USE OF THE GCTS APPARATUS FOR THE MEASUREMENT OF SOIL-WATER CHARACTERISTIC CURVES

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ABSTRACT
Details of the new GCTS pressure plate apparatus manufactured by Geotechnical Consulting and Testing Systems, Tempe, Arizona, are presented in this paper. Two series of tests were performed on Botkin silt and Processed silt using the GCTS pressure plate. The experimental results show that the water content versus matric suction measurements of the GCTS pressure plate is comparable to the University of Saskatchewan pressure plate apparatus. The equipment is capable of measuring both volume and water content change and following any stress path under K_0 loading condition. Test results are presented for: 1) Botkin silt and 2) Processed silt. The results show that the GCTS pressure plate apparatus is capable of following drying and wetting curves and determine the volume-mass soil properties provided the soil specimen does not separate from the steel confining ring.

RÉSUMÉ
Cet article présente les détails du nouvel appareil de plaque de pression de GCTS fabriqué par la Geotechnical Consulting and Testing Systems, Tempe, Arizona. Deux séries de tests ont été exécutées sur le limon de Botkin et sur le limon traité utilisant la plaque de pression de GCTS. Les résultats expérimentaux montrent que les mesures de contenu d'eau et de succion matric obtenues avec la plaque de pression de GCTS sont similaires à celles qui ont été obtenues avec l'appareil de plaque de pression de l'Université de la Saskatchewan. L'équipement est capable de mesurer le volume total et le changement de contenu d'eau suivant le chemin de tension sous la condition K_0 de chargement. Les résultats sont présentés en considérant les sols suivants: 1) le limon de Botkin et 2) e limon traité. Les résultats montrent que l'appareil de plaque de pression de GCTS est capable de suivre le séchage et le mouillage de sols et de déterminer les propriétés de volume-massifs si le spécimen de sol ne se sépare pas de l'anneau latéral.

1. INTRODUCTION

The soil-water characteristic curve represents a plot of the water content versus soil suction for a soil and provides an important unsaturated soil property in that it can be used to estimate the shear strength, permeability and volume change functions of unsaturated soils (Fredlund and Rahardjo, 1993; Vanapalli et al., 1996; Fredlund, 1999; Fredlund et al., 2000).

There are three ways in which the soil-water characteristic curves are commonly presented; namely, i) gravimetric water content versus soil suction; ii) volumetric water content versus soil suction; and iii) degree of saturation versus soil suction. The gravimetric soil-water characteristic curve can be measured using conventional pressure plate. The volumetric water content and degree of saturation soil-water characteristic curves require measurements of both water content and volume change of the soil during the test. For a low volume change soil (i.e., sand or compacted silt), it is possible to neglect volume changes during the wetting or drying processes and therefore compute volumetric water content and degree of saturation. Clay and slurry silt can have significant volume changes along the wetting and drying processes; therefore, the measurement of volume change is necessary for the computation of volumetric water content and degree of saturation.

Numerous apparatuses for measuring the SWCC have been presented in the research literature (Soilmoisture Equipment Corporation, 1985). During the pre- 1985 period, most apparatuses were designed to measure the SWCC under zero applied total stress. After 1985 and particularly in more recent years, many attempts have been made to measure both water content and volume change as the soil is tested (Jucá and Frydman, 1996; Shimuzu and Nambu, 2003). Diffusion of air through the saturated ceramic stone is one of the problems that has plagued most apparatuses. The GCTS - SWCC apparatus manufactured by Geotechnical Consulting and Testing Systems (GCTS), Tempe, Arizona, is a pressure plate apparatus with some new design features that assist in the accurate measurement of the overall volume and water content of the soil specimen and overcome several limitations of the previous apparatuses.

The description of the GCTS pressure plate is described in this paper. Two series of test on two soils are presented. Discussions concerning the application of the apparatus to unsaturated soil testing are presented.

2. DESCRIPTION OF THE APPARATUS

The GCTS pressure plate uses the axis-translation technique to control matric suction in the soil specimen (Hilf, 1956; Fredlund and Rahardjo, 1993). The GCTS pressure plate consists of two main parts (Figure 1): i) a pressure chamber and ii) a loading system. The pressure chamber was designed for measuring soil-water characteristic curves. The pressure chamber is stainless steel and can be subjected to extremely high air pressures. The soil specimen is trimmed into a stainless steel ring and placed on top of the high air entry ceramic stone. During the test, the soil specimen is subjected to a vertical load provided through the loading ram. Various soil ring diameters can be used (i.e., from 25mm up to 75 mm). Different high air entry ceramic stones can be inserted into the base of the apparatus and used for different soil types. It is also possible to use a range of ceramic stones on one soil that is tested over a wide range of matric suctions (i.e., 1 bar, 3 bars, 5 bars and 15 bars). The apparatus is capable of testing the soil specimen over a wide range of matric suctions from 0.1 kPa to 1500 kPa. At a low soil suction (i.e., from 0.1 to 10 kPa), a hanging burette can be attached to provide an accurate value of soil suction to the soil specimen. The hanging column is designed similar to that commonly used for conventional pressure plate apparatuses (not shown in figures). At higher soil suctions (i.e., from 3 kPa to 1500 kPa) the axis-translation technique is used. Dual pressure gauges and regulators are designed to accurately control the applied soil suction over the entire range.

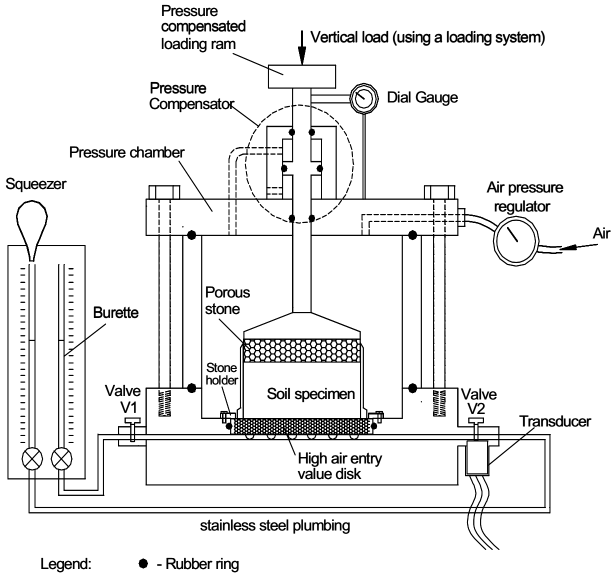

Figure 1. Schematic of the GCTS pressure plate apparatus for the measurement of water and volume changes in unsaturated soils.

The bottom of the pressure cell (i.e., below the ceramic stone) is connected to two burettes with reading accurate up to 0.07 (ml) of water. The amount of water drained out or absorbed into the soil specimen can be measured using the two burettes. At high soil suctions (i.e., close to the air entry value of the ceramic disk), the amount of the air diffusing through the ceramic stone becomes more significant. The burettes can be connected to a squeezer that is used to flush diffused air from the bottom of the pressure chamber (i.e., below the ceramic stone). In order to flush the diffused air from the bottom of the pressure cell, the following procedure is used:

- Open the two valves at the base of the pressure cell (i.e., V1 and V2) that are connect to the two burettes.
- Read each of the burettes to obtain the initial readings.
- Connect the squeezer to the top of one burette.
- Apply pressure to the squeezer and both water and diffused air in the bottom of pressure cell will move to the other burette. Hold the squeezer for about 15 seconds for the diffused air to be escaped from the water (in the other burette).
- After flushing air, take the final readings on the burettes and then cover the top of the two burettes to avoid evaporation of water from the burettes.

Figure 2. Photo of the GCTS pressure plate apparatus for measuring water content and volume changes in unsaturated soils under simultaneous control of total stress and matric suction.

A loading ram through the top of the pressure chamber is used to apply vertical load to the soil specimen. The loading ram is designed with a pressure compensating system. The pressure compensator is used to counter-balance the air pressure that acts on the loading ram in the pressure chamber. The design of the pressure compensator allows an independent control of matric suction and net vertical stress. A displacement dial gauge is attached to the loading ram to measure vertical displacement of the soil specimen. The design of the

GCTS apparatus allows the application of a wide range of net vertical stresses (i.e., from 5 kPa up to 4000 kPa). At low net vertical stresses (i.e., less than 100 kPa), several weights can be placed directly on top of the loading ram. At net mean stresses higher than 100 kPa, a loading frame can be used to provide load to the soil specimen (Figure 2). GCTS have designed a loading frame specifically for use with the GCTS pressure plate apparatus.

The GCTS pressure plate apparatus is capable of measuring changes in both soil volume and water content under changes in soil suction as well as vertical stress. In the other words, there is independent control of matric suction and total vertical stress. The GCTS pressure plate apparatus can follow a variety of total vertical stress and matric suction stress paths under K_0 loading conditions.

The vertical load system can also be used to bring the soil specimen to a stress state similar to what it experienced in the field. It is also possible to measure the initial soil suction of the soil, either under a low applied load or under in situ stress conditions. A pressure transducer connected to the water system under the ceramic stone allows the measurement of matric soil suction while using the axis-translation null-type test procedure described by Fredlund and Rahardjo (1993).

3. MATERIALS

Two soils were used in the testing program; namely, i) Botkin silt and ii) Processed silt. The Botkin silt had a liquid limit, *LL* = 28.6, plastic limit, *PL* = 14.3, specific gravity, G_s = 2.71, and a clay content of 19%. The Processed silt had a liquid limit, *LL* = 26.8, plastic limit, *PL* = 19.2, specific gravity, G_s = 2.70 with a clay content equal to 9%. The virgin compression index, C_c, of the Processed silt is 0.11 and the unloading-reloading index, C_s, is 0.019.

4. TESTING PROCEDURES

A calibration program was performed before running an actual soil test. A solid stainless steel with a diameter of 70 mm and a thickness of 30 mm was substituted for a soil specimen. It was assumed that, the solid stainless steel was rigid and did not deform. The amount of water in the burettes and the vertical displacement were then recorded under various applied vertical loads and soil suctions. The data were then used to correct the measured data measured during the actual testing of the soil. Following the calibration program, two series of tests were performed on two soils. The tests were performed to: 1) verify the performance of the new apparatus; and 2) to measure overall volume and water content of the soil while following various stress paths.

Comparison tests were performed using the University of Saskatchewan (U. of S.) pressure plate apparatuses. This apparatus has been used for several years for the measurement of soil-water characteristic curves. The soil-water characteristic curves measured using the U. of S. and the GCTS pressure plate apparatus were then compared. For verification purposes, three identical compacted Botkin silt specimens were prepared (i.e., specimens P1-1 to P1-3). The Botkin silt was compacted at a water content of 12.5% (i.e., wet of optimum). The soil-water characteristic curve of the three soil specimens were then measured using two U. of S. pressure plate apparatuses and one GCTS pressure plate apparatus.

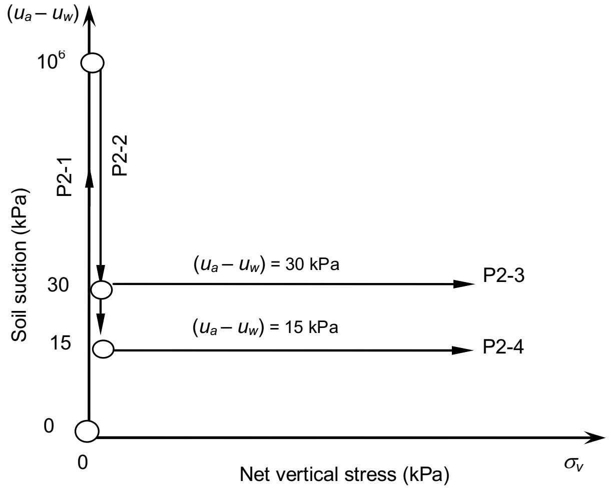

Figure 3. Stress paths followed for the four Processed silt specimens in Test Series 2 (Specimens P2-1 to P2-4).

The second series of tests was performed to study the effects of changes in soil suction and net vertical stress on the water content and the overall volume change of the Processed silt. Initially slurry soil specimens were used in the experimental program. In the second series of test, four soil specimens (P2-1 to P2-4) were tested. Stress paths for the second series of test are shown in Figure 3. The soil specimen, P2-1, was prepared as slurry soil. The soil specimen, P2-1, was used to measure the initial drying soil-water characteristic curve of the Processed silt. The specimens, P2-2, P2-3, and P2-4, were prepared as air-dried specimens (i.e., dry from initially slurry condition). The soil specimen, P2-2, was wetted from the air-dried condition to a soil suction of 2 kPa under a vertical stress of 5 kPa to measure the boundary wetting soil-water characteristic curve and volume change during the wetting process. The soil specimens, P2-3, and P2-4, were wetted from the air-dried condition to the soil suctions of 30 and 15kPa (corresponding to gravimetric water contents of 10.2% and 14.1%, respectively). The soil specimens, P2-3, and P2-4, were then loaded at a constant soil suction up to a net vertical stress of 2600 kPa.

In order to measure the volume change of the soil specimens in the GCTS pressure plate, specimens, P2-2, P2-3, and P2-4, were trimmed from non-cracked, air-dried soil specimens. The soil specimens were loaded under K_0

loading conditions in all stress paths. The following procedures were used to prepare an air-dried specimen from slurry soil:

- Mix the soil powder with water at approximate 1 to 1.5 times of liquid limit of the soil.
- Prepare the soil in a ring with a size much bigger than the expected size of the air-dried soil specimen (depending on the soil type).
- Spread thin-plastic wrapping paper in the bottom and around the wall of the soil ring.
- Place a small load of 1 kPa on top of the soil specimen and ensure there are no entrapped air bubbles in the soil specimen.
- Place the soil specimen into a small box with a hole connected to the free air. Wait for the soil specimen to dry to the completely air-dried condition (usually takes from 5 to 7days).
- Trim the air-dried soil specimen into a smaller soil ring and prepare for test.

5. TESTING RESULTS AND DISCUSSIONS

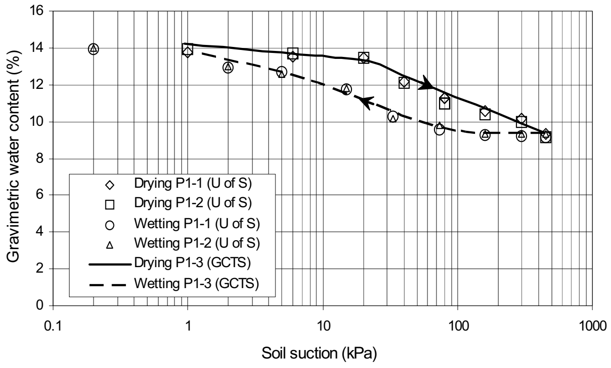

Figure 4. Comparison between the soil-water characteristic curves for the Botkin silt measured using the U. of S. pressure plate apparatus and the GCTS pressure plate apparatus (Specimens P1-1, P1-2 and P1-3).

Figure 4 summarizes the results of the Test Series #1. The two soil-water characteristic curves of the Botkin silt measured using the two U. of S. pressure plate apparatuses agree well with each other. The data measured using the U. of S. pressure plate also agrees well with the data measured using the GCTS pressure plate. There are some differences between the measured soil-water characteristic curves and the differences may be due to: i) variability in the water in the plastic tube of the U. of S. pressure plate when placing the entire cell on the balance; ii) evaporation of water from the soil specimens in either the U. of S. and GCTS pressure plate apparatuses. At high soil suctions, the diffused air that accumulates under the high air entry ceramic stone can be significant. It is found that flushing diffused air from the U. of S. pressure plate was more difficult than of using the flushing system designed for the GCTS pressure plate.

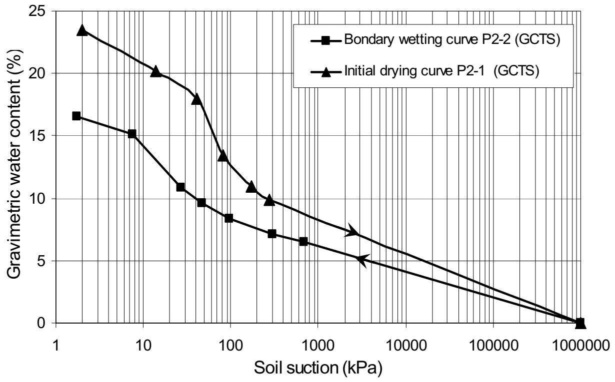

Figure 5. Initial drying curve (under zero net vertical stress) and boundary wetting curve (under 5 kPa vertical stress) for the Processed silt (Specimens P2-1 and P2-2).

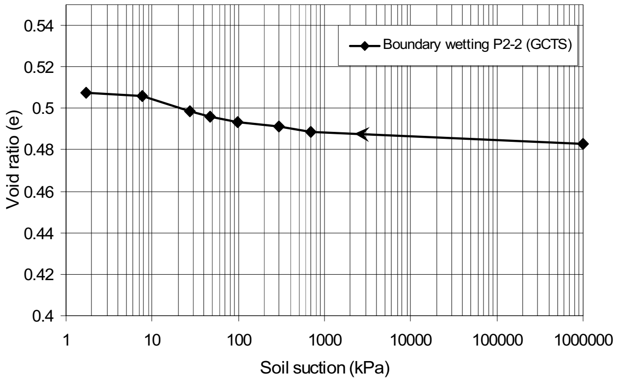

Figure 6. Void ratio during the wetting process from a soil suction of 10^6 kPa to a soil suction of 1.6 kPa under a constant net vertical stress of 5 kPa of Processed silt (Specimen P2-2).

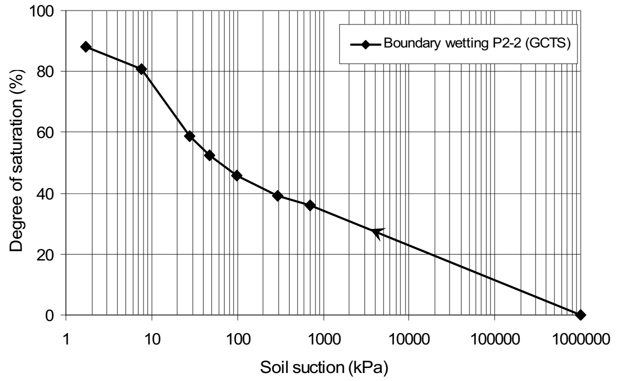

Figure 7. Degree of saturation during the wetting process from a soil suction of 10^6 kPa to a soil suction of 1.6 kPa of specimen P2-1 under a constant net vertical stress of 5kPa.

The initial drying curve and boundary wetting portion of the soil-water characteristic curve for the Processed silt is shown in Figure 5. It is impossible to measure the volume change of soil specimen, P2-1, along the initial drying curve because: i) the soil cracked during the initial drying process; and ii) it is not possible to measure lateral displacement of the soil specimen. The gravimetric soil-water characteristic curve of a slurry soil specimen is different than that of a compacted soil specimen. At soil suctions lower than the air entry value of the soil, the slope of the gravimetric soil-water characteristic curve of a sandy soil is not significant since it is quite stiff. For silt or clay soils, the slope of the gravimetric soil-water characteristic curve of the soil at soil suctions less than air entry value is significant.

Figures 6 and 7 show the void ratio and the degree of saturation of the Processed silt along the wetting process (specimen P2-2). It can be seen that, at the end of the wetting process the degree of saturation of the soil at a soil suction of 1.7 kPa is approximately 88%. The wetting process does not appear to reach a fully saturated state due to air entrapped during the drying process (Pham et al., 2003). The difference between the initial drying and the boundary wetting soil-water characteristic curves at low soil suctions (i.e., less than water entry value) results from: i) plastic volume change along the drying process from slurry conditions; and ii) air entrapped during the drying process.

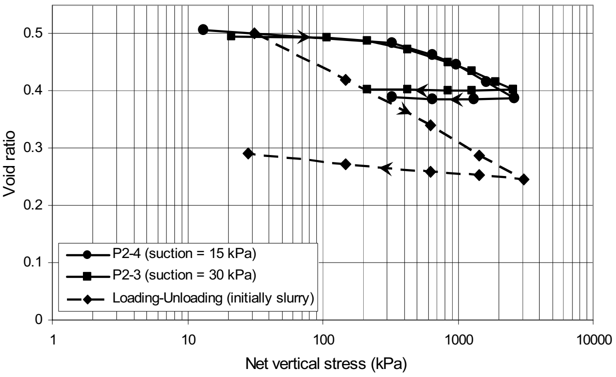

Figure 8. Void ratio of the Processed silt during the loading and unloading processes at three constant soil suctions (i.e., 15 kPa and 30 kPa and initially slurry condition).

Figure 8 shows the compression and unloading curves of the Processed silt at three different constant soil suctions: i) at a soil suction of 30 kPa (specimen P2-3); ii) at a soil suction of 15 kPa (specimen P2-4); and iii) of a slurry soil specimen (i.e., zero soil suction). The results agree with other experimental data. At higher soil suctions, the soil appears to become stiffer (Alonso et al., 1990; Wheeler and Sivakumar, 1995; Tang and Graham, 2002). Figure 9 shows the change in water content along the loading-unloading processes of the soil at three constant soil suctions. It can be seen that, the amount of water in soil specimen, P2-3, seems to show no change. The water content decreases a little for soil specimen, P2-4, and significantly decreases for the slurry soil specimen. Figure 10 shows that the degrees of saturation of soil specimens, P2-3 and P2-4, increases during the loading of the specimens. The results agree well with the data measured by Sharma (1998).

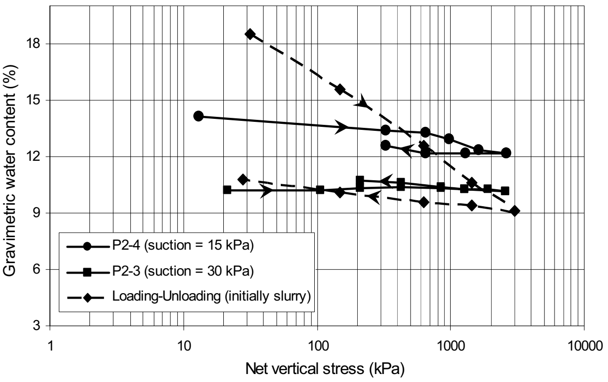

Figure 9. Gravimetric water content of the Processed silt during the loading and unloading processes at three constant soil suctions (i.e., 15 kPa and 30 kPa and initially slurry condition).

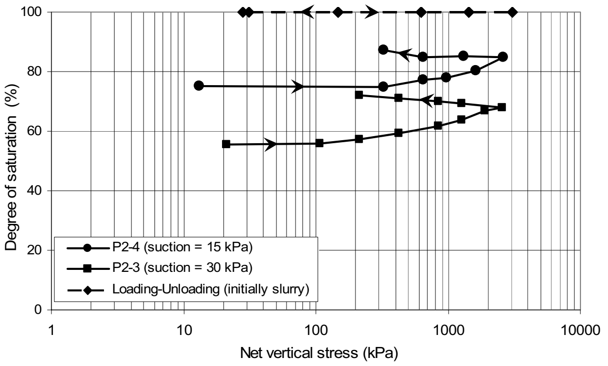

Figure 10. Degree of Saturation of the Processed silt during the loading and unloading processes at three constant soil suctions (i.e., 15 kPa and 30 kPa and initially slurry condition).

The amount of air diffusing through the saturated ceramic stone was measured during the testing program. It is found that the amount of the diffused air becomes significant as the soil suction (i.e., applied air pressure) reached the air entry value of the high air entry ceramic stone. For a 15 Bars ceramic stone with a diameter of 10 cm thickness of 0.6 cm, the volume of diffused air at 700 kPa, 500 kPa, 300 kPa 200 kPa was approximately equal to 0.50, 0.44, 0.35, 0.15 (ml per day), respectively. A complete test on an unsaturated soil specimen can take weeks to complete; therefore, the accumulation of diffused air is very significant. It is found that, the diffused air flushing system worked quite effectively and is certainly necessary for unsaturated soil testing.

6. CONCLUSIONS

The following conclusions can be drawn from the study:

- The GCTS pressure plate apparatus with a flushing system for diffused air works quite well for measuring and removing the diffused air under the base of the high air entry ceramic stone. The GCTS pressure plate provides accurate measurements of the water content in the soil specimens. The accuracy of the apparatus is comparable to the previously used U. of S. pressure plate apparatus.

- The GCTS pressure plate can follow any stress path under K_0 loading conditions with independent control of soil suction and net vertical stress.

- Hysteresis between the initial drying curve and the boundary drying curve of an initially slurry soil specimen is caused by: i) plastic deformation of the soil, and ii) air entrapped during the drying process. The higher soil suction that has been applied, the larger the amount of entrapped air there appears to be in the soil.

- The degree of saturation of unsaturated soil is increased with the vertical stress during compression at constant soil suction. In another words, changes in the volume of water in the unsaturated soil specimen are less than that of the void ratio change during compression.

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