DEFORMATION CHARACTERISTICS OF SOILS WITH VARIATIONS OF CAPILLARY PRESSURE AND WATER CONTENT

DONG-SOO KIMⁱ⁾, WON-SEOK SEOⁱⁱ⁾ and MIN-JONG KIMⁱⁱ⁾

ABSTRACT

Soil near ground surface is usually unsaturated and the modulus value is affected by the seasonal variation of water content and the corresponding capillary pressure. The Stokoe-type torsional resonant column (RC) testing equipment was modified to control the pore air and pore water pressures separately and to measure the variation of water content due to capillary pressure. Subgrade soil was collected at a test road site where the crosshole and water content measurements were performed with depth. RC tests were performed at various water contents by controlling capillary pressures using a given specimen and by using specimens compacted at various water contents. As the capillary pressure increased, the shear modulus was increased at the whole strain range due to the increase of effective stress between soil particles. The relation between maximum shear modulus ($G_{\max}$) and water content was much flatter and $G_{\max}$ value is smaller at a given water content for specimens prepared by controlling compaction water contents compared with those tested by controlling capillary pressures. The normalized modulus ($G/G_{\max}$) reduction curve was almost unique independent of compaction water content and density during sample preparation and variation of water content due to capillary pressure during testing. Field crosshole tests were also performed which showed that $G_{\max}$ values determined by crosshole tests matched well with those determined by controlling capillary pressures in the laboratory, but also showed substantial difference with results obtained by controlling compaction water contents.

Key words: capillary pressure, crosshole test, maximum shear modulus, modulus reduction curve, resonant column test, water content (IGC: D7)

INTRODUCTION

Deformational characteristics, expressed in terms of modulus and damping ratio, are important parameters in the design of geotechnical structures subjected to static and cyclic loadings. Shear modulus is generally affected by various parameters such as soil type, strain amplitude, confinement, void ratio, stress history, degree of saturation, etc. (Hardin and Drenevič, 1972). Particularly, soils near the ground surface are unsaturated and the modulus value is significantly affected by the seasonal variations of water content and its corresponding capillary pressures (Wu et al., 1984; Qian, 1990; Vinale et al., 1999).

In the design of geotechnical structures, the modulus values are determined either by performing in situ tests of water contents before construction or by conducting laboratory tests with specimens compacted at several different water contents to investigate the effect of water content. After construction, water content will vary seasonally by precipitation and frost-melting, and the current experimental methods cannot properly simulate field variations of water content and capillary pressure of

soils. To obtain reliable design parameters, the variations in modulus values with respect to seasonal variations of water content and capillary pressure should be considered in the design stage, but few studies have been performed so far.

In this study, the variations in maximum shear modulus ($G_{\max}$) and modulus reduction curve with water content and capillary pressure are investigated using resonant column (RC) testing equipment. In conventional studies, the effect of water content on modulus value was usually studied by preparing specimens of various compaction water contents (Qian, 1990; Kweon and Kim, 2000). To reproduce field conditions more reliably, in this study, the water content was varied in a given compacted specimen by controlling the capillary pressure (matric suction). The RC testing equipment was modified to control both the water content and capillary pressure separately. Finally, the crosshole test was performed at a test site where the sample for laboratory tests was gathered, and the applicability of the proposed laboratory test results was assessed by comparing modulus values determined by crosshole and RC tests at various water contents.

ⁱ⁾ Professor, Department of Civil and Environmental Engineering, Korea Advanced Institute of Science and Technology (dskim@kaist.ac.kr).

ⁱⁱ⁾ Graduate Student, ditto.

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Fig. 1. Modified top cap and bottom plate

TESTING EQUIPMENT

The Stokoe-type resonant column (RC) testing equipment (Ni, 1987; Kim, 1991) was modified to investigate the effects of water content and capillary pressure on deformational characteristics. To control the water content of the specimen by changing the capillary pressure (matric suction) which is the difference between pore air pressure and pore water pressure ($u_a - u_w$), both pore air and water pressures should be controlled separately and the variations of water content and volumetric strain should be independently measured (Vinale et al., 1999).

The top cap and bottom plate were modified as shown in Fig. 1. The bottom plate consists of two sections. The Z-shape circuit connected to the water drainage system is carved inside the 2 mm central section and then isolated from the air inside the soil specimen by using a high air entry value ceramic disk. This disk is clamped laterally inside the cavity using epoxy resin in order for the air and water not to pass between the gap. The outside, having a 117 mm thick annular cross section, contains the pore air control circuit. The surface was roughened to ensure the fixed end condition between the specimen and the bottom plate, and three holes are connected to the vacuum control system in order to apply the vacuum pressure during the testing setup.

To apply the air pressure separately, the top cap contains a hole connected to the air pressure control system. The hole is drilled at the center of the top cap so that the eccentric loading during RC testing is not applied. The

porous stone is installed at the bottom of the top cap in order to apply the air pressure uniformly and the outside surface is roughened to ensure good contact with the specimen.

The variation in water content of the specimen was measured by using the burette system as shown in Fig. 2. The volume of water passing through the high air entry ceramic disk was monitored by burette. The water pressure was maintained as an atmospheric pressure and the air pressure was controlled through the top cap. Capillary pressure was controlled using the axis translation technique by applying positive air and water pressures. To protect the drainage line from possible de-saturation caused by air diffusion through the ceramic disk, the air trap provides a place for collection of air. Because the measurement of water volume is affected by the diffused water, it was removed before burette reading. The "level mark" was placed on the stem of the air trap as a reference level and the water level was maintained to that level when removing the trapped air.

The volume change of the specimen was not measured in this study and the development of a volume change measuring system is underway. Because the specimen was compacted at a high density, it is assumed that the volume change is negligible during the stage of controlling the capillary pressure. Figure 3 shows the schematic diagram of RC testing equipment which can control the water content and capillary pressure.

Torsional RC testing was performed with a fixed-free boundary condition as shown in Fig. 3. Torsional excita-

Fig. 2. Burette system for measuring the variation in water content

Fig. 3. Schematic diagram of RC testing equipment with control system of the water content and capillary pressure

tion was applied on top of the specimen by a coil-magnet drive mechanism while the bottom of the specimen was held fixed to a rigid base pedestal. Harmonic torsional excitation with a constant maximum torque amplitude was applied to the top of the specimen over a range of frequencies, and the variation of the acceleration amplitude at the top of the specimen with frequency, which is the frequency response curve, was obtained. The resonant frequency and maximum amplitude of vibration were then determined from the response curve. These values are combined with equipment characteristics and specimen size to calculate shear wave velocity (V_s), shear modulus (G), and shearing strain amplitude (γ). Material damping ratio (D) can be also evaluated from the frequency response and free-vibration decay curves, but the damping ratio is not discussed in this paper. The confining pressure was applied by a cell pressure and the confining chamber was designed to withstand a maximum air pressure of 1 Mpa. The RC testing was operated by torque control and the shear modulus could be determined in the shearing strain ranges of $10^{-4}\%$ to $10^{-10}\%$. The

detailed descriptions of RC testing apparatus, data reduction method, and the reliability of test results have been discussed in the literatures (Ni, 1987; Kim, 1991).

TEST MATERIALS AND TESTING PROCEDURES

Test Materials

Subgrade soils were collected at the test road site of Korea Highway Corporation, where the in-situ crosshole test and water content measurement were performed to compare the water content—shear modulus relations determined by laboratory and in-situ tests. Table 1 shows the basic properties of the tested subgrade soil, which is classified as SW on Unified Soils Classification or A-1-b on AASHTO Classification. The grain size distribution of the tested soil is shown in Fig. 4.

Specimen Preparation and Testing Procedures

In this study, RC tests were performed at various water contents by controlling the capillary pressures using a given specimen, which is contrary to the conventional

testing method where to investigate the effect of water content, several specimens are prepared at different compaction water contents. To evaluate the effects of initial compaction water content and density, various specimens were prepared. Each specimen was prepared by a 5-layer undercompaction method to obtain uniform density throughout (Ladd, 1978). Each layer was compacted to a lower density than the final desired value by a predetermined amount which was defined as percent undercompaction, U_n . The U_n value in each layer was linearly varied from the bottom to the top layer, with bottom (first) layer having the maximum U_n value. The U_n value of the bottom layer was selected as 3%, and uniform density was achieved throughout the specimen. The vari-

ations of compaction water contents and dry unit weights of the tested specimens are shown in Table 2 and Fig. 5.

In test #1, the specimen was compacted at an optimum water content of 9.8% and a 95% of maximum dry density. The effective stress was maintained as 41 kPa and the capillary pressure was varied at 5 steps of 5, 20, 50, 100, and 200 kPa.

In test #2, the specimen was compacted at the same dry density but at a wet side of 3.5% higher water content to investigate the effect of compaction water content on deformation characteristics. The effective stress and the variation of capillary pressure were maintained the same as for test #1.

In test #3, the effect of specimen density was studied by preparing a specimen at a 92.5% of maximum dry density and by maintaining the other factors the same as for test #1.

In order to compare the test results obtained by controlling capillary pressures in tests #1, 2, and 3 with conventional test results obtained by varying compaction water contents, RC tests were performed as follows.

RC tests were performed at the same confining pressure of 41 kPa using three specimens of various compaction water contents without controlling capillary pressure to investigate the differences in deformation characteristics obtained by controlling capillary pressure and by controlling the compaction water contents. The specimens were prepared at a 92.5% of maximum dry density (test #4).

To investigate the differences in deformation characteristics at a given effective stress obtained by changing capillary pressure and by changing confining pressure, the RC tests were performed at the effective confining pressures of 41, 82, 164, and 328 kPa without controlling capillary pressures (test #5).

The typical testing procedure consists of the equalization stage and the RC testing stage. In the equalization stage, the capillary pressure was modified to the prescribed value by raising the specimen air pressure while maintaining the water pressure as an atmospheric pressure. The cell pressure was also increased the same amount to maintain constant effective pressure. The variation of water content was measured using the burette system during this stage. The end of this process was determined at the point where the change rate of water content was less than 0.04%/day (Fredlund, 1995) and it usually took 2–3 days. After the equalization, the RC

Table 1. Basic properties of the tested subgrade soil

Grain size distribution	D_{max} (mm)	15.1
	D_{95} (mm)	4.7
	D_{50} (mm)	1.1
	C_c	1.2
	C_u	7.5
	#200 percent passing	2.5
	#4 percent passing	94
Soil particle density		2.66
Plasticity index (PI, %)		NP
Soil classification	USCS	SW
	AASHTO	A-1-b
Compaction test	OMC (%)	9.7
	Maximum dry density (kN/m^3)	19.7

Fig. 4. Grain size distribution of the tested soil

Table 2. Specimen preparation and testing conditions of five test sets

Test number	Compaction condition				Stress condition	
	Water content (%)	Dry unit weight (kN/m^3)	Void ratio	Degree of compaction (%)	Confinement pressure (kPa)	Capillary pressure (kPa)
Test #1	9.8	18.7	0.39	94.9	41	5/20/50/100/200
Test #2	13.2	18.7	0.39	94.9	41	5/20/50/100/200
Test #3	9.7	18.2	0.43	92.4	41	5/20/50/100/200
Test #4	6.9/8.6/10.0	18.2	0.43	92.4	41	—
Test #5	10.0	18.2	0.43	92.4	41/82/164/328	—

Fig. 5. Compaction conditions of five test sets

Fig. 6. Moisture characteristic curves of tests #1, #2, and #3

tests were performed by increasing the strain amplitude up to about 0.05%.

Moisture characteristic curves of tests #1, #2, and #3 were determined and the relationships between the capillary pressure and degree of saturation are shown in Fig. 6.

TEST RESULTS

Laboratory Test Results

Typical variations in shear modulus with the shearing strain amplitude at various capillary pressures are shown in Fig. 7. By increasing the capillary pressure, the shear modulus was increased at the whole strain range due to the increase of effective stress between soil particles, which is achieved by increasing the cell pressure in the conventional test.

At small strains below the elastic threshold of about $10^{-3}\%$, the maximum shear modulus ($G_{\max}$) values were determined for tests #1, 2, and 3 and the variations in $G_{\max}$ with water content and capillary pressure are plotted in Fig. 8. $G_{\max}$ increases linearly as water content decreases due to capillary pressure. For the specimens which were prepared at the same initial compaction water content (tests #1 and 3), $G_{\max}$ values are located in a

Fig. 7. Typical shear modulus reduction curve with capillary pressure (test #1)

similar region independent of dry density as shown in Fig. 8(a), whereas for the specimen compacted at wet side (test #2), the corresponding $G_{\max}$ value is obtained at a higher water content of 1.5%. When the modulus value is evaluated based on the water content, therefore, it is of importance to prepare the specimen in the laboratory at the same compaction water content as in the field.

The variations in $G_{\max}$ with capillary pressure for the tests #1, 2, and 3 are shown in Fig. 8(b). At the low capillary pressures, the $G_{\max}$ values are similar but as the capillary pressure increases, the difference becomes large. For the specimen compacted at low density (92.5% of maximum), $G_{\max}$ value is consistently lower than $G_{\max}$ of the specimens compacted at 95% of maximum. Contrary to the case with respect to the water content (Fig. 8(a)), $G_{\max}$ values of the specimens of the same density compacted at both optimum moisture content (test #1), and values for the wet side (test #2) are similar in the range of capillary pressure up to 100 kPa. It is interesting to note that $G_{\max}$ is affected by the compaction water content in the relation between $G_{\max}$ and water content, whereas $G_{\max}$ is more affected by the compaction density of the specimen than the water content in the relation between $G_{\max}$ and capillary pressure. In the field, accurate measurement of capillary pressure is so difficult that it is of

Fig. 8. The variations in maximum shear modulus with water content and capillary pressure

value to get a relation between $G_{\max}$ and water content in the laboratory to compare with field values.

In order to compare $G_{\max}$ values determined by controlling capillary pressure with those by controlling the compaction water contents, three specimens of same density were compacted at water contents similar to those in test #3 and RC tests were performed at a same effective stress of 41 kPa (test #4). Testing water contents in both tests of #3 and #4 are similar, but it is achieved by controlling capillary pressure using one specimen in test #3 whereas in test #4 three specimens were prepared at different compaction water contents. As shown in Fig. 9, the relations between $G_{\max}$ and water content are quite different in tests #3 and #4. For the specimens prepared by controlling compaction water contents, the variation in $G_{\max}$ with water content is much flatter and $G_{\max}$ value is smaller at a given water content compared with that for the specimens prepared by controlling capillary pressure. It is worthy to note that the situation in field is similar to the test #3, where one specimen is prepared and the capillary pressure is controlled by seasonal variation of water contents; but, in conventional tests, the compaction water contents are varied as in test #4 to simulate the field condition.

In order to investigate the effect of capillary pressure on strain dependent modulus value, RC tests were performed by increasing the strain amplitude up to about 0.05%. The variations in normalized shear modulus ($G/G_{\max}$) with strain amplitude determined in tests #1, #2, and #3 are shown in Fig. 10. The modulus reduction curves are almost merged to an identical curve independent of compaction water content and density during sample preparation and also independent of variation of water content due to capillary pressure as shown in the figure. This unique trend, which is similar to the test results obtained by Vinale et al. (1999), provides the advantages in determining strain-dependent modulus values combined with the $G_{\max}$ values determined by field seismic method.

In previous studies, however, modulus reduction curve

Fig. 9. Comparison of $G_{\max}$ values in tests #3 and #4

of cohesionless soil is generally affected by the confining pressures, showing that $G/G_{\max}$ increases at a given strain amplitude as the confinement increases (Seed and Idriss, 1970; Kim, 1991; Kim and Stokoe, 1992). The variations in $G/G_{\max}$ with strain amplitude were also determined at the various confining pressures by controlling cell pressures as a conventional way (test #5) and the results were compared with the results obtained by controlling capillary pressures in Fig. 11. The modulus reduction curves obtained by controlling cell pressure do not match with the results determined by controlling the capillary pressure and were affected by the confinement, showing a similar trend with the previous results. Even if the effective stress between the soil particles is identical, the one is achieved by controlling the capillary pressure whereas the other is achieved by increasing cell pressures. The reasons of difference are now being studied and the further study is underway.

Field Test Results

In the pavement system, the subgrade soils are unsaturated and the water contents vary seasonally by precipita-

Fig. 10. Normalized shear modulus reduction curves in tests #1, #2 and #3

Fig. 11. Comparison of normalized shear modulus reduction curves in tests #1, #2, #3 and #5

tion and freeze-thaw. The effective stress between soil particles is affected by the capillary pressure induced by the variation of water content. To assess the applicability of the laboratory test results, the in-situ crosshole tests were performed at a test road site where the samples for laboratory tests were collected.

The test road site is located at the Chungbu Inland Expressway which is now being constructed by Korea Highway Corporation. The construction was finished up to the final level of subgrade soil and two test holes were installed to the depth of 1.5 m with 2.6 m spacing. The crosshole tests were performed at 0.1 m interval and the shear wave velocity was measured at each depth by monitoring the arrival time of the shear wave. The maximum shear modulus was calculated by using the average

density of 1.85 t/m^3 measured by sand cones. The schematic diagram of the crosshole test and the typical measured signals are shown in Fig. 12.

The variation in water content of the site with depth was measured by collecting the samples with an auger. Two days before the field testing, it rained and the water content of the subgrade soil was varied, decreasing with depth as shown in Fig. 13(a). The variations in shear wave velocity and the calculated maximum shear modulus with depth were determined by crosshole tests and plotted in Fig. 13(b) and Fig. 13(c), respectively.

Water content increased near the ground surface to the depth of 0.4 m due to the infiltration of rainfall, and below 0.4 m it was maintained as about 8% which is similar to the compaction water content in the field. The shear

Fig. 12. Crosshole test configuration and typical signal

Fig. 13. Field water content and results of field crosshole test

wave velocity and the corresponding $G_{\max}$ increased with depth as the water content decreased up to the depth of 0.4 m, similarly as shown in the laboratory tests. The slight increase of shear wave velocity below 0.6 m can be explained by the increase of confinement with depth.

The variations in shear wave velocity and $G_{\max}$ with water content determined by crosshole tests are plotted in Fig. 14. The laboratory test results determined by controlling capillary pressures (tests #1, 2, and 3) and by controlling compaction water contents (test #4) are also plotted in the same graph for the purpose of comparison. The effect of confinement was not corrected for in the comparison because the difference in overburden pressure is negligibly small and the correct value of earth pressure

coefficient at rest is difficult to estimate. It is very interesting to note that the shear wave velocities determined by in-situ crosshole tests match well with those determined in the laboratory tests by controlling capillary pressures (tests #1, 2, and 3), but show a substantial difference with results obtained by controlling compaction water contents (test #4). In order to correlate the field and laboratory results, therefore, it can be concluded that it is better to get a relationship between the maximum shear modulus and the water content by controlling capillary pressures using one specimen compacted in the field condition rather than by performing conventional tests which use specimens prepared at various compaction water contents. This indicates the advantage of the developed

Fig. 14. Comparison of field crosshole tests and laboratory tests

testing system and also shows the potential for use in the estimation of in-situ shear modulus of subgrade soils with seasonal variation of water contents. Once the shear wave velocity and/or $G_{\max}$ is determined either directly by performing in-situ seismic test or by adopting the correlation between $G_{\max}$ and water content developed by the proposed laboratory test, the strain dependent shear modulus of subgrade soil can be estimated at a certain water content by employing the normalized modulus ($G/G_{\max}$) reduction curve.

CONCLUSIONS

The water content of soil near the ground surface varies seasonally, and shear modulus of soil is significantly affected by the variations of water content and corresponding capillary pressure. Contrary to previous studies which used various specimens of different compaction water contents, the influences of water content and capillary pressure on shear modulus were investigated using a given specimen and controlling capillary pressure. The Stokoe-type torsional resonant column (RC) testing equipment was modified to control the pore air and pore water pressures separately and to measure the variation of water content due to capillary pressure.

Based on this study, it was found that the shear modulus was increased at the whole strain range due to the increase of effective stress between soil particles as the capillary pressure increased. The maximum shear modulus ($G_{\max}$) was increased with decreasing water content and $G_{\max}$ value was smaller at a given water content for specimens prepared by controlling compaction water contents compared with those tested by controlling capillary pressures. The normalized modulus ($G/G_{\max}$) reduction curve was almost unique independent of compaction water content and density during sample preparation and variation of water content due to capillary pressure during testing. Field crosshole tests were also performed and showed that $G_{\max}$ values determined by crosshole tests matched well with those determined by controlling capil-

lary pressures in the laboratory but showed substantial differences with results obtained by controlling compaction water contents.

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