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13. ABSTRACT *(Maximum 200 words)*

The primary objective of the study was to develop an understanding of the stress-strain relationship and other related geotechnical properties of cohesive materials such as clays from a microstructural point of view. In the theoretical area, several theories were developed for quantifying the physico-chemical forces between two clay particles, immersed either in water or in a chemical contaminant. With the aid of these theories, a numerical modeling technique, based on the discrete element method, was developed to study the micromechanical behavior of clays. Experiments were conducted to examine the effects of chemicals on the behavior of cohesive soils. On the basis of the numerical and experimental results, the stress-strain behavior of clays is studied from a microstructural view point.

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FINAL TECHNICAL REPORT

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OBJECTIVES

The primary objective of the study was to develop an understanding of the stress-strain relationship and other related geotechnical properties of cohesive materials such as clays from a microstructural point of view.

To achieve the goals, it was proposed (1) to develop a numerical simulation technique based on the discrete element method (DEM), (2) to perform laboratory experiments to acquire the necessary microscopic and macroscopic data, and (3) to use the numerical tool developed in (1) and the data gathered in (2) to develop the desired microscopic understanding.

Specific goals of the proposed study were:

1. development of a method of simulating bending of clay particles,
2. development of a method of quantifying the electrical double-layer repulsive force between two nonparallel clay particles,
3. development of a method of quantifying the van der Waals attractive force between two nonparallel clay particles,
4. development of a method of using theories developed in (2) and (3) above in computing the interparticle physico-chemical force between two particles in an assembly of many particles,

5. development of a suitable DEM strategy, including a variable time stepping scheme,

6. development of a scalar, two-dimensional computer code,

7. development of a parallel, two-dimensional computer code,

8. Performing triaxial experiments on clays saturated in various chemicals (e.g., water, benzene, heptane, etc.),

9. Measuring, during one-dimensional compression and triaxial experiments, the variation of fabric anisotropy with the aid of a nondestructive electrical method, and

10. development of desired fundamental understanding using the computer codes developed in (6) and (7), and the experimental data gathered in (8) and (9).

RESULTS

The goals (1) through (9) have been achieved completely. Significant progress has been made towards achieving the goal (10).

The results of the study have been disseminated as follows: (a) six (6) journal papers have been published and/or are in press, and three (3) journal papers have been submitted for possible publication, (b) twelve (12) conference papers have been written and presented and/or are scheduled to be presented, (c) three doctoral theses have been published, (d) four journal papers are currently under preparation (from the results of one of the Ph.D thesis; a copy of which is attached). In addition, during the period of the project, five (5) invited lectures have been given on the basis of the results from the study. The publications are listed below.

PUBLICATIONS

Journal Papers Published/in Press

1. Anandarajah, A., Kuganenthira, N. and Zhao, D., "Variation of Fabric Anisotropy of Kaolinite in Triaxial Loading," *J. Geo. Engr. Div.*, ASCE, Vol. 122, No. 8, Aug. 1996, pp. 633-640.

2. Anandarajah, A. and Chen, J., "Single Correction Function for Retarded van der Waals Attraction," *J. Colloid Interface Sci.*, Vol. 176, No. 2, 1995, pp. 293-300.

3. Chen, J. and Anandarajah, A., "Van der Waals Attractive Force Between Spherical Particles," *J. Colloid Interface Sci.*, Vol. 180, 1996, pp. 519-523.

4. Anandarajah, A., "Structure of Sediments of Kaolinite," *Engineering Geology* (in press).

5. Anandarajah, A. and Chen, J., "Van der Waals Attractive Force Between Clay Particles in Water and Contaminant," *Soils and Foundations*, Japanese Society of Soil Mechanics and Foundation Engineering, June 1996, Vol. 37, No. 7.

6. Kuganenthira, N., Zhao, D. and Anandarajah, A., "Measurement of Fabric Anisotropy in Triaxial Shearing," *Geotechnique*, Vol. 46, No. 3, 1996.

Journal Papers Currently in Review

1. Chen, J. and Anandarajah, A., "Influence of Pore Fluid Chemistry on Fabric and Volume of Sediments in Kaolinite Suspensions," *Clays and Clay Minerals.*

2. Anandarajah, A., Influence of Particle Orientation on One-Dimensional Compression of Montmorillonite," *J. Coll. Int. Sci.*.

3. Chen, J. and Anandarajah, A., "Numerical Simulation of One-Dimensional Behavior of Clay Suspensions," *Computing in Civil Engineering*, ASCE.

Conference Papers, Written for Publication in Proceedings and Presented

1. Anandarajah, A.,and Yao, M. "Discrete Element Analysis of Clays on a Parallel Computer," *Proc. Fourth Congress on Computing in Civil Engineering*, ASCE, Philadelphia, Pennsylvania, June 16-18, 1997.

2. Anandarajah, A.,and Yao, M. "Parallel Algorithm for Discrete Element Analysis of Clays," *Proc. Joint ASCE/ASME Conference: McNu'97*, Northwestern University, June 29-July 2, 1997.

3. Anandarajah, A., "Numerical Analysis of Clay Particle Assembly," *IUTAM Symp. on Mechanics of Granular and Porous Materials*, Cambridge University, England, UK, July 15-17, 1996.

4. Anandarajah, A., "Discrete Element Method for Platy Colloidal Particles," *ASME Mechanics and Materials Conf.*, The Johns Hopkins University, Baltimore, Maryland, June 12-14, 1996.

5. Anandarajah, A. and Chen, J., "Theoretical and Experimental Investigation of the Behavior of Contaminated Clays," *3rd Intl. Symp. on Environmental Geotechnology*, San Diego, California, (eds. H-Y. Fang and H.I. Inyang),Technomic Publishing Co., June 10-12, 1996, pp. 170-179.

6. Anandarajah, A. and Zhao, D., "Stress-Strain Behavior of Contaminated Kaolinite," *3rd Intl. Symp. on Environmental Geotechnology*, San Diego, California, (eds. H-Y. Fang and H.I. Inyang),Technomic Publishing Co., June 10-12, 1996, pp. 180-188.

7. Anandarajah, A., "Fabric Anisotropy and Its Relationship to Macroscopic Constitutive Behavior of Clays," *11th EMD Specialty Conf., ASCE*, Fort Lauderdale, Florida, May 19-22, 1996.

8. Anandarajah, A., "Macroscopic Constitutive Behavior of Clays from Microscopic Considerations," *11th EMD Specialty Conf., ASCE*, Fort Lauderdale, Florida, May 19-22, 1996.

9. Anandarajah, A. "Physico-Chemical Interactions Between Clay Particles," *Proc. 5th International Symposium on Numerical Models in Geomechanics*, Davos, Switzerland (eds. G. N. Pande and S. Pietruszczak), A. A. Balkema Publishers, 6-8 September 1995, pp. 89-94.

10. Anandarajah, A., "Theoretical and Experimental Studies of Microstructural Processes Related to Inelastic Stress-Strain Behavior of Cohesive Soils," *Proc. AFOSR Particulate Mech. Contractor/Grantee Meeting*, 22-23 Sept. 1995, Tyndall AFB, Panama City, Florida.

11. Anandarajah, A., Chen, J. and Lu, N., "Discrete Element Analysis of Clays," Proc. EMD Specialty Conference, ASCE, Boulder, Colorado, May 21-24, 1995.

12. Anandarajah, A., "Micromechanics of Clays Evaluated by the Discrete Element Method," *8th Int. Conf. Computer Meth. and Advances in Geomechanics*, West Virginia, May 22-28, 1994.

Doctoral Theses Published

1. Kuganenthira, N., "Experimental Study of Fabric Anisotropy of Soils During One-Dimensional and Triaxial Loading," The Johns Hopkins University, October 1995.

2. Zhao, D., "Experimental Study of Stress-Strain and Shear Strength Behavior of Contaminated Cohesive Soils," The Johns Hopkins University, February, 1996.

3. Chen, J., "Physico-Chemical Analysis of Contaminated Clays," The Johns Hopkins University, February, 1996.

Invited Lectures on the Subject

1. Anandarajah, A., "Discrete Element Simulation of the Microstructure of Marine Cohesive Sediments," Naval Research Laboratory, Stennis Space Center, August 25, 1996.

2. Anandarajah, A. "Quantitative Analysis of Contaminated Clays with Special Consideration to van der Waals Attractive and Double-Layer Repulsive Forces," Department of Civil Engineering, University of California, Davis, October June 4, 1996.

3. Anandarajah, A. "Interaction Between Clay Particles in a Fluid", *Proc. intl. workshop on "Hydro-Thermo-Mechanics of Engineered Clay Barriers and Geologic Barriers"*, Montreal, Quebec, Canada, July 5-7, 1995.

4. Anandarajah, A., "Study of the Mechanics and Physics of Cohesive Particle Behavior," *Proc. Workshop. on "Sediment Geoacoustical & Geotechnical Constitutive Modeling*, November 13-14, 1995, University of Rhode Island, Narragansett, Rhode Island.

5. Anandarajah, A., "Surface Interaction Between Clay Particles and Numerical Modeling of a System of Clay Particles," *Proc. Workshop on Mechanics and Statistical Physics of Particulate Media*, La Jolla, San Diego, June 8-10, 1994.