Georgia Tech Sponsored Research

Project	E-20-604
Project director	Rix Glenn
Research unit	CEE
Title	Attenuation Mechanisms & Measurements
Project date	12/31/2000

20

Final Report for Period: 10/1997 - 09/2000 **Submitted on:** 02/07/2001

Principal Investigator: Rix, Glenn J.

Award ID: 9616013

Organization: GA Tech Res Corp - GIT

Attenuation Mechanisms and Measurements

Project Participants

Senior Personnel

Name: Rix, Glenn
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: Santamarina, J. Carlos
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Wang, Yu-Hsing
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate research assistant working with Dr. Santamarina on attenuation mechanisms at the micro scale.

Name: Fratta, Dante
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate research assistant working with Dr. Santamarina on tomographic inversion of velocity and attenuation data.

Name: Zywicki, Daren
Worked for more than 160 Hours: Yes
Contribution to Project:
Graduate research assistant working with Dr. Rix on array-based signal processing of active and passive surface wave dispersion and attenuation.

Name: Fernandez, Americo
Worked for more than 160 Hours: Yes
Contribution to Project:
Americo Fernandez worked as a Graduate Research Assistant under the supervision of Dr. Carlo Santamarina

Name: Valdes, Julio
Worked for more than 160 Hours: Yes
Contribution to Project:
Julio Valdes worked as a Graduate Research Assistant under the supervision of Dr. Glenn J. Rix

Name: Meng, Jiewu
Worked for more than 160 Hours: Yes
Contribution to Project:
Jiewu Meng worked as a Graduate Research Assistant under the supervision of Dr. Glenn J. Rix

Name: Yoon, Sungsoo
Worked for more than 160 Hours: No
Contribution to Project:
Sungsoo Yoon worked as a Graduate Research Assistant under the supervision of Dr. Glenn J. Rix

Name: Hebeler, Gregory
Worked for more than 160 Hours: No

Contribution to Project:
Greg Hebeler worked as a Graduate Research Assistant under the supervision of Dr. Glenn J. Rix

Undergraduate Student

Organizational Partners

UNAM
Dr. A. Diaz Rodriguez - dynamic behavior of soft sediments

INTEVEP
Dynamic behavior and liquefaction of loose, saturated soils

Mid-America Earthquake Center
Dynamic behavior of partially saturated soils
Post-liquefaction strength of soils
Dynamic soil properties in the central U.S.
Ground motion amplification in deep soil deposits

Other Collaborators or Contacts

U.S. Geological Survey - Memphis, TN: We employed the in situ methods of measuring attenuation and damping developed in this study to characterize 11 sites in the Memphis, TN area during the summer of 2000.

ANSS-MA: During the summer of 2001, we will perform additional tests to help characterize dynamic soil properties at the sites of planned strong motion stations for the Advanced National Seisimic System (ANSS) deployment in Mid-America.

Activities and Findings

Project Activities and Findings:
Material damping is a fundamental soil property that provides insight into the mechanics of particulate media and strongly influences the response of soils to dynamic loads. The objective of this project was to improve our understanding of the mechanisms that contribute to energy losses in soils and to develop innovative methods for measuring attenuation and damping in the field and lab.

FUNDAMENTAL ATTENUATION AND DAMPING MECHANISMS

The study involved an extensive literature review, extending to all related areas including soil mechanics, geophysics and material science.

It was clearly recognized that small-strain attenuation cannot be justified with standard frictional models. Consider a propagating wave that causes 10-7 strain. The relative displacement between the centers of 1 mm particles is 10-10 m. Even if all this displacement is localized at contacts, it would not be enough to break atomic bonds. Alternative explanations were sought.

The first one area involved a critical review of measurement difficulties. Special emphasis was placed in clarifying energy losses in the instrumentation. In particular the counter electromotive effect in resonant column was resolved.

Material losses in dry sands at very-small to small-strain level were explored in relation to thermal-mechanical coupling. The experimental investigation involved using sophisticated devices such as high thermal resolution IR cameras in association with photoelastic studies of force distribution in granular media. Results highlight the relevance of multiple length scales (contact scale, chain scale and wavelength scale).

The attenuation in moist sands at very-small to small-strain level could not be explained with Biot-type and hydrodynamic pendular-water analyses. New physical processes were identified related to the hysteresis in contact generation and loss between asperities coated with monolayers of water. The microscale experimental studies were conducted with the stylus of an AFM under environmentally controlled relative humidity conditions. The macroscale studies were conducted in a modified resonant column.

Non-linear dynamic effects in frictional geomaterials were also studied. The relationship between friction, damping, and the non-linear energy coupling in granular material was studied in the context of stochastic resonance phenomena. Single mineral interface and soils were tested.

ATTENUATION AND DAMPING MEASUREMENTS IN THE FIELD AND LAB

Field-related studies included theoretical studies and modeling of seismic surface wave fields and estimation algorithms, field testing with spatial arrays, and implementation of advanced signal processing methods to extract optimum estimates of attenuation. We applied and optimized spatial array processing techniques for geotechnical surface wave testing and performed simulations using synthetic data. A suite of computer software algorithms to implement these theoretical and simulation studies was developed.

We also performed various field tests using spatial array measurements at sites in the Atlanta, GA and Memphis, TN areas. The field tests required the deployment of two dimensional spatial arrays along the ground surface and sampling of the ambient seismic wave field with a multichannel dynamic signal analyzer. The system control software, including array and signal processing setup, sampling characteristics, and the ability to view some real-time, in-field results were also developed.

The experimental data were analyzed using various multidimensional and advanced signal processing power spectrum estimators. Active and passive surface wave data were analyzed with the different algorithms to determine the applicability of the methods to different problems. We also focused on developing an optimum method to estimate passive wave attenuation coefficients, depending on signal and noise wave field characteristics.

In addition, emphasis was placed on developing methods that allow for the simultaneous inversion of velocity and attenuation. Much emphasis on tomographic inversion with seismic waves has been placed on travel time tomography; we have extended the methodology to amplitude-based tomography. Matrix based algorithms were modified to apply a similar set of numerical formalisms to amplitude data (e.g., regularized least squares, with fuzzy-logic based initial guess).

Project Training and Development:
The laboratory experimental study has led to: (1) the definitive correction of inherent measurement biases in resonant column testing, (2) the clarification of the role of various internal scales in thermo-mechanical coupling, (3) the identification of new loss mechanisms such as the hysteresis of adsorbed layers around asperities, and (4) recognizing stochastic resonance as an important phenomenon in frictional materials.

The application of advanced signal processing methods to the analysis of surface wave dispersion and attenuation has:
1. enabled us to understand the spectral properties of various array geometries, number of sensors, and weighting of the sensor outputs via the array smoothing function;
2. enhanced our ability to identify and resolve multiple modes of surface wave propagation; and
3. allowed us to incorporate body wave interference and near field effects with accurate cylindrical wave field modeling and advanced spectrum estimators.

We have demonstrated that amplitude-based tomography not only complements travel time tomography, but it can render more robust inversions. This is particularly the case when thin anomalies are present in the medium: they cause very small phase shift but significant amplitude decay. Simultaneous measurement and inversion of surface wave velocity and attenuation also results in more robust estimates of shear wave velocity and material damping ratio.

Research Training:
Information learned in this research has already been included in four advanced graduate courses:

'Signal Processing and Inverse Problem Solving'
'Soils Behavior and Wave-based Characterization'
'Dynamic Analysis in Geotechnical Engineering'
'Geotechnical Earthquake Engineering'

Outreach Activities:
A short course on geophysical methods has been taught at two ASCE Geo-Insitute Conferences (Seattle'98 and Urbana'99) and two EEGS Symposia on the Application of Geophysics to Envrionmental and Engineering Problems (Reno'98 and Washington, DC '00).

The PIs have presented seminars on the results of this study at leading institutions including MIT, UC-Berkeley, UC-Davis, Duke U., UT-Austin, Louisiana State U., and U. Colorado Boulder.

Journal Publications

Prada, J., Fratta, D., and Santamarina, J.C., "Tomographic Detection of Low-velocity Anomalies With Limited Data Sets (Velocity and Attenuation)", *ASTM Geotechnical Testing Journal*, p. 472, vol. 23, (4).) Published
Rix, G.J., Lai, C.G., and Foti, S., "Simultaneous Measurement of Surface Wave Dispersion and Attenuation Curves", *ASTM Geotechnical Testing Journal*, p. , vol. , (2001).) Accepted
Lai, C.G. and Rix, G.J., "Solution of the Rayleigh Eigenproblem in Viscoelastic Media", *Bulletin of the Seismological Society of America*, p. , vol. , ().) Submitted
Fernandez, A. and Santamarina, J.C., "The Effect of Cementation on the Small Strain Parameters of Sands", *Canadian Geotechnical Journal*, p. , vol. 2001, ().) Accepted
Santamarina, J.C. and Fratta, D.O., "Dynamic energy coupling - Electro-seismic and Seismo-electric effects", *J. Transport in Porous Media*, p. , vol. 2001, ().) Submitted
Wang, Y. H., and Santamarina, J.C., "Non-Linear Dynamic Effects in Frictional Geomaterials - Stochastic Resonance", *J. Geotechnical and Geoenvironmental Engineering*, p. , vol. 2001, ().) Submitted

Books or Other One-time Publications

Santamarina, J.C., Klein, K., and Fam, M., "Soils and Waves", (2001). *Book*, Published
Bibliography: John Wiley and Sons

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Editor(s): P.K. Robertson and P.W. Mayne
Collection: Geotechnical Site Characterization
Bibliography: Balkema, Rotterdam

Zywicki, D.J., and G.J. Rix, "Frequency-Wavenumber Analysis of Passive Surface Waves", (1999). *Conference paper*, Published
Collection: Proceedings, Symposium on the Application of Geophysics to Engineering and Environmental Problems
Bibliography: pp. 75-84

Rix, G.J., C.G. Lai, M.C. Orozco, G.L. Hebeler, and V. Roma, "Recent Advances in Surface Wave Methods for Geotechnical Site Characterization", (2001). *Conference Proceedings*, Accepted
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Valdes, J.R., "Simultaneous Determination of Frequency-Dependent Modulus and Damping from Resonant Column Tests", (1999). *Thesis*, Published
Bibliography: Master's Thesis, Georgia Institute of Technology

Stokoe, K.H. and Santamarina, J.C., "Seismic-Wave-Based Testing in Geotechnical Engineering", (2000). *Conference Proceedings*, Published
Collection: Proceedings, GeoEng 2000, Melbourne, Australia
Bibliography: pp. 1490-1536

Web/Internet Sites

URL(s):
http://www.ce.gatech.edu/~grix/
http://www.ce.gatech.edu/~carlos/Laboratory/labmain.html
http://www.ce.gatech.edu/~carlos/Laboratory/P&R/YHW-poster.jpg
http://www.ce.gatech.edu/~carlos/Laboratory/P&R/YHW_res.html

Description:
Surface wave forward modeling and inversion software developed on this project is made available for use by others and results related to material behavior and energy losses are presented.

Other Specific Products

Product Type: Software (or netware)
Product Description:
Matlab-based software to control data acquisition for passive surface wave measurements using a multichannel Agilent VXI system.

Sharing Information:
This program will be added to others available at http://www.ce.gatech.edu/~grix for surface wave analysis.

Product Type: Software (or netware)
Product Description:
Matlab and Fortran 90 programs for forward modeling and inversion of surface wave dispersion and attenuation.

Sharing Information:
Available via http://www.ce.gatech.edu/~grix

Contributions

Contributions within Discipline:
1. Development/enhancement of a unique facility for fundamental research in soil behavior;

2. Understanding of loss mechanisms in soils and particulate materials in general (geotechnical engineering and material science);

3. Correction of inherent measurement biases in resonant column testing.;

4. Multiscale understanding of thermo-mechanical coupling;

5. Evaluation of energy loss associated to adsorbed layers in particulate media;

6. Stochastic resonance in frictional materials;

7. Improvements to experimental analysis of surface waves via the application of advanced, array-based signal processing methods (non-invasive, near-surface geophysics); and

8. Enhanced inverse problem solving taking into consideration both velocity and attenuation in separate or joint inversion (geotechnical engineering, geophysics)

Contributions to Other Disciplines:

Contributions to Human Resource Development:
Support from the grant has allowed several students to receive training and education towards advanced degrees.
Contributions to Science and Technology Infrastructure:

Beyond Science and Engineering:
Improved understanding of dynamic soil behavior and rapid, lower cost methods to measure these properties will result in more widespread use of site-specific earthquake hazards analyses and therefore, more effective hazard mitigation.

Categories for which nothing is reported:

Contributions: To Any Other Disciplines
Contributions: To Any Science or Technology Infrastructure

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Web/Internet Sites

URL(s):
http://www.ce.gatech.edu/~grix/
http://www.ce.gatech.edu/~carlos/Laboratory/labmain.html
http://www.ce.gatech.edu/~carlos/Laboratory/P&R/YHW-poster.jpg
http://www.ce.gatech.edu/~carlos/Laboratory/P&R/YHW_res.html

Description:
Surface wave forward modeling and inversion software developed on this project is made available for use by others and results related to material behavior and energy losses are presented.

Other Specific Products

Product Type: Software (or netware)
Product Description:
Matlab-based software to control data acquisition for passive surface wave measurements using a multichannel Agilent VXI system.

Sharing Information:
This program will be added to others available at http://www.ce.gatech.edu/~grix for surface wave analysis.

Product Type: Software (or netware)
Product Description:
Matlab and Fortran 90 programs for forward modeling and inversion of surface wave dispersion and attenuation.

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Contributions

Contributions within Discipline:
1. Development/enhancement of a unique facility for fundamental research in soil behavior;

2. Understanding of loss mechanisms in soils and particulate materials in general (geotechnical engineering and material science);

3. Correction of inherent measurement biases in resonant column testing.;

4. Multiscale understanding of thermo-mechanical coupling;

5. Evaluation of energy loss associated to adsorbed layers in particulate media;

6. Stochastic resonance in frictional materials;

7. Improvements to experimental analysis of surface waves via the application of advanced, array-based signal processing methods (non-invasive, near-surface geophysics); and

8. Enhanced inverse problem solving taking into consideration both velocity and attenuation in separate or joint inversion (geotechnical engineering, geophysics)

Contributions to Other Disciplines:

Contributions to Human Resource Development:
Support from the grant has allowed several students to receive training and education towards advanced degrees.
Contributions to Science and Technology Infrastructure:

Beyond Science and Engineering:
Improved understanding of dynamic soil behavior and rapid, lower cost methods to measure these properties will result in more widespread use of site-specific earthquake hazards analyses and therefore, more effective hazard mitigation.

Categories for which nothing is reported:

Contributions: To Any Other Disciplines
Contributions: To Any Science or Technology Infrastructure