# 3D printing of soil structure for evaluation of mechanical behavior

*Matsumura, S. and Mizutani, T.*
*Foundations Group, Geotechnical Engineering Field*
*Port and Airport Research Institute*
*Japan*
*matsumura-s@pari.go.jp*

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## Introduction

Soil particles have variable sizes, shapes and physical properties, and form the ground with pore parts filled with the air and/or the water. Accordingly, the soil focused on in engineering generally is composed of inhomogeneous structure. In soil mechanics, therefore, it has been required to investigate and evaluate quantitatively the mechanical properties of such inhomogeneous soil. Some researchers have discussed how the structure, i.e., the particle arrangement, influenced the mechanical response based on some experimental approaches [1]. The prior results, however, are supposed to contain more or less uncertainty due to the soil structure, because so far it may not be possible to reconstitute the soil sample that has exactly the same structure as before, once the sample collapses by the mechanical test.

The objective of this study is to evaluate the above-mentioned uncertainty using the 3D printing technique and to reveal the effect of the soil structure on the mechanical response of soil. In the study, we scanned a natural gravel soil by means of the X-ray CT for the 3D printing, and performed the typical triaxial compression test with the original soil and the replica made by the high-resolution 3D printer. The interesting approaches for the granular materials using the 3D printing can be also found [2]. This study, however, differs from those in terms of reconstructing the particle arrangement in addition to the individual particle shapes. In this paper, the applicability of the 3D printing for the evaluation of the soil structure and its influence on the mechanical response will be discussed.

## Equipments, Materials and Methods

In order to achieve the objective, we mainly applied three equipments; the triaxial compression test apparatus, the X-ray CT scanner and the 3D printer shown in Figures 1, 2 and 3, respectively. The brief procedures of this study are as follows.

1. Triaxial compression test and X-ray CT scanning using a granular material

For the triaxial compression test, the natural gravel soil (see Figure 4a) was used to reconstitute the cylindrical triaxial sample of 50mm in diameter and 100mm in height. The whole procedure of the test, i.e., the isotropical confinement of 50kPa and the axial compression, operated inside the X-ray CT scanner as seen in Figure 2. In the experiment, the X-ray CT image for the packing triaxial sample was taken prior to loading.

2. Image processing for 3D printing

Figure 4b shows a certain horizontal section of the sample packed with the original granular material obtained by the X-ray CT scanning. In this study, the image processing procedures for the 3D printing can be mainly categorized into three processes; threshold, watershed and erode in order, using the image analysis tool; ImageJ [3]. These processing methods were adopted as the result of trial and error to achieve the required 3D printed samples, that is, the granular aggregation that has the desired bonding at the grain contacts.

3. 3D printing of granular material and investigating its mechanical behavior

The raster image made via the aforementioned processing was converted to the surface image for the 3D printing. In the study, we used the high-resolution 3D printer, AGILISTA-3100 provided by KEYENCE corp. shown in Figure 3, which employs the UV-curable 3D printing technique. To achieve our objective, the most important and required feature of the 3D printer is to enable the 3D printed sample to be reconstituted without destroying the original particle arrangement. The equipment used can build up the solid and the pore part separately with the different acrylic materials, and the water-soluble material forming the pore part melts in the water after printed. In this study, we conducted the triaxial compression tests using the 3D printed material as well as the natural granular material.

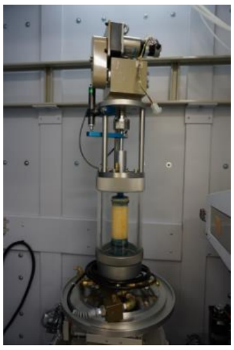

**Figure 1. Whole view of the triaxial compression test apparatus.** This apparatus was developed so that it can be operated inside the X-ray CT scanner.

**Figure 2. Whole view of the X-ray CT scanner.** The maximum of X-ray tube voltage and current are 225kV and 600μA, respectively. The triaxial test apparatus installed into the X-ray CT scanner can be operated from outside with the pressure and water control panel plcaed at the right side in the figure.

**Figure 3. Whole view of the 3D printer.** The maximum layer thickness of 3D printing is 15μm. The spatial resolution is 635×400dpi.

## Results and Discussion

We discuss the geometrical and mechanical reproducibility of the 3D printed particles and the aggregation (see Figures 5a and 6) as follows;

1. Geometrical reproducibility

To show how accurately the soil structure can be reconstructed by the 3D printing, Figure 7 indicates the comparison of the particle arrangements between the original sample and the duplicated one. Here we focused on the angular distribution of the longitudinal direction of each particle from the X-axis shown in Figures 4b and 5b. The overall tendency of the three duplicated samples agrees well to that of the original one. The subtle difference, on the other hand, can be also found. It is inferred to result from the insufficient accuracy in the image processing or the X-ray CT scanning rather than that in the 3D printing.

Figure 8 demonstrates the content rate of the particles smaller than the specific particle area which corresponds to the plotted value in the X-axis. While the particle areas of the duplicated samples are consistent with one another, they tend to be totally smaller than that of the original sample. This is because the erode processing for the 3D printing shrunk the particles.

2. Mechanical reproducibility

Figure 9 shows the resulting axial load-displacement curves. In this study, we conducted the triaxial compression test for three kinds of samples. One is the samples jammed with the natural granular material, which is described as the original samples. The duplicated samples are the 3D printed ones based on the original sample 1 in Figure 9. The third ones are the samples packing again with the 3D printing particles after destroyed the structure of the duplicated samples, shown as the duplicated and reconstituted samples. Then, those were set in the same packing density as that of the duplicated samples. We repeated the above-mentioned tests three times for each kind of sample.

From the figure, the strength and the stiffness of the original samples are likely to be higher than the others reconstructed using the 3D printed material. In addition, the axial load becomes to fluctuate with the axial load evolving. Those implies that the difference in the material—particularly, the surface friction—can be significant in evaluating the mechanical response of soil, even though the particle size and arrangement are similar by the 3D printing.

On the other hand, it is clear that the effect of the particle arrangement on the resulting load-displacement curves emerges. In comparison of the duplicated samples, the results of the duplicated and reconstituted samples varies more widely. Such tendency, further, is likely to be conspicuous for the behavior at the lower displacement less than around 3mm. In terms of these two kinds of samples, because the difference is supposed to result from whether or not the duplicated structure was maintained until the axial compression, it could be understood that the results varying widely are attributed to the influence of the particle arrangement.

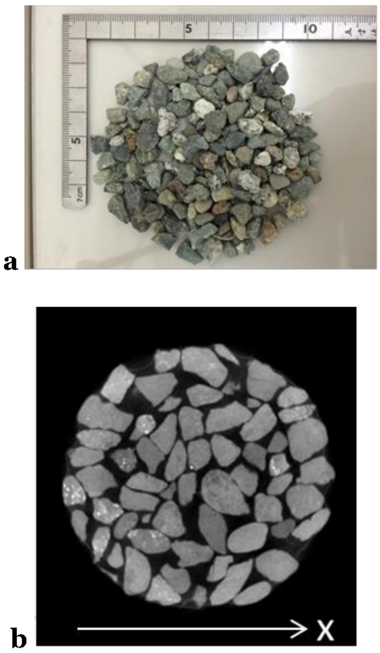


**Figure 4. Original granular material. a,** Particle image of the gravel used. **b,** Horizontal section of the original sample obtained by X-ray CT scanning.

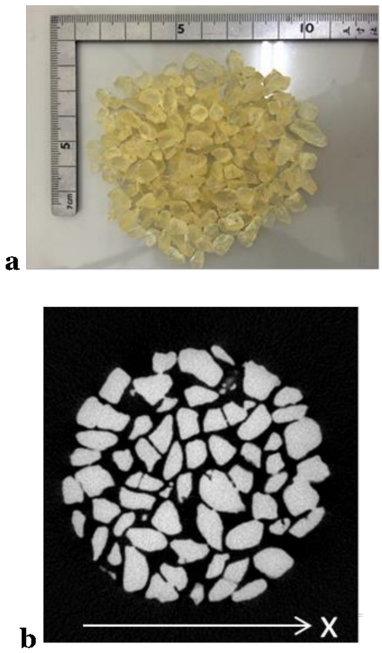


**Figure 5. Duplicated granular material. a,** Particle image of the 3D printed material. **b,** Horizontal section of the duplicated sample obtained by X-ray CT scanning.

**Figure 6. Duplicated sample for triaxial compression test.** The sample size is 50mm in diameter and 100mm in height as well as the original sample.

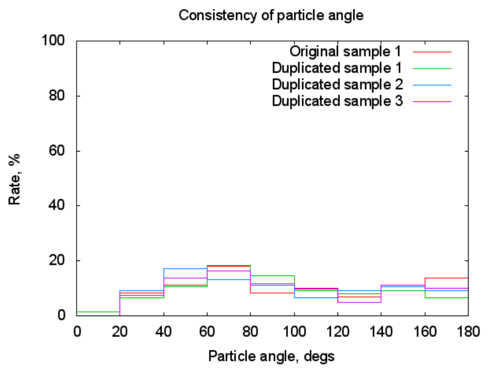


**Figure 7. Particle arrangement distribution.** The particle angle was calculated by the angle of longitudinal direction from the X-axis shown in Figures 4b and 5b.

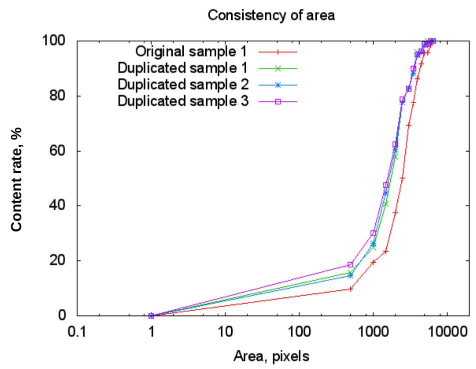


**Figure 8. Particle area distribution.** The content rate of the particles smaller than the specific particle area which corresponds to the plotted value in the X-axis.

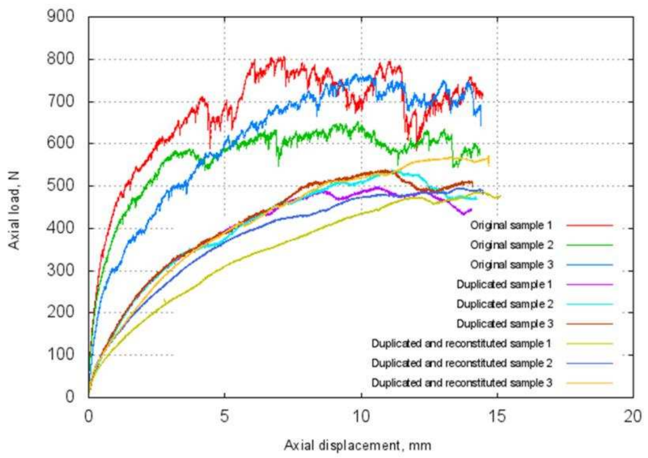


**Figure 9. Triaxial compression test result.** The results of the original samples 1 ~ 3, the duplicated samples 1 ~ 3 and the duplicated and reconstituted samples 1 ~ 3 are shown. The three samples at individual kinds were set and tested via exactly the same procedures. The confining stress was isotropically applied at 50kPa by the air pressure. The loading rate was 0.1mm/min. The modification for the bedding error was carried out.

## Conclusion

In order to evaluate the effect of the soil structure, i.e., the particle arrangement, on the mechanical behavior of soil, we applied the 3D printing technique for soil mechanics and conducted the typical triaxial compression test using the natural gravel soil and the 3D printed samples. It is confirmed that it can reconstitute the samples that have the same structure as that of the original one. Further, we concluded that even though the granular sample could be reconstituted at the same packing density, the difference of particle arrangement made the mechanical response vary more widely.

## References

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