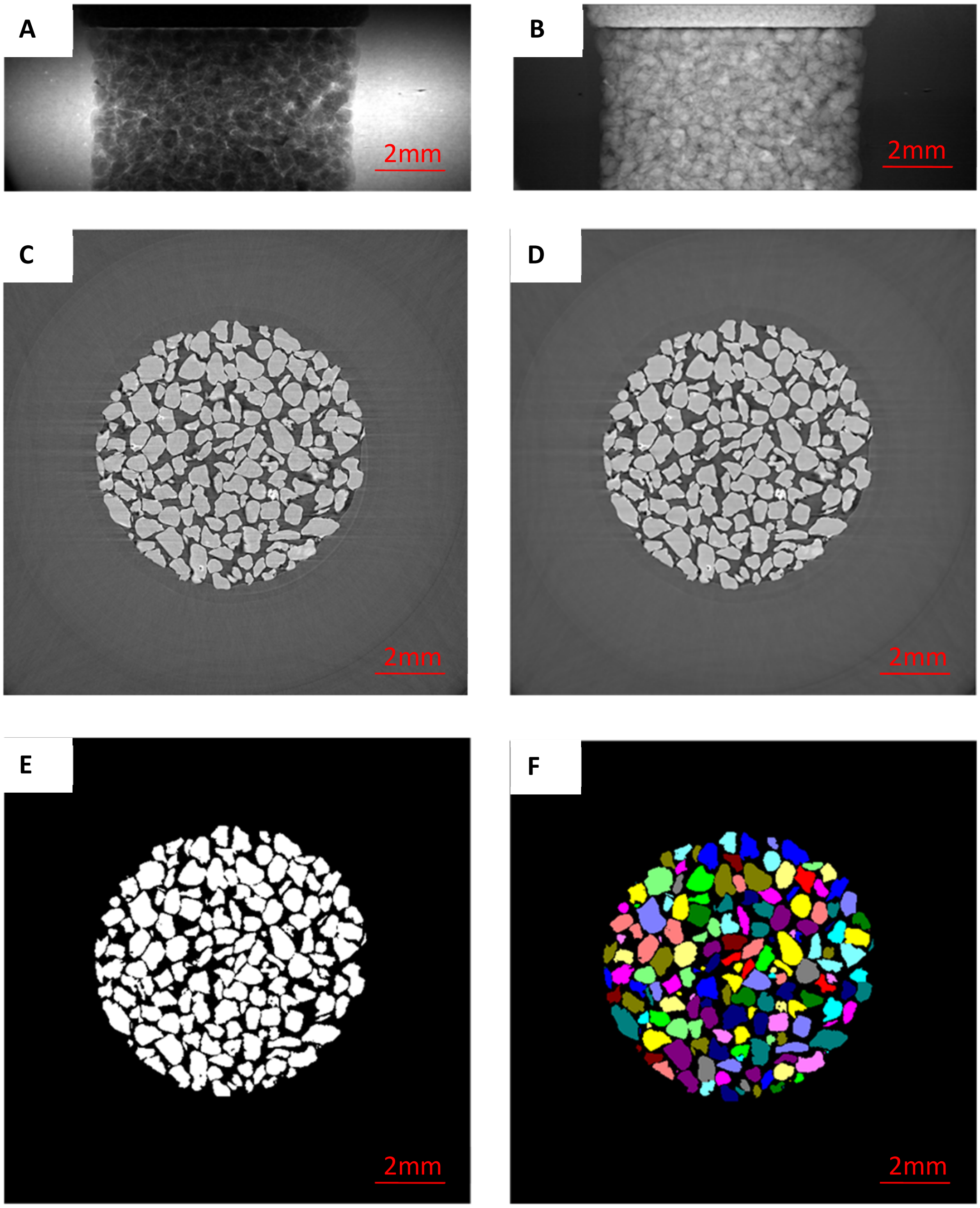
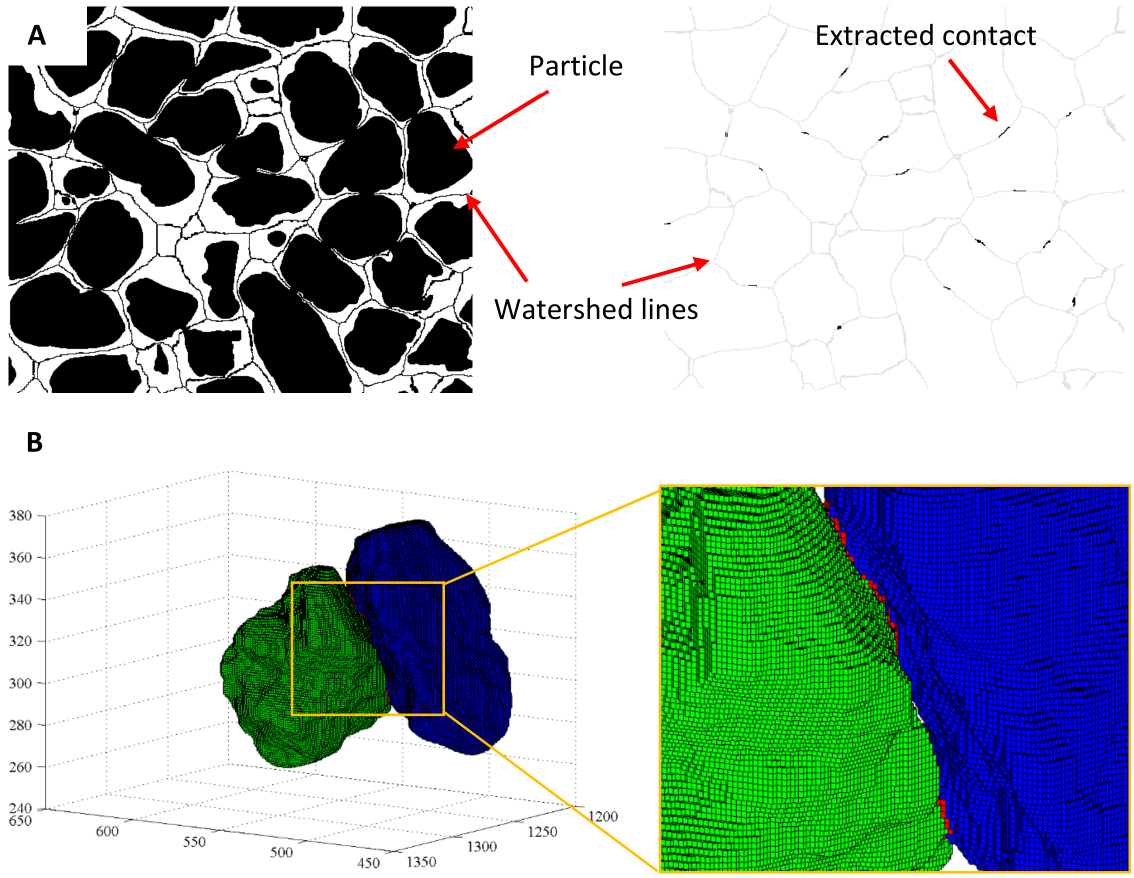


Figure 3



A
Particle
Watershed lines
Extracted contact
B
380
360
340
320
300
280
260
240
650
600
550
500
450
1350
1300
1250
1200

Figure 4

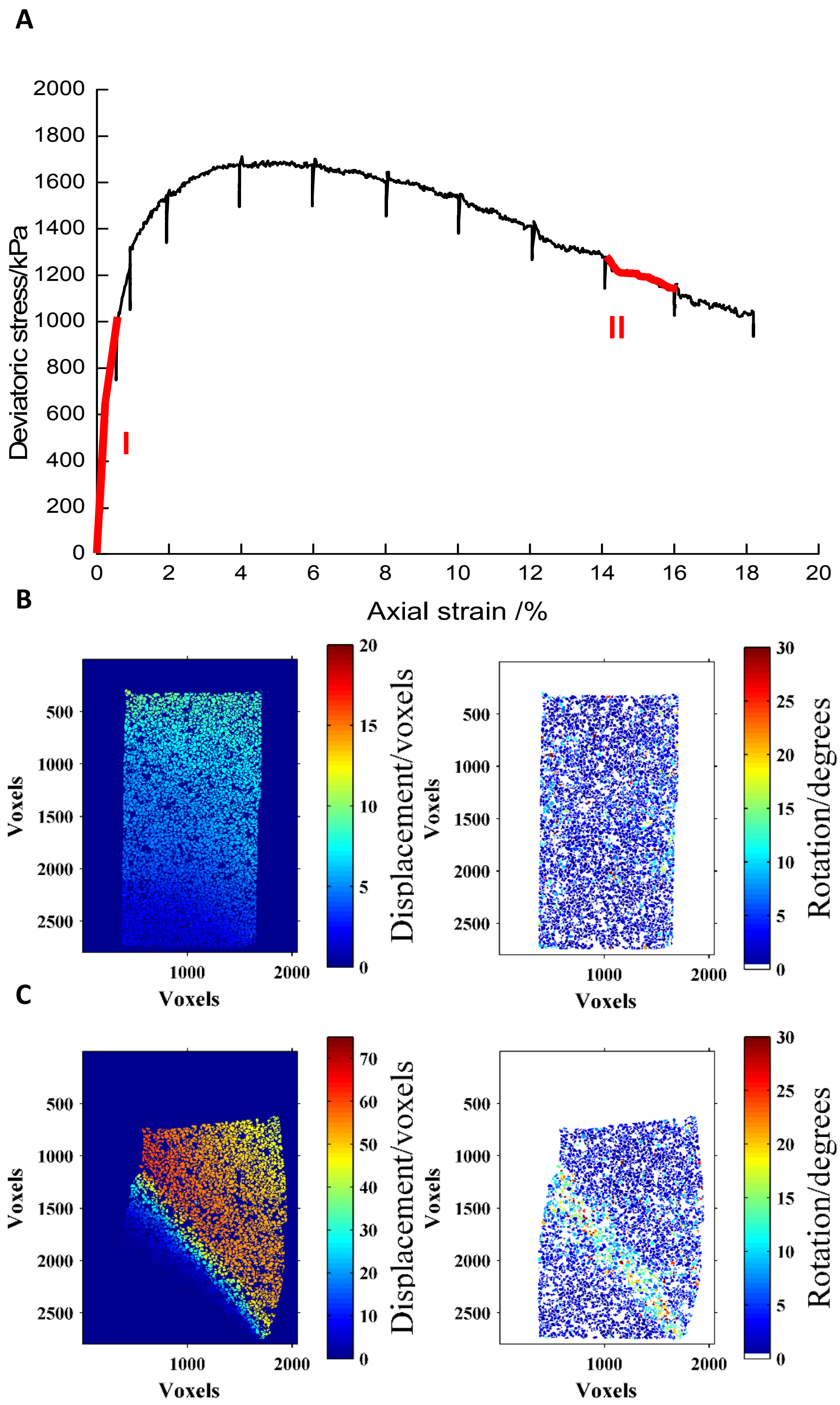

A
B
C
Deviatoric stress/kPa
Axial strain /%
I
II
Displacement/voxels
Rotation/degrees
Voxels

Figure 5

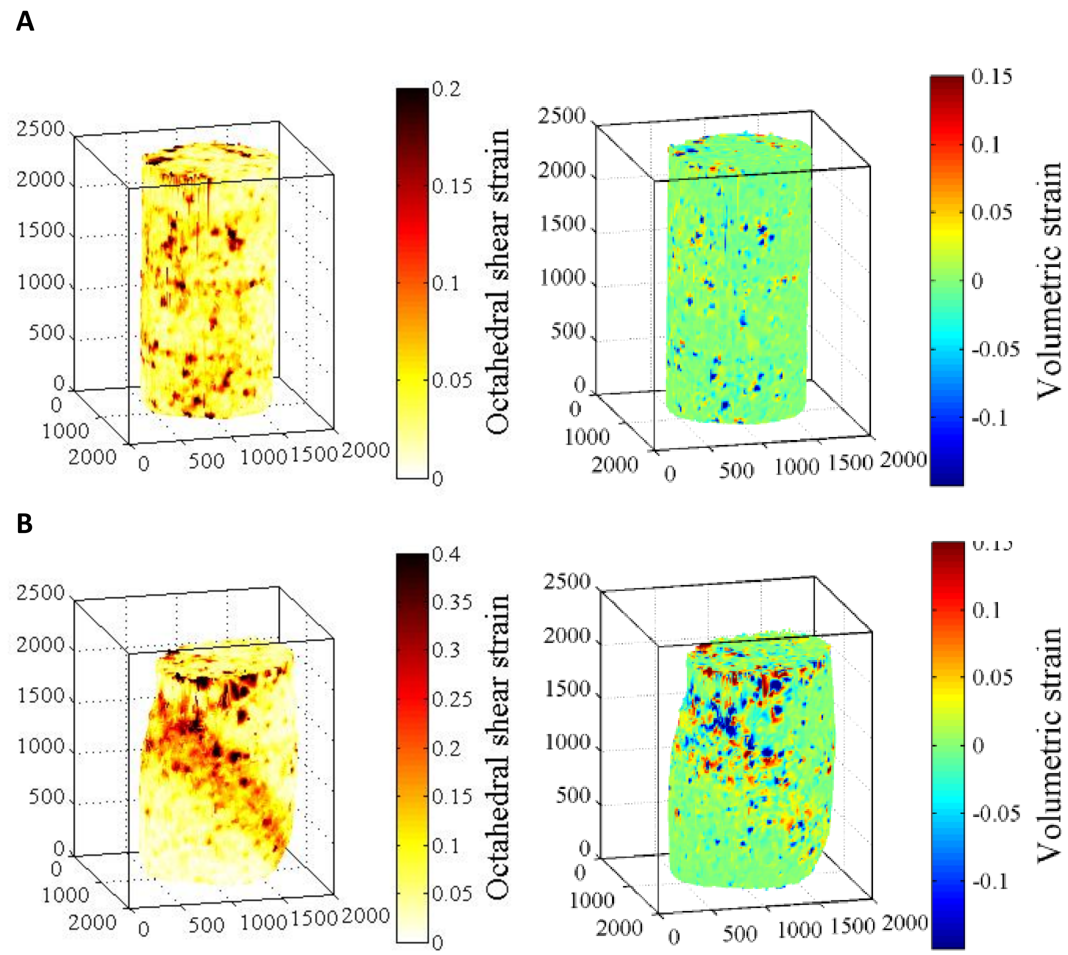

A
B
Octahedral shear strain
Volumetric strain
2500
2000
1500
1000
500
0
0
1000
2000
0
500
1000
1500
2000
0.2
0.15
0.1
0.05
0
0.15
0.1
0.05
0
-0.05
-0.1
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

Figure 6

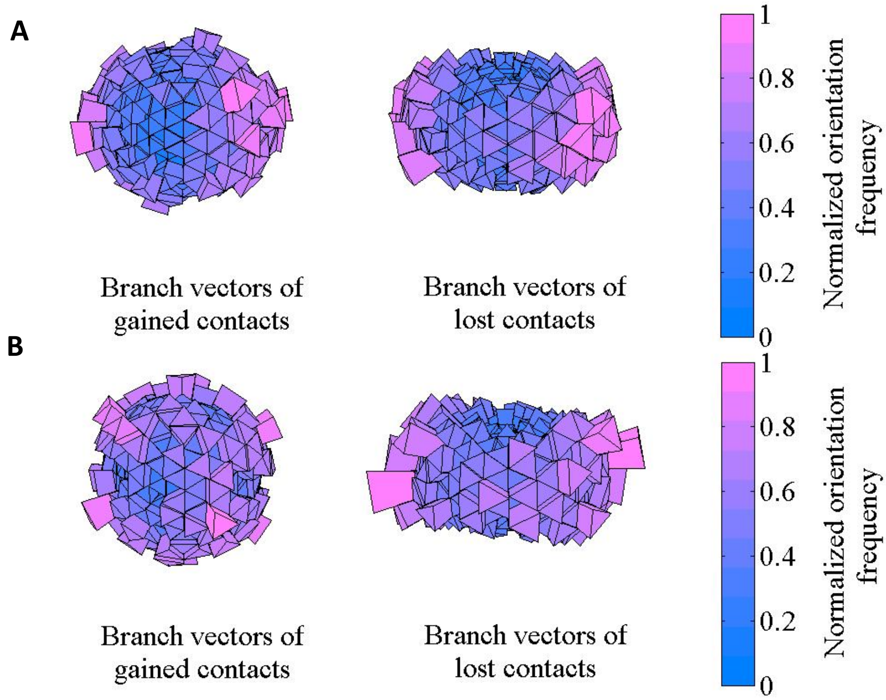

A
Branch vectors of gained contacts
Branch vectors of lost contacts
1
0.8
0.6
0.4
0.2
0
Normalized orientation frequency
B
Branch vectors of gained contacts
Branch vectors of lost contacts
1
0.8
0.6
0.4
0.2
0
Normalized orientation frequency

Figure 7

Figure 1psd

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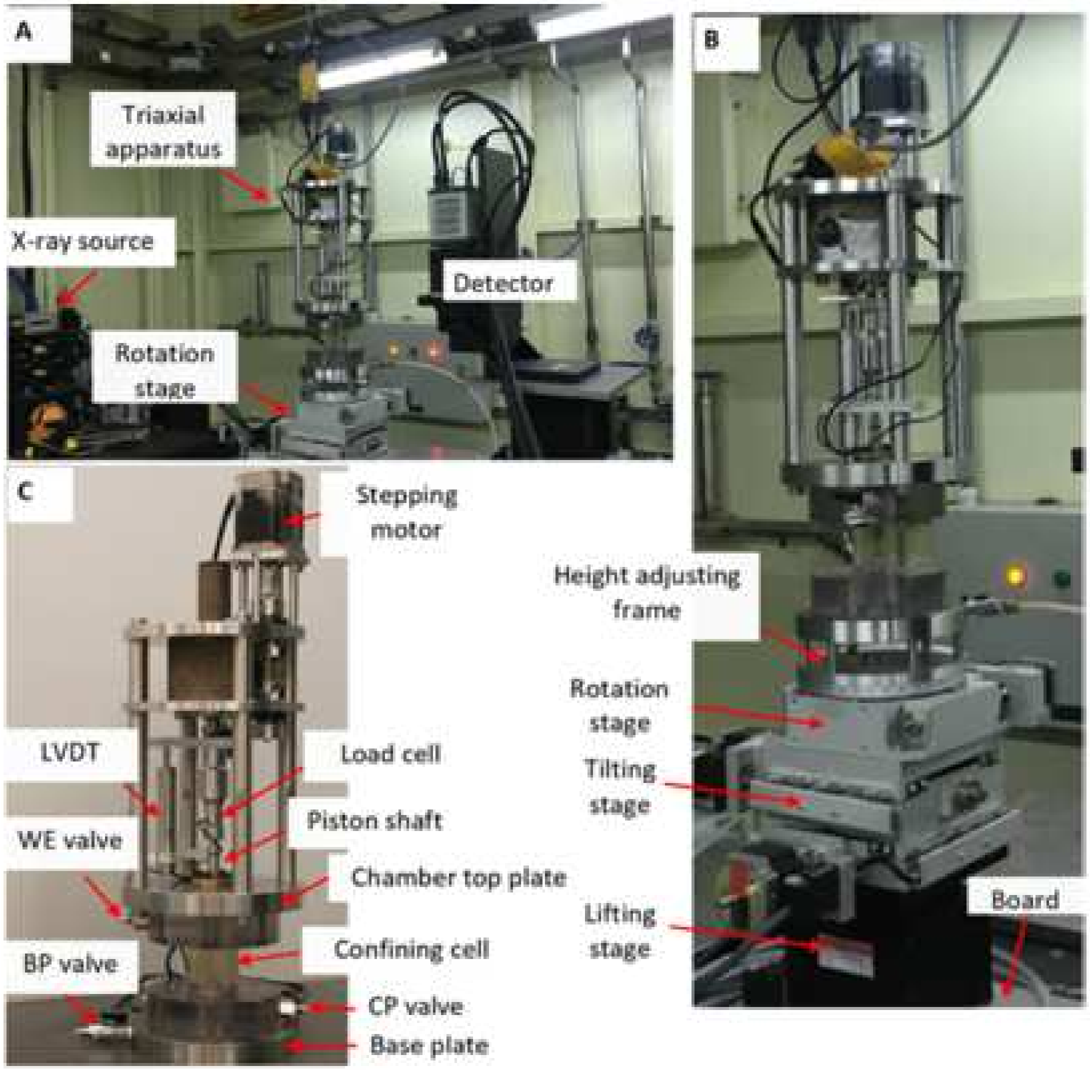

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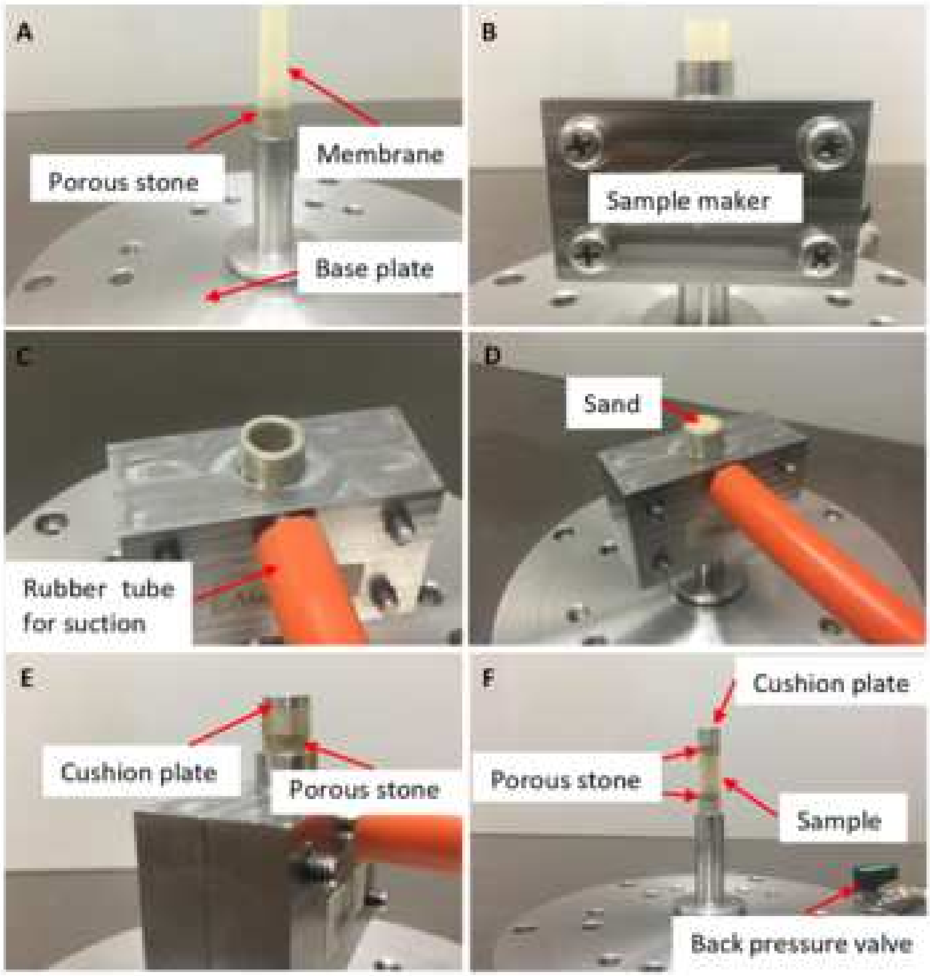

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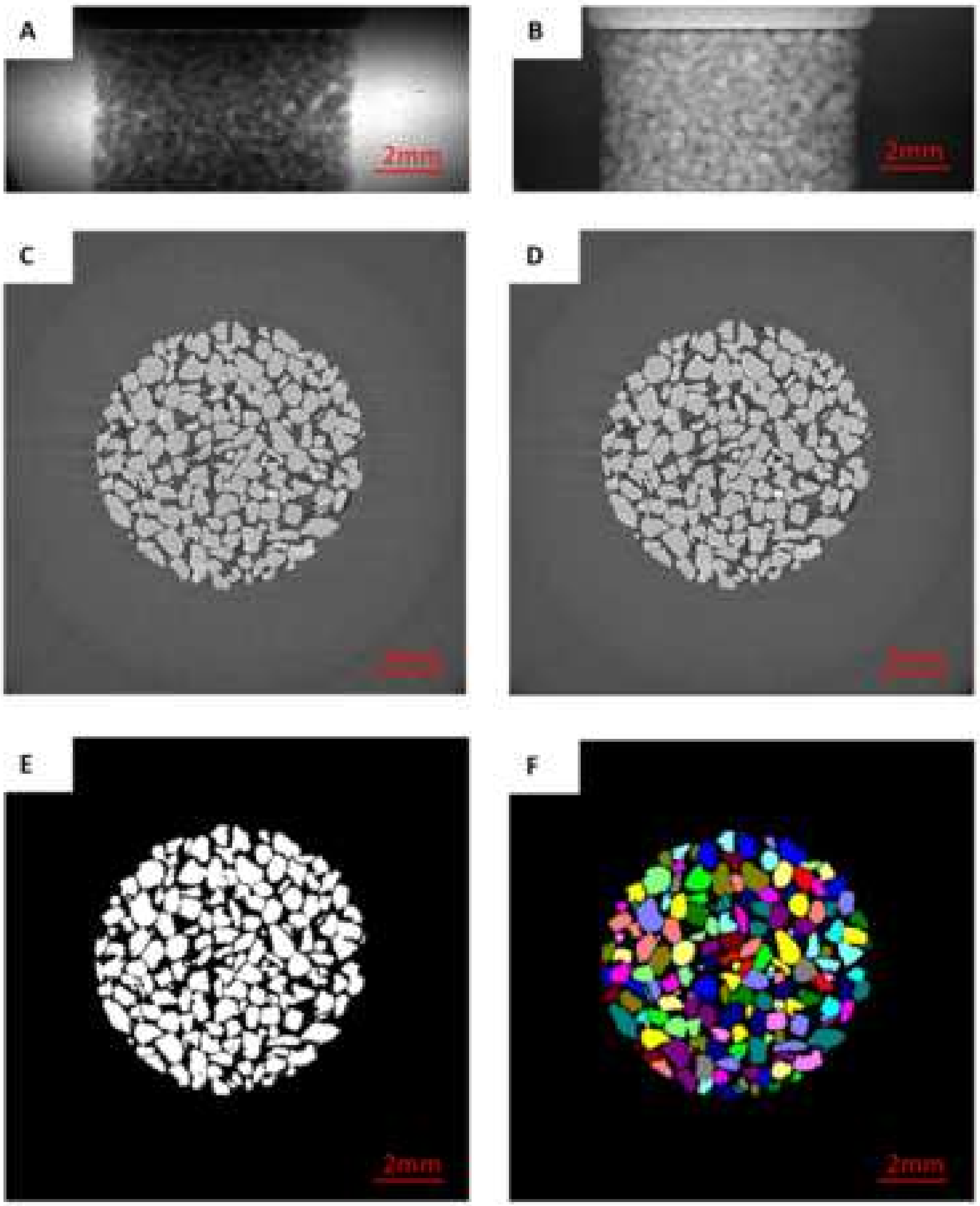

Figure 4psd

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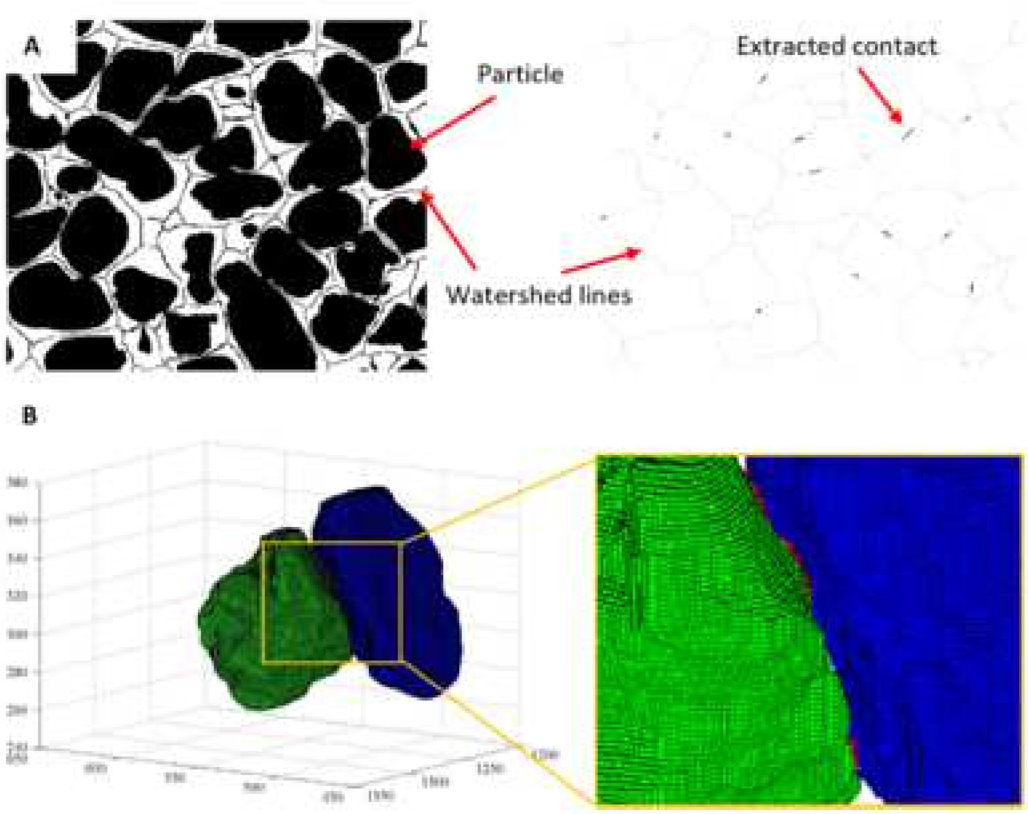

Figure 5psd

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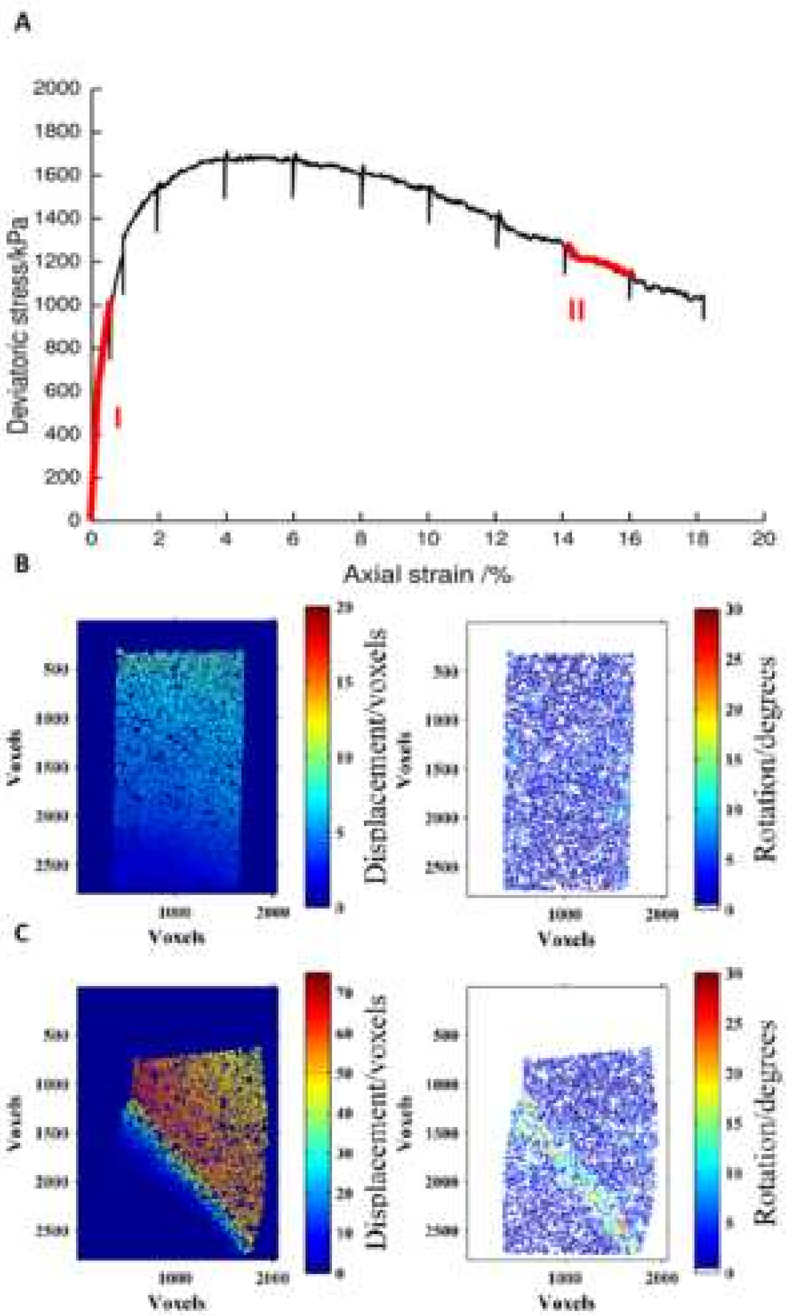
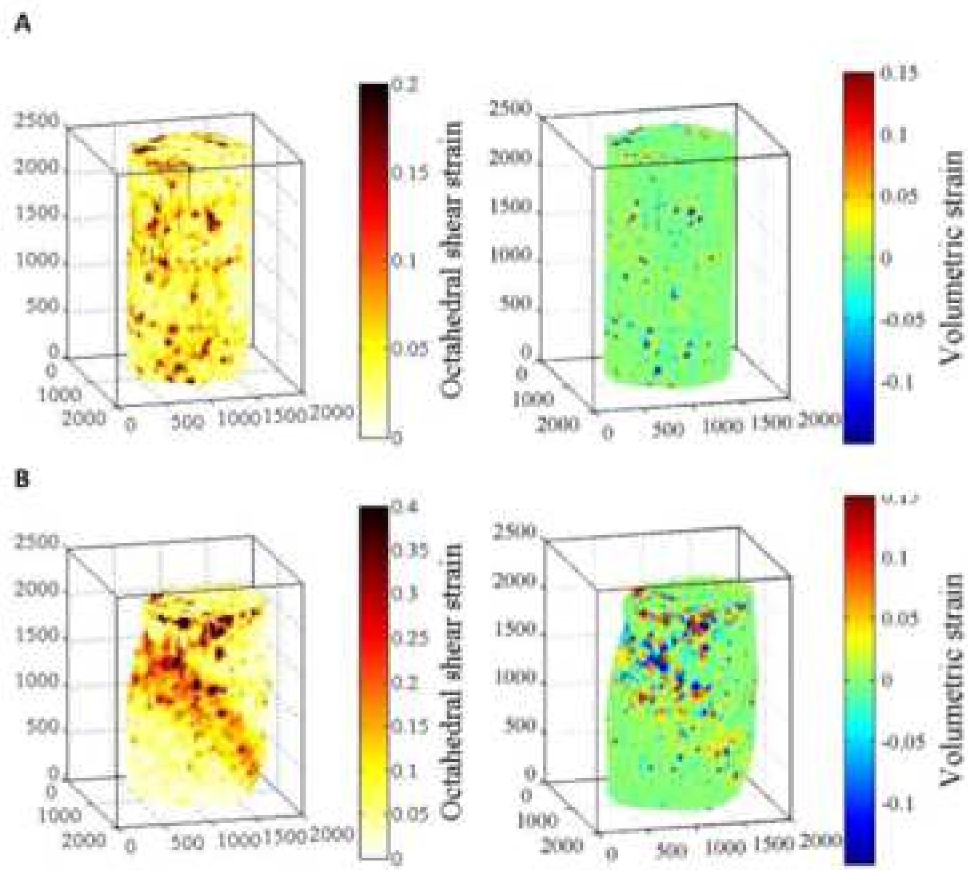
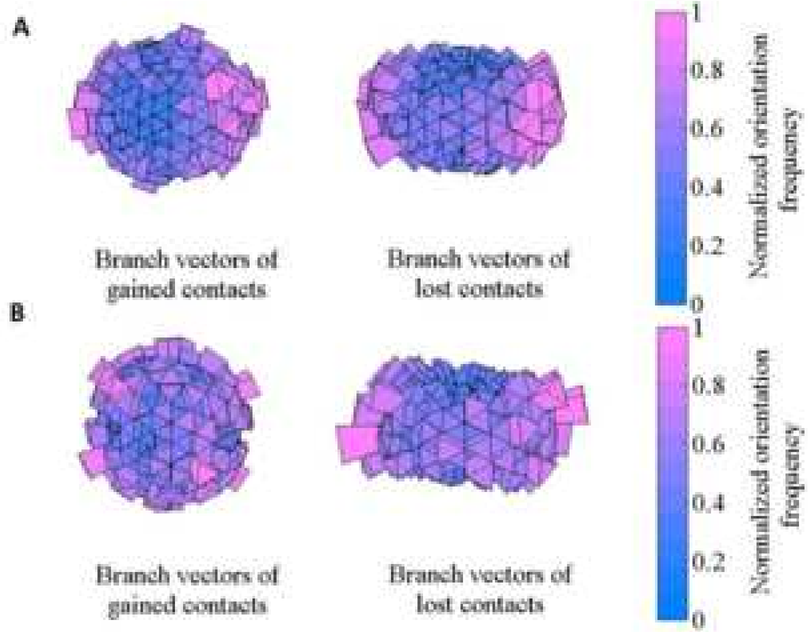


Figure 6psd

Click here to access/download;Figure;Figure 6.psd




A
Branch vectors of gained contacts
Branch vectors of lost contacts
1
0.8
0.6
0.4
0.2
0
Normalized orientation frequency
B
Branch vectors of gained contacts
Branch vectors of lost contacts
1
0.8
0.6
0.4
0.2
0
Normalized orientation frequency

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Name	**Company**	**Catalog Number**	**comments**
Confining pressure offering device	GDS	STDDPC	
De-aired water	N/A	N/A	Water de-aired in the lab
Leighton Buzzard sand	Artificial Grass Cambridge	Drained Industrial Sand 25 kg	Can be replaced with different soils
Miniature triaxial loading device	N/A	N/A	The miniature loading device is specially fabricated by the authors
Silicon grease	RS company	RS 494-124	
Synchrotron radiation X-ray micro CT setup	Shanghai Synchrotron Radiation Facility Center (SSRF)	13W1	The triaxial testing is carried out at the BL13W beam-line of the SSRF
Vacuum pump	Hong Kong Labware Co., ltd.	Rocker 300	

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Response to Editorial Comments

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'Visualization of failure and the associated grain-scale mechanical behavior of granular soils under shear using synchrotron X-ray micro-tomography' by Cheng Z. and Wang J.

The authors thank the editor and the editorial reviewer for their further comments on our manuscript. Our response to each comment is presented below.

For the ease of visualization, the revised texts are highlighted in red, while the filmable content is highlighted in yellow in the manuscript.

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1. Please do not highlight steps without highlighting any of the sub-steps (step 2.4, step 2.13).

Response: The relevant sub-steps are also highlighted in the revised manuscript.

2. Please revise the text in Protocol to avoid the use of any personal pronouns (e.g., "we", "you", "our" etc.).

Response: The manuscript is revised to ensure that no personal pronouns are used.

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