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Electrical Conductivity for Evaluating Fabric and Mechanical Behavior of Granular Soils

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SYNOPSIS: In this study, an auto-compensation conductivity measurement system has been developed. This system is expected to offer a possible means for describing the granular soil fabric and mechanical behaviors. A series of cyclic triaxial compression, extension, and unloading tests with resistance measurement were performed. The correlation between granular soil friction angle ϕ, and vertical formation factor, F_v under maximum shear stress ratio has been studied. The test results have shown that the electrical conductivity could be used to evaluate the fabric behavior during the process of loading. The fabric ellipsoid function, which has been used to simulate the orientation strength for sedimentation granular soil, was described.

INTRODUCTION

During the process of alluvial sedimentation, the granular soil grains deposited under gravity and then subjected to one-dimensional compression loading, are likely to develop an prefered orientation. Oda(1972a, b) and Mitchell et al.(1976) have shown that the initial fabric has great influences on mechanical properties and governs its anisotropic and the deformation behaviors during shearing process. The fabric properties of granular soils can be described by "Packing" and "Grain Properties"(Arulmoli et al.,1985). In recent studies(Arulanadan et al., 1978, Arulmoli, 1983), it has been shown that the electrical conductivity is a possible measurement for granular soil fabric, and it is also recognized that formation factor is a dependent of the shape, the arrangement, and the gradation of the particles. However, no experiment has been performed to evaluate the fabric of soil during loading process. In this study, an electrical experiment system is developed to evaluate the initial fabric and the fabric change during the cyclic loading process. By use of various types of stress paths, it is expected that sedimentation orientation effect on the mechanical behavior of granular soil can be simulated. The electrical parameters are also monitored to study its correlation with the mechanical behaviors.

CONDUCTIVITY SYSTEM DEVELOPMENT AND DESIGN

The electrical conductivity measurement must consider the effects of temperature, solution concentration, cell constant and alternating current frequency(Li et al., 1988). In this study, cell constant and temperature are the two major affecting factors being investigated.

Principle of Conductivity Measurement

The basic principle of conductivity measurement is the Ohm's Law. By use of a standard resistor R_s(Figure 1) as a reference for comparison. A sine wave of 300 mV at 1k Hz was used as power supply between standard resistor and measurement electrodes. The resistance to be measured can be computed with:

$$R_{sp} = (V_{sp} / V_s) R_s \tag{1}$$

in which V_s = the potential drop on reference resistor; V_{sp} = the voltage measured between the electordes. Since the compensations of cell constant and temperature effects measurement process have been considered, the conductivity of saturated sand fabric could be obtained.

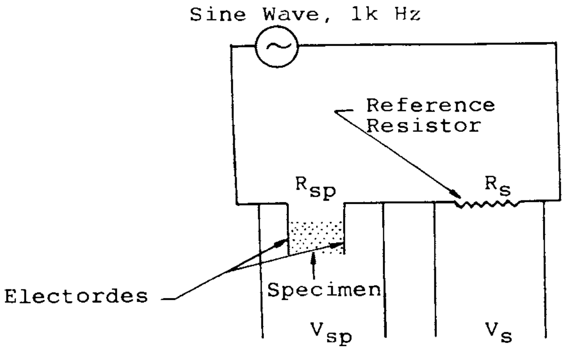

Fig. 1 Simple Current for Resistance Measurement.

Conductivity Measurement System Design

According to the sensitivity test of the various factors stated above, an auto-compensation measurement system has been developed(Chien, et al., 1988). Figure 2 shows the schematic of the complete instrumentation system for this investigation. In this system, by use of platinum probe at 1k ohm, temperature effect could be compensated automatically to the selected reference temperature(typically at 25°C). In addition, cell constant could also be selected. The equipment resolution has been as high as 16 bits.

SAND CHARACTERISTICS AND SPECIMEN PREPARATION

Three different sands were used in the testing

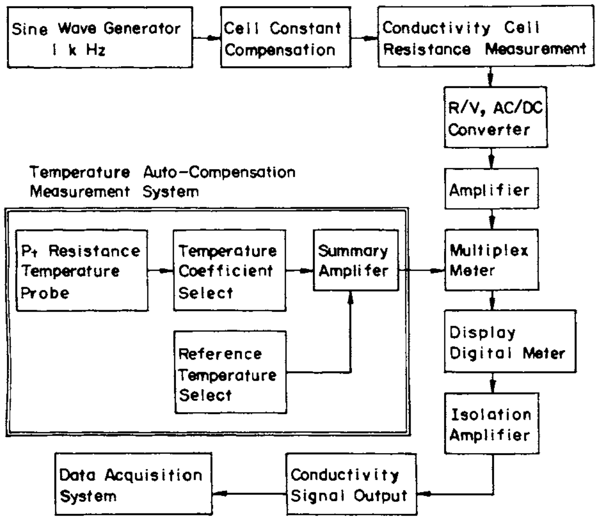

Fig. 2 Schematic Diagram of Sand Conductivity Measurement System.

program. All samples have been washed in distilled and deioned water. The particle size is sieved to No. 100 - No. 40. In order to determine the particles size and shape properties, scanning electronic microscope were used. The characteristics of the samples are summarized in Table 1.

The specimens were prepared by multiple sieving pluviation method(MSP method, Vaid et al., 1984) and Moist tamping method(MT method, Mitchell et al.,1976) for three different sands under various porosities.

ORIENTATION STRENGTH

The degree of interlocking of naturally deposited granular sand are different for various orientation. Therefore, the frictional resistance various with the orientation. Strength in various orientations may be back calculated from compression tests on samples with various bedding plane angle. The frictional angle, ϕ can be determined by the ratio of major to minor principal stresses at failure as follows:

$$\sigma_1 \,/\, \sigma_3 = \tan^2(45 + \phi/2) \qquad (2)$$

Chien et al.(1988) investigated specimens prepared by MSP method. The axis coincides with the gravitational direction associated with the sample preparation. Two sets of horizontal direction formation factor, F_{h1}, F_{h2} are close, therefore it has a tendency to align the axis of the particles in the horizontal plane.

To investigate the mechanical behavior of granular sands with different sedimentation angle, specimens were loaded to various major principal stress direction using electrical cyclic triaxial compression test(CTC test). The major principal stress for this test is perpendicular to the long axis direction of grains and the angle between major principal stress and particle deposition direction, which may be represented as α, is 0° . For electrical cyclic triaxial extension test(CTE test), the major principal stress is parallel to the long axis direction of grains and the angle α is 90°. Using Eq. 2, the frictional angles of planes with various orientations are computed from the failure stress ratio σ_1/σ_3 for cyclic electrical triaxial tests. From the formation factor, results have shown that the sedimentation granular sand properties are axisymmetrical to the axis perpendicular to the deposit plane, thus the frictional angle, may be described by the fabric ellipsoidal function as follows:

$$\phi = \frac{\phi_{max}}{\left(\cos^2\alpha + (\phi_{max}/\ \phi_{min})^2 \sin^2\alpha\ \right)^{1/2}} \qquad (3)$$

in which ϕ is maximum when α = 0° and is minimum when α = 90°. For an isotropic strength granular soil, Eq. 3 becomes a spherical function with equal strength with respect to all orientations. Using Eq. 2, the soil frictional angles, ϕ with variousorientations are computed from the principal stress ratio at failure for CTC tests and CTE tests(Figure 3). The calculated frictional angles are plotted in Figure 4 under different relative densities for Fulong sand. Comparisons between the test points and the ellipsoidal curve from Eq. 3 have good correlation.

The initial sand fabric properties is very important for understanding mechanical behaviors. In this study, the initial vertical formation factor, F_{vo} is also used to describe the initial fabric properties. The test results have shown that the frictional angle of granular soil increases with increasing initial vertical formation factor. Figure 5 shows that initial fabric of granular sand and frictional

Table 1 Sands Characteristics.

Sand	G_s	D_{50} (mm)	C_u[1]	γ_{max}[2] (g/cm^3)	γ_{min}[2] (g/cm^3)	Average Axial Ratio, PR_{ave}[3]	Particle Description
Ottawa C-109	2.63	0.28	1.58	1.769	1.479	0.755	Sub-Round
Fulong Sand	2.66	0.20	1.25	1.613	1.311	0.738	Sub-Angular
Tan-Shui Sand	2.67	0.24	1.49	1.577	1.240	0.698	Angular

[1] C_u = coefficient of uniformity D_{60}/D_{10}.

[2] In accordance with JSF T26-81T test for maximum(γ_{max}) and minmum(γ_{min}) dry unit weight.

[3] PR_{ave} = average axial ratio, short axis / long axis(Oda, 1977).

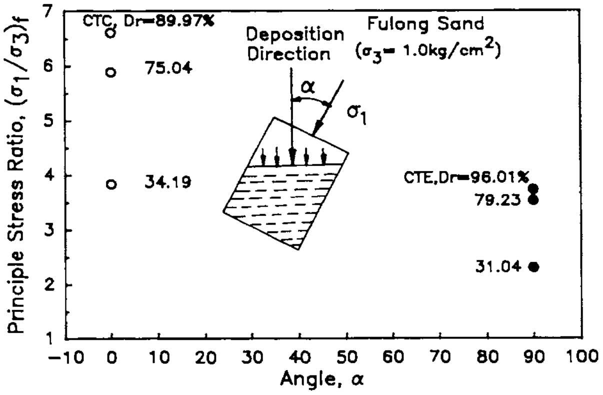

Fig. 3 Correlation Between Different Sedimentation Angles(CTC, $\alpha = 0°$; CTE, $\alpha = 90°$) and Principal Stress Ratio at Failure under Various Relative Density.

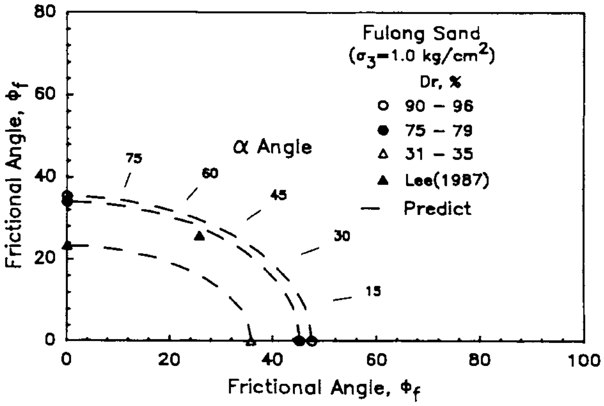

Fig. 4 Correlation Between Sedimentation Angles and the Failure of Frictional Angles.

angle have good correlation, and may be described by equations as following:

Fulong sand,

$$\phi_f = -23.60 + 17.88\ F_{vo},\ R = 0.996 \tag{4a}$$

Ottawa C-109 sand,

$$\phi_f = -\ 8.95 + 10.08\ F_{vo},\ R = 0.999 \tag{4b}$$

in which ϕ_f = the frictional angle at failure; R = correletion coefficient.

FABRIC CHANGE DURING SHEARING PROCESS

When a saturated sand is deformed, neighboring particles may form new contacts, and induce the change of the fabric. According to Chien et al. (1988), the measured conductivity, $\kappa_m(t)$ at any strain state by using the conductivity measurement system should include two components; one is resulted by the electrode distance change, $\kappa_c(t)$ another is resulted by the fabric change, $\kappa_f(t)$.

$$\kappa_m(t) = \kappa_c(t) + \kappa_f(t) \tag{5}$$

The conductivity resulted by the fabric change may be computed as follows:

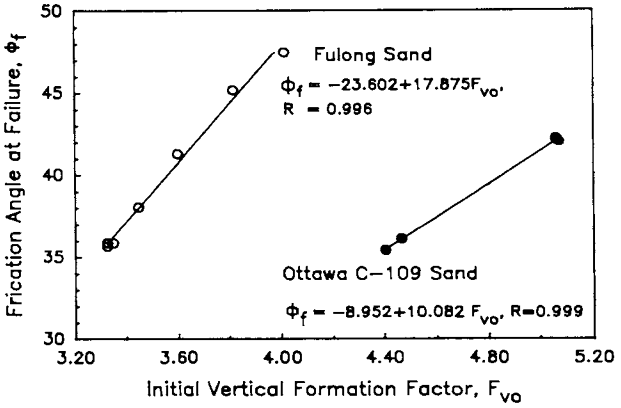

Fig. 5 Relationship Between Initial Vertical Formation Factor and Friction Angle at Failure for Different Sands.

$$\kappa_f(t) = \kappa_m(t)\cdot(C_c(t)/C_{co}) \tag{6}$$

in which C_{co} = initial cell constant at initial measured adjustment (expressed in the unit of cm^{-1}); $C_c(t)$ = the effective cell constant at any strain state. According to Archie's(1942), the formation factor definition, the vertical formation factor, $F_v(t)$ during the shearing process may be calculated by equation as following:

$$F_v(t) = \kappa_s\ /\ \kappa_f(t) \tag{7}$$

in which κ_s = the conductivity of the pore solution (expressed in the unit of m-mho/cm), and can be observed by conductivity meter. Using Eq. 6 and Eq. 7 it is possible to computed $\kappa_f(t)$, the conductivity induced by fabric change during the shearing deformation and the vertical formation factor, $F_v(t)$ at the same time. Fig. 6 shows the fabric of granular sands at initial state and failure state in relation to vertical formation factor, F_v.

From the test results, it is indicated that F_v decreased at maximum principle stress ratio for CTC tests($\alpha = 0°$). The difference of F_v value between the initial state and that of after shearing deformation has shown an increasing tendency with decreasing porosity of granular sands. On the contrary, there is a diferent tendency in CTE tests($\alpha = 90°$). This may be explained by the fact that the long axis orientation of the particles for the fabric of granular sands are generally rotated to support the external stress during deformation process. Therefore, the long axis direction of the particles is generally perpendicular to the direction of the major principal stress.

Fig. 7 shows the variation of sand fabric under cyclic loading and unloading process. This may indicate that only a part of fabric of sample recovers during unloading. The fabric has reached a new state and can not go back to the original state. It also shows that the conductivity measurement system can be used to describe the change of the fabric for an saturated sand under shearing deformation.

CONCLUSIONS

Considering the effects of the electrical

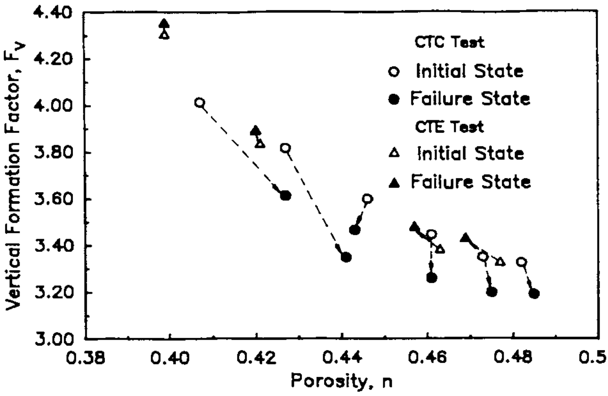

Fig. 6 Vertical Formation Factor vs. Porosity Relationship Between Initial State and Failure State under Cyclic Loading.

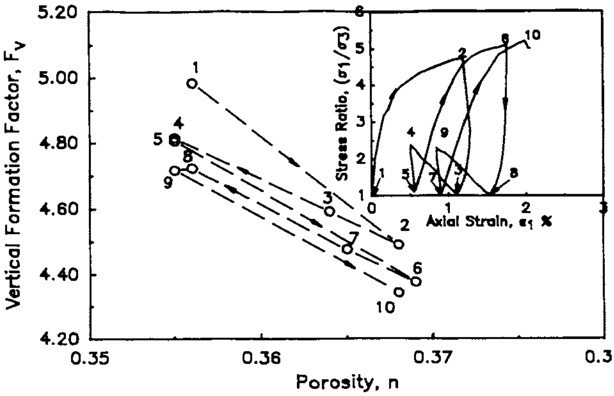

Fig. 7 The Various of Sand Fabric Under Cyclic Loading and Unloading Process.

conductivity of saturated granular soil, an auto-compensation conductivity measurement system has been developed. From above analysis, the validity of this system was checked and could be used to evaluate the initial fabric and the mechanical behavior of granular soil under shearing deformation. The generalized relationship between the vertical formation factor and orientation strength has been obtained using electrical theory and laboratory electrical measurements on sand. The fabric ellipsoid function, which has been used to simulate the orientation strength for sedimentation granular soil, was described. Reasonable agreement between predicted and simulated characteristics do exist. It can be concluded that electrical conductivity investigation system can be used to evaluate the mechanical behavior of the granular soil fabric.

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