

Acoustics Of Porous Media Including Marine Sediments

M. J. Buckingham

Marine Physical Laboratory

Scripps Institution of Oceanography

University of California, San Diego

9500 Gilman Drive

La Jolla, California 92093-0213

phone: (858) 534-7977 fax: (858) 534-7132 email: mjb@mpl.ucsd.edu

Award number: N00014-93-1-0054

<http://extreme.ucsd.edu/ADONIS.html>

LONG-TERM GOALS

The objective is to develop a unified theory of wave propagation in saturated granular media, particularly marine sediments. The theory should: 1) be consistent with the experimental data that have been published over the past 30 years or thereabouts; 2) be internally consistent; 3) include compressional, shear, and interface waves; and 4) be based on a well-identified physical mechanism.

SCIENTIFIC OBJECTIVES

Porous granular materials such as unconsolidated sediments and consolidated rocks support compressional and shear waves. The properties of these waves are complicated. For instance, the wave speeds show a distinct dependence on the grain size. Simple theories based on Wood's or Gassman's equations are known to be unsatisfactory for these materials; and Biot's theory of wave propagation in granular media, although it has been applied to sediments, gives rise to results which are difficult to reconcile with experimental observations. Biot's theory, for example, predicts fairly strong dispersion, whereas experiments show the dispersion to be very weak. Also, Biot's theory predicts a so-called slow wave, but careful observations in saturated sands and other unconsolidated granular materials have always failed to detect such a wave.

The objective of the current research is to take a new approach by constructing a wave theory of granular media based on the internal stress relaxation that occurs when a wave passes through the material.

APPROACH

Central to the new theoretical development is a relationship between the stress and strain at a point in the medium. This relationship takes the form of a temporal convolution between a material response function, $h(t)$, and the rate of strain. By expressing the stress relaxation in this way, a form of Navier-Stokes equation may be derived for the granular medium. By separating the modified Navier-Stokes equation into two wave equations, one for compressional and the other for shear waves, the wave speeds and attenuations are determined.

Theoretically, the wave speeds are found to show very weak, logarithmic dispersion, and the attenuations scale with the first power of frequency. Both properties are in accord with experimental observations on unconsolidated marine sediments. The stress-strain relationship describes inter-

Report Documentation Page

Form Approved
OMB No. 0704-0188

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE 30 SEP 1999	2. REPORT TYPE	3. DATES COVERED 00-00-1999 to 00-00-1999			
4. TITLE AND SUBTITLE Acoustics Of Porous Media Including Marine Sediments		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California, San Diego, Scripps Institute of Oceanography, 9500 Gilman Drive, La Jolla, CA, 92093		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a REPORT unclassified	b ABSTRACT unclassified	c THIS PAGE unclassified			

granular sliding on a microscopic scale and hence a number of the wave properties turn out to depend on grain size, again in accord with observation. A new rough -particle, random packing model links the grain size to the porosity and density of the medium, and thus the latter two properties are also linked to the wave properties. In effect, the complete theory provides the correlations between the wave speeds, attenuations, grain size, porosity and density. All these correlations compare very favorably with published experimental data.

WORK COMPLETED

A unified theory of wave propagation in saturated granular materials has been developed and published in four papers in the Journal of the Acoustical Society of America. This work includes: 1) a theoretical treatment of compressional, shear and interface wave propagation in unconsolidated granular media (marine sediments) ; and 2) a theoretical treatment of compressional and shear waves in consolidated, granular materials (sedimentary rocks such as limestone and sandstone). In these papers, the predictions of the theory are compared with extensive experimental data sets and excellent agreement is demonstrated.

Two at-sea experiments in the Gulf of Mexico, one off Panama City and the other off Pensacola (SAX'99), have been performed, using a vertical line array of four elements to collect ambient noise data in a very shallow (• 20 m) environment. The noise data are inverted using the new theory of wave propagation in sediments, to recover the geoacoustic parameters of the bottom. Our estimates of bottom properties can be compared with “ground truth” information that is available for the two sites, since both have been extensively surveyed using a variety of techniques, including coring.

ACCOMPLISHMENTS AND RESULTS

The theory that has been developed is complete as it stands and gives an accurate description of the properties of waves in unconsolidated marine sediments. For the potential user, it is easy to interpret and, perhaps more importantly, it is fast and simple to evaluate on a desktop computer.

The new work on sediments was recently written up as an “Oceans Watch” article in the San Diego Union Tribune. It was also presented as the subject of the Keynote paper at the Fourth European Conference on Underwater Acoustics, Rome, Italy, 21-25 September 1998; and as an Invited paper at the 2nd EAA International Conference on Hydroacoustics, Gdansk-Jurata, Poland, 24-27 May 1999. The work has also been presented as Invited papers in international conferences on acoustics in: Beijing, China; Istanbul, Turkey; Qingdao, China; Heraklion, Crete; and Carvoeiro, Portugal.

IMPACT/APPLICATIONS

The new approach to wave propagation in sediments is important for all underwater acoustic propagation modeling, especially in shallow water, where bottom interactions are significant. It is also relevant to shallow-water ambient noise modeling. Perhaps most importantly, the theory can be used as the basis of various inversion techniques for estimating the geoacoustic properties of the bottom from measurements of the sound field in the water column.

TRANSITION/INTEGRATION

Since the theory is still under development, it is really too early to consider transitioning. However, one group, headed by Dr. K. A. Naugolnykh, CIRES, University of Colorado/NOAA, Environmental Technology Laboratory, Boulder, Colorado, has applied the theoretical ideas to the case of non-linear, laser-generated sound pulses in a granular medium. They found that the theory agreed very satisfactorily with their results.

INTERNATIONAL COLLABORATION AND RESEARCH

United Kingdom

1. Dr. Sam Marks, Defence Evaluation and Research Agency (DERA), Winfrith, holds an extensive data set of sediment properties from world-wide locations. We are currently ways of using these data to help in the theoretical development.

France

1. Dr. Jean-Pierre Sessarego, Laboratoire de Mecanique et d'Acoustique, C.N.R.S., Marseille, has a laboratory-based experimental program on acoustic waves in sediments. We are currently planning a cooperative effort with this laboratory aimed at testing, under controlled conditions, some of the predictions of the new theory.

RELATED REFERENCES

1. M.J. Buckingham, "Theory of acoustic attenuation, dispersion, and pulse propagation in unconsolidated granular materials including marine sediments," *J. Acoust. Soc. Am.* **102**, 2579-2596 (1997).
2. M.J. Buckingham and N.M. Carbone, "Source depth and the spatial coherence of ambient noise in the ocean," *J. Acoust. Soc. Am.* **102**, 2637-2644 (1997).
3. M.J. Buckingham, "Acoustics of marine sediments," INVITED paper, in *Proceedings of the Third International Conference on Theoretical and Computational Acoustics*, Newark, New Jersey, (1997)
4. M.J. Buckingham, "Geoacoustic theory of unconsolidated marine sediments," INVITED paper in *Shallow-Water Acoustics*, China Ocean Press, Beijing, pp. 133-138 (1997)
5. M.J. Buckingham, "Theory of compressional, transverse and interface waves in porous media," INVITED paper in *Euromech Colloquium 376: Waves in Two-Phase Flows*, editors C.F. Delale and D.G. Crighton, Istanbul, Turkey. p. 4-5 (1998).
6. M.J. Buckingham, "Seismic wave propagation in rocks and marine sediments: a new theoretical approach," KEYNOTE paper in *Proceedings of the 4th European Conference on Underwater Acoustics*, editors A. Allippi and G. B. Cannelli, Italian National Research Council, Rome, pp. 301-306 (1998).

7. M.J. Buckingham, "Theory of compressional and shear waves in fluid-like marine sediments," *J. Acoust. Soc. Am.* **103**, 288-299 (1998).
8. M.J. Buckingham, "Acoustics of marine sediments: a new approach," INVITED paper in *Proceedings of PORSEC'98-Qingdao*, editors Ming-Xia He and Ge Chen, Qingdao, China, pp. 689-692 (1998).
9. M.J. Buckingham, "A new theory of sediment acoustics for geoacoustic inversions," INVITED paper in *1st Workshop on Inverse Problems in Underwater Acoustics*, editor M. Taroudakis, Heraklion, Crete (1999).
10. M.J. Buckingham, "A new theoretical approach to sediment acoustics," INVITED paper in *2nd EAA International Symposium on Hydroacoustics*, editor A. Stepnowski, Gdansk, Poland (1999).
11. M.J. Buckingham, *Waves of grains could be key to sound transmission*, in *The San Diego Union-Tribune*, San Diego. p. E-2 (14 July 1999).
12. M.J. Buckingham, "On the phase speed and attenuation of an interface wave in an unconsolidated marine sediment," *J. Acoust. Soc. Am.* **106**, 1694-1703 (1999).
13. M.J. Buckingham, "Theory of compressional and transverse wave propagation in consolidated porous media," *J. Acoust. Soc. Am.* **106**, 575-581 (1999).
14. M.J. Buckingham, "New theoretical basis for determining the geoacoustic parameters of the seabed," INVITED paper in *Experimental Acoustic Inversion Methods for Exploration of the Shallow Water Environment*, editors J. P. Hermand, M. B. Porter, S. M. Jesus, and A. Caiti, Kluwer, Pisa (1999).