

Wave Propagation in Granular Media Including Marine Sediments

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Award number: N00014-93-1-0054
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LONG-TERM GOALS

The long term objective of our marine-sediment research program is to develop an experimentally validated, unified, internally consistent description of wave propagation in granular materials.

OBJECTIVES

The first part of the research initiative is to develop an internally consistent theory of compressional and shear wave propagation in unconsolidated sediments.

Secondly, supporting data will be collected from controlled experiments on an "ideal" sediment consisting of uniform glass beads in a laboratory tank.

Thirdly, at-sea experiments will be performed to yield wave speed and attenuation data from *in-situ* sources and receivers in the sediment, which will be used to validate the theory.

Fourthly, normal-incidence bottom-loss measurements will be made in shallow ocean channels for comparison with theoretical predictions and also to provide insight into reported large variations in the normal-incidence reflection coefficient.

Fifthly, air-to-water acoustic transmission will be experimentally investigated with an airborne source (light aircraft) over the ocean, ultimately with a view to performing acoustic inversions to obtain bottom properties.

APPROACH

Part 1. Theory. An analysis of wave propagation has been developed based on grain-to-grain sliding. The intergranular interactions give rise to dissipation and dispersion, and these effects are accommodated by new terms in the wave equation. The theory itself is analytical, yielding simple algebraic expressions for the wave speeds and attenuations. The physics underlying the theoretical results is based on the non-linear properties of the thin film of fluid separating grains.

Part 2. Tank experiments. Our laboratory tank is 2 x 3 m in area and 1.6 m deep. It has been half filled with six tonnes of uniform, spherical, 300 μ m diameter glass beads, whose mechanical properties are completely known. Freshwater is used in the tank, but continually circulating under UV light to

Report Documentation Page

*Form Approved
OMB No. 0704-0188*

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1. REPORT DATE 30 SEP 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Wave Propagation in Granular 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) Marine Physical Laboratory,,Scripps Institution of Oceanography,University of California, San Diego,,9500 Gilman Drive,,La Jolla,,CA, 92093-				8. PERFORMING ORGANIZATION REPORT NUMBER	
				10. SPONSOR/MONITOR'S ACRONYM(S)	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
				12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited	
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The long term objective of our marine-sediment research program is to develop an experimentally validated, unified, internally consistent description of wave propagation in granular materials.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 6	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

eliminate contamination by microbial organisms. Small quantities of chlorine help maintain the cleanliness of the water and sediment. Air was removed from the glass-bead sediment by vacuum pumping before installation in the tank. *In-situ* probes (sources and receivers) in a four element configuration will be used for measuring compressional and shear wave properties over as many decades of frequency as possible. Reflection-coefficient measurements of the sediment surface will also be made.

Part 3. At-sea measurements of sediment properties will be made using *in-situ* probes in the sediment. This work will be performed with Michael Richardson, NRL Stennis, using his ISSAMS frame.

Part 4. Bottom reflection measurements. *In-situ* measurements of the normal-incidence bottom reflection coefficient are being made in shallow water in the Gulf of Mexico. The experimental procedure is based on a pyramid-type structure formed by thin, nylon fishing line. The corners of the pyramid are attached to screw anchors in the sediment, and a vertically aligned source and receiver are suspended from the apex, which is a couple of meters above the bottom. This arrangement minimizes interference from spurious reflections from the supporting structure. Divers install the system at each deployment, taking about 20 minutes to insert the screw anchors, arrange the pyramid, and attach the source and receiver. The technique is simple and successful, yielding large data sets quickly and economically.

Part 5. Air-to-water transmission. A light aircraft piloted by one of my group (T. Berger, F. Simonet and/or myself) will be used as an airborne sound source to conduct controlled experiments on air-to-water acoustic transmission. Prior to the flights, supporting data such as the bathymetry of the channel, soundings for the atmospheric sound speed profile, the sub-surface temperature profile from an XBT, etc. will be collected. A microphone will be deployed above the sea surface, an array of hydrophones below, and onboard GPS coupled into a laptop will automatically monitor and record aircraft position. The acoustic coupling will be determined as a function of range, of aircraft altitude, and of surface roughness. Also the effect of swell will be investigated by flying parallel to and perpendicular to the crests, and on tracks offset from the receivers.

Once the coupling experiments are complete, attempts will be made to take propagation data using the airborne source and to perform inversions to obtain bottom properties.

WORK COMPLETED

The unified theory of wave propagation in saturated granular materials has been developed and published in a series of five papers in the Journal of the Acoustical Society of America. A discussion of the high-precision correlations emerging from the theory has been published in the Journal of Computational Acoustics.

Two at-sea experiments in the Gulf of Mexico, one off Panama City and the other off Destin at the SAX'99 site have been performed in which the normal-incidence reflection coefficient of the seabed was measured over a range of frequencies between 5 and 40 kHz.

RESULTS

The new theory of wave propagation in marine sediments accurately represents the speed and attenuation data for compressional waves above about 2 kHz. It also matches the few shear wave data that are available. The theory is internally consistent and will yield many of the sediments properties

once the compressional speed has been specified. Nevertheless, there is a pressing need for more data, particularly at low frequencies, below 2 kHz, for the compressional wave and at all frequencies for shear. Shear attenuation data are important for testing the theory but are largely unavailable at present.

The reflection coefficient experiments show that the ripple field of the natural, sandy seabed causes significant variations in the reflection coefficient, anywhere between -6 and -15 dB. The variability is interpreted as being due to the focusing and defocusing by the troughs and peaks, respectively. After divers smoothed the seabed, the reflection coefficient was found to be much more stable at approximately -8 dB, which agrees with Rayleigh.

IMPACT/APPLICATIONS

The new theoretical and experimental work on 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. In addition, the correlations emerging from the theory can be used as the basis of various inversion techniques, for instance, matched field processing, for estimating the geoacoustic properties of the bottom from measurements of the sound field in the water column. The strong correlations between certain wave properties that are identified in the theory could be applied with advantage to reduce the number of unknown parameters appearing in inversion schemes.

The airborne-source as a means of obtaining bottom properties has not been investigated before. If successful, it would provide an inexpensive technique for the very rapid acquisition of sediment properties as a function of position along the aircraft track. The computations underlying the inversions are relatively simple, so much so that the bottom information would be available in real time from an onboard laptop computer as the aircraft makes its pass.

TRANSITIONS

Since the work on sediments is still under way, it is 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 new theory agreed very satisfactorily with their results.

RELATED PROJECTS

U.S.A.

1. Dr. Michael Richardson, N.R.L., Stennis, and I are collaborating on the interpretation of sediment wave property data obtained using his ISSAMS frame.
2. Prof. Giorgio Gratta, Stanford, and I are collaborating on the underwater acoustic detection of extremely high energy neutrinos. Data for this project are being obtained from the U.S. Navy's AUTECH range off Andros Island, Bahamas.

Canada

1. Prof. Ross Chapman, University of Victoria, B.C., and I are collaborating on a "hush-gun" technique, a sort of quiet air-gun, for measuring the wave properties of the bottom in shallow water.

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 exploring ways of using these data to help in the theoretical development.
2. Dr. Gary Heald, DERA, Winfrith and Dr. Nicholas Pace, University of Bath (currently at SACLANTCEN, La Spezia, Italy) are collaborating with me in developing laboratory and in situ experiments aimed at determining sediment wave properties, particularly P-wave dispersion, from measurements of the reflection coefficient of the seafloor.
3. Dr Alastair Cowley, DERA, Winfrith is collaborating with me on phased array techniques applied to acoustic daylight imaging.

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.

PUBLICATIONS

1. 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).
2. M.J. Buckingham, "Theory of compressional and transverse wave propagation in consolidated porous media," *J. Acoust. Soc. Am.*, **106**, 575-581 (1999).
3. M.J. Buckingham, "Acoustic daylight imaging in the ocean," in *Handbook on Computer Vision and Applications*, vol. 1, Sensors and Imaging, B. Jähne, H. Haubecker, and P. Geibler, Eds. San Diego: Academic Press, 1999, pp. 415-424.
4. C. L. Epifanio, J. R. Potter, G. B. Deane, M. L. Readhead, and M. J. Buckingham, "Imaging in the ocean with ambient noise: the ORB experiments", *J. Acoust. Soc. Am.*, **106**, (6), 3211-3225 (1999)
5. M.J. Buckingham, "New theoretical basis for determining the geoacoustic parameters of the seabed," in *Experimental Acoustic Inversion Methods for exploration of the shallow water environment*, A. Caiti, J.-P. Hermand, S.M. Jesus, and M.B. Porter, Eds. Dordrecht: Kluwer, 2000, pp. 195-209. [INVITED].

6. M.J. Buckingham, "Wave propagation, stress relaxation, and grain-to-grain shearing in saturated, unconsolidated marine sediments," *J. Acoust. Soc. Am.*, **108**, (6), 2796-2815 (2000).
7. M.J. Buckingham, "Wave propagation in saturated porous media," in *Proceedings of the First International Conference on Acoustics, Noise and Vibration*, vol. **in press**, A. Guran, Ed. Montreal, (2000). [KEYNOTE ADDRESS].
8. M.J. Buckingham and M.S. Garcés, "Airborne acoustics of explosive volcanic eruptions," *J. Comp. Acoust.*, **in press** (2000). [KEYNOTE ADDRESS].
9. M.J. Buckingham, "Precision correlations between the geoacoustic parameters of an unconsolidated, sandy marine sediment," *J. Comp. Acoust.*, **9**, (1), 101-123 (2001). [INVITED].
10. A. Cowley, R.A. O'Leary, F. Simonet, T.K. Berger, and M.J. Buckingham, "Acoustic Daylight imaging in underwater environments," Proc. Fifth European Conference on Underwater Acoustics, Lyons, **1**, 375-380 (2000).
11. M.D. Richardson, K.B. Briggs, D.L. Bibee, P.A. Jumars, W.B. Sawyer, D.B. Albert, T.B. Berger, M.J. Buckingham, N.P. Chotiros, P.H. Dahl, *et al.*, "Overview of SAX99: environmental considerations," *IEEE J. Ocean. Eng.*, **26**, (1), 26-53 (2001).
12. M. J. Buckingham, "Acoustical oceanography in perspective", Proc. Inst. Acoust. Conf. on Acoustical Oceanography, T. G. Leighton, G. J. Heald, H. D. Griffiths, and G. Griffiths (eds), Bath Univ. Press, **23**, 2, 1-10, (2001) [KEYNOTE ADDRESS].
13. M. J. Buckingham, "Wave propagation in dispersive marine sediments: a memorial to David G. Crighton", Proc. Fifth Int. Conf. Theoretical & Computational Acoustics, Beijing, May 21-25, E. C. Shang (ed.), 32-33 (2001) [KEYNOTE ADDRESS].
14. N. G. Lehtinen, A. Shaffique, G. Gratta, T. K. Berger, M. J. Buckingham, "Sensitivity of an underwater acoustics array to ultra-high energy neutrinos", *J. Astroparticle Physics*, **in press** (2001).
15. M. J. Buckingham and T. K. Berger, "Low frequency sound from a bubble plume", Proc. 17th Int. Conf. on Acoustics, Rome, Italy, A. Alippi (ed.), pp. 2 (2001) [KEYNOTE ADDRESS].