Title: Nonlinear Response of granular and other materials*

PI: P. A. Johnson
Post Doc: Donatella Pasqualini
Students: Fred Pearce (MIT), Marie Muller (University of Paris VII)
Collaborators: Xiaoping Jia (University Marne-la-Vallee, France);
R. A. Guyer (U. Mass. Amherst);
Joan Gomberg (USGS)

**(The research topic has been modified due to personnel and therefore interest changes.)*

Project Objectives and Brief Summary. Our work has changed direction in the last year because of personnel (student) changes. The original plan to focus on theory and modeling results of neutron scattering experiments for monitoring nonlinear response under quasistatic tests. Because the doctoral student changed topics, we redirected based on the interests of two new students. Our related, but new direction is elastic nonlinear properties of granular media and of bone. Our objectives from the study of granular media and from bone include (1) determining whether or not active experiments can by employed to induce elastic nonlinear behavior; (2) if so, determine the physical nature of the elastic nonlinearity extracted from the change in modulus or resonance frequency with drive level; (3) determine whether or not we can observe the recovery process of slow dynamics seen in the lab, and if so, (4) what is the physical nature of the recovery. From an earthquake engineering perspective of granular media, the goal is to devise the methodology to conduct in situ nonlinear characterization for structural design.

Summary of Research Results to Date.

Granular media. Nonlinear soil response has been observed in laboratory studies and in the field, from strong ground motion studies. Active-source field studies have been attempted by our group, and by others, but none have shown convincing results. No studies have been conducted applying a source to induce standing waves (resonance). That was the focus of a field experiment conducted at Garner Valley on August 18, 2004, in collaboration with the USGS, with UCSB, UT Austin and others.

The goal of this study was to verify observed laboratory behaviors of elastic nonlinear behavior, in particular modulus softening and the phenomenon of slow dynamics. Modulus softening was first observed during the 1994 Northridge earthquake. Slow dynamics have never before been explored in field experiments.

The experiment was a remarkable success. We observe strong nonlinear effects from a single vibrator (Vibroseis) source, in addition to slow dynamics. In the experiment, the source is frequency-swept through an interval corresponding to one or more modes of the layers known to exist at Garner Valley. Specifically, in both shear and compression, the source was stepped from 30-5 Hz at 0.25 Hz intervals. In a simplistic manner the modes are calculated as follows. A 1-D layered system loaded at the base by the earth and the other end free gives resonance frequencies f_r corresponding to $Kf_r=c/4L$ where c is wavespeed (P or S), K is an integer corresponding to mode number, and L is layer thickness. As there is a gradational change in velocity in addition to three-dimensional effects, one can only estimate the resonance modes. For a shear source, the water table at 3 m would have a fundamental, shear resonance near 14-15 Hz. The compressional mode would be near 100Hz, out of the range of the experiment. The 6 m later interface would have shear resonance at approximately 7.3 Hz and compression near 60 Hz. Our focus in this discussion is the water table interface.

Figure 1 illustrates the nonlinear fast dynamics of the soil system.

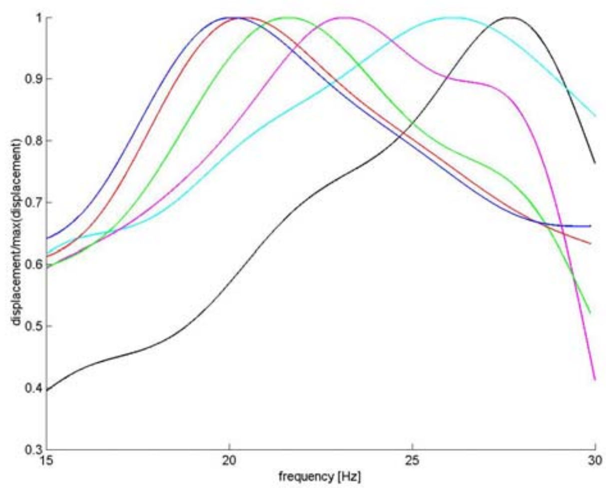

Figure 1. Results showing *in situ* nonlinear response from a large, surface vibrator source. Nonlinear soil response has been observed in laboratory studies and in the field, from strong ground motion studies from earthquakes. Active-source field studies have been attempted by our group, and by others, but none have shown convincing results. No studies have been conducted applying a source to induce standing waves (resonance). That was the focus of a field experiment conducted at Garner Valley on August 18, 2004, in collaboration with the USGS, with UCSB, UT Austin and others.
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The figure illustrates the nonlinear fast dynamics of the soil system for increasing applied force level. The curves represent the time-average displacement amplitudes over the frequency band indicated, normalized to the peak-amplitudes, representing the resonances of the top 3-m thick layer. The amazing aspect is the resonance peak shift downward with increasing source force level, color coded as black, blue, pink, green and red, respectively. The curves represent a decrease of more than 25% in the material modulus. We have never before observed such strong nonlinear response in lab studies, and the results indicate that the soil system is more nonlinear than most people believe. The import of this statement cannot be overstated for engineers designing structures. Their job is to be sure that soil resonances do not couple into structures. The design must accommodate such enormous frequency changes due to nonlinear soils response. In addition, the study is gratifying because we believe that a commercial system could be developed for the earthquake engineering problem (From Pearce et al. (2004).

*Work in bone***.** In collaboration with the University of Paris 6 medical School, we are applying the same diagnostics to study of bone with the goal of application to bone density changes due to osteoporosis. The student working with us, Marie Muller, has been at Los Alamos for the last three months conducting experiments studying progressive damage in bone from pressure cycling. It is premature to present results; however the method of applying nonlinear response to progressive damage as has been done in rock, appears to be working.

Any new insights or challenges in meeting project objectives. Yes. Since we lost our student, we have been forced to re-direct.

Any complications in meeting project objectives. Yes, for the same reasons. On the other hand, we have made a lot of progress and have exciting results in the area of strong ground motion.

List of publications, including submissions

Papers In Preparation

Pearce. F. P. Johnson and J. Gomberg, Nonlinear soil response induced by an active source, J. Geophys. Res. *in preparation* (November 2004).

Pasqualini, D. and P. Johnson, Can Thermal Gradients Explain Slow Dynamics?, Physical Review Letters. in preparation *(November 2004).*

Pasqualini, D., K. Heitmann,J.A. TenCate,S. Habib, D. Higdon, and P.A. Johnson Nonequilibrium and Nonlinear Dynamics in Geomaterials I: The Low Strain Regime, J. Geophys. Res, in preparation *(November 2004).*

Habib, S., K. Heitmann, and D. Pasqualini, Conditioning and Slow Dynamics in geomaterials a theoretical description, Physical Review B, in preparation *(November 2004).*

Refereed Papers In Review and in Press (*following work is partially funded by IGPP)*

Johnson, P. A. and X. Jia, Nonlinear dynamics, granular media and dynamic earthquake triggering, Nature, *in review* (November 2004)

Refereed Journal Papers Published

TenCate, J., D. Pasqualini, S. Habib, K. Heitmann, D. Higdon, and P. Johnson, Nonlinear and nonequilibrium dynamics in geomaterials, Physical Review Letters, 93, 06551-06555 (2004).

List of Presentations/abstracts

Johnson, P., Nonlinear elastic wave spectroscopy (NEWS) applied to damage diagnostics in bone, 17th International Bone Density Workshop, Annecy, France, June 20-24, 2004 (Invited).

Pasqualini, D. Investigation of the Transition to nonlinear acoustics in driven rods, AGU Fall Meeting 2003, EOS Transactions of the American Geophysical Union,

Pasqualini, D. Nonlinear and Nonequilibrium Dynamics in Geomaterials at very low strain, Ninth International Workshop on Nonlinear Elasticity in Materials (IWNEM9/Natemis Workshop), Karlskrona, Sweden, (2004).

Pasqualini, D., Rocks: an example of nonlinear materials, Department of Physics, Politecnico di Torino. Torino, Italy, at the June 10 2004.

Name of grad student and/or postdoc
Post Doc: Donatella Pasqualini
Students: Fred Pearce (MIT),
Marie Muller (University of Paris VII)

Progress towards PhD, if graduate student
Pearce: The work described above will either be a generals paper or the primary topic of his doctoral dissertation at MIT.
Muller: The work begun at Los Alamos over the last three months is the basis of her doctoral dissertation.

Documentation of visits to LANL and/or to University
Pearce has been working here since last July.
Muller has been working here since late August. She departs on 11/13 to return to U. Paris and will return in March.

LANL and/or facilities used in the research
Nonlinear acoustics lab at LANL

Budget details
The Required Format for the Budget Summary is:

		MIT	U. Paris	LANL
1.	Salaries and Fringe Benefits	$10K	0	$15.7K*
2.	Burden (campuses, none)			$3.2 K
3.	Supplies	$1K	0	
4.	Computer Usage			
5.	Travel	$7K	0	$2.5K

6. Equipment
7. Other

TOTALS

Total request for campus + Laboratory = 39.400

* salary for students at LANL

Efforts to secure further funding from other agencies.
We have garnered some support for Johnson, Guyer and TenCate from OBES.