Wave Propagation And Inversion In Shallow Water And Poroelastic Sediment

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LONG-TERM GOALS

To create a suite of computer codes (programs) that accurately model wave propagation and scattering in shallow water, to quantify the effects of poroelastic, stratified sediment and elastic mode conversion on wave propagation in shallow water at frequencies ranging from 10 Hz to several hundred kHz.

To relate these effects to sonar system behavior and efficient design of sonar capable of finding buried/semi-buried/proud mines in shallow water environments, in the presence of poroelastic sediment and bubble layers.

To understand the fundamental linear and nonlinear physics of wave propagation in poroelastic sediment with bubbles.

OBJECTIVES

To continue development and testing of K-space Integral Equation codes (K-SIE), finite difference time domain codes (FDTD), and Hybrid Parabolic marching/Finite difference (HP-MFD) and Hybrid Integral Equation/Finite Difference (HIEFD) methods for fast and accurate scattering and inverse scattering of objects buried in sediment with poroelastic (Biot) properties and containing bubble populations.

To develop a Java-based, interactive, web site http://borup.aim.utah.edu [41] to make pseudo-analytic, FDTD, Integral Equation, and HIEFD and HP-MFD calculation methods in 3D and 2D, available to other researchers over the web.

RESULTS

Our results encompass five main types of codes: (1) **FDTD** (Finite Difference Time Domain); (2) **K-SIE** (K-Space Integral Equation); (3) **P-AC** (pseudo-analytic code); and the two hybrid methods: (4)

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HIEFD (Hybrid Integral Equation Finite Difference); and (5) **HP-MFD** (Hybrid Parabolic-Marching Finite Difference). Concepts found in references [1-45] have proven to be very useful in this research.

1. Results with FDTD codes (Finite Difference Time Domain)

We have finished the initial phases of the adaptation of a **FDTD**, 2D, geophysics Biot code (given to us) to the P-SV wave elastic Biot [12] problem in 2D. In doing so we uncovered an error in the gifted code, and have generalized it to include non-homogeneities in porosity, permeability, bulk moduli, shear modulus, and viscosity of the pore-filling fluid.

We have incorporated our "pill-box" scheme into a hybrid IEFD for the acoustic scalar case, wherein, the IE code is used outside and the FDTD code is used inside the same pillbox.

Forward scattering code for the time domain scattering in two and three dimensions with the advanced Berenger-type Perfectly Matched Layer absorbing boundary. These effective boundary conditions reduce the anomalous scattering from grid edges by 71 dB, versus approximately 40 dB reduction provided by the standard absorbing BC's of Mur [31].

We have extended the 2D and 3D forward scattering time domain code to include the effects of dispersion as dictated by the Kramers-Kronig relations in two distinct ways: (1) using a Z-transform approach developed by Sullivan [43]; and (2) a state variable approach developed by us [31]. These alternative methods are compared to one another for accuracy. Furthermore, we have incorporated the new PML absorbing BC's in the [31] state variable approach.

2. Results with K-SIE codes (K-Space Integral Equation)

*a. Dictionary***.** By encoded the Biot Green's function (point response function) as described in [Boutin et al we have uncovered an important physical misinterpretation that could render the point response function, as displayed in [8] incomplete from a physical point of view. This is true even though on a purely mathematical level the Green's function is strictly correct. Furthermore, we have established a convenient dictionary that allows one to pass from the set of terminology favored by the "French school" (Boutin, Bourbie' Bonnet, etc.) [8,18,19,28] to the terminology common to Stoll [29], Kibblewhite [30], Johnson and Plona [1], etc. This discrepancy in terminology arises primarily from the use of homogenization theory in the French school, and a stricter adherence to the Biot approach in Stoll/Kibblewhite [29,30].

We are also in the midst of carrying out model wave propagation simulations with the parameters espoused by Chotiros [39]. We have generalized the method of Kibblewhite & Wu [30] for the determination of reflection coefficients in visco-elastic porous layered half-spaces to yield a layered Biot point response function for arbitrary layered porous media, using the technique we previous developed for the acoustic case [42].

We have developed a dictionary for the various notations employed by:

"The Rock Physics Handbook", Mavko et al. [27],
"Wave Interactions as a Seismo-acoustic Source", Kibblewhite and Wu [30]
"Acoustics of Porous Media", Bourbie' et. al. [28]
"Sediment Acoustics", Robert Stoll [29],
Several papers (Johnson & Plona [1], Boutin et. al.[8], Bonnet et. al. [8,18,19], Chotiros) [39].

An example of the relationship and utility of such cross-reference is the following: Defining β=porosity, **u**=averaged "solid" displacement, **U**=averaged "fluid" displacement, **w**=β(**u-U**) the "increment of fluid content" of [Stoll, 1989], we can write:

$$\mu\nabla^2\mathbf{u} + (H-2\mu)\nabla e - C\nabla\varsigma = \rho\mathbf{u_{tt}} - \rho_f\mathbf{w_{tt}}$$
$$C\nabla e - M\nabla\varsigma = \rho_f\mathbf{u_{tt}} - m\mathbf{w_{tt}} - (\eta/\kappa)\mathbf{w}_t$$

In the above equations, e, ζ, μ, H, C, M, ρ,ρ_f, η, κ are all as defined by Stoll [29]. These equations can be rewritten in the form used the "French school" [8,18,19]. This results in the identification of parameters: for example, the ratio $C/M = \alpha_{Boutin} \equiv 1 - K_b/K_s$ in the Boutin [8], which in turn is essentially the "Biot coefficient" discussed in Bourbie's book [28]. Also β serves as porosity in Stoll/Kibblewhite notation, but is $\beta \equiv (\alpha-\phi)/K_s + \phi/K_f$ in the Boutin et al. [8], although Boutin uses n not ϕ for porosity. This β is equivalent to 1/M in the notation of Bourbie' [28]

A careful analysis of the equations reveals that the *m* parameter in Stoll/Kibblewhite notation m = $\tau\rho f/\phi$, can be replaced by $m \rightarrow m + \eta F_2/(\kappa\omega)$, where F_2 is the imaginary part of the complex *F,* the Biot frequency dependent structure factor, and plays a role analogous to the imaginary part of **H**, the inverse of the generalized Darcy coefficient of homogenization theory. The real part of *F*, F_R is analogous to the real part of the inverse **H** of the generalized Darcy coefficient of homogenization theory.

These identifications allow for accurate model parameters (with physically relevant values) to be input into the Biot Green's function developed within the context of homogenization theory. These identifications also allow for theory to be compared with experiment and thus ultimately inversion methods based on reduction of residual (model minus measurement) error.

b. Free space background codes. The *2D forward and inverse* code for the scattering of an elastic object in an elastic background medium, with Lame' parameter λ allowed to vary, and μ held fixed is running. The *2D forward scattering* code is running for the scattering of an elastic wave off of an elastic object in a fully elastic medium: i.e. both λ and μ are allowed to vary. The *3D forward scattering code*, for elastic scattering from an elastic inhomogeneity within an elastic medium (Lame' parameter λ is spatially dependent, but μ is held to be fixed spatially) has been written and is being tested against certain pseudo-analytic solutions. We have also finished the development and testing of the associated *3D inversion code* in transmission mode, and are in the process of generalizing to the important problem of multi-static reflection mode inversion. We have improved the convergence of our K-SIE codes by replacing the forward problem solver with the Stabilized version of Bi-CG [34]. We have also improved the overall convergence of the inverse problem by use of the fully nonlinear Ribiere-Polak conjugate gradient method.

The elastic Green's function in the free space case has a well-known non-integrable singularity which we handle by careful use of sinc functions, $\mathrm{sinc}(x) \equiv [\sin(\pi x)]/[\pi x]$, and sinc-convolution. We also address the problem of the existence of derivative operators acting inside the integral on the displacement functions by means of augmenting the integral equations of motion with explicit integral equations for the strain tensor components.

c. *Born analysis of the elastic imaging problem* We have also carried out a theoretical analysis based upon the Born assumption, and the integral equation formulation for elastic scattering, that determines what set of sediment elastic parameters (λ, μ, ρ) can be successfully inverted when sources and receivers are located in water. We derived the Born approximation to the volume elastic integral equation for an elastic object imbedded in an elastic medium in order to examine the invertability for the three isotropic media parameters, ρ, μ, λ. The analysis shows that all three parameters can be imaged independently if a shear wave source is available. Also, only a pressure receiver is needed (s-source, s-receiver data is not needed). In 2D, it turns out that μ can be independently imaged with a shear source and pressure receiver (i.e., only perturbations in μ scatter for this case in 2D). The other two parameters, ρ and λ, can then be imaged with p-source, p-receiver data in an analogous manner to ρ and κ for the acoustic imaging problem.

d. Layered Background Code. We have developed a layered Green's function and concomitant K-space integral equation for arbitrarily layered media. The construction we have employed mirrors the construction in [42], and is specifically designed to preserve the use of the Fast Fourier Transform (FFT) even in the vertical direction (the direction of the arbitrary layering).

These 2D and 3D codes and Green's functions are used in two contexts: (1) volume scattering for remote sources and receivers, and (2) as a propagator within the context of the hybrid FDIE (finite difference/integral equation) method. When the codes are utilized in the context of volume scattering special care must be taken to handle the singular nature of the self-term. We have utilized "sinc" functions, and a unique expression for the sinc-convolved Green's function (a pseudo-analytic series expansion in orthogonal polynomials), *which was developed at CIPIT, to address this problem***.**

3. Results with P-AC (pseudo-analytic code)

We have developed so-call Pseudo-analytic solutions. These solutions, based on Bessel and Hankel function expansions, are embodied in code developed at our Center for Inverse Problems, Imaging and Tomography (CIPIT), and will be made available over the Web, in a manner similar to the interface that is presently available over the net at http://borup.aim.utah.edu . This code will enable researchers from remote sites to test their developed code (finite difference, marching methods, boundary integral equations, etc.) against analytic solutions for simple objects (layered spheres and cylinders, and finite groups thereof) in free space. For a single, layered, analytic object, there is no inversion, only calculation. For two such objects, there is only a recursion (even in 2D or 3D). Extension to more or overlapping objects is possible.

4. Results with HIEFD codes (Hybrid Integral Equation Finite Difference)

The 2D pillbox code has been written and tested; further testing is underway. See **Figure 1** for a geometrical description of the location of the pillbox with respect to the ocean and sediment.

The 2D "pill-box" approach requires that equivalent sources be located on the boundary of a finite difference grid to allow the external incident field to be propagated into the grid, where it can interact with field inhomogeneities and rescatter. The external field is propagated to the pillbox in this case by the fast calculation of the layered impulse response function (a Hankel transform is evaluated). Since the layered impulse response function is a frequency domain object the field is calculated at several frequencies, then a Fast Fourier Transform (FFT) is applied to transform the field on the boundary to the time domain (the equivalent sources mentioned above). When the interaction has been completely simulated via finite differences (FD), the field is then re-transformed back to the Fourier domain, and the Green's function, and its normal derivative, are used to propagate the fields back to receivers. The finite difference codes required to complete the Hybrid IEFD method have been completed and checked in 2D and 3D

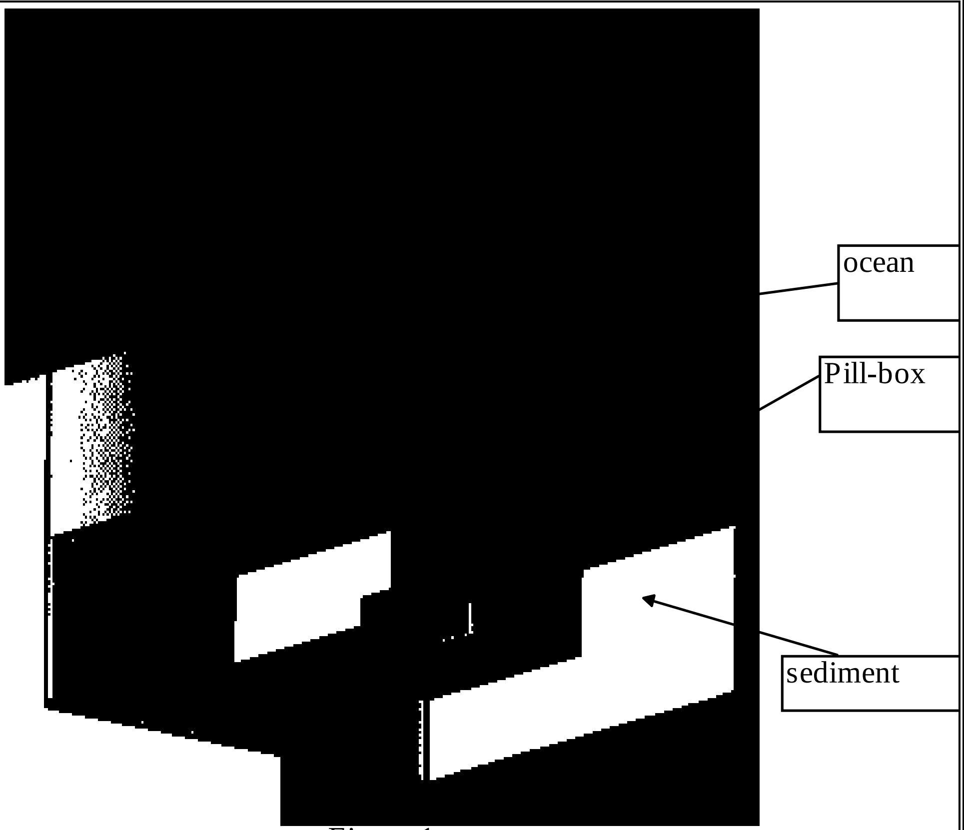

Figure 1
Cutaway view of ocean, sediment and buried pillbox as employed in the hybrid pillbox method.

5. Results with HP-MFD codes (Hybrid Parabolic-Marching Finite Difference)The 2D and 3D pillbox propagators have been coded, and tested. The 2 and 3D pillbox propagators use parabolic-marching methods for increased speed over **HIEFD** methods, but at the price of some loss of accuracy. The fast calculation feature of the parabolic-marching method propagates the external field to the pillbox in this case. After matching boundary conditions at the pillbox surface, the field is then propagated by FDTD methods inside of the pillbox. The scattered field on the surface of the pillbox is matched to the parabolic-marching method and then propagated through the sediment to the ocean and then outward to required receivers. In the case of a homogeneous ocean, calculation time may be saved by use of Green's functions for in-ocean propagation, for both hybrid codes. See **Figure 1** for pillbox geometry.

IMPACT/APPLICATIONS

The development of the generalized layered elastic porous Green's function mentioned above, will enable, with the combination of this approach with the FDTD code mentioned earlier, for the 2D elastic porous media, the modeling of reverberation and scattering from buried and semi-buried objects in sediment. The hybrid approach enables the efficient modeling of high contrast, as well as low contrast buried mines, as insonified from remote sources and receivers. The use of the Green's propagator allows the accurate propagation from remote receivers into the porous sediment, which may vary horizontally in porosity, permeability, bulk moduli, shear moduli, viscosity, etc.

The Navy is very interested in applying recently developed remotely operated vehicle (ROV's) technology to the problem of mine detection via multi-static sonar. The hybrid methods developed by our group and made available over the Web will enable the accurate and efficient modeling of these multi-static, multi-platform sonar experiments.

The K-SIE methods allow the accurate propagation over large distances, and the PE methods allow propagation over range dependent environments. Our PE code will propagate to the buried or semi-buried pillbox in the range dependent case, and the K-SIE methods will be used in the range-independent environment. Once at the pillbox, whichever method is used, the FDTD codes will be employed to determine the accurate scattered field even for high contrast objects that are buried in porous elastic sediment. The scattered field is then Fourier transformed at the boundary of the pillbox, and propagated to remote receivers either in mult-static or mono-static configurations.

For extremely high contrast objects, the method recently developed by Ghosh Roy and co-workers will enable the detection of buried and semi-buried mines in sediment (i.e. high contrast with density, speed of sound, etc.). It is particularly well suited to the multistatic case. For monostatic data from high contrast objects, the FDTD forward code and inversion is most appropriate. The forward scattering time domain code employs 4th order differencing with Berenger PML [31[absorbing boundary conditions that enable the accurate simulation of larger sized areas of seabed The FDTD forward code exists in 2D and 3D forms. The associated inversion code exists in the 2D version, and employs the Tarantola [44,45] method of time domain regularized inversion. It has been tested, both the time domain calculation of the Jacobian and its adjoint have been coded and tested.

By extending the size, accuracy and efficiency of our codes to more accurately reflect recent advances in understanding sediments and Biot theory we increase the capability of the Navy to find buried/semi-buried mines in surf-zones. In particular, in keeping with our bio-engineering background we desire to mimic the remarkable, documented ability of the dolphin to detect prey and other objects buried in sediment using frequencies ranging from 10 to 150 kHz [39].

We will also combine the results of our research in the use of low frequency EM (diffusion approximation) using some variant of Dempster-Schaeffer evidential theory, and standard techniques of data fusion to greatly enhance the capability of environmental scientists, and navy researchers to detect and identify buried ordnance in bubble-containing and reverberant surf-zones.

We are also contributing to the fundamental understanding of wave scattering, transmission and reverberation in shallow water, and at low, medium and high frequencies by being able to compare data collected in the ocean environment against our codes, which accurately model, attenuation, Kramers-Kronig type dispersion, poro-elastic (Biot) effects, and stratification.

We have also contributed to theoretical understandings by explicitly relating the correspondence between the various parameters used in homogenization theory approaches adopted by the "French school" (Bourbie', Boutin, Bonnet, Bard, Kazi-Aoul, etc.) [8,18,19,28] and the Biot parameters as defined originally by Biot, and adapted by Chotiros, Stoll, Kibblewhite and Wu, Stern, and others [39,29,30]. In particular the generalized complex Darcy coefficient arising in Boutin et al. [8], is related to the equivalent mass parameter of Stoll and others, and Biot theory.

TRANSITIONS

Transitioning to others, of technology developed under this project and funding, are of two types: (1) use of this technology within our group and industrial partners (e.g.: TechniScan, Inc [36], EMI [37]; and (2) use of this technology outside of this larger set. In the first category, we and our sponsors [38] for breast cancer imaging and detection, are benefiting from advances in parabolic methods for fast inverse imaging of speed of sound, which is one prominent indicator for cancer. Also, the AFOSR sponsored project for detecting buried objects by ground penetrating radar, has benefited by use of the PML FDTD codes. In the second category, our PML FDTD codes have enhanced the work of EMI [37] and Waag [40].

RELATED PROJECTS

Some the related projects are described in the first category listed above in the TRANSITONS section. A further related project is sponsored by the ONR and used EM Diffusion imaging to detect buried mines in the surf zone (J. Kravitz, Ph.D., program manager). The Green's function imaging theory can be used directly or in an approximate, but faster form *called EM Migration*.

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35. Dilip Ghosh Roy, Ph.D. is a mathematical physicist at the Naval Research Lab, Washington, DC, that specializes in scattering (and inverse scattering) theory and application programming. He has published one monograph, with CRC Press, on scattering and inverse scattering and is working with our group on another.
36. TechniScan Inc., (TSI), is a high-technology spin-off company from the University of Utah. TSI is located at 825 North, 200 West, Suite 102, Salt Lake City, UT 84103, Tel.: (801) 521-0444, http://www.NetUtah.Net/~TechScan .
37. Electromagnetic Instruments, Inc. (EMI), Richmond, CA. http://www.EMIinc.com .
38. For example: NCI, private foundations, and hopefully soon capital sources.
39. N. P. Chotiros, "Acoustic Detection of Buried Objects by a Dolphin", talk given Sept. 19, 1997 for Applied Research laboratories, University of Texas, Austin Texas/.
40. Private communication. We donated to code to Dr. Robert Waag, Dept. Elec. Engineering, Univ. of Rochester, NY. His work, in modeling of ultasound propagation in tissue, has been enhanced by an order of magnitude in speed and accuracy, by our PML FDTD codes.
41. A Java-based, interactive, web site at http://borup.aim.utah.edu is now operative to make FDTD, K-SIE, P-AC, HIEFD and HP-MFD calcualtion methods in 3D and 2D, available to other researcher over the web.
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