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THESIS

**POROELASTIC PROPERTIES FOR MODELING THE
WATER-SEDIMENT INTERFACE IN THE
NORTHEASTERN SOUTH CHINA SEA**

by

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March 2020

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**POROELASTIC PROPERTIES FOR MODELING THE WATER-SEDIMENT
INTERFACE IN THE NORTHEASTERN SOUTH CHINA SEA**

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ABSTRACT

The transmission of underwater sound and its interactions with the sediment layer of the ocean floor has impacts across many areas of naval warfare. There are numerous physical parameters influencing acoustics at the water-sediment interface. A numerical modeling approach, using the equation of motion from Biot's theory of poroelasticity is useful in determining if variations in the physical parameters will have implications on acoustic reflections, transmissions, and bottom loss. These modeling efforts can inform decisions related to antisubmarine warfare, mine warfare, and hydrography as well as other areas of U.S. naval operations. This thesis examined variations in characteristic pore size, dynamic viscosity, permeability, and porosity and assessed the impacts of these variations on the acoustic reflection and transmission coefficients and bottom loss at the water-sediment interface. Our analyses determined that porosity and characteristic pore size, individually, had the largest impacts on the acoustical transmissions within the water-sediment interface for the parameters studied. Future research is suggested to study the interrelationships of these modeled physical parameters.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACPR	pressure acoustics, frequency domain
AOIN	angle of intromission
ARWSI	acoustic reflections off a water-sediment interface
ASW	antisubmarine warfare
COTS	commercial off-the-shelf
CS	coarse sand
CSFG	course sand and fine gravel
FEM	Finite Element Method
FS	fine sand
HYDRO	hydrography
LOGDEC	logarithmic decrement
MBES	multi-beam echo sounder
MIW	mine warfare
NRL	Naval Research Laboratory
OAML	Oceanographic and Atmospheric Master Library
ONR	Office of Naval Research
PELW	poroelastic waves
PDE	partial differential equation
PML	perfectly matched layer
PSU	practical salinity unit
PWR	plane wave reflection
SA	sand
SBES	single-beam echo sounder
SC	silty clay
SCS	South China Sea
SS	silty sand
SSS	side scan sonar
SONAR	sound navigation and ranging
SOSE	soft sediment
TDA	tactical decision aid

UNESCO	United Nations Educational, Scientific, and Cultural Organization
VGS	viscous grain-shearing
WWI	World War I
WWII	World War II

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I. INTRODUCTION

A. IMPORTANCE OF ACOUSTIC INTERACTION AT THE WATER SEDIMENT INTERFACE

The study of modern underwater acoustics began as early as 1490 with Leonardo da Vinci, but did not fully develop into quantitative measurements until 1827 when Daniel Colladon and Charles Sturm conducted an experiment on Lake Geneva in Switzerland (Urick 1983) to measure the speed of sound. Their experiment set the stage for all future measurements of underwater sound. As ocean vessel traffic steadily increased in the late 19th century, so did concerns of safe navigation. In 1889, Lucien Blake devised an underwater bell and microphone system designed to provide increased warning distances for navigational safety over traditional methods (Discovery of Sound in the Sea 2017). Advancements in both technology and science continued to evolve and other factors began to influence interest in underwater acoustics. The 1912 collision of the RMS *Titanic* with an iceberg raised awareness among scientists, sailors, and leaders alike on the detection of underwater dangers, quickly becoming an interest of economic necessity. The invention of sound navigation and ranging (SONAR) in 1914 enabled under water communications and echo ranging, provided for increases in distance detection of hazardous underwater objects, and is a prominent example of how the study and application of underwater acoustics continued to evolve.

World War I (WWI) brought heightened interest in underwater acoustics as a different underwater threat emerged—the modern submarine. Although submarines date back to the 16th century, advances in batteries, diesel and diesel-electric propulsion, and other shipboard technologies significantly increased the capabilities of German submarines, commonly known as U-boats. Germany's strategic employment of U-boats in commerce raiding and enforcing naval blockades occurred during WWI. U-boats sank 10 battleships, 18 cruisers, numerous smaller naval vessels, and 5,708 merchant and fishing vessels with a combined loss totaling 11,018,865 tons and over 15,000 sailors (Clodfelter 2017). The war ended, but the United States and its allies saw the need to overcome this threat regardless.

Renowned scientist Maurice Biot began his work in non-linear elasticity and stability and published seven papers between 1937 and 1940 (Biot 1965). At the outbreak of World War II (WWII), Biot enlisted in the U. S. Navy and worked on the theories and applications of explosions and armor penetration (Tolstoy 1986). Additionally, he was involved in aviation studies in wing flutter and earthquake engineering (Biot 1943). After the conclusion of WWII Biot continued his earlier research and published the monograph *Mechanics of Incremental Deformation* in 1956. This monograph presented his theories on elasticity and viscoelasticity, in both solids and fluids, and highlighted his desire to present simple methods in mathematical formulations while properly representing fundamental physical properties (Biot 1965). Additionally, the basis of this monograph is seven of his published works between 1934 and 1940, in which Biot himself commented on his pause in research due to WWII (Biot 1965). Before the monograph was publicly available, Biot continued his work on poroelasticity and published numerous papers describing the interrelationships of fluid flow and solid deformation in porous media. His theory development began with considering soils under a load (Biot 1941a) and then expanded to settlement and consolidation problems (Biot 1941b, 1941c, 1942). Next Biot examined effects when solids contained compressible viscous fluids (Biot 1955). He then returned to more general solutions of the theory of elasticity (Biot 1956c). Immediately following the publishing of his general theory of elasticity, Biot published two additional papers in the Journal of the Acoustical Society of America in the fall of 1956. In these two papers, he presented his Theory of Propagation of Elastic Waves in fluid-saturated porous solids, including the low-frequency range (Biot 1956a) and the higher frequency range (Biot 1956b). In acoustics, this is Biot's theory. Section D further examines Biot's Theory and its applications to this thesis.

B. U.S. NAVAL APPLICATIONS

Antisubmarine warfare (ASW), mine warfare (MIW), and hydrography (HYDRO) are three of the U.S. Navy's Title 10 mission requirement sets (Title 10 §5062; Title 10 §5038; Title 10 §7921 2014). The U. S. Navy employs multiple sonar systems to carry out these missions. The system performance depends on numerous acoustic algorithms and accurate representations of the sea floor. Physical properties relevant to system performance include information such as sediment type, composition, and roughness of the sea floor.

U.S. naval shipboard systems and personnel operate various types of sonar processing software, which incorporate sediment composition into their algorithms. Most algorithms do not incorporate seafloor roughness, although it is one of the essential components of scattering properties at the water-sediment interface (Newhall and Johnson 2017). Sediments may show strong impacts from scattering properties, like porosity, an element within the Biot Theory (Williams et al. 2001). Systems and software that incorporate composition and roughness of the seafloor can aid in predicting and assessing the performance of these systems.

The U.S. Navy maintains seafloor and physical ocean property databases, such as the Oceanographic and Atmospheric Master Library (OAML) (Phelps et al. 2001). The OAML database information is an accumulation of data from sediment grabs, sediment core sampling, water column sampling, satellite data, and geoacoustic inversion techniques among others. Additionally, the U.S. Navy leverages international data collection, sharing, and scientific partnership agreements for added data ingest. Data sharing partnerships also exist among governmental organizations, non-governmental organizations, academic institutions, and numerous commercial industries. These databases contain many types of information related to the physical properties of the ocean and sea floor, but about 90 percent of the world's ocean bottom has not been surveyed to modern standards (Ward and Bessero 2013), and even less of the ocean bottom has been accurately analyzed for sediment type analysis (Dutkiewicz et al. 2015). Other physical properties that affect underwater acoustics such as sound speed, density, and attenuation as a function of frequency are not regularly measured.

The culmination of sediment information, physical properties, and seafloor characteristics within these databases afford better use of U.S. Navy acoustic sound sources, receivers, and processing software. Improvements in sediment and acoustic propagation models, knowledge, and data availability enhance the effectiveness of the data collectors, database users, and analysts. Furthermore, better understanding of the sediments, as well as other physical properties at the water-sediment interface will assist the Naval Research Laboratories (NRL), the Office of Naval Research (ONR), and Fleet operators in decision making on matters pertaining to seafloor acoustics and impacts of acoustic interactions.

Physical properties can have impacts on sonar sound transmissions and their interactions with the ocean floor (Sinex and Winokur 1993). The selection of sediment type

in sonar systems, processing systems, and tactical decision aids (TDA) alters transmission loss estimates output by propagation models, and affects decision making for ASW operators and analysts (Chandler and Alphonso 2002). In deep water or areas where bottom interactions are unlikely to occur (depth excess), discernable differences are less likely. However, in shallow water areas where bottom interaction occurs, identifying the bottom type and physical properties accurately can play a large role in ASW prediction and battlespace awareness. In specific geographic locations, or where significant acoustic criteria are present, the work of this thesis has potential applications to inform ASW operations and decision-making.

For MIW, a typical mission consists of collecting and analyzing post-processed acoustical side scan sonar (SSS) data, referred to as acoustic imagery. One commonly deployed MIW acoustic platform is the EdgeTech dual frequency 600 /1,600 kHz side scan sonar (EdgeTech 2018). The SSS provides acoustic imagery data for processing through commercial off-the-shelf (COTS) software for analysis. The COTS software enables users to identify bottom sediment type for inclusion in data processing algorithms. Additionally, quantitative and qualitative analyses provide warfighters information about the seafloor. In areas the U.S. Navy surveys for bottom type analysis, or where obtaining sediment data is not available, the work of this thesis may be applicable to MIW.

In HYDRO, common acoustical sensors include multi-beam echo sounders (MBES), single beam echo sounders (SBES), and SSS. The data collected by these systems aid in creation of nautical charts, which includes identification of underwater features and hazards to navigation. Several of the COTS software programs for processing these types of acoustic data have integrated sediment data information (Preston 2009). An emerging HYDRO technique uses superimposed images of MBES and SSS to make use of backscatter strength data to aid in seafloor classification and determination of physical characteristics of the sediments (Zhao et al. 2017). In areas of unknown sediment type, or unexpected acoustic response from these sensors, the work of this thesis may have potential applications to HYDRO and further increasing the accuracy of its analyzed data.

C. MODELS OF SOUND PROPAGATION IN SEDIMENTS

There are several models in underwater acoustics related to acoustic interaction with the water-sediment interface. These models primarily differ in their treatment of energy loss mechanisms and dispersion. These models begin with Newton's second law of motion and examine forces acting on small volumetric elements. Each model contains different assumptions of the strains and stresses, and generally reduce to an equivalent form of Hooke's law. These approximations enable examining the displacement of the fluid and sediments, specifically for plane waves propagating and interacting with a flat bottom, the water-sediment interface, as an ideal case.

The classical fluid model is the simplest case, which allows the sediment to act as a lossy fluid, only incorporating stress from acoustic pressure (Jackson and Richardson 2007). Fluid models provide the governing equations for plane wave motion and sets boundary conditions for continuity of pressure and continuity of displacement normal to the boundary, based on the linearized Navier-Stokes equation. Sediments have a certain degree of rigidity, but this model ignores the contact between the sediment grains and the resulting forces, resulting in a fluid approximation (Jackson and Richardson 2007). The simplifications within this model lead to the Helmholtz equation, and the only stress considered is acoustic pressure.

Increasing the complexity of the fluid model leads to the elastic model. The elastic model allows for water-saturated sediment systems to include shear forces. The addition of shear increases both the mathematical and physical complexity of the models, supporting compressional and shear waves in the sediment (Jackson and Richardson 2007). The inclusion of stresses and strains lead to use of tensor notation, accounting for all the forces in the system, and replaces the pressure in classical fluid model. Many of the mathematical complexities in the isotropic case stemming from the use of tensors simplify due to symmetry (Biot 1962a). This model allows for a reflected compressional wave in the fluid, and transmitted compressional and shear waves in the sediment. Elastic models provide a correction to classical fluid models, but have significantly different results when the sediment shear wave speed is not small compared to the fluid sound speed. This situation leads to significant transmission of energy into the sediment (Jackson and Richardson 2007). An extension of the elastic theory model is Buckingham's viscous grain shear (VGS) model. In this, Buckingham

considers the viscosity of a molecularly thin layer of pore fluid between sediment grains (Buckingham 2007). The VGS model is equivalent to the elastic model for a fixed frequency, and if shear is neglected, to the classical fluid model (Jackson and Richardson 2007). The VGS model is the biggest competitor to Biot's model.

The poroelastic model, sometimes known as Biot theory, allows for consideration of linear, porous media with elastic properties within the sediments and a compressible fluid saturating the pores (Beebe, McDaniel, and Rubano 1982). This model allows for the sediment and the fluid to move as a coupled system (Jackson and Richardson 2007). The coupled system gives rise to three waves in the sediment, two longitudinal waves and one shear wave. The longitudinal waves, also referred to as dilatational or compressional waves, are categorized as waves of the first kind (Type I; fast) and waves of the second kind (Type II; slow). Type I waves correspond to compressional waves in the elastic model but are frequency dependent (Buchanan et al. 2004). The Type II waves are strongly attenuated, highly dispersive, slower, and are not present in the elastic model. Type II waves occur when the fluid particle motion is out of phase with the frame (Stoll and Kan 1981). Type I and shear waves propagate with little dispersion (Stoll and Bryan 1970). Additionally, to account for the frequency dependence of viscous flow, Biot applied a complex correction factor to the fluid viscosity (Stoll 1989). Stoll modified Biot's theory to form another subset model (Stoll 1977), referred to as the Biot-Stoll model (Bonomo and Isakson 2018). Stoll introduces three modifications to make Biot's work applicable to real sediments. Stoll postulates that the viscous resistance to fluid flow must be frequency dependent to correct for deviations arising from Poiseuille flow (Stoll 1989). Additionally, he accounts for frictional losses and intergranular bonds due to the inelastic nature of the skeletal frame - the sediment (Stoll 1989). Finally, he accounts for the losses resulting from motion near the intergranular contacts (Stoll 1989). The Biot-Stoll model replaces several of the physical parameters treated as constants in the Biot model with effective parameters. These parameters are defined by operators that consider viscoelastic or "slightly" nonlinear properties, accounting for the inelasticity of the skeletal frame and effects from local viscous damping due to the squeeze film motion (Stoll 1989). Squeeze film motion is the local motion of the fluid in to, out of, or between sediment grains, their pores, and the intergranular contacts. Specifically, the local losses arising from

the fluid viscosity that may produce additional energy dissipation (Biot 1962b). This thesis follows the Biot-Stoll model of Biot theory. A more complete derivation of Biot's governing equations, descriptions of boundary conditions, and identification of assumptions and restrictions on this type of plane wave modeling are further described in Biot (1956a), Buchanan et al. (2004), and Stoll and Kan (1981).

D. RESEARCH QUESTIONS

The work of this thesis examined Biot theory through mathematical modeling and analyses of acoustic plane wave reflection from a poroelastic water-sediment interface, as presented in the Biot-Stoll model. Characterizing and understanding acoustic interactions at the water-sediment interface is an important precursor to any underwater acoustic activity. Knowledge of seafloor sediment type improves understanding of how the physical parameters of sediments influence sound propagation and is advantageous for many naval applications. Physical parameters include sediment grain size, sediment composition, grain properties, speed of sound in the fluid, speed of sound in the sediment, porosity, characteristic pore size, permeability, and many others. When the seafloor sediment type is unknown, predicting and modeling seafloor interactions can be challenging.

While several studies have analyzed plane wave interactions at the water-sediment interface, few have addressed relationships between variability of parameters in Biot's model and propagation effects within and from the sediment. Accurate and comprehensive analyses of many physical characteristics and parameters are difficult to conduct, measure, and verify but numerical modeling and experimentation may enable a better understanding of this variability and its impacts on sonar interactions with the sea floor. This thesis employed numerical methods to relate variations in selected sediment parameters to variability in the reflection coefficient and bottom loss. Variability in bottom loss influences variability of acoustic propagation in the ocean.

This thesis examined several aspects of the acoustic interactions that occur at the water-sediment interface. Specifically, this thesis systematically varied four of the 13 Biot parameters, and analyzed its effect on the plane wave reflection coefficient. We analyzed the following Biot parameters: characteristic pore size, (dynamic) viscosity, permeability, and

porosity. The literature review highlighted the importance in the modeling efforts of acoustic interaction at the sea floor for these four parameters (Stoll 1980 and 1989; Holland and Brunson 1988; Williams et al. 2002; and Bonomo and Isakson 2018). Using conditions from a cruise conducted in 2013, we modeled these four parameters using COMSOL and MATLAB software programs. Chapter II describes several simplifications and assumptions that enabled our modeling efforts.

We used control data from several sources to verify the initial model set up and results, and for comparison against field data results. The field data used in this thesis were collected from May 8–14, 2013, in the northeastern South China Sea onboard the Research Vessels OCEAN RESEARCHER 5 and 2. This cruise was part of a multi-year project sponsored by ONR and in collaboration with Taiwanese scientists. Previous cruises in the experiment area revealed large amplitude submarine sand dunes on the upper slope of the northeastern South China Sea (Reeder et al. 2011). This particular cruise’s goal was to investigate the effects of these submarine sand dunes on acoustic propagation and reverberation. The sand dunes occur in approximately 400 meters of water. Surveys of the data collection area, using MBES several times over the course of a few years, indicated their persistent presence in the South China Sea (Reeder, Ma, and Yang 2009). Analyses of the collected acoustic data from the multi-year experiments used numerous methods, including inversion to determine the geoacoustic parameters (Chiu et al. 2013a, 2013b, 2013c). While geoacoustic inversion techniques are not performed in this thesis, the concept of taking acoustic data and inverting it to derive geoacoustic parameters, namely sediment parameter data, provide a base knowledge in understating acoustic interaction at the water-sediment interface. It is similarly important to understand and characterize the dependence of variability in bottom loss due to variability of the sediment parameters. The results of this thesis may further understanding of the acoustical interactions at the water-sediment interface and allow sediment information to be ascertained and aid in determining the four parameters studied in this thesis from measured acoustic data.

Tables 1, 2, and 3 identify the notation used for the parameters, and document each source of information. A comparison of the notation, enabled parameter comparison across multiple source documents and computer programs. This was critical in ensuring that the

equations presented in the literature were consistent with the finite element modeling equations in both COMSOL and MATLAB.

Table 1. Frequency Independent Parameters

Parameter	Parameter Symbol Biot	Parameter Symbol Buchanan	Parameter Symbol Bonomo	Parameter Symbol COMSOL	Parameter Symbol MATLAB
Porosity	β	β	ε_p	ε_p	beta1
Mass density of grains	ρ_r	ρ_r	N/A	ρ_s	rho_r
Mass density of pore fluid	ρ_f	ρ_f	ρ_f	ρ_f	rho_f
Bulk modulus of sediment grains	K_r	K_r	N/A	K_s	K_r
Bulk modulus of pore fluid	K_f	K_f	N / A	K_f	K_f

Adapted from Biot (1956a); Buchanan et al. (2004); Bonomo et al. (2013); and COMSOL (2015b).

Table 2. Parameters Affecting Global Fluid Motion

Parameter	Parameter Symbol Biot	Parameter Symbol Buchanan	Parameter Symbol Bonomo	Parameter Symbol COMSOL	MATLAB Symbol Notation
Permeability	k	k	κ	κ_p	perma
Viscosity of pore fluid	η	η	μ_f	μ_f	eta
Pore-size parameter	a	a	N/A	a	script_a
Structure factor	α	α	τ	α	tau

Adapted from Biot (1956a); Buchanan et al. (2004); Bonomo et al. (2013); and COMSOL (2015b).

Table 3. Parameters Controlling Frequency-dependent Response of Frame

Parameter	Parameter Symbol Biot	Parameter Symbol Buchanan	Parameter Symbol Bonomo	Parameter Symbol COMSOL	MATLAB Parameter Symbol
Shear modulus of skeletal frame	$\bar{\mu} = \mu_r(\omega) + i\mu_i(\omega)$	$\mu^* = \mu_r(\omega) + i\mu_i(\omega)$	G	$G_c = G + \log dec / \pi \times K_b \times i$	$mu_x = mu_r + (1i \times mu_i)$
Bulk modulus of skeletal frame	$\bar{K} = K_{br}(\omega) + iK_{bi}(\omega)$	$K_b^* = K_{br}(\omega) + iK_{bi}(\omega)$	K	$K_{bc} = K_b + \log dec / \pi \times K_b \times i$	$K_b = K_br + (1i \times K_bi)$

Adapted from Biot (1956a); Buchanan et al. (2004); Bonomo et al. (2013); and COMSOL (2015b).

Tables 4, 5, and 6 are a compilation of sediment parameter data used in this study. The first set of sediment parameter data presented in Table 4 are from Buchanan et al. (2004), Stoll and Kan (1981), and Stoll (1977). The data presented in Table 4 were used as the control sediment parameter data for both the COMSOL and MATLAB model testing. The sediments listed in Table 4 are fine sand (FS), coarse sand (CS), coarse sand and fine gravel (CSFG), silty sand (SS), silty clay (SC), sand (SA), and soft sediment (SOSE). The second set of sediment parameter data are from the 2013 South China Sea cruise (Chiu et al. 2013b and c), as presented in Table 5. Initial model testing data are presented in Table 6. These data are a compilation of Table 4 data for CS and SA, and representative data for C4 and LST. The data shown in Table 6 were determined from calculations based on the 2013 South China Sea cruise data and the literature review for similar sediments to obtain the remaining physical characteristics needed for modeling. All the imaginary parameters were set to zero, as they were not available for the South China Sea data and the literature review did not contain these data. All data contained in Table 6 are referenced to fresh water conditions and were used in model verification. Chapter III presents the subsets of the data as presented in Table 6, analyzed in both COMSOL and MATLAB. Additionally, Table 14 presents the data from Table 6 but are based on salt water oceanographic conditions as observed from the 2013 South China Sea cruise report.

Table 4. Control Sediment Parameter Data

Parameter	FS	CS	CSFG	SS	SC	SA	SOSE
K_r	4.0e10	5.6e10	4.0e10	3.8e10	3.5e10	3.6e10	3.6e10
K_f	2.4e9	2.4e9	2.4e9	2.4e9	2.4e9	2.0e9	2.0e9
μ_i	4.3e6	4.7e6	5.3e6	1.3e6	7.2e6	0	0
μ_r	6.7e7	7.4e7	8.3e7	2.9e7	3.4e7	2.61e7	2.21e7
K_{bi}	6.7e5	7.4e5	8.2e5	1.3e6	1.2e6	0	0
K_{br}	4.8e7	5.3e7	5.9e7	2.9e7	2.6e7	4.36e7	3.69e7
β_1	0.43	0.38	0.30	0.65	0.68	0.47	0.76
ρ_{ma}	3.12e-14	7.5e-11	2.58e-10	6.33e-15	5.2e-14	5e-13	1.6e-15
ρ_f	1000	1000	1000	1000	1000	1000	1000
ρ_r	2670	2710	2680	2670	2680	2650	2650
α	1.20e-6	6.28e-5	1.31e-4	4.25e-7	1.24e-6	1.2e-5	1.31e-7
τ	1.25	1.25	1.25	3.0	3.0	1.25	1.35
η	1.01e-3	1.01e-3	1.01e-3	1.01e-3	1.01e-3	1.01e-3	1.01e-3
f_{req1}	Varies with model runs, but a general value: $\logspace(0,6,5000)$						

Adapted from Buchanan et al. (2004); Stoll and Kan (1981); and Stoll (1977).

Table 5. 2013 South China Sea Cruise Report Sediment Data

Name	Description	Mean grain size (m)
C4	Yellow coarse sand, Qtz.	$707.8e-6$
C5	Black mid-sand, 10% shell fragment	$235.8e-6$
C6	Greyish yellow coarse sand	$193.7e-6$
C7	Yellow coarse sand and gravel, Qtz.	$> 2000e-6$
C8	Black mid-sand, 20% shell fragment	$340.6e-6$
EEP	Black mid-sand, 10% shell fragment	$221.4e-6$
LSP	Yellow coarse sand and gravel, Qtz.	$> 2000e-6$
LST	Grey mud	$10.10e-6$
M1	Greyish yellow coarse sand	$285.9e-6$

Adapted from Chiu et al. (2013b and 2013c).

Table 6. 2013 South China Sea Cruise Report Sediment Data Estimation of Parameters and Control Sediment Parameter Data

Parameter	CS	C4	SA	LST
K_r	$5.6e10$	$3.2e10$	$3.6e10$	$3.6e10$
K_f	$2.4e9$	$2.395e9$	$2.0e9$	$2.25e9$
mu_i	0	0	0	0
mu_r	$7.4e7$	$2.92e7$	$2.61e7$	$2.21e7$
K_bi	0	0	0	0
K_br	$5.3e7$	$4.36e7$	$4.36e7$	$3.69e7$
beta1	0.38	0.385	0.47	0.76
perma	$7.5e-11$	$2.5e-11$	$5.0e-13$	$2.6e-11$
rho_f	1000	1000	1000	1000
rho_r	2710	2690	2650	2650
script_a	$6.28e-5$	$2.65e-5$	$1.2e-5$	$1.31e-7$
tau	1.25	1.25	1.25	1.35
eta	$1.01e-3$	$1.01e-3$	$1.01e-3$	$1.01e-3$
freq1	Varies with model runs, but a general value: logspace(0,6,5000)			

Adapted from Chiu et al. (2013b and 2013c); Buchanan et al. (2004); Williams et al. (2002); Stoll and Kan (1981); Stoll (1977); and Badiey et al. (1998).

E. MODELING THE WATER-SEDIMENT INTERFACE

Biot's governing equations for plane waves in a porous, elastic fluid-filled medium are derived from Newton's second law. Biot then accounted for stress, strain, viscous drag effects and losses due to the fluid-frame interaction, and inelasticity of the skeletal frame (Beebe et al. 1982). Additionally, the physical properties studied that influenced the fluid-frame system were characteristic pore size, viscosity, permeability, and porosity. These interactions and their effects are discussed further in Chapter III.

The system considered is constituted by a fluid half-space and a porous half-space as depicted in Figure 1. The fluid half-space consists of water. The porous half-space is the sediment layer, consisting of the sediment grains, saturated with the fluid. The uppermost boundary of the porous half-space is considered the boundary between the two and is assumed to be a flat surface in this thesis. The representation of uniform sediment in Figure 1 is an idealized case of spherical, uniform sediments. The poroelastic half-space consists of the solid frame of the individual grains, any fluid contained within this boundary, and the fluid in between the individual grains. This treatment allows for motion of the frame, the fluid contained within, and the coupled fluid-frame system. An example of a realistic solid frame is shown in Figure 2.

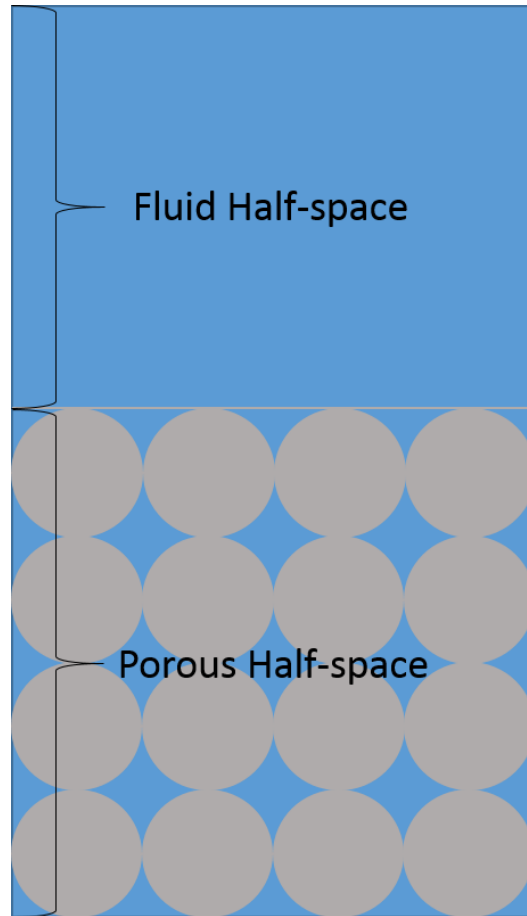
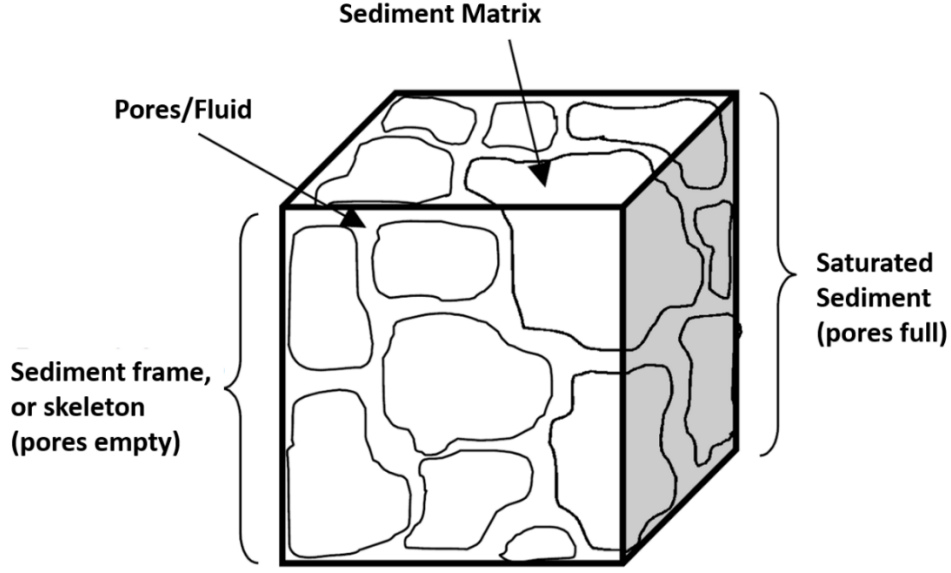


Figure 1. Fluid and Porous Half-space



Adapted from Russell et al. (2008).

Figure 2. Realistic Poroelastic Half-space

The equations of motion account for the motion of the fluid moving into or out of the skeletal frame and the motion of the fluid relative to the frame. These two equations are a system of coupled partial differential equations in the Cartesian coordinate system that assume constant coefficients and $e^{i\omega t}$ time dependent motion (Bonomo et al. 2013). The equations of motion in Biot theory are (Buchanan et al. 2004)

$$\mu \nabla^2 \vec{u} + \nabla[(\lambda + \mu)e + Q\varepsilon] = \frac{\partial^2}{\partial t^2}[\rho_{11}\vec{u} + \rho_{12}\vec{U}] + b \frac{\partial}{\partial t}(\vec{u} - \vec{U}) \quad (0.1)$$

and

$$\nabla[Qe + R\varepsilon] = \frac{\partial^2}{\partial t^2}[\rho_{12}\vec{u} + \rho_{22}\vec{U}] - b \frac{\partial}{\partial t}(\vec{u} - \vec{U}), \quad (0.2)$$

where $\vec{u}$ is the displacement of the frame and $\vec{U}$ is the displacement of the fluid. These displacements describe the flow of fluid into or out of the frame. The four elastic constant coefficients representing the stress and strains are λ , μ , Q , and R . The Lamé coefficients for the frame, similar to those in elastic theory, are denoted by μ for the shear coefficient

and λ for the compressional coefficient (Biot 1956a). Attenuation is incorporated into the system by allowing the two Lamé coefficients to be complex (Buchanan et al. 2004).

The divergence of the fluid dilatations, ε , is denoted by $\varepsilon = \nabla \bullet \vec{U}$ and represents the relative volumetric increment divergence (Buchanan et al. 2004), derived from the average volume flow through the pores (Biot and Willis 1957). The divergence of the frame dilatations is denoted as e , and is denoted by $e = \nabla \bullet \vec{u}$, representing the relative volumetric increment due to deformation of the frame. The elastic constant Q represents the volumetric fluid flow rate through the medium governed, and describes the coupling between the volume change of the solid and the fluid (Biot 1956a). This elastic constant is denoted by $Q = \beta(\alpha - \beta)M$ (Biot 1962a). The Biot-Willis coefficient is denoted as α , and is denoted by $\alpha = \frac{K_r - K_b}{K_r}$ and constrained by $\beta < \alpha < 1$. The Biot-Willis coefficient accounts for the non-uniform flow of the pore fluid, the geometry of the pore system, and the pore fluid flow is not generally in the direction of the macroscopic pressure gradient (Stoll and Bryan 1970). The bulk modulus of the sediment grains is denoted by K_r and indicates how the grains respond to isostatic pressure. The bulk modulus of the skeletal frame is denoted by K_b and indicates how the skeletal frame responds to isostatic pressure. The bulk and shear moduli are allowed to be complex values which accounts for various forms of energy dissipation that may be occurring at the grain contacts (Stoll and Kan 1981). The porosity is denoted by β . The porosity is the ratio of the volume of the pores in the sediment to the volume of fluid, and is connected with the bulk motion of the fluid relative to the solid represented by the interconnecting void space (Biot 1956c).

The elastic constant M represents the fluid volume that can be forced into the sediment under pressure while the volume of the sediment is kept constant, to include the effects of dissipation (Biot 1941a), and is denoted by $M = \frac{K_r^2}{D - K_b}$. Rayleigh's dissipation parameter is denoted by D , and is governed by $D = K_r[1 + \beta(\frac{K_r}{K_f} - 1)]$, where K_f is the bulk modulus of the fluid. The elastic constant denoted by R , is a measure of the pressure

required on the fluid to force a certain volume of the fluid into the aggregate while the total volume remains constant (Biot 1956a). This constant is governed by $R = \beta^2 M$. The effective mass density of the frame is denoted by ρ_{11} , the effective mass density of the frame-fluid interaction is denoted by ρ_{12} , and the effective mass density of the fluid is denoted by ρ_{22} . Effective densities account for motion of the fluid relative to the frame (Buchanan et al. 2004). The dissipation parameter is denoted by $b = \frac{\eta \beta^2}{\kappa} F(\omega)$, where η is the viscosity and κ is Darcy's coefficient of permeability (Biot 1956b), and $F(\omega)$ is the complex correction factor.

Biot devised the complex correction factor to account for the deviation from Poiseuille flow friction in the pores as a function of frequency due to the fluid viscosity, dependent on the general shape and size of the pores. Assuming pores with uniform size, Biot showed that the effects of pore cross sections behave in a similar manner for flat ellipses and circles, less a frequency correction factor. He accounted for this phenomenon through the complex function, $F(\omega)$. As presented by Stoll (1977), for oscillatory motion this function utilizes the ratio of the friction force exerted by the fluid on the frame to the average relative motion, and is given by

$$F(\chi) = F_r(\chi) + iF_i(\chi) = \frac{1}{4} \frac{\chi T(\chi)}{1 - \frac{2T(\chi)}{i\chi}} \quad (0.3)$$

where

$$T(\chi) = \frac{ber'(\chi) + ibei'(\chi)}{ber(\chi) + ibei(\chi)} \quad (0.4)$$

and $\chi = a \sqrt{\frac{\omega \rho_f}{\eta}}$. The real and imaginary parts of the Kelvin function are $ber(\chi)$ and $bei(\chi)$, respectively. The angular frequency is denoted by ω , and the parameter governing the size and shape of the pores is denoted by a , and is commonly referred to as the characteristic pore size parameter.

In the high frequency range, viscous forces are comparable to the inertial forces, which is also where the assumption of Poiseuille flow breaks down (Biot 1956b). In this regime, the characteristic pore size is used to determine a reference frequency, f_r , and is denoted by

$$f_r = \frac{\eta}{2\pi a^2 \rho_f} \quad (0.5)$$

and

$$\bar{\eta}_f = \eta F\left(\sqrt{\frac{f}{f_r}}\right), \quad (0.6)$$

where η is the viscosity of the pore fluid and $\bar{\eta}$ is the notation for the complex viscosity correction factor of the pore fluid. This is the equivalent of replacing the quantity η/κ with $F\eta/\kappa$ in the frequency domain as given in Stoll (Stoll 1989). The correction factor accounts for the relative scale difference between the pore diameter and the acoustic boundary layer thickness (Biot 1956b). In practice, this frequency is measured or its value is empirically determined from the literature (COMSOL 2015a).

Assuming two-dimensional plane-wave reflection from the fluid/porous media interface, potential functions are introduced that separate the compressional (dilatational) and the rotational (shear) portions of the fluid and solid displacements.

$$\vec{u} = e^{i\omega t} [\nabla \phi_s + \nabla \times \vec{\psi}_s] \quad (0.7)$$

$$\vec{U} = e^{i\omega t} [\nabla \phi_f + \nabla \times \vec{\psi}_f] \quad (0.8)$$

Substituting these expressions into equations (0.1) and (0.2) and applying the divergence operator, the following coupled equations for the compressional potentials result:

$$(\lambda_c + 2\mu)\nabla^2 \phi_s + \alpha M \nabla^2 \phi_f = -\rho \omega^2 \phi_s - \rho_f \omega^2 \phi_f \quad (0.9)$$

and

$$\alpha M \nabla^2 \phi_s + \mu \nabla^2 \phi_f = -\rho_f \omega^2 \phi_s + \left[\frac{i\omega\eta}{\chi} F(\omega) - m\omega^2 \right] \phi_f, \quad (0.10)$$

where $\rho = (1 - \beta)\rho_s + \beta\rho_f$ and $\lambda_c = \lambda + M\alpha^2$.

Substituting equations for $\vec{u}$ and $\vec{U}$ into (0.1) and (0.2) and taking the curl of each leads to the coupled equations for the rotational potentials:

$$\mu \nabla^2 \vec{\psi}_s = -\rho \omega^2 \vec{\psi}_s - \rho_f \omega^2 \vec{\psi}_f \quad (0.11)$$

$$\rho_f \vec{\psi}_s = \left[\frac{i\eta}{\omega\chi} - m \right] \psi_f \hat{j}. \quad (0.12)$$

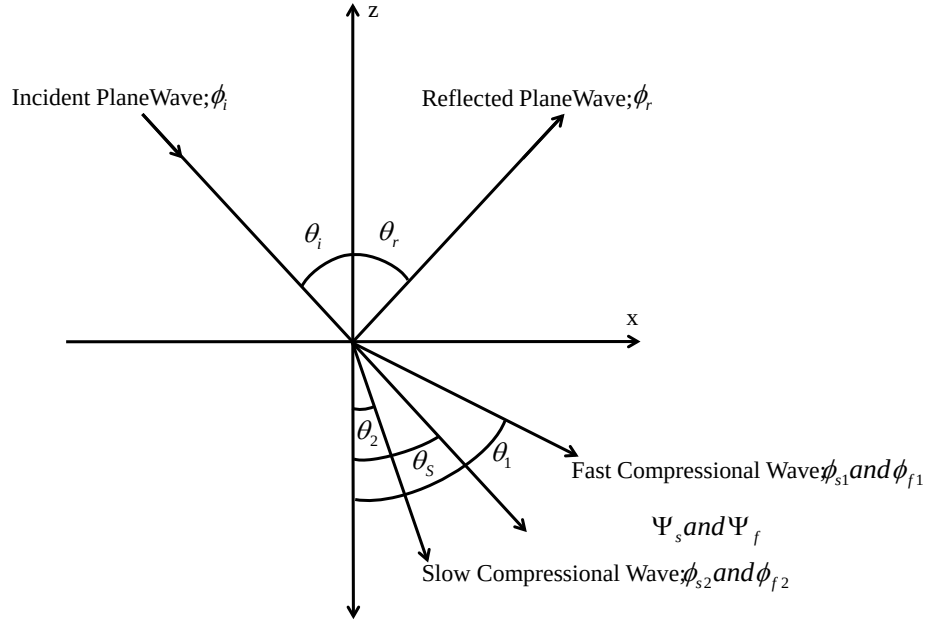
Because the problem is two-dimensional (in the x-z plane), the rotational potentials can be written

$$\vec{\psi}_s = \psi_s \hat{j} \text{ and } \vec{\psi}_f = \psi_f \hat{j}, \quad (0.13)$$

where $\hat{j}$ is the unit vector in the y direction of the Cartesian grid. From this point the rotational potential will refer only to the scalar components of the rotational vector potentials.

Figure 3 depicts the spatial representation of the x and z-axes in the Cartesian coordinate system. The incident plane wave in the fluid half-space is described by the displacement potential, ϕ_i , and the angle, θ_i . The incident angle is measured from normal, and $\theta_i = \theta_0$, where θ_0 is the incident angle measured from normal. The reflected plane wave in the fluid half-space is described by the displacement potential, ϕ_r , and the angle, θ_r . In the porous half-space, there exist three refracted displacement potentials and their complex angles. Together, along with the complex amplitudes and the complex wavenumbers, these characteristics describe the motion of the two compressional waves and the shear wave in the fluid saturated sediment. In a similar manner, the fast compressional wave is described by the displacement potentials ϕ_{s1} and ϕ_{f1} , for the sediment and fluid respectively. Additionally, the slow compressional wave is described by the displacement potentials ϕ_{s2} and ϕ_{f2} , for the sediment and fluid respectively. The

shear wave is described by the displacement potentials ψ_s and ψ_f , for the sediment and fluid respectively. Like the reflected plane wave, these other types of waves are also characterized by their complex amplitudes and wavenumbers.



Adapted from Stoll and Kan (1981).

Figure 3. Incident, Reflected, and Refracted Displacement Potentials and Angles

To determine the displacement potentials and angles, which represents the reflection and refraction at the water-sediment interface, four boundary conditions are imposed on the governing equations. These boundary conditions must be satisfied at the water-sediment interface, where $z = 0$. At this boundary, continuity of the vertical fluid displacement is described by

$$\left[\frac{\partial \phi_s}{\partial z} + \frac{\partial \psi_s}{\partial x} + \frac{\partial \phi_f}{\partial z} + \frac{\partial \psi_f}{\partial x} = \frac{\partial \phi_i}{\partial z} + \frac{\partial \phi_r}{\partial z} \right]_{z=0} . \quad (0.14)$$

Additionally, continuity of the normal tractions is described by

$$[\lambda_c \nabla^2 \phi_s + 2\mu(\frac{\partial^2 \phi_s}{\partial z^2} + \frac{\partial^2 \psi_s}{\partial z \partial x}) + \alpha M \nabla^2 \phi_f = -\omega^2 \rho_f (\phi_i + \phi_r)]_{z=0}. \quad (0.15)$$

The adiabatic Lamé coefficient is denoted by λ_c , the fluid density is denoted by ρ_f , and the angular frequency is denoted by ω . Continuity of the fluid pressure at the interface is described by

$$[M \nabla^2 \phi_f + \alpha M \nabla^2 \phi_s = -\omega^2 \rho_f (\phi_i + \phi_r)]_{z=0}. \quad (0.16)$$

Finally, the vanishing shear stress is described by

$$[2 \frac{\partial^2 \phi_s}{\partial x \partial z} + \frac{\partial^2 \psi_s}{\partial x^2} - \frac{\partial^2 \psi_s}{\partial z^2} = 0]_{z=0}. \quad (0.17)$$

Incident and reflected plane wave potentials are:

$$\phi_i = I e^{i(\omega t - k_w x \sin \theta_i + k_w z \cos \theta_i)} \quad (0.18)$$

and

$$\phi_r = R e^{i(\omega t - k_w x \sin \theta_r - k_w z \cos \theta_r)}, \quad (0.19)$$

where $k_w = \frac{\omega}{c_f}$ and c_f is the fluid wave speed. Plane wave potentials for the fast compressional waves, Type I, are

$$\phi_{s_1} = A_1 e^{i(\omega t - k_1 x \sin \theta_1 + k_1 z \cos \theta_1)} \quad (0.20)$$

and

$$\phi_{f_1} = g_1 A_1 e^{i(\omega t - k_1 x \sin \theta_1 + k_1 z \cos \theta_1)}. \quad (0.21)$$

Plane wave potentials for the slow compressional waves, Type II, are

$$\phi_{s_2} = A_2 e^{i(\omega t - k_2 x \sin \theta_2 + k_2 z \cos \theta_2)} \quad (0.22)$$

and

$$\phi_{f_2} = g_2 A_2 e^{i(\omega t - k_2 x \sin \theta_2 + k_2 z \cos \theta_2)}. \quad (0.23)$$

Finally, plane wave potentials for the shear waves are

$$\psi_s = Ce^{i(\omega t - k_s x \sin \theta_s + k_s z \cos \theta_s)} \quad (0.24)$$

and

$$\psi_f = g_s Ce^{i(\omega t - k_s x \sin \theta_s - k_s z \cos \theta_s)}. \quad (0.25)$$

Expressions for g_1 , g_2 , and g_s will be given shortly.

Wave numbers for the slow and fast compressional potentials in the porous medium, as well as g_1 and g_2 are found by substituting ϕ_s and ϕ_f into equations (0.9) and (0.10) leading to the following matrix equation using $\nabla^2 \phi_s = -k^2 \phi_s$ and $\nabla^2 \phi_f = -k^2 \phi_f$.

$$\begin{pmatrix} \rho\omega^2 - k^2(\lambda_c + 2\mu) & \rho_f\omega^2 - k^2\alpha M \\ \rho_f\omega^2 - k^2\alpha M & m\omega^2 - k^2M - \frac{i\omega\eta F(\omega)}{\kappa} \end{pmatrix} \begin{pmatrix} \phi_s \\ \phi_f \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}. \quad (0.26)$$

Note that k_1 is chosen to be the smaller of the roots and corresponds to the fast compressional wave, or Type I wave. Similarly, k_2 is chosen to be the larger of the roots and corresponds to the slow compressional wave, or Type II wave. Fixing k^2 to be either k_1^2 or k_2^2 in the first equation of (0.26) one can solve for g_1 or g_2 .

$$g_1 = \frac{k_1^2(\lambda_c + 2\mu) - \rho\omega^2}{\rho_f\omega^2 - k_1^2\alpha M} \quad (0.27)$$

and

$$g_2 = \frac{k_2^2(\lambda_c + 2\mu) - \rho\omega^2}{\rho_f\omega^2 - k_2^2\alpha M}. \quad (0.28)$$

Similarly, substituting the rotational potentials (using $\nabla^2 \psi_s = -k_s^2 \psi_s$ and $\nabla^2 \psi_f = -k_s^2 \psi_f$) into equations (0.11) and (0.12), one finds

$$g_s = \frac{\mu k_s^2 - \rho\omega^2}{\rho_f\omega^2} \quad (0.29)$$

and

$$k_s^2 = \frac{\omega^2}{\mu} \left(\rho + \frac{\rho_f^2 \omega \kappa}{i\eta F(\omega) - m\omega \kappa} \right). \quad (0.30)$$

Returning to equation (0.26), k_1 and k_2 are found by setting the determinant of the coefficient matrix equal to zero.

$$\det \begin{pmatrix} \rho\omega^2 - k^2(\lambda_c + 2\mu) & \rho_f\omega^2 - k^2\alpha M \\ \rho_f\omega^2 - k^2\alpha M & m\omega^2 - k^2M - \frac{i\omega\eta F(\omega)}{\kappa} \end{pmatrix} = 0. \quad (0.31)$$

Letting

$$a_1 = (\lambda_c + 2\mu)M - \alpha^2 M^2, \quad (0.32)$$

$$a_2 = \frac{1}{2} \left(m\omega^2 - \frac{i\omega\eta F(\omega)}{\kappa} \right) (\lambda_c + 2\mu) + \frac{M\rho\omega^2}{2} - \alpha M \rho_f \omega^2, \quad (0.33)$$

and

$$a_3 = \rho\omega^2 \left(m\omega^2 - \frac{i\omega\eta F(\omega)}{\kappa} \right) - \rho_f^2 \omega^4. \quad (0.34)$$

The determinant results in a quadratic in k^2 ; $a_1(k^2)^2 - 2a_2(k^2) + a_3 = 0$. Using the quadratic formula, we find

$$k^2 = \frac{a_2}{a_1} \pm \sqrt{\left(\frac{a_2}{a_1} \right)^2 - \left(\frac{a_3}{a_1} \right)}. \quad (0.35)$$

Finally, the unknown coefficients A_1 , A_2 , C , and R are found by solving the interface boundary condition equations as presented in matrix form.

$$\begin{pmatrix}
(1+g_1)k_1 \cos \theta_1 & (1+g_2)k_2 \cos \theta_2 & -(1+g_s)k_w \sin \theta_i & k_w \cos \theta_i \\
-(k_1^2 \lambda_c + 2\mu k_w^2 \sin^2 \theta_i + \alpha M k_1^2 g_1) & -(k_2^2 \lambda_c + 2\mu k_w^2 \sin^2 \theta_i + \alpha M k_2^2 g_2) & 2\mu k_s k_w \sin \theta_i \cos \theta_s & \omega^2 \rho_f \\
(\alpha + g_1)M k_1^2 & (\alpha + g_2)k_2^2 M & 0 & -\omega^2 \rho_f \\
2k_w k_1 \sin \theta_i \cos \theta_1 & 2k_w k_2 \sin \theta_i \cos \theta_2 & k_s^2 \cos^2 \theta_s - k_w^2 \sin^2 \theta_i & 0
\end{pmatrix}
\begin{pmatrix}
A_1 \\
A_2 \\
C \\
R
\end{pmatrix}
=
\begin{pmatrix}
I k_w \cos \theta_i \\
-\omega^2 \rho_f I \\
\omega^2 \rho_f I \\
0
\end{pmatrix}, \quad (0.36)$$

where the coefficient A_1 describes the fast wave amplitude, the coefficient A_2 describes the slow wave amplitude, the coefficient C describes the shear wave amplitude, and the coefficient R describes the reflection coefficient. These coefficients quantify each wave's complex amplitude based on model input variables and parameters, and their values are presented in Chapter III for selected sediments. The finite element method (FEM) was used to explore the variations of four Biot parameters. MATLAB software, through coding of plane wave propagation, was used to verify the results from the COMSOL modeling. A set of control sediment data parameters were obtained from Buchanan et al. (2004) and Stoll and Kan (1981) and modeled in both COMSOL and MATLAB. The results were compared against the published results for model verification.

The MATLAB code outputs data at multiple sub-steps in the derivation of Biot's governing equations, enabling output of physical properties and parameters for further analysis. Examples of these properties are reflected wave coefficients, reflected wave speeds, reflected wave phases, and attenuated wave coefficients. The output of data at these sub-steps enabled comparison of the control data to the literature, further enhancing our confidence in both the MATLAB code and COMSOL model testing prior to examining the 2013 South China Sea cruise data (Chiu et al. 2013a, 2013b, 2013c).

To determine the attenuation for each wave type, we allowed for complex wave numbers and solved the following equations:

$$c_{1,2} = \frac{\omega}{\text{Re}(k_{1,2})} \quad (0.37)$$

$$c_s = \frac{\omega}{\text{Re}(k_s)} \quad (0.38)$$

and

$$\gamma_{1,2} = \frac{\text{Im } k_{1,2}}{\nu \text{Re}(k_{1,2})} \quad (0.39)$$

$$\gamma_s = \frac{\text{Im}(k_s)}{\nu \text{Re}(k_s)}, \quad (0.40)$$

where $\nu = \frac{\ln 10}{40\pi}$. Due to the employed coordinate system, having the two longitudinal waves propagating and decaying in the negative z direction, and $\cos \theta_1$, $\cos \theta_2$, and $\cos \theta_s$ are all positive, the imaginary parts of k_1 , k_2 , and k_s must be negative.

Analysis for this thesis began with identifying the specified Biot parameter values, adhering to the boundary and modeling conditions, reconstituting the governing equations in MATLAB, and then conducting numerical analyses from the outputs of the COMSOL model runs. The COMSOL Multiphysics Reference Manual (2015c) and the Acoustics Modules Users Guide (2015a) contain the full listing of the COMSOL equations. The appendix contains the MATLAB code of Biot's governing equations.

F. INTENT OF STUDY

This thesis examined variations in characteristic pore size, dynamic viscosity, permeability, and porosity and assessed the impacts of these variations on the acoustic reflection coefficient and bottom loss at the water-sediment interface. We modeled the variation of characteristics of the sediment data using the FEM models in COMSOL and MATLAB, examined the variations of a subset of the control data parameters, and analyzed the results from our variation studies on the variability in the reflection coefficient and bottom loss. Similarly, we modeled a subset of the 2013 South China cruise data using the FEM models in COMSOL and MATLAB, examined the variations of a subset of these data, and analyzed the results from our variation studies on the variability in the reflection coefficient and bottom loss. Comparison of the analytic reflection and transmission coefficient magnitudes with the COMSOL simulation results revealed consistent results. Additionally, correlations between the selected parameters of the control data and the 2013 South China Sea cruise data were identified. We evaluated the correlations and suggest implications these variations may have on Navy acoustics. Interpretation and investigation of our results were made while considering the following research questions:

1. Can we properly simulate the acoustical conditions observed in the 2013 South China Sea cruise data?
2. Can we estimate the appropriate Biot parameters and their variability to understand and explain the observed acoustic interactions in the collection area?
3. Can we use this information to predict other areas where these conditions are likely to occur?

Applying knowledge gained from studies such as this can assist with sensor employment for U.S. Naval assets in applications such as ASW, MIW, and HYDRO surveying. The capability to understand the environment and predict how underwater acoustics will behave has the potential of positively influencing the U.S. Navy through enabling better decision making.

This thesis is organized into the following chapters: Chapter II discusses the FEM, the COMSOL Multiphysics and MATLAB models, as well as information on the control and field data used in the conducting of this research. It also describes the sensitivity analyses methodology used in this research. Chapter III presents results from the analyses, Chapter IV discusses our results. Chapter V contains conclusions and recommendations for future research.

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II. MODEL DESCRIPTION, DATA DESCRIPTION, AND METHODOLOGY

A. OVERVIEW

In this thesis, we used published data from multiple sources and field data from the 2013 South China Sea cruise report (Chiu et al. 2013a, 2013b, 2013c) to examine variations in pore size, viscosity, permeability, and porosity. This chapter discusses the FEM, the COMSOL and MATLAB models, our selected data sets, and the methods used to study our selected parameters. The model results are discussed in more detail in Chapter III.

B. DESCRIPTION OF THE FINITE ELEMENT METHOD

In the case of poroelastic materials, we used Biot's theory and solutions to the partial differential equations, Equations (0.1) and (0.2), to describe how the acoustic waves behaved in the poroelastic half-space and in the fluid half-space. Our models examined the pressure waves in the fluid half-space and elastic waves in the porous half-space (COMSOL 2015a). To solve these partial differential equations numerically, the volume was divided into elements bounded by nodes (also termed vertices). The field variables in the poroelastic half-space are the displacement field $\vec{u}(u, v)$ in meters and the pressure p in Pascals. The field variables in the fluid half-space is the pressure p_2 in Pascals. The field variables were approximated by piecewise continuous polynomials over each element. We used Lagrange elements of order two in the COMSOL modeling. These elements were specified by basis functions which are used for finding solutions to boundary-value problems by approximating the solution with a finite linear combination of basis functions (Gerald and Wheatley 2004). The introduction of local coordinates, denoted by ξ , simplifies the description of the basis functions.

The standard d-dimensional simplex $\xi_1 \geq 0, \xi_2 \geq 0, \dots, \xi_d \geq 0, \xi_1 + \dots + \xi_d \leq 1$, which resides in the local coordinate space is parameterized by the local coordinates $\xi_1, \xi_2, \dots, \xi_d$ (COMSOL 2015d). For our triangular mesh, $d = 2$. This represents the mesh element as a linear transformation of the standard simplex, and when described in terms of

local coordinates the basis functions assume one of a few basic shapes, the shape functions for our case describe the triangular mesh (COMSOL 2015d).

The basis functions for our mesh are governed by $u = \sum_i^k U_i \varphi_i$, where u denotes the piecewise polynomials of degree k whose local coordinates are integer multiples of $\frac{1}{k}$. In the governance of the basis functions, u represents the second order polynomials on each interval associated with the respective field variable(s) being calculated. Node points are introduced at the midpoint of each interval and the associated degrees of freedom are governed by $U_i - u(x_i)$.

For our triangular mesh, $k = 2$. For each node point p_i , the degree of freedom is governed by $U_i = u(p_i)$ and a basis function φ_i . The basis function for the triangular and edge mesh elements are defined in Table 7. The restriction of the basis function φ_i to a mesh element is a function in $Lag_k(T)$ such that $\varphi_i = 1$ at node i and $\varphi_i = 0$ at all other node points. The Lagrange element of order k is denoted by Lag_k , and T represents the tangential derivative variable. For example, uTx describes the x-component of the tangential projection of the gradient (COMSOL 2015d). The Lagrange elements are constrained by $0 \leq l$, $0 \leq m$, and $l + m \leq k$, where k is the order of the Lagrange Element.

Table 7. Shape Functions for Edge and Triangular Mesh Elements

Edge Mesh Elements	
For order $k = 2$ the Lagrange shape space has dimension 3 and the following basis:	
Node Point p_i	Shape Function
0	$(1 - \xi_1)(1 - 2\xi_1)$
$\frac{1}{2}$	$4\xi_1(1 - \xi_1)$
1	$\xi_1(2\xi_1 - 1)$

Triangular Mesh Elements	
For order $k = 2$ the Lagrange shape space has dimension 6 and the following basis:	
Node Point P_i	Shape Function
$(0, 0)$	$(1 - \xi_1 - \xi_2)(1 - 2\xi_1 - 2\xi_2)$
$(\frac{1}{2}, 0)$	$4\xi_1(1 - \xi_1 - \xi_2)$
$(1, 0)$	$\xi_1(2\xi_1 - 1)$
$(0, \frac{1}{2})$	$4\xi_2(1 - \xi_1 - \xi_2)$
$(\frac{1}{2}, \frac{1}{2})$	$4\xi_1\xi_2$
$(0, 1)$	$\xi_2(2\xi_2 - 1)$

Adapted from COMSOL (2015d).

To solve for the coefficients of the polynomials in COMSOL, the Galerkin method was applied to the PDEs. The Galerkin method is a way to restate the PDEs into integral form, and is commonly referred to as the weak form of the PDEs. The following presents the one-dimensional version of the Galerkin method. To begin, the second-order linear boundary value problem is divided into elements, where x_i are the nodes of the interval, $[a, b]$, and is defined by

$$y'' + Q(s)y = F(x), \quad (0.41)$$

where $y(a) = 0$, $y(b) = y_n$ (Gerald and Wheatley 2004). Then the Galerkin method was applied to each element separately to interpolate between the nodal values, that is where the u 's are approximations the $y(x_i)$'s, the true solution to the PDEs. This was accomplished by introducing trial functions, defined by

$$I[u] = \int_a^b \left[\left(\frac{du}{dx} \right)^2 - Qu^2 + 2Fu \right] dx, \quad (0.42)$$

and are chosen such that $u(x)$ are close to the true solutions of $y(x)$. The individual trial functions, v_i , are linearly independent and must satisfy the boundary conditions. To minimize

I , we take its partial derivatives with respect to each unknown c and set to zero (Gerald and Wheatley 2004). Then the solution is approximated through the summation of the linear

combination of the trial functions, given by $u(x) = c_0 v_0(x) + c_1 v_1 + \dots + c_n v_n(x) = \sum_{i=0}^n c_i v_i(x)$.

The Galerkin method set the residual, $R(x)$, to $R(x) = y'' + Qy - F$, and incorporated weighting functions on the residual. Once the trial functions are chosen, the unknown coefficients are computed by setting the integral over a small interval of the weighted residual

to zero: $\int_a^b W_i(x) R(x) dx = 0$, $i = 0, 1, \dots, n$ and $W_i(x) = v_i$, where the weighting function is

denoted by $W_i(x)$, and the interval evaluated is $[a, b]$. Once this was done for each element, the equations that remain involve all the nodal values. The element equations are combined to produce a system of linear equations that can be solved for the unknown nodal values. The equations are adjusted for the boundary conditions and solved to get approximations to $y(x)$ at the nodes (Gerald and Wheatley 2004).

C. DESCRIPTION OF THE COMSOL MODEL

Our COMSOL model setup follows the “Acoustic Reflections off a Water-Sediment Interface” (ARWSI) using the acoustics module and guided by the model wizard (COMSOL 2015b). The ARWSI model is two-dimensional, without axial symmetry, specifically comprising the Poroelastic Waves (PELW) and Pressure Acoustics (ACPR) physics interfaces in the frequency domain. The ACPR consists of the fluid half-space, and computes for the pressure field in this domain. The ACPR is a linear elastic fluid model, with the density and sound speed of the fluid specified by the input parameters. The background pressure field, p_b , is used to model the incident pressure wave and to study the scattered pressure field, p_s , which is governed by $p_t = p_b + p_s$ where p_t is the total acoustic pressure. For our ARWSI model, the background pressure field is defined as p_{in} , and is governed by

the equation $R = \frac{p_s}{p_{in}} = \frac{p_t - p_{in}}{p_{in}}$. This incorporates the scattered field formulation into the

model, where the dependent variable is the scattered field and is governed by $p = p_s$. The

incident pressure, p_{in} , occurs in the fluid domain. Additionally, COMSOL automatically applies the total field pressure, p_t , on the internal boundaries between the fluid domain and the sediment domain.

The PEWL domain consists of the fluid saturated porous half-space. In this domain the pressure and displacement of the sediment in the porous domain are computed. The reference pressure, or incident pressure amplitude, in this domain is $p_{ref,SPL} = 1\mu Pa$. The porous half-space is governed by the porous model for an isotropic, drained matrix with the bulk modulus and the shear modulus controlling the sediment's resistance to volume changes and shear deformations, respectively (COMSOL 2015a). Additionally, the Biot-Willis coefficient, α_B is defined for the sediment, and is used to signal if the sediment frame is limp or rigid. For the limp configuration, the value of α_B is close to 1. For the rigid configuration, the value of α_B is close to the value of the porosity, ε_p . The inclusion of this coefficient benefits the model in that an equivalent fluid model can be used to reduce the computation expense. In our set up, the Johnson-Champoux-Allard equivalent fluid model is used and accounts for the thermal and viscous losses at the acoustic boundary layer at the pore walls (Xu et al. 2015). When this equivalent fluid model cannot be implemented, that is the frame is neither limp nor rigid, the full Biot model must be utilized.

To begin, the model definition set-up requires definition of material parameters and model variables, as shown in Tables 8 and 9, respectively.

Table 8. COMSOL Material Parameters

Parameter	Description
k_0	Wave number of incident field
$k_0 x$	Wave vector x-component of incident field
$k_0 y$	Wave vector of y-component of incident field
P_{in}	Incident pressure field
R	Reflection coefficient
$ R $	Magnitude of reflection coefficient
α	Absorption coefficient, relative absorbed energy

Adapted from COMSOL (2015b).

Table 9. COMSOL Material Variables

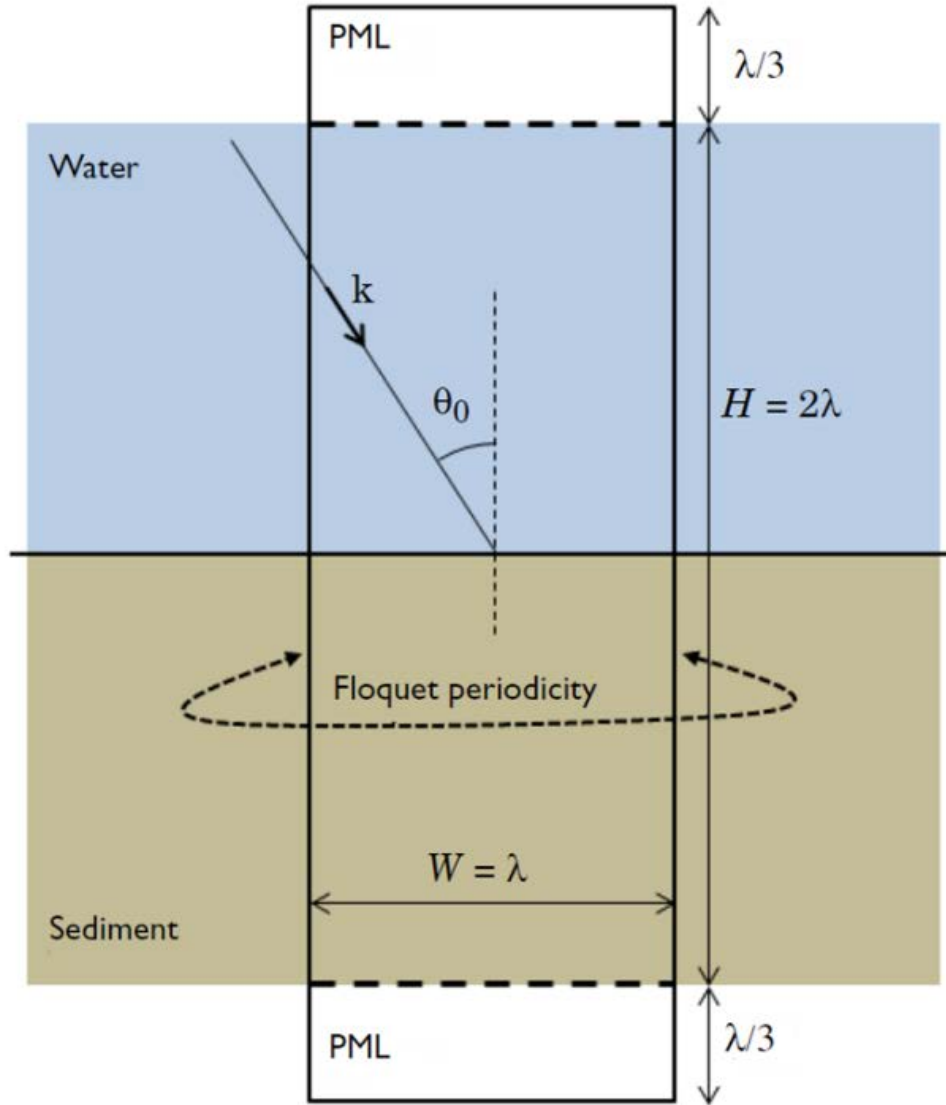
Variable	Description
f_0	Driving frequency
θ_0	Incidence angle from normal
c_0	Speed of sound in water
λ_0	Wavelength at f_0
ε	Porosity
μ_f	Fluid viscosity
ρ_f	Fluid density
κ_p	Permeability
K	Bulk modulus of frame
K_c	Complex bulk modulus of frame
K_s	Bulk modulus of solid grains
K_f	Bulk modulus of fluid
G	Shear modulus of frame
G_c	Complex shear modulus of frame
α_B	Biot-Willis coefficient
$\log_{dec}$	Logarithmic decrement for frame vibrations
ρ_s	Solid density
ρ_d	Drained density
τ	Tortuosity
a	Pore size parameter
W	Domain width
H	Domain height
H_{pml}	PML height

Adapted from COMSOL (2015b).

The model's geometric parameters are the same for each sediment modeled. The numerical material parameter inputs are different for each of the sediments modeled. Chapter I contains the material parameters for each sediment examined in our model.

The model consists of a two-dimensional computational domain, as shown in Figure 4. The model domain is one wavelength wide and two wavelengths tall in both the water domain and the sediment domain. The incoming plane wave has an incident angle, θ_0 , measured from the normal to the interface. The model's upper and lower boundaries are composed of perfectly matched layers (PML) that are one-third wavelength beyond the upper and lower boundaries. PMLs introduce artificial boundaries into the model to act as a non-reflecting layer. The PML is a perfectly absorbing domain which is a modeling

alternative to a non-reflecting layer (COMSOL 2015a). The PML imposes a complex-valued coordinate transformation within the layer in order to eliminate reflections at the PML-domain interface (COMSOL 2015a). The PML mesh is rectangular for our model.



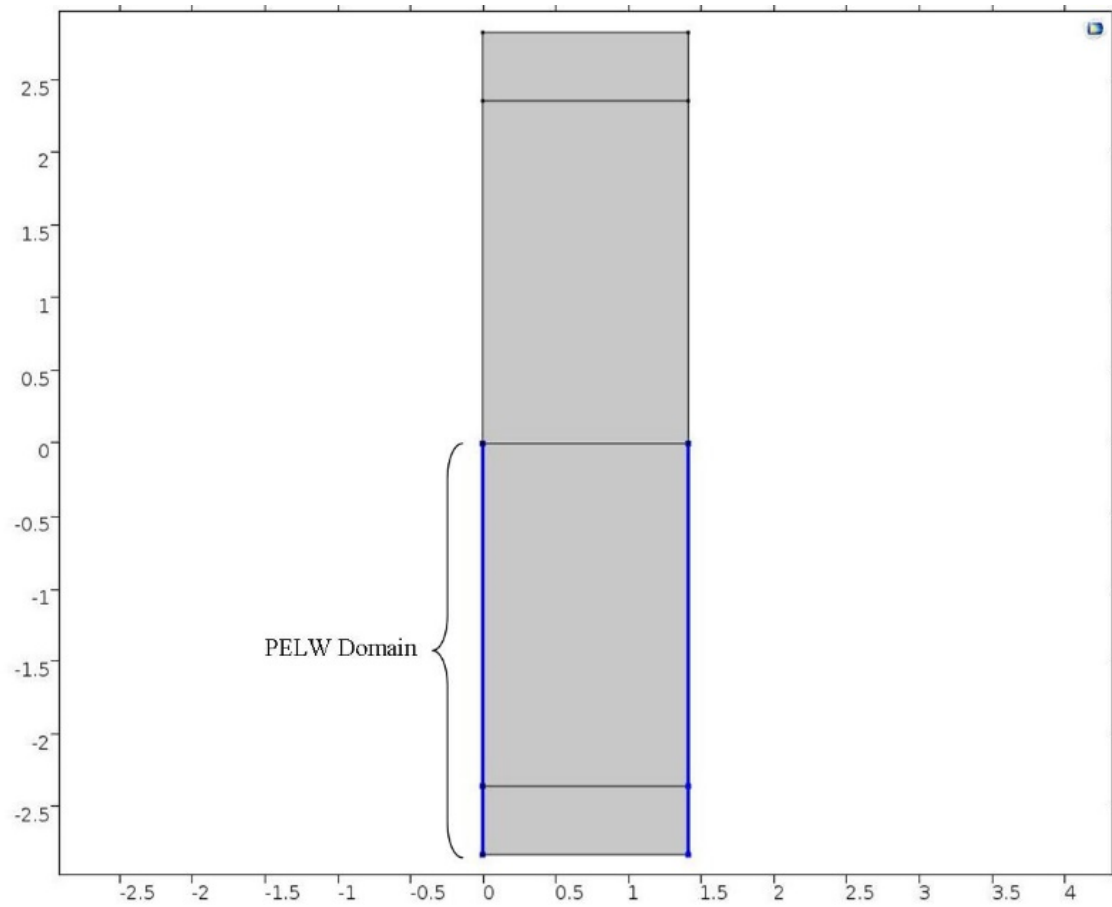
Source: COMSOL (2015b).

Figure 4. COMSOL Model Geometry

The model's vertical boundaries are imposed with Floquet periodicity. This additional boundary condition aids in reduction of the model size through use of

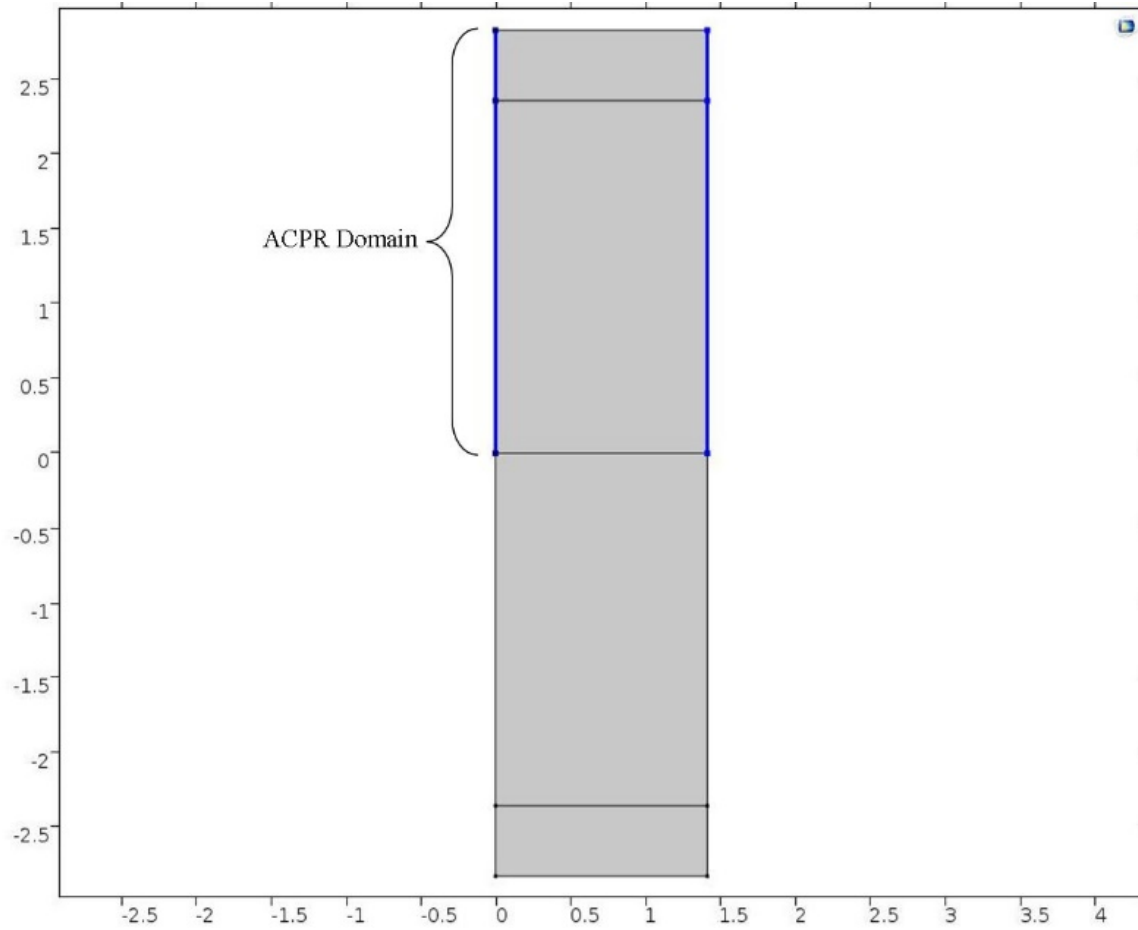
symmetries and periodicities in the geometry and physics interfaces being modeled (COMSOL 2015a). Specifically, for the x and y components in our model, this enables COMSOL to model periodic structures with non-normal incident pressure fields or excitations at the boundary (COMSOL 2015a).

The sediment domain is the PELW domain, and consists of the bottom PML and the sediment layer. The vertical model walls of the sediment domain have Floquet periodicity, indicated by blue lines in Figure 5. The porous matrix properties and fluid properties are set from the sediment material definitions as shown in Tables 10 and 11. The fluid domain is the ACPR domain and consists of the top PML and the water layer. The vertical model cell walls of the water domain have Floquet periodicity, indicated by blue lines in Figure 6.



Adapted from COMSOL (2015b).

Figure 5. COMSOL PELW Domain and Boundaries



Adapted from COMSOL (2015b).

Figure 6. COMSOL ACPR Domain and Boundaries

Table 10. COMSOL Material Contents Water Domain

Property	Name	Value	Unit	Property group
Density	ρ	ρ_f	$\frac{kg}{m^3}$	Basic
Dynamic viscosity	$\mu(\eta)$	μ_f	$Pa \cdot s$	Basic
Compressibility of fluid	χ_f	$\frac{1}{K_f}$	$\frac{1}{Pa}$	Basic
Speed of sound	c	c_o	$\frac{m}{s}$	Basic

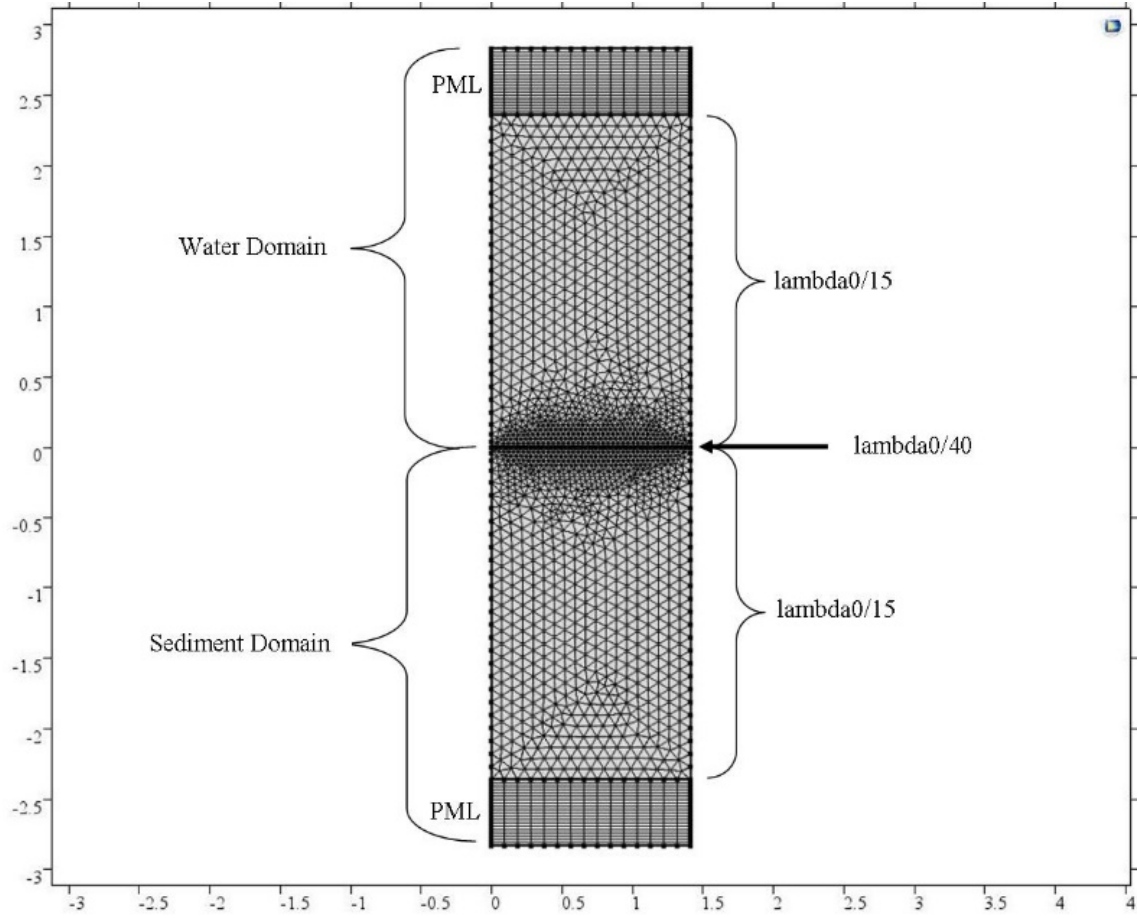
Adapted from COMSOL (2015b).

Table 11. COMSOL Material Contents Sediment Domain

Property	Name	Value	Unit	Property group
Bulk modulus	K	K_{bc}	Pa	Bulk modulus and shear modulus
Shear modulus	G	G_c	Pa	Bulk modulus and shear modulus
Density	ρ	ρ_d	$\frac{kg}{m^3}$	Basic
Porosity	ε	ε_p	1	Basic
Permeability	κ	κ_p	m^2	Basic
Biot-Willis coefficient	α_B	α_{B0}	1	Poroelastic material
Tortuosity factor	τ	τ_0	1	Poroelastic material

Adapted from COMSOL (2015b).

The upper and lower vertical edges of the water and sediment domains are limited to a maximum element size of $\frac{\lambda_0}{16}$, and the connecting boundary interface is limited to a maximum element size of $\frac{\lambda_0}{40}$. A free triangular mesh is employed in these two domains, again with the same maximum element sizes, as shown in Figure 7.



Adapted from COMSOL (2015b).

Figure 7. COMSOL Mesh

The PML domains have a fixed rectangular element mesh with 20 elements. The sediment layer is a boundary layer. COMSOL uses this layer for fluid flow problems to resolve the thin boundary layers along the no-slip boundaries (COMSOL 2015a).

The frequency domain is selected to input the study settings, in this model the driving frequency in hertz, f_0 , is selected. Additionally, this is where the user specifies the physics interfaces. Then, a parametric sweep directed over the range of f_0 and θ_0 , in radians, for all combinations of these two parameters.

D. DESCRIPTION OF MATLAB MODEL

The MATLAB model follows the governing equations as presented in Buchanan et al. (2004). The sediment properties listed, and their respective nomenclature, are presented in Table 12. These properties quantify each sediment's characteristics and are used as model input variables and parameters. Numerical values for selected sediments are presented in Chapter III.

Table 12. MATLAB User Inputs

Property	Name	Units
Bulk modulus of grains	K_r	Pa
Bulk modulus of pore fluid	K_f	Pa
Shear modulus of skeletal frame, imaginary part	mi_i	Pa
Shear modulus of skeletal frame, real part	mu_r	Pa
Porosity	β_1	1
Bulk modulus of skeletal frame, imaginary part	K_{bi}	Pa
Bulk modulus of skeletal frame, real part	K_{br}	Pa
Permeability	$perma$	m^2
Density of pore fluid	ρ_f	$\frac{kg}{m^3}$
Density of grains	ρ_r	$\frac{kg}{m^3}$
Pore-size parameter	$script_a$	m
Structure factor (Tortuosity)	τ	1
Viscosity of pore fluid	η	$1PI = 1Pa \cdot s$
Frequency	$freq1$	Hz

E. DESCRIPTION OF DATA

Numerical values for all parameters as listed in Tables 4, 5, and 6 are needed to run the COMSOL and MATLAB models. The values for the parameters from a literature review and data from a 2013 scientific cruise in the South China Sea. Numerous sources were required to find parameter values that fit the scenario we intended to model (e.g., sea water for predetermined conditions). Many of the literature values and graphs found referenced fresh water conditions, these were used for a general understanding of sound interaction with the sediments. A few literature values and graphs found referenced salt

water, although their conditions did not match our predetermined modeling conditions. These values were used for comparison of parameter variation trends.

1. Control Data

To select the control data for initial model testing, a literature review was conducted. We selected sediments from Buchanan et al. (2004) and Stoll and Kan (1981). These sources were selected because they contained the necessary information to run our models, and also provided information on the reflection coefficients, attenuation, sound speeds, and reflection angles so that a validation of our modeling outputs could be obtained. Once the testing of control data model outputs was verified, the 2013 South China Sea cruise sediment data were examined.

Five sediments are presented in *Shallow Oceans Over Poroelastic Seabeds* (Buchanan et al. 2004): fine sand (FS), coarse sand (CS), coarse sand fine gravel (CSFG), silty sand (SS), and silty clay (SC). Two sediments are presented in *Reflection of Acoustic Waves at a Water-Sediment Interface* (Stoll and Kan 1981): sand (SA) and soft sediment (SOSE). We used a subset of these sediments as control data for modeling, and their characteristics are presented in Chapter I. The sediments selected for control data as presented in the literature, contain information on wave speeds, attenuations, and reflection coefficients, enabling direct comparison of numerical results from COMSOL and MATLAB.

The models were computed at frequencies between 10 Hz and 1,000 Hz. Incident angles were examined from 0° through 90°, as measured from the vertical. The model uses isovelocity conditions in the fluid and the sediment was assumed to be acoustically isotropic. The sediment is also assumed to be well compacted; have uniform, symmetric pore shape; and uniform porosity. The seafloor was modeled as a flat interface.

2. 2013 South China Sea Field Data

Chiu et al. (2013a) collected sediment samples and acoustic measurements in the northeastern South China Sea from May 8–14, 2013. This cruise was part of a multi-year field program collaboration among the National University Taiwan, the Taiwan Naval

Academy, the National Taiwan Ocean University, the National Sun Yet-Sen University, and the Naval Postgraduate School under the sponsorship of the ONR. Sediments were collected at the peaks and troughs of the submarine sand dunes using box cores. The sediment sampling locations, a brief description, and water depths are presented in Table 13. The sediments were analyzed by a Beckman Coulter LS Particle Size Analyzer.

Table 13. 2013 South China Sea Sediment Information

Name	Latitude (Degrees Decimal Minutes)	Longitude (Degrees Decimal Minutes)	Water Depth (m)	Sediment Description
C4	N21 52.012	E117 34.993	343	Yellow coarse sand, Qtz
C5	N21 52.010	E117 35.079	337	Black mid-sand, 10% shell fragment
C6	N21 52.038	E117 35.179	340	Greyish yellow coarse sand
C7	N21 52.408	E117 35.358	322	Yellow coarse sand and gravel, Qtz
C8	N21 40.030	E117 43.426	505	Black mid-sand, 20% shell fragment
EEP	N21 37.050	E117 45.501	587	Black mid-sand, 10% shell fragment
LSP	N21 52.129	E117 35.748	343.7	Yellow coarse sand and gravel, Qtz
LST	N21 52.000	E117 35.908	341.4	Grey mud
M1	N21 50.979	E117 39.008	369	Greyish yellow coarse sand

Adapted from Chiu et al. (2013b).

The sound speed of the South China Sea measurement location was determined to be 1495.8 meters per second using the Mackenzie nine-term formulation for a water depth (Mackenzie 1981) of 350 meters, temperature of 11°C and a salinity of 34.45 practical salinity units (PSU). The oceanographic conditions were obtained from (Chiu et al. 2013a) and used to determine the reference temperature, depth, and salinity. In the MATLAB code, the sound speed of the fluid, c_o , is computed using $c_o = \sqrt{\frac{K_f}{\rho_f}}$, where K_f is the bulk modulus of the fluid and ρ_f is the density of the fluid. For consistency, the modeling and computed sound speed for the fluid is set to 1495.8 m/s. The bulk modulus of sea water is dependent on the oceanographic conditions. Brunson and Molinelli determined the bulk modulus to be 2.3×10^9 Pa (Brunson and Molinelli 1982). The density of the seawater at depth is 1027.9738 kg/m^3 , and was determined using Dr. Daniel E. Kelley's online UNESCO calculator (Brown 2013) from the *in-situ* values presented in this section.

F. METHODOLOGY

There are 13 parameters of the Biot-Stoll model. From a literature review of these basic physical parameters the characteristic pore size, viscosity, permeability, and porosity were determined to be the most important for this study. These four parameters are embedded in Biot's frequency correction function and have impacts on the reflection and attenuation coefficients, wave speeds, angles, and bottom loss. Our assumption was that variations in each of these four parameters would have impacts on acoustic interactions at the water-sediment interface. Specifically, if the sediment behaves in a poroelastic manner, variations in these parameters will present acoustically significant effects in the reflection and attenuation coefficients, wave speeds, angles, and bottom loss. Additionally, the effects will be more impactful at certain frequencies. The results of the variations for each parameter are presented in Chapter III.

The availability of these four parameters and results of their wave speeds, attenuation, and reflection coefficients are presented in the literature and enabled testing the validity of the COMSOL and MATLAB model outputs for consistency and correctness.

Once the COMSOL and MATLAB model results were verified against published results, we tested the variations in the four parameters.

SA and SC were the selected control data sediments. These sediments were selected to represent a wide range of physical parameters, and when possible, to approximate the 2013 South China Sea cruise sediment data. Numerical parameter values were available for the control data for all of the selected parameters, however for the 2013 South China Sea cruise sediment data the only physical characteristic information available was the mean grain size and associated statistics. The selected 2013 South China Sea sediments were C4 and LST. For these sediments, the unknown parameters were determined from the literature. The sediment parameter values are presented in Chapter I.

Each of the parameters was varied independently for the selected sediments. We examined the sensitivity of the reflection coefficient to variations in these four model parameters. The first step in the sensitivity analysis was to determine the upper and lower bounds for the four parameters for each of the control sediments. Once the bounds were determined, the COMSOL and MATLAB models were run and their results were recorded. Then, the sensitivity analyses were conducted on the selected South China Sea sediments, in the same manner as the control sediment data. Finally, the control sediment data results were compared with the South China Sea sediment results and examined for impacts to the reflection and attenuation coefficients, speeds, angles, and bottom loss.

G. SEDIMENT INFORMATION FOR MODELING

This chapter presents COMSOL and MATLAB model results from the variation of the characteristic pore size, viscosity, permeability, and porosity. The control sediments, SA and SC, had published values for all of the selected parameters. The available information for the 2013 South China Sea sediments, C4 and LST, were the mean grain size and percent composition of clay, silt, and sand. A literature review of similar sediments provided the remaining sediment parameter information needed to run both models.

The parameter values for the sediments modeled are presented in Table 14. The values for the density of the fluid have been changed to that for the ocean conditions

observed in the South China Sea in 2013, otherwise the values are as presented in Table 6. The sound speed of the fluid is 1495.8 m/s, as presented in Chapter II.

Table 14. 2013 South China Sea Cruise Report Sediment Data Estimation of Parameters and Control Sediment Parameter Data

Parameter	CS	C4	SA	LST
K _r	5.6e10	3.2e10	3.6e10	3.6e10
K _f	2.3e9	2.3e9	2.3e9	2.3e9
mu _i	0	0	0	0
mu _r	7.4e7	2.92e7	2.61e7	2.21e7
K _{bi}	0	0	0	0
K _{br}	5.3e7	4.36e7	4.36e7	3.69e7
beta1	0.38	0.385	0.47	0.76
perma	7.5e-11	2.5e-11	5.0e-13	2.6e-11
rho _f	1027.97	1027.97	1027.97	1027.97
rho _r	2710	2690	2650	2650
script _a	6.28e-5	2.65e-5	1.2e-5	1.31e-7
tau	1.25	1.25	1.25	1.35
eta	1.01e-3	1.01e-3	1.01e-3	1.01e-3
freq1	Varies with model runs, but a general value: logspace(0,6,5000)			

Adapted from Chiu et al. (2013b, c); Buchanan et al. (2004); Williams et al. (2002); Stoll and Kan (1981); Stoll (1977); and Badiy et al. (1998).

H. DESCRIPTION AND RATIONALE FOR SELECTED BIOT PARAMETERS

This thesis examined the variation of four Biot parameters: characteristic pore size, viscosity, permeability, and porosity. We hypothesized these four parameters to have the greatest impact to the acoustic interaction at the water-sediment interface. A brief synopsis of each parameter's hypothesized effects based on the governing equations are presented in this section.

1. Characteristic Pore Size

The characteristic pore size, a , is determined by the dimensions and geometry of the pores of the sediment frame (Buchanan 2005). In sediments, pore sizes are typically specified by an effective radius, or the space that is not the sediment itself. The characteristic pore size is one of the influencing factors that describes how the fluid

interacts with the sediment frame. It can be an indication of how much fluid will flow into and around the sediment grains. If the sediment grains are treated as spherical, the pore size is the space between the individual grains as shown in Figure 1. If the sediment grains are of random shape, the pore size remains the space between the individual grains but is geometrically more complicated, as shown in Figure 2.

In the Biot-Stoll model, it is assumed that the sediment grains are spherical and the geometry of the pore size is similar to that which is depicted in Figure 1. Along with the homogeneous sediment assumption, these assumptions simplify the mathematical equations and negates the need to know the exact geometry of the sediment grains which is typically unknown.

The characteristic pore size parameter is embedded in the governing equations within the correction factor $F(\chi)$, or $F(\omega)$ (frequency dependent), which accounts for the friction force by the motion of the fluid on the frame. In Biot's formulation, there are several geometries considered and depending on the selected geometry this parameter may have different scaling factors. Biot elected not to account for the differences in geometric factors such as sinuosity and cross-section shape, as he assumed the results to be practically the same for all pores (Biot 1956b). Hovem and Ingram prefer to retain the frequency correction factor initially introduced by Biot (Hovem and Ingram 1979). Stoll and Bryan generally follow Biot, but account for the scale factor within the characteristic pore size parameter so that they do not have to introduce yet another parameter (Stoll and Bryan 1970). Lastly, Buchanan et al. state the general assumption that the pore size parameter is proportional to the square root of the permeability (Buchanan et al. 2004), but cite numerical values from Beebe et al. (Beebe et al. 1982) and Holland and Brunson (Holland and Brunson 1988) for their sediments. All authors note the difficulty in measuring the characteristic pore size *in situ* for seafloor sediments.

It follows that the characteristic pore size will have effects on the reflection and attenuation coefficients, the reflected and transmitted waves and their angles due to this parameter being contained in the frequency correction factor given by Biot. We

hypothesized that increasing the characteristic pore size would increase magnitude of the reflection and transmission coefficients.

2. Viscosity

The dynamic viscosity, $\bar{\eta}$, is a measure of the viscous resistance to fluid flow. For highly viscous fluids, the fluid flow in the interstitial motion may cause the coupled system to act more like a solid. For fluids with low viscosity, the system may act more like a fluid. In conjunction with the characteristic pore size and sediment type, the dynamic viscosity is another indicator that describes how the fluid interacts with and within the sediment grains.

Biot argues that the viscosity of the fluid acts dynamically (Biot 1956b), and therefore introduces the dynamic viscosity correction factor in lieu of the static viscosity coefficient, η . This correction accounts for the deviation from Poiseuille friction that occurs as the frequency increases from zero to a critical frequency, denoted by f_t , and is also dependent on the dynamic viscosity and the size of the pores (Biot 1965a). That is, the Poiseuille flow breaks down when the quarter wavelength of the boundary layer is on the order of the diameter of the pores, i.e., for frequencies higher than $f_t = \frac{\pi\nu}{4d}$, where the kinematic viscosity is ν , the frequency when Poiseuille flow begins to break down is f_t , and the diameter of the pores is d (Biot 1956a). The kinematic viscosity is governed by $\nu = \frac{\eta}{\rho_f}$, where the fluid dynamic viscosity is η (Biot 1956a). Similarly, Kargl and Lim introduce the dynamic viscosity into the dissipation function, citing that the frictional dissipation due to finite fluid viscosity is a function of frequency (Kargl and Lim 1993). Badiy et al. also account for the dynamic viscosity in their function for viscosity correction (Badiy et al. 1998).

Again, it follows that the dynamic viscosity will have effects on the reflection and attenuation coefficients, the reflected and transmitted waves and their angles due to this parameter being contained in the frequency correction factor. A system with higher

dynamic viscosity will experience more shear stress and strain, reducing the available energy of the reflected and transmitted waves. We hypothesized that increasing the dynamic viscosity would decrease the magnitude of the reflection and transmission coefficients.

3. Permeability

Permeability (κ) is a measure of the fluid flow through a sediment, or the network of sediment grains and the void space between them. This characteristic is generally defined by pore size and porosity, and is controlled by the geometry of the pore network that lies between the sediment grains (Shock 2004). The permeability is also influenced by the individual composition or mixture of the sediments, different types of sediments will have different properties relating to fluid flow; the temperature of the saturating fluid, namely it changes the viscosity; consolidation of the sediment grains; and looser or tighter packing of the sediment grains (Fraser 1935).

Stoll and Bryan highlight the importance of the pore size parameter in determining permeability (Stoll and Bryan 1970). The generally accepted formula for permeability is the Carman-Kozeny equation, given by $\kappa = 5.5 \times 10^{-3} d_{mean}^2 \frac{\beta^3}{(1-\beta)^2}$, where d_{mean} is the mean sediment grain size and β is the sediment porosity (Badiey et al. 1998). Permeability is one of the major parameters on the transition region for dispersion (Isakson and Neilsen 2006). Again, because the permeability is contained in the frequency correction factor given by Biot, the permeability will have a large role in the value of the attenuation coefficients (Badiey et al. 1998). Likewise, the reflection coefficients, the reflected and transmitted waves and their angles will also show impacts from the variability in the permeability. A system of low permeability has sediments with fewer spaces in between the sediments, allowing for less fluid in between the sediments. A system with high permeability provides more opportunity for the acoustic waves to interact with the fluid in between the sediments and possibly less interaction with the sediments directly. We hypothesized that increasing the permeability would increase the magnitude of the reflection and transmission coefficients.

4. Porosity

The porosity of a sediment, denoted by β , is the fraction of the total sediment volume that is taken up by the pore space, or the amount of space available to the fluid within the sediment frame (Nimmo 2004). Another practical measure of β is the ratio of the volume of voids to the volume of sediment grains (Hamilton 1971). The β of a sediment is influenced by the amount of compaction or consolidation, the range and amount of particle size distribution, the shape of the sediment grains, and cementing. Larger gaps between sediments, specifically those of irregular shape, will have greater changes in their β value compared to the ideal case we considered in this thesis.

Porosity is difficult to measure *in situ*, as any disturbance in the sediment layer can cause compaction or redistribution of the sediment grains. In addition to indicating the upper limit of volumetric water content, the β is also an indicator of the complexity of the sediment grains (Nimmo 2004). A value of zero porosity, or 0 %, corresponds to elastic solids and a value of one, or 100 %, corresponds to a fluid (Corredor et al. 2014).

If porosity is known, permeability can be determined and vice versa, provided tortuosity is known. The governing equation for this relationship is the Kozeny-Carmen equation, $\kappa = \frac{a^2 \beta}{8\tau}$ (Isakson and Neilsen 2006). The structure factor, also known as the tortuosity, is denoted by τ and is a dimensionless parameter. Similarly, porosity and the bulk modulus of the fluid are coupled parameters. Porosity is a sensitive parameter across all frequency bands (Isakson and Neilsen 2006), and can lead to variations in the reflection and transmission coefficients. Like characteristic pore size, viscosity, and permeability the porosity is contained in the complex frequency correction factor and the dissipation parameter within the governing equations and will have effects on the reflection and attenuation coefficients, the reflected and transmitted waves and their angles due to the fully embedded nature of this parameter. We hypothesize that increasing the porosity will increase the magnitude of the reflection and transmission coefficients.

I. ANALYSES OF MODELING RESULTS

Selected modeling results are presented in this section. Each parameter was analyzed independently. Discussion of these results are presented in Chapter IV.

1. Characteristic Pore Size

For each sediment, the characteristic pore size (a) was examined, with all other parameters held at the values as shown in Table 14. Variations for selected sediments are presented in Table 15. The sediments, arranged in size from smallest to largest value of pore size, are LST, SA, C4, and CS. From our hypothesis, we predicted that the change in magnitude of the reflection and transmission coefficient values on LST would be the smallest and CS the largest as we varied the pore size values.

Table 15. Characteristic Pore Size Variations for LST, SA, C4, and CS in meters

LST	SA	C4	CS
$1.572e-7$	$1.44e-5$	$3.18e-5$	$7.536e-5$
$1.5065e-7$	$1.38e-5$	$3.0475e-5$	$7.222e-5$
$1.441e-7$	$1.32e-5$	$2.915e-5$	$6.908e-5$
$1.375e-7$	$1.26e-5$	$2.7825e-5$	$6.594e-5$
$1.31e-7$	$1.2e-5$	$2.65e-5$	$6.28e-5$
$1.2445e-7$	$1.14e-5$	$2.5175e-5$	$5.966e-5$
$1.179e-7$	$1.08e-5$	$2.385e-5$	$5.652e-5$
$1.1135e-7$	$1.02e-5$	$2.2525e-5$	$5.338e-5$
$1.048e-7$	$9.6e-6$	$2.12e-5$	$5.024e-5$

For plane wave reflection, we found the values for the reflection coefficient magnitudes did not change as the pore size values were increased. The magnitudes of the transmission coefficients for the fast, slow, and shear waves also did not change as pore size increased. The changes in the values of the coefficient magnitudes only occurred as the driving frequency was increased.

LST was no exception to this, the values of the reflection coefficient magnitudes gradually decreased until reaching the angle of intromission (AOIN) at 77° from normal,

13° grazing, and then began to increase, for all frequencies. An example of the reflection coefficient after AOIN is presented in Figure 8.

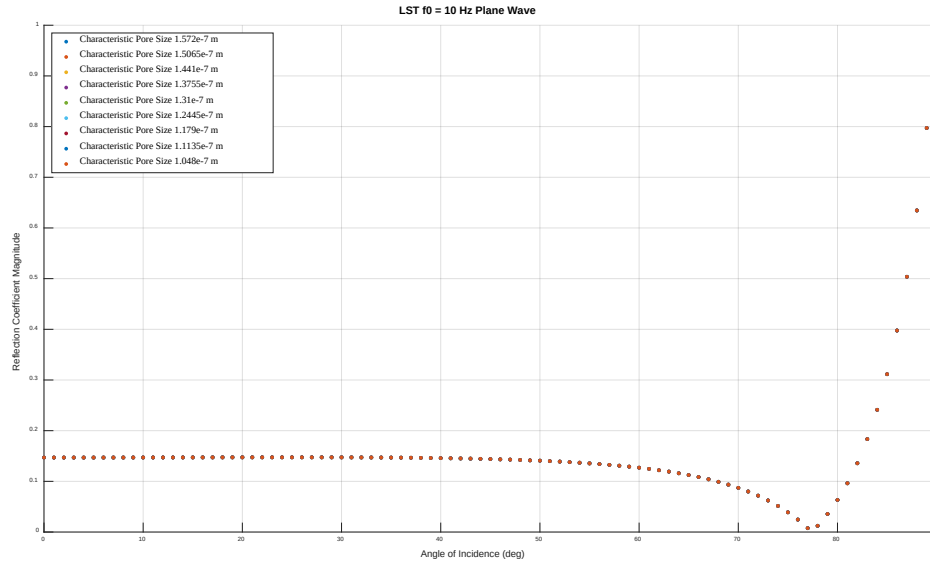


Figure 8. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for LST Characteristic Pore Size

The only changes observed from the variation of pore size values for all of the sediments modeled occurred specifically to wave speeds and attenuations. The wave speeds slowly increased with decreasing pore size values and driving frequencies. An example of the slow wave speed values are presented in Figure 9. The total increase in wave speeds for the fast wave were 0.8 m/s, the slow wave were 6 m/s, and the shear wave were 0.09 m/s at 10,000 Hz, respectively. Similarly, the wave attenuations slowly increased with increasing pore size and driving frequency. The total change in wave attenuation spread values for the fast waves were 0.269 dB/m, the slow wave attenuation spread in values were 6.90 dB/m, and the shear wave attenuation spread in values were 0.089 dB/m at 10,000 Hz, respectively. An example plot of the slow wave attenuation values is shown in Figure 10.

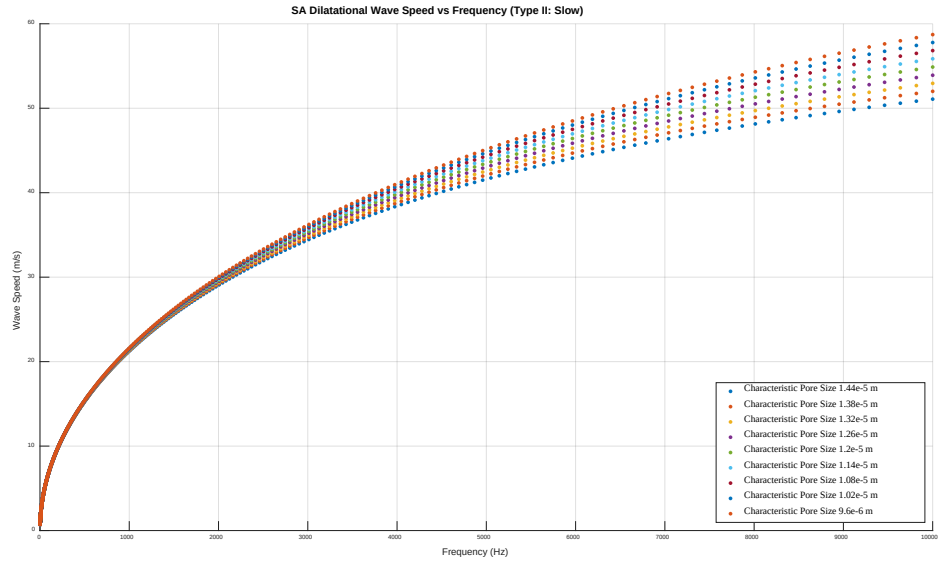


Figure 9. Slow Wave Speed (m/s) vs. Frequency (Hz) for all Variations for SA Characteristic Pore Size

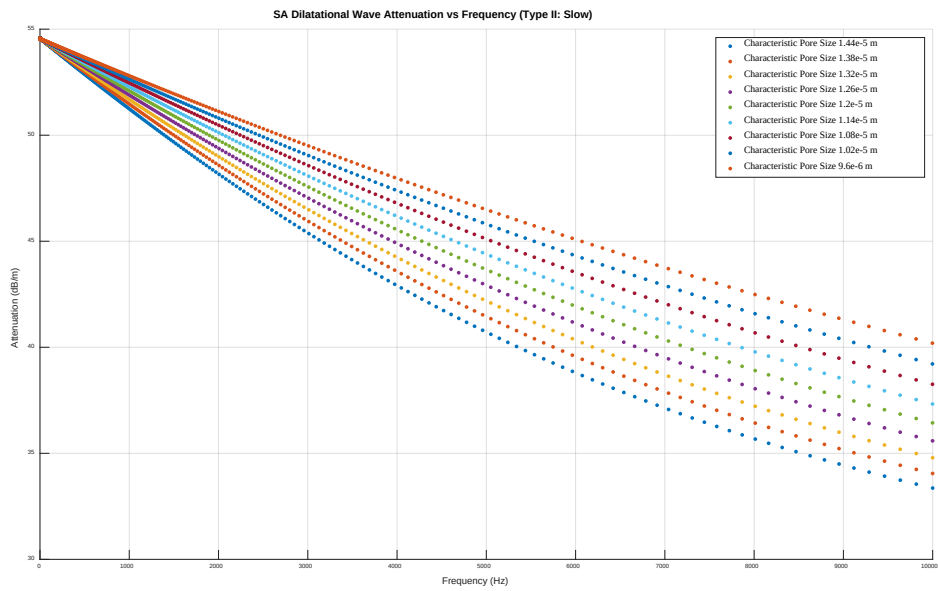


Figure 10. Slow Wave Attenuation (dB/m) vs. Frequency (Hz) for all Variations for SA Characteristic Pore Size

Additionally, for SA the slow wave phase was -90° until the critical angle at 72° from normal, and then decreased nearly linearly to -170.8° phase at 89° from normal. Then the slow wave phase separated into two distinct groups; the first, ranging from 149.7° to 179.8° phase, and the second group, ranging from -162.1° to -179.5° phase at 90° from normal, respectively. The SA pore size scatter in phase values at 90° from normal were checked for patterns, any patterns found for the parameters are as discussed. A representative example of the slow wave phase is presented in Figure 11.

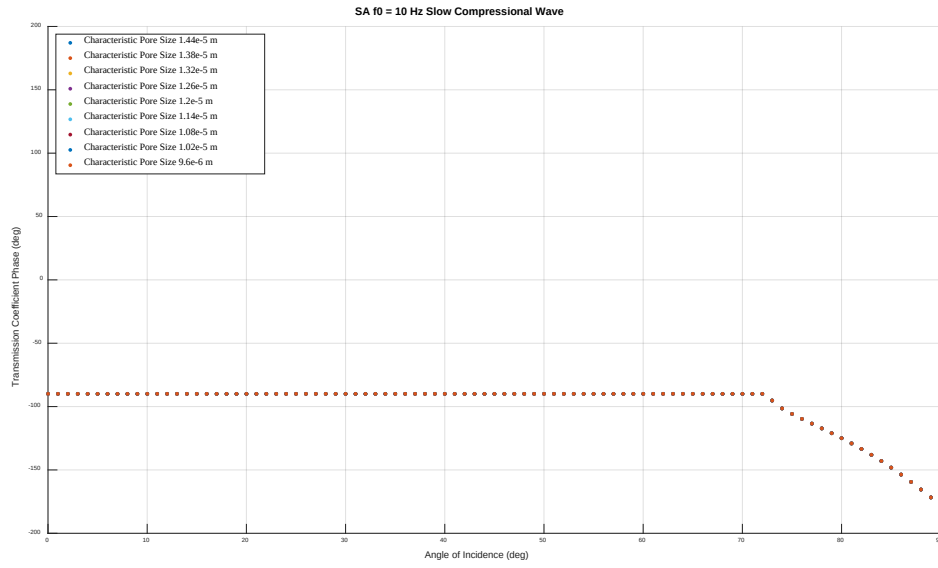


Figure 11. 10 Hz Slow Wave Transmission Coefficient Phase (deg) vs. Angle of Incidence (deg) for SA Characteristic Pore Size

2. Viscosity

For each sediment, the (dynamic) viscosity (η) was varied, with all other parameters held at the values as shown in Table 14. All values of the variations in η are the same for LST, SA, C4, and CS. The range of values of η are presented in Table 16. From our hypothesis, we predicted that the change in magnitude of the reflection and transmission coefficients would decrease as we increased η . Our hypothesis held for the slow wave transmission and shear wave transmission coefficients for LST.

Table 16. Viscosity Variations for LST, SA, C4, and CS in Pa s

LST, SA C4, and CS (Pa s)
$1.212e-3$
$1.1615e-3$
$1.111e-3$
$1.0605e-3$
$1.01e-3$
$9.595e-4$
$9.09e-4$
$8.585e-4$
$8.08e-4$

The reflection coefficient magnitude for the plane wave of LST slowly decreased from 0° until the AOIN at 77° from normal, then increased to 90° angle of incidence from normal as depicted in Figure 12.

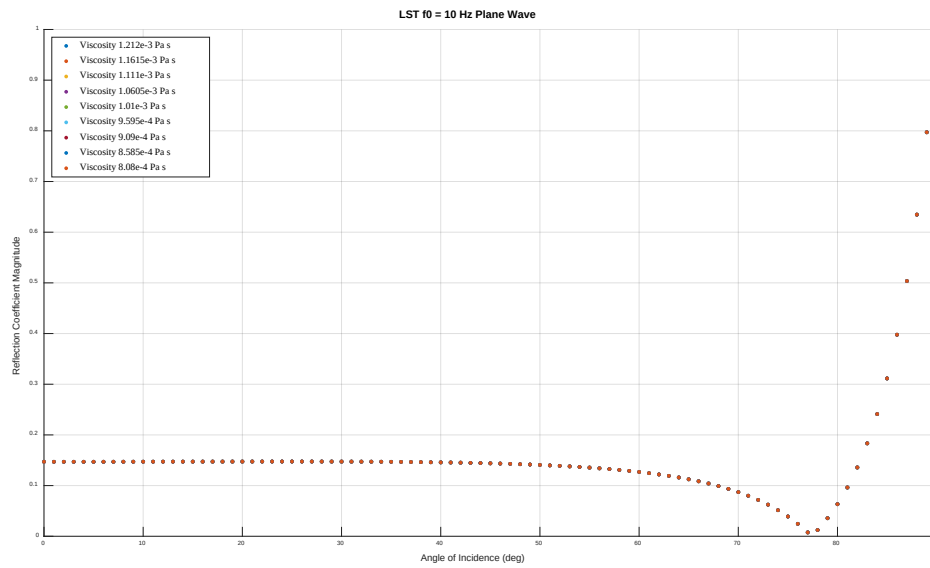


Figure 12. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for LST Viscosity (PA s)

The reflection coefficient magnitude values for the plane wave η variation of SA steadily increased from 0.314 until the critical angle at 72° from normal to 0.999, then increased to 1.0 at 90° as depicted in Figure 13. The reflection coefficient magnitude values for the plane wave η variation of C4 exhibited a similar pattern to that of SA. The reflection coefficient magnitude values for the plane wave η variation of C4 steadily increased from 0.368 until the critical angle at 67° from normal to 0.994, then increased to 1.0 at 90° as depicted in Figure 14.

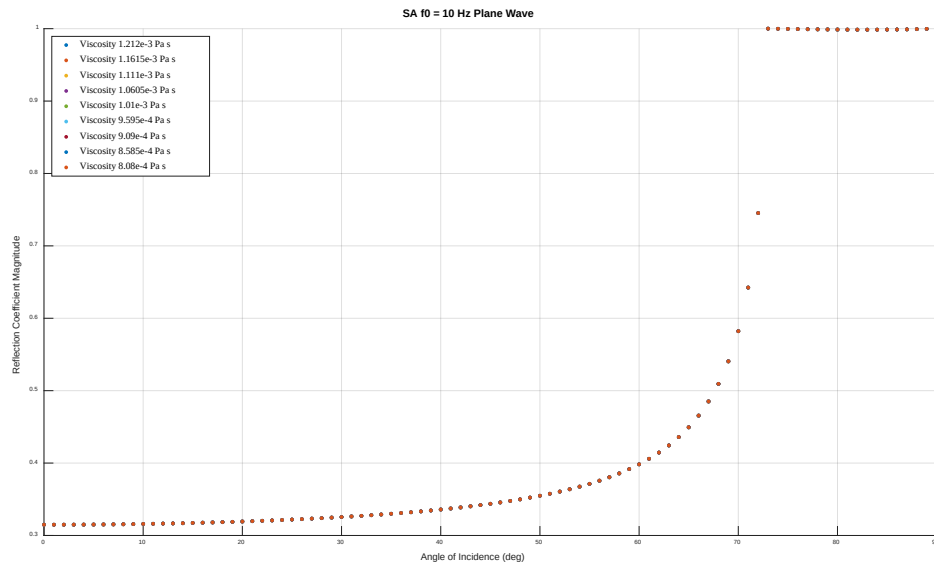


Figure 13. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for SA Viscosity (Pa s)

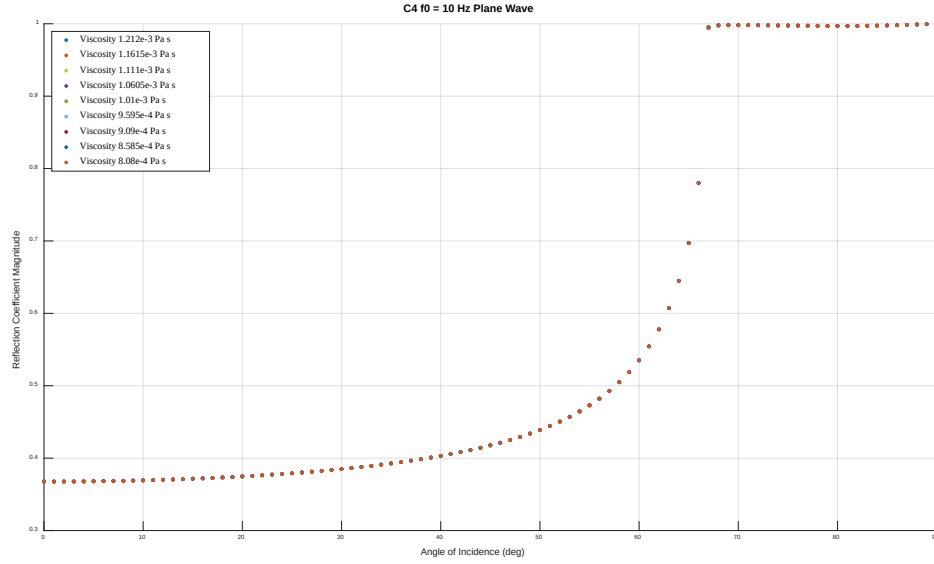


Figure 14. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for C4 Viscosity (Pa s)

The reflection coefficient magnitude values for the plane wave η of CS steadily increased from 0.370 until the critical angle at 63° from normal to 0.999, then increased to 1.0 at 90° from normal as depicted in Figure 15. There was a slight spread and decrease in the reflection coefficient magnitude values beyond the critical angle before returning to 1.0 at 90° from normal.

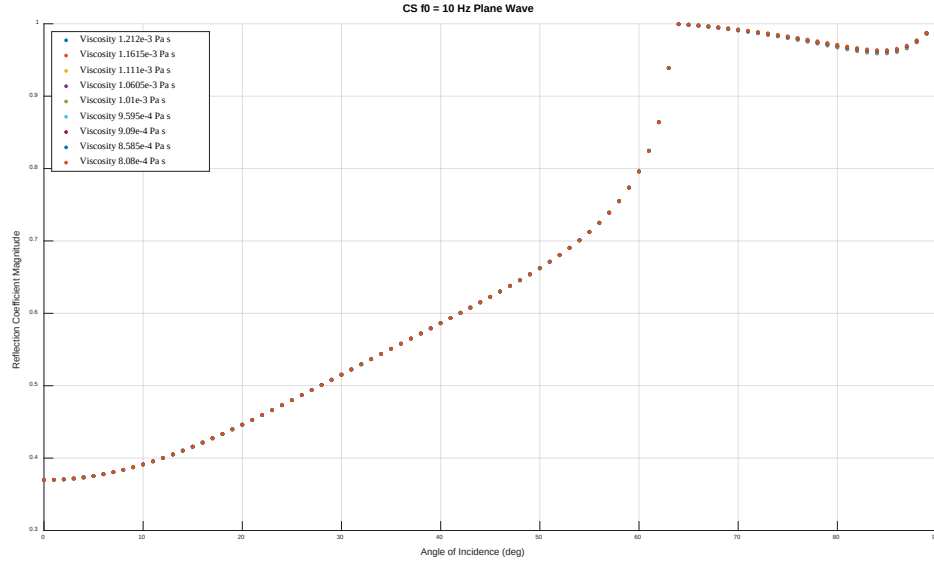


Figure 15. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for CS Viscosity (Pa s)

The largest change in η variation, which was very small, of the transmission coefficient values of the slow wave occurred for LST at 10,000 Hz. There was spread at all angles of incidence, less 90° from normal. The slow wave transmission coefficient began at $0.29e-5$ to $0.44e-5$, then peaked at 70° from normal with values of $0.87e-6$ to $1.31e-5$, then decreased to 0 at 90° from normal as depicted in Figure 16.

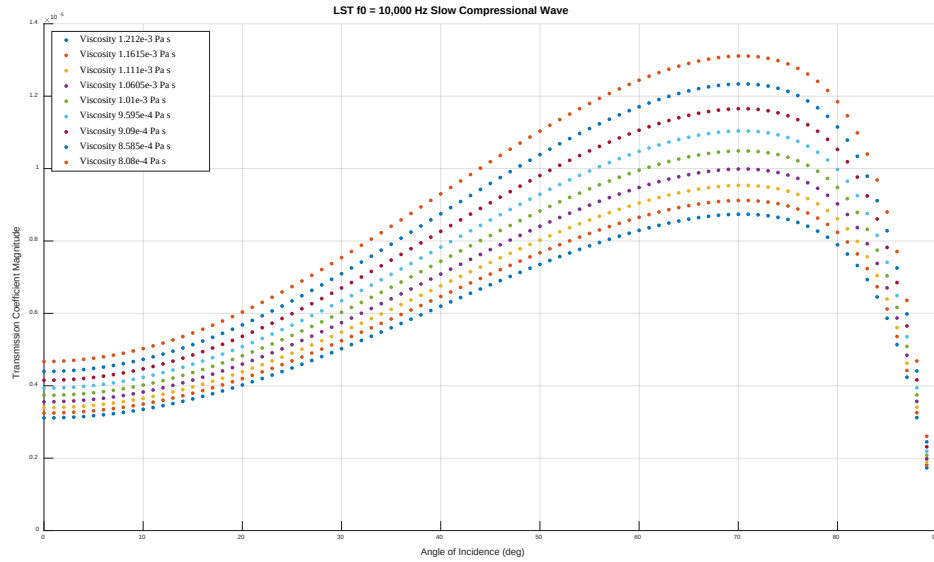


Figure 16. 10,000 Hz Slow Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for LST Viscosity (Pa s)

The fast wave transmission coefficient magnitude values for the η variations of CS steadily decreased from 0.706 until 57° and 58° from normal to 0.454, then slightly increased to the critical angle at 63° from normal to 0.506, then decreased to $2.9e-16$ at 90° from normal as depicted in Figure 17. There was slight spread in the transmission coefficient magnitude values beyond 0° from normal, with the largest spread at any given angle of incidence no larger than 0.002.

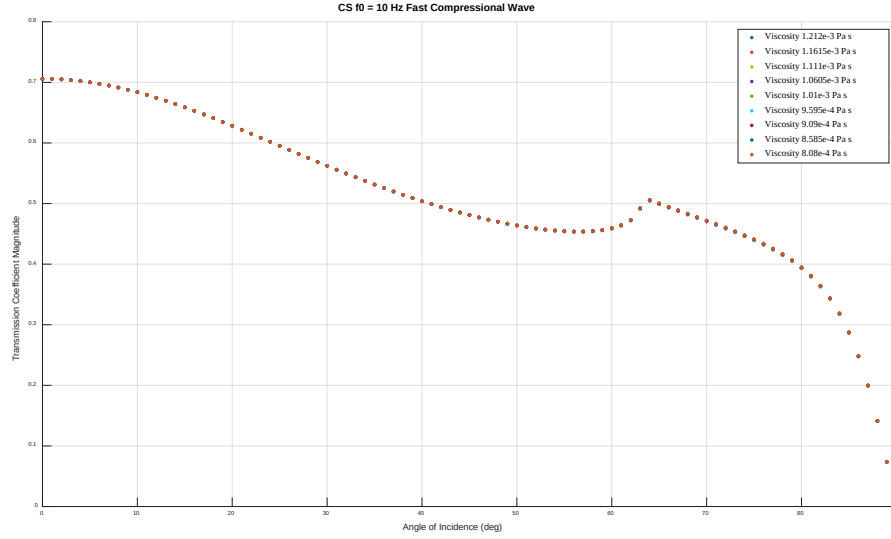


Figure 17. 10 Hz Fast Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for CS Viscosity (Pa s)

The transmission coefficient magnitude values for the shear wave η variation of LST steadily increased from 0 at 0° from normal until peaking at 45° from normal to $5.93e-3$, then decreased to 0 at 90° from normal as depicted in Figure 18.

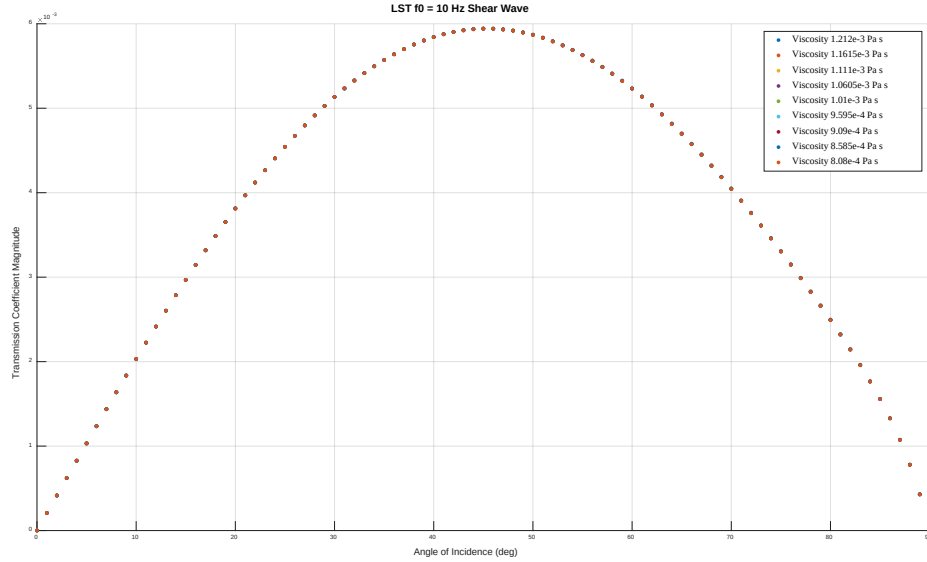


Figure 18. 10 Hz Shear Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for LST Viscosity (Pa s)

The transmission coefficient magnitude values for the shear wave η variation of SA, C4, and CS exhibited double peaks with CS having the largest variations. The transmission coefficient magnitude values for the shear wave η variation of CS steadily increased from 0 at 0° from normal until the first peak at 31° angle of incidence from normal, then decreased until 62° angle of incidence from normal, then increased to 64° angle of incidence from normal, then finally decreased until 90° angle of incidence from normal as depicted in Figure 19. The spread in variation values increased from approximately 20° until 89° angle of incidence from normal across all frequencies for the shear waves.

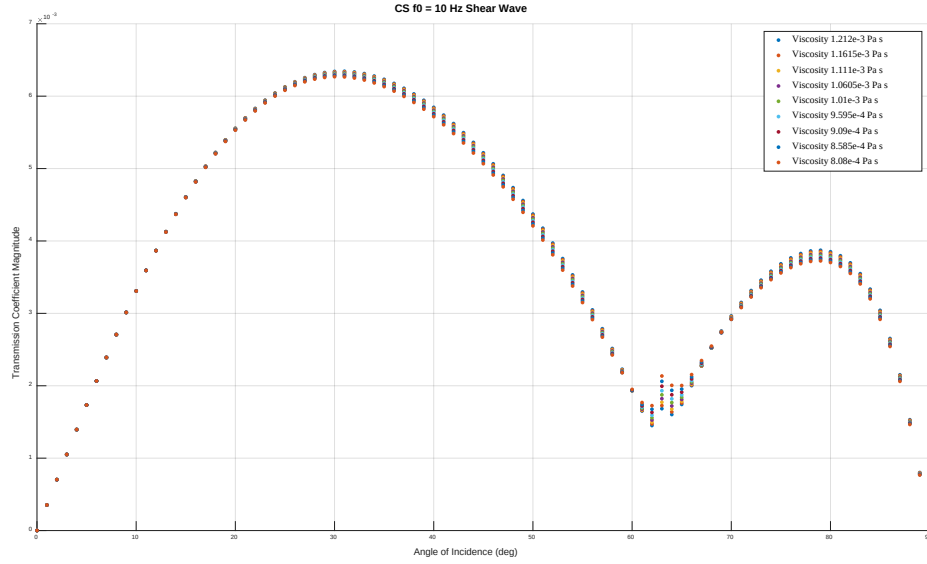


Figure 19. 10 Hz Shear Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for CS Viscosity (Pa s)

3. Permeability

For each sediment, the permeability (χ) was examined, with all other parameters held at the values as shown in Table 14. The permeability variations for selected sediments are presented in Table 17. The sediments, arranged in size from smallest to largest value of χ , are SA, C4, LST, and CS. From our hypothesis, we predicted that the change in magnitude of the reflection and transmission coefficients would increase as χ increased. SA would present the smallest change in magnitude of the reflection and transmission coefficients and CS would present the largest changes as we varied the χ values. We also predicted that the overall change in values of the reflection and transmission coefficient magnitudes would be smallest for SA and largest for CS.

Table 17. Permeability Variations for SA, C4, LST and CS in m^2

SA	C4	LST	CS
$6e-13$	$3e-11$	$3.12e-11$	$9e-11$
$5.75e-13$	$2.875e-11$	$2.99e-11$	$8.625e-11$
$5.5e-13$	$2.75e-11$	$2.86e-11$	$8.25e-11$
$5.25e-13$	$2.625e-11$	$2.73e-11$	$7.87e-11$
$5e-13$	$2.5e-11$	$2.6e-11$	$7.5e-11$
$4.75e-13$	$2.375e-11$	$2.47e-11$	$7.125e-11$
$4.5e-13$	$2.25e-11$	$2.34e-11$	$6.75e-11$
$4.25e-13$	$2.125e-11$	$2.21e-11$	$6.375e-11$
$4e-13$	$2e-11$	$2.08e-11$	$6e-11$

For the plane wave reflection coefficient, SA, C4, and CS all exhibited similar results. Their coefficient magnitudes increased until their respective critical angles, then approached the value 1.0 at 90° from normal, with slight decreases in magnitude between the critical angle and 90° from normal. SA at 10 Hz is presented as a representative example in Figure 20. The plane wave reflection coefficient magnitude for SA began at 0.315 at 0° from normal to 0.398 at 60° from normal then to 0.582 at 70° from normal to 0.999 at the critical angle at 72° from normal. Then there was a slight decrease to 0.998 at 80° from normal, then back up to 1.0 at 90° from normal. As the χ increased, the reflection coefficient magnitude values increased as hypothesized. Only LST did not follow as expected.

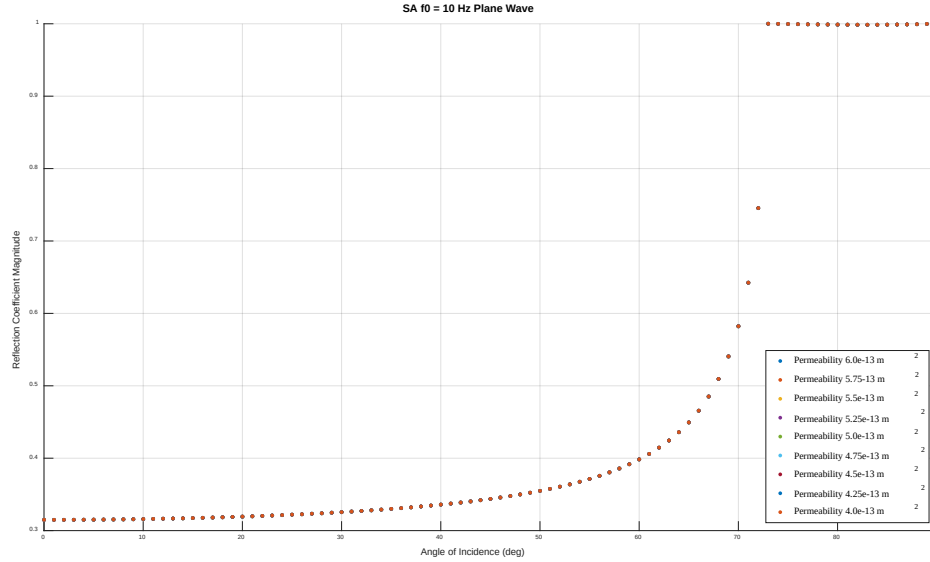


Figure 20. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for SA Permeability

A representative of the fast wave transmission coefficient magnitude for C4 is presented in Figure 21. The fast wave transmission coefficient magnitude began at 0.688 at 0° from normal, then increased to 0.747 at 60° from normal up to 0.968 at the critical angle at 67° from normal. Then steadily decreased to 0.933 at 70° from normal, to 0.684 at 80° from normal, and then down to 0 at 90° from normal. SA exhibited similar trends in the fast wave transmission coefficient, but with smaller magnitudes up to the critical angle at 72° from normal, then decreased in a similar manner until reaching 0 at 90° from normal. The CS fast wave transmission coefficient magnitude exhibited a similar trend as presented in Figure 18. The fast wave transmission coefficient magnitude value for CS was the same at 0.706 at 0° from normal and was 0.46 at 60° from normal, which was slightly lower than the same point in the η variation. At the critical angle of 63° from normal the value was 0.506 then decreased to 0.472 at 70° from normal then to 0.3951 at 80° from normal and is $2.95e-16$ at 90° from normal. The CS values showed slight spread after 0° from normal, but were never greater than 0.002 for any angle of incidence.

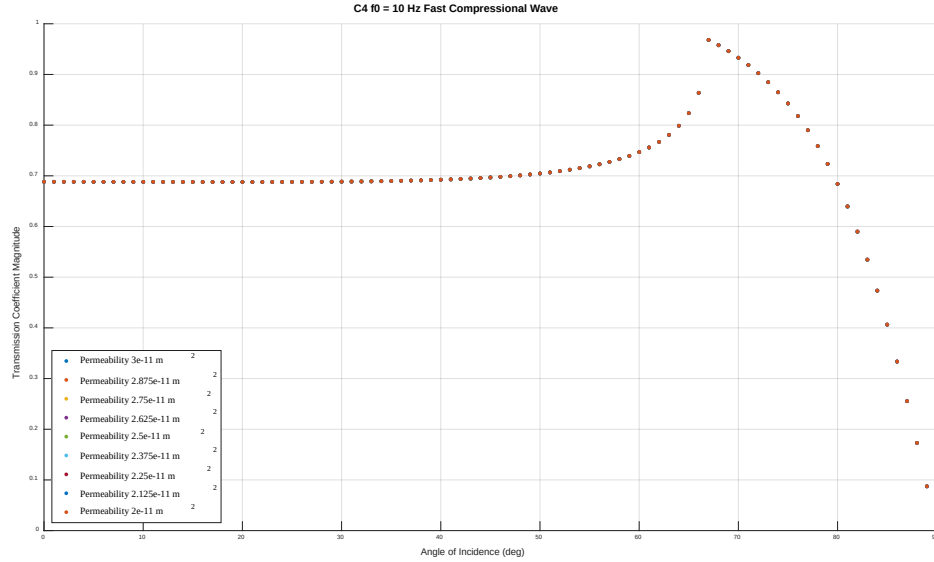


Figure 21. 10 Hz Fast Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for C4 Permeability

The LST plane wave reflection coefficient values were below those of SA, C4, and CS for all angles of incidence and exhibited a trend similar to that as presented in Figure 13. The fast wave transmission coefficient values for LST were above the values SA, C4, and CS except for C4 values between 63° and 89° and for SA values between 66° and 89°, from normal respectively. A representative LST fast wave transmission coefficient magnitude is presented in Figure 22. The LST fast wave reflection coefficient magnitude began at 0.834 at 0° from normal, then decreased to 0.792 at 60° from normal to 0.76 at 70° from normal, to 0.653 at 80° from normal then to 0 at 90° from normal. The fast wave speed of LST was less than the speed of sound for the South China Sea (SCS) water until reaching 5,251 Hz for the upper bound of the permeability variation and 7,723 Hz for the lower bound of the permeability variation. The implications of the LST fast wave speed above and below the speed of sound in the SCS water is discussed in Chapter IV.

The largest spread in the permeability values occurred for all sediments in the slow wave transmission coefficient magnitude although the values for the slow wave transmission coefficients were relatively small. The smallest values in slow wave transmission coefficient magnitude spread occurred for SA and are on the order of

$1.0e-7$, and the largest values for slow wave transmission coefficient magnitude spread occurred for CS and are on the order of $1.0e-4$. A representative LST slow wave transmission coefficient magnitude is presented in Figure 23. The LST slow wave transmission coefficient magnitude began at $0.28e-5$ to $0.42e-5$ at 0° from normal, then increased to $0.76e-5$ to $1.16e-5$ at 60° from normal. The value further increased to peak value at $0.81e-5$ to $1.21e-5$ at 70° from normal, then decreased to $0.74e-5$ to $1.2e-5$ at 80° from normal, and finally came to 0 at 90° from normal. LST was selected because its peak slow wave transmission coefficient magnitude, and spread, occurred at 70° , which is before the AOIN at 77° angle of incidence from normal.

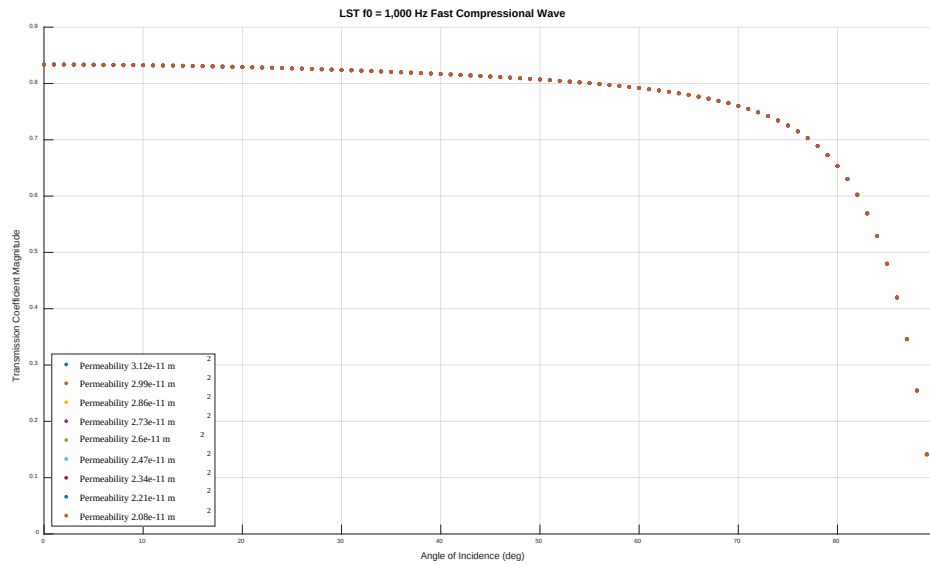


Figure 22. 1,000 Hz Fast Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for LST Permeability

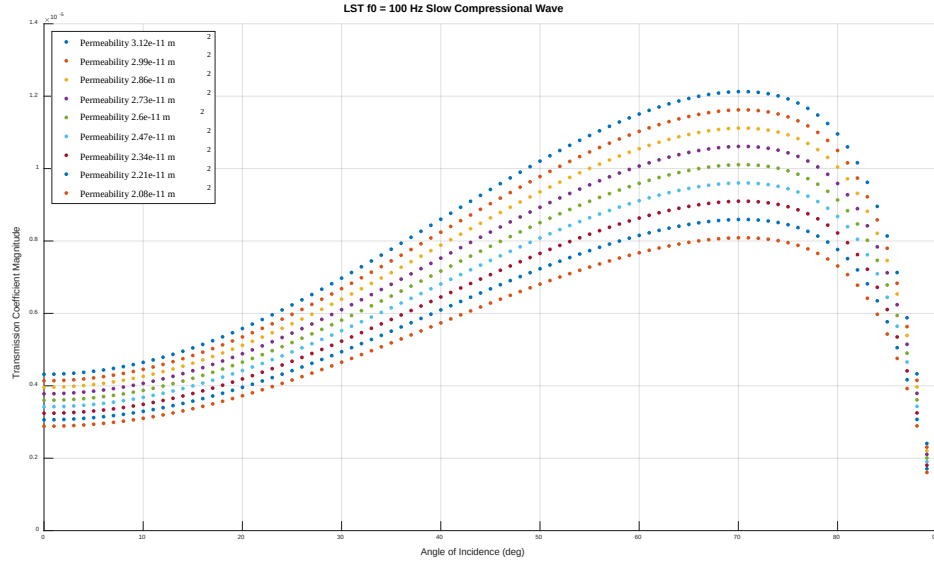


Figure 23. 100 Hz Slow Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for LST Permeability

The LST shear wave transmission coefficient magnitude for variation in the permeability values was similar in shape to that as presented in Figure 18. The shear wave reflection coefficient magnitude value for LST began at 0 at 0° from normal then increased to its peak at 45° from normal, then continued to decrease until 90° angle of incidence from normal.

4. Porosity

For each sediment, the porosity (β) was examined, with all other parameters held at the values as shown in Table 14. The porosity variations for selected sediments are presented in Table 18. The sediments, arranged in size from smallest to largest value of β , are CS, C4, SA, and LST. From our hypothesis, we predicted that the change in magnitude of the reflection and transmission coefficient values on CS would be the smallest and LST the largest as we varied the β values. We also predicted that the overall change in values of the reflection and transmission coefficient magnitudes would increase as we increased the β values.

Table 18. Porosity Variation of CS, C4, SA, and LST (dimensionless)

CS	C4	SA	LST
0.456	0.462	0.564	0.912
0.437	0.44275	0.5405	0.874
0.418	0.4235	0.517	0.836
0.399	0.40425	0.4935	0.798
0.38	0.385	0.47	0.76
0.361	0.36575	0.4465	0.722
0.342	0.3465	0.423	0.684
0.323	0.32725	0.3995	0.646
0.304	0.308	0.376	0.608

For plane wave reflection, we found the values for the reflection coefficient magnitudes decreased as the β values were increased. The reflection and transmission coefficient magnitudes stayed the same value as the driving frequency was increased for the plane waves and the fast waves, respectively. The transmission coefficient magnitudes for the slow waves generally decreased as the β values were increased, except for SA. These values were less than the values for CS, C4, and LST. The transmission coefficient magnitudes for the shear waves generally decreased as the β values were increased, except for LST, which were larger than SA.

The plane wave reflection coefficient for LST had the largest spread in values as the β was increased. A representative plane wave reflection coefficient for LST is presented in Figure 24. The values for the plane wave reflection coefficient magnitude began at 0.059 to 0.23 at 0° from normal then slightly decreased to 0.058 to 0.23 at 60° from normal. At 70° from normal the values spanned 0.041 to 0.23 then decreased to 0.017 to 0.19 at 80° from normal, and finally decreased to 0 at 90° from normal. For LST, the largest porosity values had the smallest reflection coefficient magnitude and the smallest porosity value had the largest reflection coefficient magnitude. This trend held through approximately 64° from normal. Beyond this angle, the value of the porosities did not follow the previous trends, additionally beyond the critical angle at 77° from normal none of the porosity values followed any trend.

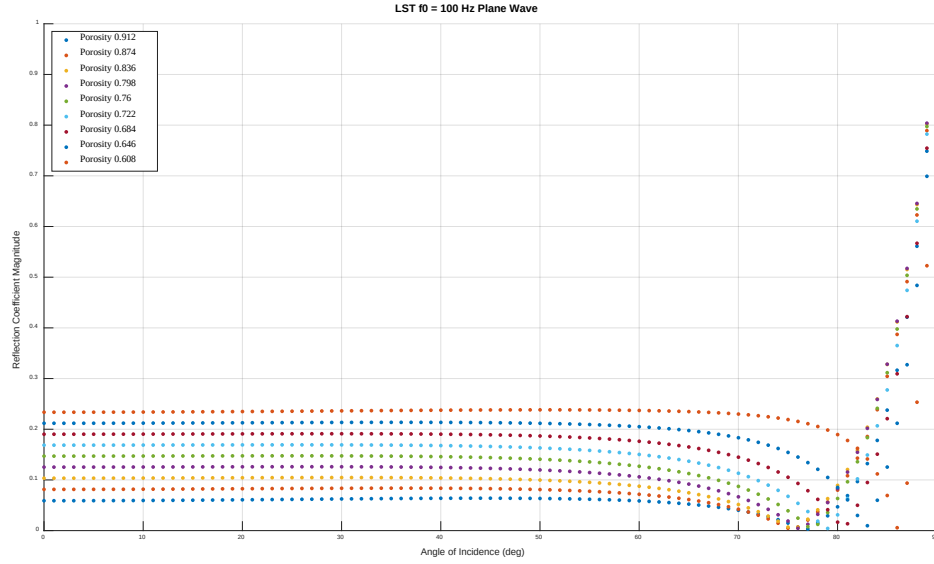


Figure 24. 100 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for LST Porosity

The slow wave transmission coefficient magnitude for SA had the smallest spread in values as the β values were increased. The values for the slow wave transmission coefficient magnitude began at $4.5e-8$ to $6.5e-8$ at 0° from normal and slightly increased to $1.8e-7$ to $1.93e-7$ at 60° from normal. The values increased again at 70° from normal to $2.1e-7$ to $2.6e-7$, then to $1.78e-7$ to $3.2e-7$ at 80° from normal before they decreased to 0 at 90° from normal. A representative slow wave transmission coefficient for SA is presented in Figure 25. The critical angles for SA porosity variations occurred between 65° and 83° from normal, after reaching their respective critical angle the values steadily decreased until reaching 0 at 90° from normal. After each critical angle, the lower valued porosities for SA had lower valued transmission coefficient values, indicating that the interactions for SA are sensitive to porosity in this region. It is possible that the energy is being transmitted along the sediment in this region. The values for the slow wave reflection coefficient magnitudes also generally decreased as the β values were increased.

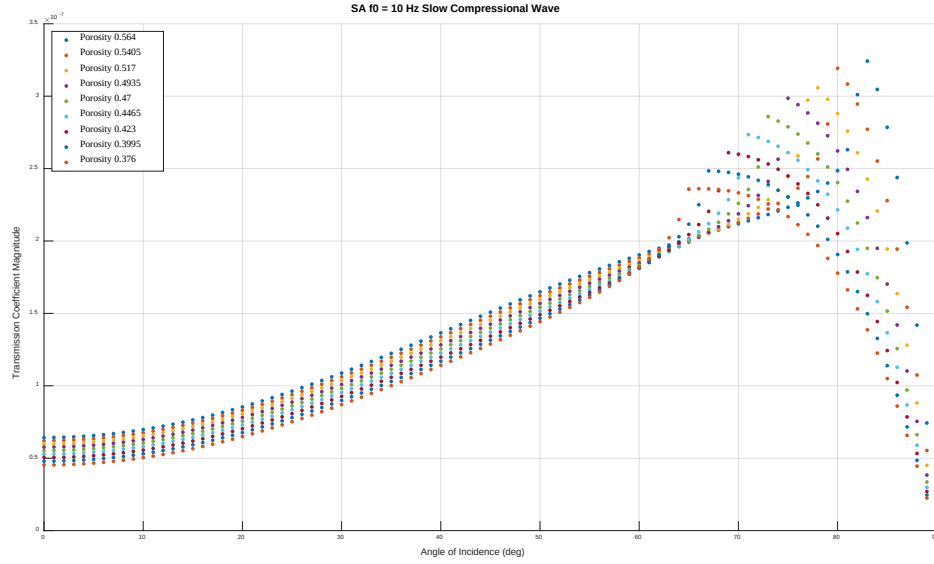


Figure 25. 10 Hz Slow Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for SA Porosity

As we increased the β values the fast wave transmission coefficient values also increased. The general trend is the larger original values for β led to larger increases in the fast wave transmission coefficient, except for C4. The fast wave transmission coefficient and values for C4 fell below CS at 0° from normal, above all the other sediments at 70° from normal, and as expected, above CS and below SA, respectively, for all other angles. None of the sediments showed increase in fast wave transmission coefficient with increasing driving frequency. The fast wave transmission coefficient magnitude for CS β is represented in Figure 26. The fast wave transmission coefficient magnitude began from 0.691 to 0.725 at 0° from normal, then decreased to 0.435 to 0.516 at 60° , then slightly increased to 0.445 to 0.498 at 70° from normal before decreasing to 0.36 to 0.433 at 80° from normal and then to 0 at 90° from normal. An inversion occurs between 35° and 55° from normal. After 57° from normal, CS exhibits smaller but similar characteristics as LST in Figure 25. It is possible that for CS, the energy is being transmitted along the sediment, showing that CS is also sensitive to porosity in this region.

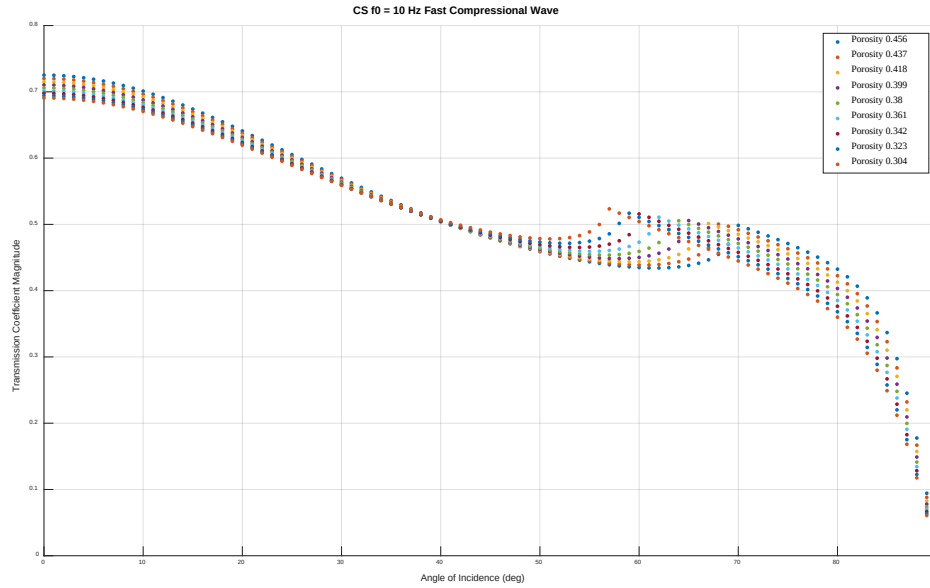


Figure 26. 10 Hz Fast Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for CS Porosity

The shear wave transmission coefficient values were hypothesized to increase as the β values increased. For the sediments CS, C4, and SA, the shear wave exhibited two maxima. The shear wave transmission coefficient magnitude began at 0 at 0° from normal then increased to the first maximum value at $7.3e-3$ for 31° from normal down to $5.32e-3$ for 29° from normal for CS, at $4.4e-3$ for 43° from normal down to $3.07e-3$ for 39° from normal for C4, and at $4.9e-3$ for 44° from normal down to $3.3e-3$ for 41° from normal for SA. The first listed value of the maximum value pairs occurred for the upper bound of the respective β values and the second value of the maximum value pairs occurred for the lower bound of the respective β values, with the other values of the β in ascending order from the lowest β value to the highest β value. The shear wave transmission coefficient magnitude values then decreased until near the range of critical angles for each sediment, which exhibited spread based on the input β values, and then increased to a second maximum value. The second maximum value occurred at $4.4e-3$ for 76° from normal down to $3.2e-3$ for 81° from normal for CS, at $3.6e-3$ for 74° from normal down to $2.5e-3$ for 81° from normal for C4, and at

$3.2e-3$ for 76° from normal down to $1.3e-3$ for 85° from normal for SA. The first value of the second maximum value pairs occurred for the lower bound of the respective β values and the second value of the second maximum value pairs occurred for the upper bound of the respective β values, with the other values of the β in descending order from the highest β value to the lowest β value. Finally, the shear wave transmission coefficient magnitude values decreased again to 0 at 90° from normal. A representative shear wave reflection coefficient for SA is presented in Figure 27.

The LST shear wave transmission coefficient magnitude consisted of one maximum and was similar to that as shown in Figure 18. The LST values associated with the shear wave transmission coefficient magnitude spanned from the smallest $1.6e-3$ at 80° angle of incidence from normal to the largest at $6.8e-3$ at 60° angle of incidence from normal. The β variation is another case where some of the LST fast wave speeds exceeded that of the SCS sound speed and are discussed in Chapter IV.

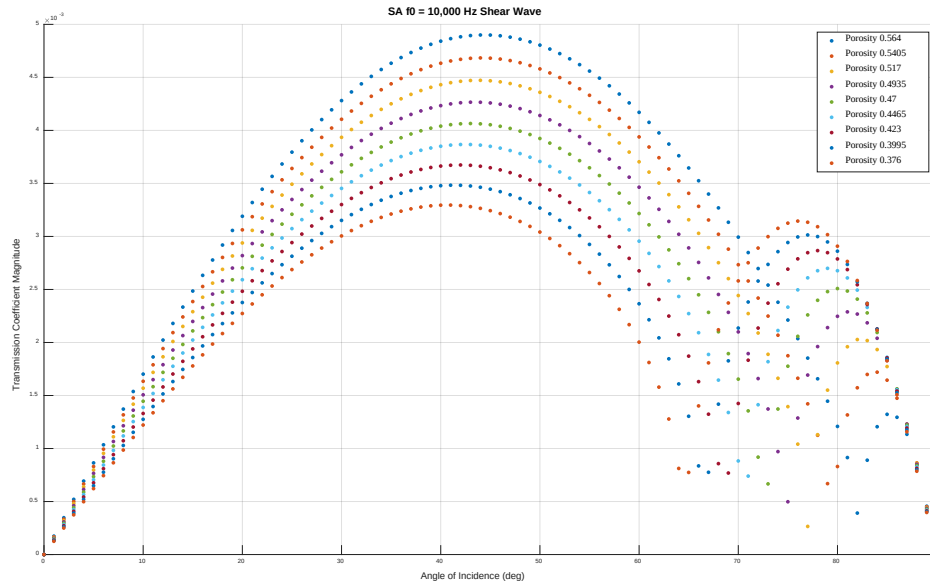


Figure 27. 10,000 Shear Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for SA Porosity

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III. DISCUSSION

This chapter discusses results from the selected sediment studies.

A. HOW MUCH VARIABILITY EXISTS IN THE MODELED BIOT PARAMETERS

The variability in the modeled Biot parameters was examined individually for each sediment. Our findings are discussed in this chapter. The implications of our findings on Naval Applications are presented in Chapter V.

1. Control Sediment Data

The sediments selected from the Control Sediment Data for further evaluation were SA and CS. These sediments were selected because they closely align in physical properties with sediments from the SCS data collected. Additionally, these sediments were found in multiple published locations which enabled comparison of results with those from our study.

a. Sand (SA)

This section presents discussions of the results from the variation studies of the characteristic pore size, dynamic viscosity, permeability, and porosity for SA.

(1) Characteristic Pore Size

The pore size of SA is on the order of both C4 and CS. We hypothesized that increasing the pore size would increase the reflection and transmission coefficients, but our hypothesis did not hold for pore size for SA. The variations in pore size had no effect on SA. It is possible that the pore size of SA began at a sufficiently large size such that the range of pore size values that could impact changes in the reflection and transmission coefficients was already exceeded. Additionally, when we varied the pore size values, we did not make any adjustments to the porosity (strongly correlated), the permeability (weakly correlated), or the density of the sediment (weakly correlated) as would be expected with changes in pore size (Schock 2004).

Despite our hypotheses not holding, our results resemble those of Nolle et al. as reproduced in Jackson and Richardson (Jackson and Richardson 2007) Figure 11.6. Nolle et al.'s sediment was fresh water filled and compacted sand close in porosity to SA. Their sound speed ratio was slightly more than that for our case, and their driving frequencies were 400 to 1,000 kHz, much larger in magnitude than our modeled frequencies. Despite these differences, our results are consistent, accounting for the aforementioned differences, with Nolle et al.'s results indicating that our model accounts for the poroelastic nature of the water-sediment interface.

Additionally, the 10 Hz plane wave reflection versus angle of incidence from normal as presented in Figure 28, are consistent with Stoll (Stoll 1989) Figure 2.10. This further supports that our model accounts for the poroelastic nature of the water-sediment interface. For this particular set of parameter values, SA behaved more like a viscoelastic sediment from 0° until the critical angle at 72° angle of incidence from normal. At this low frequency, the properties of the skeletal frame are important and the frequency-dependent viscous losses in the fluid are less important (Stoll 1989), but still present. Beyond the critical angle, SA behaved more like an elastic sediment, the combination of these two behaviors in the same sediment over a range of angles is more consistent with poroelastic modeling. Beyond the critical angle, there are only slight reductions in the reflection coefficient magnitude highlighting (vice very large reductions) that the elastic model would not capture the frame damping losses for this sediment in this angle region.

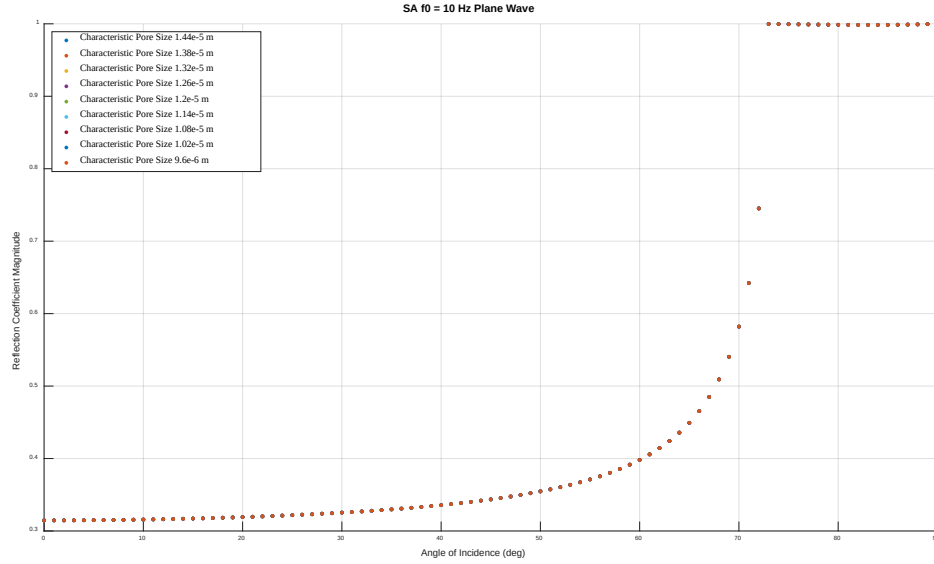


Figure 28. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for SA Characteristic Pore Size

Both C4 and CS exhibited similar features as discussed for pore size for SA. The SA pore size 10 Hz fast wave attenuation (Nepers/m) versus frequency (Hz) are presented in Figure 29. Despite the slight differences in the sediment parameter values, our attenuation behavior is consistent with Figure 1.5 from Stoll (1989) and Figure 3 from Williams (2001). Again, these agreements support our use of the poroelastic model for examination of the water-sediment interface.

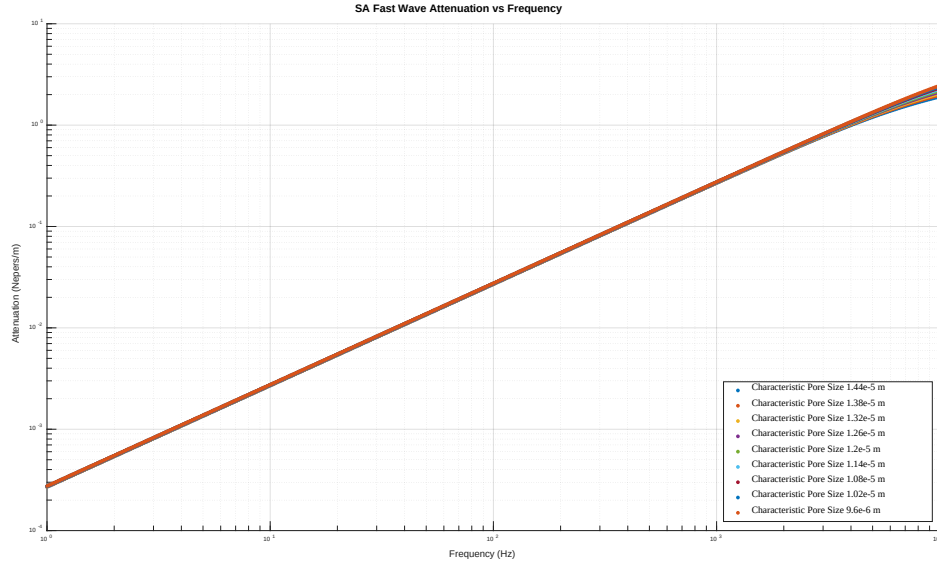


Figure 29. 10 Hz Fast Wave Attenuation (Nepers/m) vs. Frequency (Hz) for SA Characteristic Pore Size

(2) Viscosity

We found that increasing the η values did not decrease the reflection and transmission coefficient values, with the exception of the slow wave transmission coefficient values - despite having very small values our hypothesis holds for this wave type. We thus conclude that our hypothesis did not hold for the viscosity variations for the plane wave reflection coefficients, the fast wave transmission coefficients, or the shear wave transmission coefficients for SA.

(3) Permeability

We hypothesized that increasing the permeability values would increase the magnitude of the reflection and transmission coefficient values. We found that increasing these values did not increase the reflection and transmission coefficient values, with the exception of the slow wave transmission coefficients - despite having very small values the hypothesis holds for the slow wave transmission coefficient variations. The permeability curves for the reflection and transmission coefficient values were similar in magnitude and shape to the pore size and viscosity variation curves for SA. All

permeability slow wave attenuation values were below the viscosity slow wave attenuation values at all frequencies. All permeability slow wave attenuation values are above the pore size lower bound slow wave attenuation values until 7,500 Hz, implying that permeability variation has more impact on bottom loss for SA from 0 Hz to 7,500 Hz, and pore size variations have more impact on bottom loss for SA at higher frequencies.

The bottom loss for permeability variations did not increase with increasing driving frequency, like the viscosity and pore size bottom loss curves.

(4) Porosity

The β of SA is 0.47. Several variations in SA for the porosity overlapped those of both C4 and CS, which allowed for some comparison of the results of the effects of this parameter's variation across these three sediments. In the plane wave reflection, the lower porosity values had higher reflection coefficient values. A representative plane wave reflection coefficient magnitude versus angle of incidence from normal for β variations for SA is depicted in Figure 30.

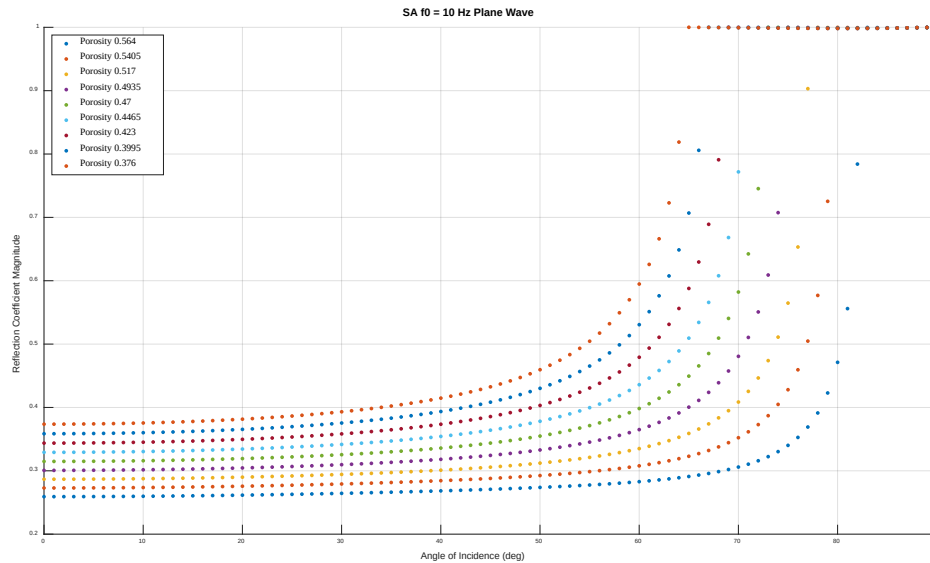


Figure 30. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for SA Porosity

We found that increasing the β values did not always increase the reflection and transmission coefficients, thus our hypothesis did not hold for SA. The β interactions are complicated, and have multiple transitions. For example our hypothesis holds for the β variations in the shear wave transmission coefficient from 0° angle of incidence from normal until the 66° angle of incidence from normal, and then again at 89° angle of incidence from normal, but not in-between. A representative of the shear wave transmission interaction is shown in Figure 31. Similarly, our hypothesis held for the fast wave transmission coefficients from 0° angle of incidence from normal until the transition began at 44° angle of incidence from normal, then again at 89° angle of incidence from normal, but not in-between. These results indicate that reflection and transmission coefficients for SA are sensitive to β variations for some angles of incidence from normal and not for other angles of incidence from normal. For our range of driving frequencies, it is important to know when increasing β will increase the reflection and transmission coefficients as angles of incidence from normal changes – understanding this relationship may assist in avoiding erroneous conclusions when interpreting sonar data. To further complicate matters, this β vs. angle of incidence from normal relationship is just one interaction that stems from the larger family of parameter relationships. We did not evaluate combinations of parameter interactions in this study.

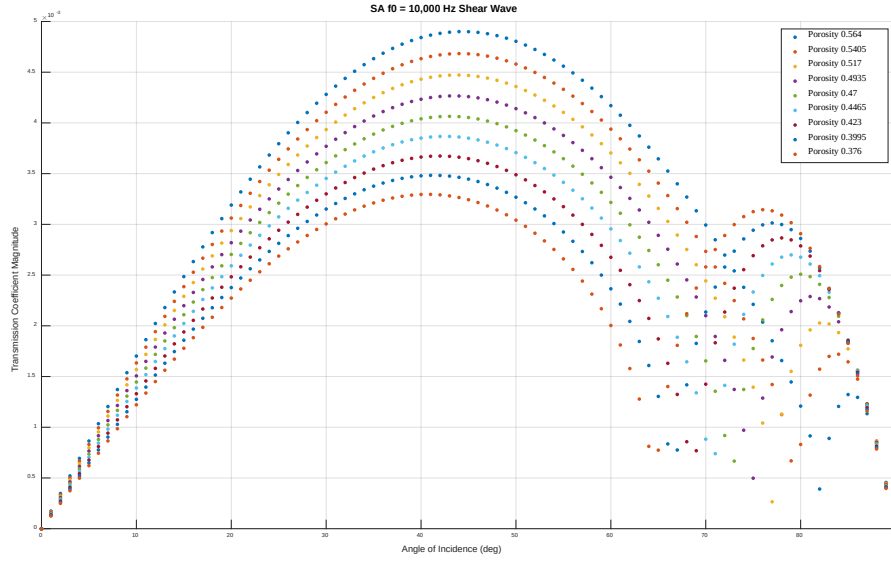


Figure 31. 10,000 Hz Shear Wave Transmission Coefficient Magnitude vs. Angle of Incidence (deg) for SA for porosity

Bottom loss for the β variations did not increase with increasing driving frequency. A representative bottom loss versus grazing angle for variations in β for SA is presented in Figure 32. As presented in Williams et al. (2002), “These varying conclusions further indicate the complexity of sand as an acoustic medium.”

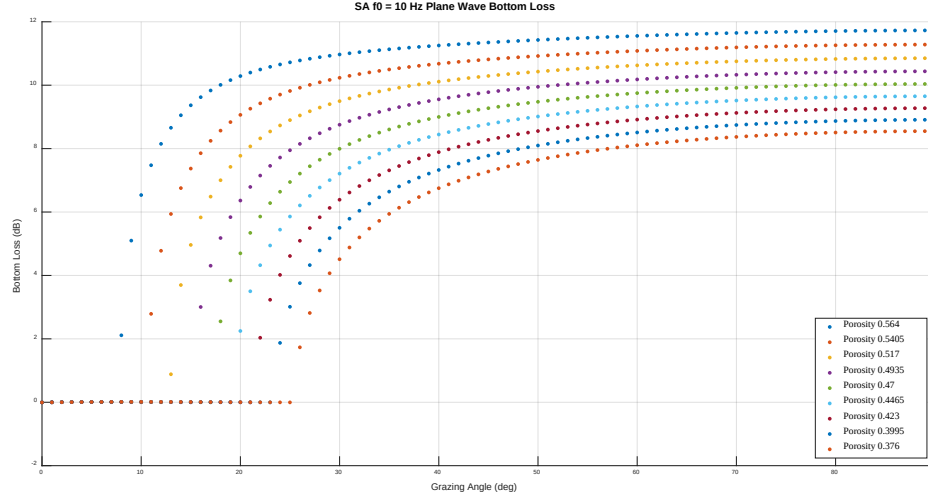


Figure 32. 10 Hz Plane Wave Bottom Loss (dB) vs. Grazing Angle (deg) for SA Porosity

b. Coarse Sand (CS)

This section presents discussions of the results from the variation studies of the characteristic pore size, dynamic viscosity, permeability, and porosity for CS.

(1) Characteristic Pore Size

Unlike SA which variations in pore size had no effect, the pore size variations for CS had the smallest and largest attenuation peaks. The pore size variations for CS also had the largest and overall spread in fast wave transmission attenuation.

(2) Viscosity

The slow wave transmission coefficient values increased as the viscosity variations values increased. This behavior was different from the behavior exhibited by SA, which our hypothesis held for the slow and shear wave transmission coefficients.

(3) Permeability

Similar to SA, our hypothesis only held for the viscosity variations for the slow wave transmission coefficients - despite having very small values the hypothesis holds for the slow wave transmission coefficient variations. Increasing the permeability variation

values did increase the values for the shear wave transmission coefficients, but only from 60° to 68° angle of incidence from normal range, otherwise our hypothesis did not hold.

(4) Porosity

Similar to SA, we found that our hypothesis held for the β variations the fast wave transmissions, only between 0° and 29° angle of incidence from normal and again between 71° and 89° angle of incidence from normal, and for the shear wave transmission, between 0° and 56° angle of incidence from normal and again between 89° and 90° angle of incidence from normal. CS also held for additional wave types compared to SA - for the plane wave reflections, only from 70° to 89° angle of incidence from normal and the slow wave transmissions, between 7° and 46° angle of incidence from normal and again between 70° and 89° angle of incidence from normal.

The bottom loss for CS β variations are similar in shape to that of SA, but have some notable differences. To begin there is a local maximum for CS at 7° grazing angle with values ranging from 0.439 dB to 0.208 dB. For SA, the local maximum occurs for all β variations at 10° grazing, except for the β upper bound, with values ranging from $1.66e-2$ dB to 1.72 dB. After reaching their respective critical angles, both bottom loss curves exhibit similar shape. The CS however exhibits fluctuations in bottom loss values from 40° through 80° grazing angle, and SA did not exhibit these fluctuations. Both sediments reached maximum bottom loss value at 90° grazing angle. SA had higher values, ranging from 8.56 dB to 11.73 dB, than SA whose values were 7.47 dB to 9.89 dB. Both parameters are sensitive to β variations, where SA is more sensitive for larger grazing angles and CS was more sensitive for smaller grazing angles.

2. 2013 South China Sea Sediment Data

For the 2013 South China Sea data discussions, only parameters that caused significant variations in the reflection or transmission coefficients are presented.

a. C4

This section presents discussions of the results from the variation studies of the dynamic viscosity and porosity for C4.

(1) Viscosity

The viscosity lower bound variation reached maximum attenuation first, and had one of the smallest range of frequencies at maximum attenuation. The viscosity upper bound variation reached maximum attenuation last, but did not have the largest range of frequencies at maximum attenuation. The viscosity variation, $9.595e-4$, had the largest range of frequencies at maximum attenuation. The bottom loss values for the viscosity variations before the critical angle are slightly higher than the bottom loss values for the pore size variations, which implied that variations in viscosity have more influence on bottom loss than pore size variations for an individual characteristic trait at shallow grazing angles. The most rapid rate of change in the viscosity variations for bottom loss occurred between 27° and 30° grazing, immediately following the critical angles, as in the pore size variations. Overall, the viscosity bottom loss value at the local minima of 22° grazing was the largest for all the parameters analyzed for C4. A closer look for the bottom loss for viscosity variations for C4 for 0° to 23° grazing angle is presented in Figure 33.

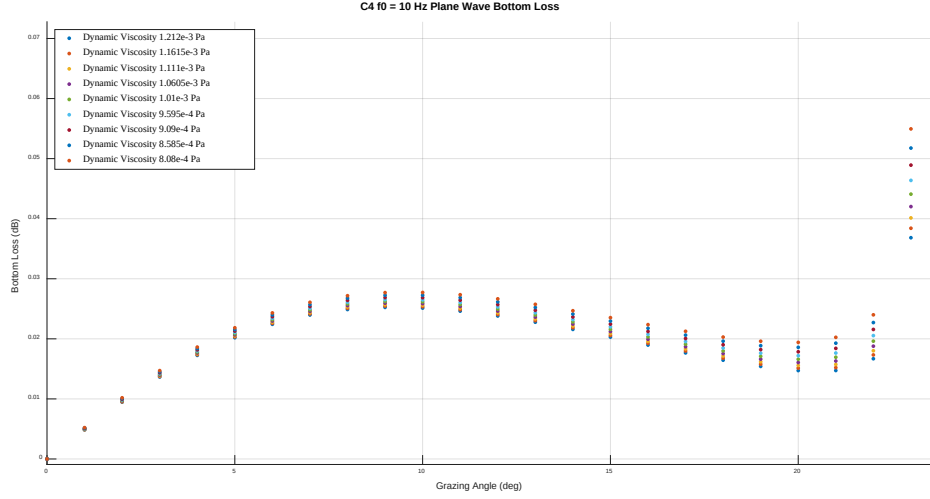


Figure 33. 10 Hz Bottom Loss (dB) vs. Grazing Angle (deg) for C4 for Dynamic Viscosity, 0° through 23° Grazing Angle

(2) Porosity

Several C4 variations in the β overlapped those of both CS and SA, which allowed for some comparison in the results of the effects of this parameter's variation across these three sediments. In the reflection coefficient the lower β variation values had higher reflection coefficient values from 0° angle of incidence from normal until their respective critical angles. The higher β variation values had lower reflection coefficient values from their respective critical angles with little variation beyond 89° angle of incidence. Increasing the driving frequency did not change the plane wave reflection coefficient values. The β variations greater than the original value were greater in value than all the plane wave reflection coefficient and phase values for the pore size, the viscosity, and the permeability variations. The β variations less than the original value were less in value than all the plane wave reflection coefficient and phase values for the pore size, the η , and the permeability variations. The β variations for C4 had the most impact on the plane wave reflection coefficient magnitudes and phase values. The 10 Hz plane wave reflection coefficient magnitude versus angle of incidence from normal for the C4 β variations are depicted in Figure 34.

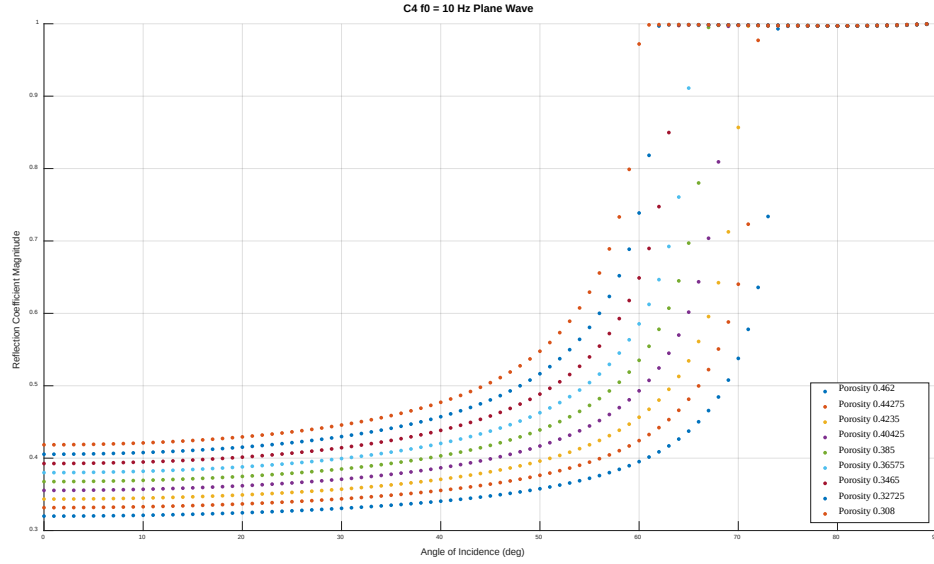


Figure 34. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for C4 for Porosity

b. LST

This section presents discussions of the results from the variation studies of the dynamic viscosity, permeability, and porosity for LST.

(1) Viscosity

The fast wave speeds were all below the SCS sound speed at 1 Hz. The frequency at which each LST viscosity variation first exceed the SCS sound speed are presented in Table 19. For the viscosity fast wave speeds, the spread in fast wave speeds was approximately the same as the permeability fast wave speeds. Similarly, the fast wave speed for the viscosity upper bound was faster than the permeability lower bound and the fast wave speed for the viscosity lower bound was faster than the permeability upper bound.

Table 19. Frequency (Hz) at which the Fast Wave Speed for the LST Viscosity Variation (Pa s) First Exceeded the SCS Sound Speed.

LST Viscosity Variation ($Pa \cdot s$)	Frequency (Hz)
$1.21e-3$ (Upper Bound)	7,582
$1.1615e-3$	7,173
$1.111e-3$	6,913
$1.0605e-3$	6,541
$1.01e-3$ (Original Value)	6,304
$9.595e-4$	5,964
$9.09e-4$	5,643
$8.585e-4$	5,339
$8.08e-4$ (Lower Bound)	5,251

(2) Permeability

The fast wave speeds for all variations of LST for permeability were again above the SCS sound speed for some frequencies, as presented in Table 20.

Table 20. Frequency (Hz) at which the Fast Wave Speeds for the LST Permeability variations (m^2) First Exceeded the SCS Sound Speed.

LST Permeability Variation (m^2)	Frequency (Hz)
$3.12e-11$ (Upper Bound)	5,145
$2.99e-11$	5,339
$2.86e-11$	5,643
$2.73e-11$	5,855
$2.6e-11$ (Original Value)	6,188
$2.47e-11$	6,421
$2.34e-11$	6,787
$2.21e-11$	7,173
$2.08e-11$ (Lower Bound)	7,723

(3) Porosity

For the plane wave reflection, the lower porosity variation values had higher reflection coefficient values from 0° angle of incidence from normal until the AOIN. The higher porosity variation values had higher reflection coefficient values from the AOIN until 89° angle of incidence from normal. At 90° angle of incidence from normal, all porosity variation values had the same reflection coefficient value. Increasing the driving frequency did not change the plane wave reflection coefficient values. A representative plane wave reflection coefficient magnitude versus angle of incidence from normal for porosity variations is depicted in Figure 35.

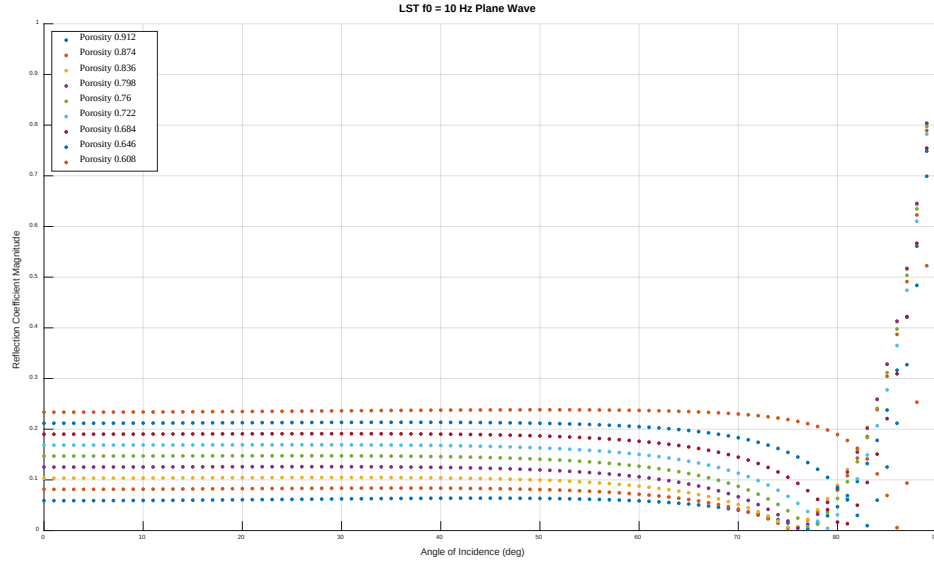


Figure 35. 10 Hz Plane Wave Reflection Coefficient Magnitude vs. Angle of Incidence (deg) for LST for Porosity

B. RESEARCH QUESTIONS

1. Can we properly simulate the acoustical conditions observed in the 2013 South China Sea cruise data?

We found that our model sufficiently simulated the conditions observed in the 2013 South China Sea cruise data. The challenge in simulating the acoustical conditions observed lies in determining the 13 Biot Parameters, and their likely range in variations. We found that our selection in range for parameter variations for pore size may have been outside of the range of impacts possible from the variations in this parameter. A recommendation for future study is to decrease the range in the parameter variations for pore size to see if impacts from the pore size variation can be captured. The poroelastic treatment of the water-sediment interface is complicated, but worth the computation time to fully explore the acoustic interactions.

2. Can we estimate the appropriate Biot parameters and their variability to understand and explain the observed acoustic interactions in the collection area?

We found that our parameter values and variability selections were generally appropriate representations for the 2013 South China Sea cruise data. The pore size variation ranges remain as previously discussed. We also conclude that using our range of variations for the selected sediments may not capture the full range of impacts, specifically for the viscosity variations. It is unlikely that the sandy sediments will have the same range in viscosity as the mud sediment. A future study could examine a different selection of viscosity variations for the sediments studied in this thesis.

3. Can we use this information to predict other areas where these conditions are likely to occur?

The results of this study have the potential to be useful in future acoustic studies as presented in Chapter V.

IV. CONCLUSIONS

A. CONCLUSIONS BASED ON THE RESULTS OF THE PRESENT STUDY AND OTHER LITERATURE

The water sediment interface should be modeled as a poroelastic medium to better account for the losses and changes that occur at the water-sediment interface.

Variations in the four parameters selected have shown effects on sound propagation and bottom loss, which are dependent on the bottom sediment type and the characteristics of the water-sediment interface studied. Within our limited study, we have identified several frequency ranges and angle of incidence from normal where our parameter variations will impact SONAR results for several naval systems.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Based on our results, the following recommendations for future research should be considered.

Recommendations for ongoing research based on the results of this study

a. Explore the tactical implications

A future research question is “Are there other geographic areas where these conditions are likely to occur?”

The results of the data analysis indicate that modeling the water-sediment interface as a poroelastic interface may influence many areas of interest to the Navy. The challenge lies in that many of the parameters examined in this study are difficult to measure or accurately determine, especially outside of the laboratory environment. In recent years, the use of geoacoustic inversion techniques on acoustic data has afforded information on identifying several of the physical properties presented in this thesis. There is potential use of the geoacoustic inversion techniques to inform future modeling of the water-sediment interface. Meteorology and Oceanography (METOC) personnel may be able to use these, or similar techniques, to study geographic areas with sparse data to determine if similar acoustic properties exist without detailed *in situ* data. The potential to exploit this

environmental information may influence the way decisions are made for areas determined to be acoustically similar. ASW, MIW, and HYDRO are areas where future research may benefit greatly from studies of this type.

b. Explore the near shore implications

A future research question is “Are near shore processes, under the same conditions, acoustically similar enough to glean information from them and do they translate into deep water?”.

The near shore environment poses additional considerations for acoustics. Specifically, the impact of bubbles on acoustics at the water-sediment interface may have large impacts to acoustics, acoustical properties, and acoustic modeling in this environment. This study assumes no gases are present in the water-sediment interface, which is unlikely, especially within the near shore environment. This thesis does not account for wind waves or swell, both of which are present in the near shore environment and can introduce bubbles and other gasses into the water-sediment interface. Future studies should include analysis of the water-sediment interface in the near shore acoustic environment, accounting for bubbles and other gasses that may be present.

We assumed a constant temperature of the water at the water-sediment interface in this thesis. In the near shore environment, temperature plays a significant role and can vary widely both spatially and temporally. Additional future studies should include analysis of the water column temperature as it varies with depth down to and within the water-sediment interface.

c. Explore applications in the Arctic

The challenge in applying these results to the Arctic will be similar to that of any area that is data sparse—how to determine the parameters and their range of variability? Additionally, the water temperature and salinity may have significant implications. Future studies in the laboratory may be useful for modeling the Arctic’s acoustic impacts at the water-sediment interface.

APPENDIX. MATLAB CODE

The MATLAB coding was adapted after Stoll and Kan (1981) and Buchanan et al. (2004). The MATLAB codes require input files that contain data for each sediment. The two .m-files then calculate the output results of plane wave reflection.

```
% LCDR Laura-Michel DeHaan
% Assistance from Clyde Scandrett & Steve Baker
% Created: 11 NOV 2015
% Last Updated: 14 FEB 2019
% Thesis FEM Code
% Solving for the plane wave reflection

% Inputs
% rho_f, density of the fluid (kg/m^3)
% rho_r, density of the grain (kg/m^3)
% K_b, Bulk modulus of skeletal frame (Pa)
% mu_x, Shear modulus (Pa)
% K_r, Bulk modulus of grain (Pa)
% K_f, Bulk modulus of fluid (Pa)
% beta1, porosity, dimensionless
% eta, viscosity of the pore fluid Poiseuille(PI) 1PI = 1Pa*s = 1kg/ms
% tau, tortuosity, dimensionless, is listed as alpha in Biot parameters
% omega, frequency (rads/s)
% script_a, pore size parameter (m)

% thetaI, incidence angle (in radians) <--- set this
% theta1, fast compressional wave angle (in radians)
% theta2, slow compressional wave angle (in radians)
% thetaS, shear compressional angle (in radians)
format long
Chapter_5_Buchanan_Wave_Speed_and_Attenuation_11NOV15
ThetaS=[];Theta1=[];Theta2=[];AA1=[];AA2=[];AC=[];RR=[];
costhetaS=[];costheta1=[];costheta2=[];
k_w=[];k_sw_cpx=[];k_1_cpx=[];k_2_cpx=[];g_s=[];g_1=[];g_2=[];
for ll=1:length(omega)
    alpha_str=(K_r-K_b)/K_r; % structure factor
    D_pwr=K_r.*(1+beta1.*((K_r/K_f)-1)); %Compute D_pwr
    % (pwr = plane wave reflection)
    M_pwr=K_r.^2./(D_pwr-K_b); %Compute M_pwr
    rho_pwr=((1-beta1).*rho_r)+(beta1*rho_f); %Average volume density
    m_pwr=tau.*rho_f./beta1; %Compute m_pwr, added mass term
    lambda_c_pwr=K_b-(2/3.*mu_x)+(M_pwr.*alpha_str.^2); %Compute
    % lambda_c_pwr

    % computing k's, g's etc.
```

```

% using k_sw for the shear wave, since k_s is used in
% Wave_Speed_and_Attenuation code already.
k_w(ll)=omega(ll)./c_f; %plane waves, always real
k_sw_cpx(ll)=sqrt(omega_2(ll)./mu_x.*(rho_pwr+((rho_f.^2.*omega(ll)...
.*perma)./((1i.*eta.*F_kappa(ll))-(m_pwr.*omega(ll).*perma)))));
% complex k_sw
k_1_cpx(ll)=k_p_fast(ll); %complex k_1
k_2_cpx(ll)=k_p_slow(ll); %complex k_2
g_s(ll)=((mu_x.*k_sw_cpx(ll).^2)-(rho_pwr.*omega_2(ll)))/...
.(rho_f.*omega_2(ll)); % Laura changed k_sw to k_sw_cpx on 11NOV15
g_1(ll)=(k_1_cpx(ll).^2.*(lambda_c_pwr+(2*mu_x))-...
(rho_pwr.*omega_2(ll)))/((rho_f.*omega_2(ll))-...
(k_1_cpx(ll).^2.*alpha_str.*M_pwr));
g_2(ll)=(k_2_cpx(ll).^2.*(lambda_c_pwr+(2*mu_x))-...
(rho_pwr.*omega_2(ll)))/((rho_f.*omega_2(ll))-...
(k_2_cpx(ll).^2.*alpha_str.*M_pwr));

% for thet_i=[.5235,.6981,.8726,1.0471,1.2217,1.3962]
% for plotting Fig 3, pg5 COMSOL
for thet_i=0:pi/2/39:pi/2
    thetaI=thet_i;
    costhetaS(ll)=sqrt((((omega_2(ll)./c_s_cpx(ll).^2)-...
    (omega_2(ll)/c_f.^2))+((omega_2(ll)/c_f.^2)*cos(thetaI).^2))/...
    ./(omega_2(ll)./c_s_cpx(ll).^2)); %from Steve meeting 9NOV15
    ThetaS=[ThetaS;costhetaS(ll)];
    costheta1(ll)=sqrt((((omega_2(ll)./c_p_fast_cpx(ll).^2)-...
    (omega_2(ll)/c_f.^2))+((omega_2(ll)/c_f.^2)*cos(thetaI).^2))/...
    ./(omega_2(ll)./c_p_fast_cpx(ll).^2));
    % from Steve meeting 9NOV15
    Theta1=[Theta1;costheta1(ll)];
    costheta2(ll)=sqrt((((omega_2(ll)./c_p_slow_cpx(ll).^2)-...
    (omega_2(ll)/c_f.^2))+((omega_2(ll)/c_f.^2)*cos(thetaI).^2))/...
    ./(omega_2(ll)./c_p_slow_cpx(ll).^2));
    % from Steve meeting 9NOV15
    Theta2=[Theta2;costheta2(ll)];

% The Matrix Equations
% PW*CC=AM, where PW is the 4x4 Plane Wave,
% CC is the matrix containing the coefficients A1, A2, C,and R
% we are solving for, and AM is the
PW11=(1+g_1(ll)).*k_1_cpx(ll).*costheta1(ll);
PW21=-((k_1_cpx(ll).^2.*lambda_c_pwr)+...
(2.*mu_x.*k_w(ll).^2.*sin(thetaI).^2)+...
(alpha_str.*M_pwr.*k_1_cpx(ll).^2.*g_1(ll)));
PW31=(alpha_str+g_1(ll)).*M_pwr.*k_1_cpx(ll).^2;
PW41=2.*k_w(ll).*k_1_cpx(ll).*sin(thetaI).*costheta1(ll);
PW12=(1+g_2(ll)).*k_2_cpx(ll).*costheta2(ll);
PW22=-((k_2_cpx(ll).^2.*lambda_c_pwr)+...
(2.*mu_x.*k_w(ll).^2.*sin(thetaI).^2)+...
(alpha_str.*M_pwr.*k_2_cpx(ll).^2.*g_2(ll)));
PW32=(alpha_str+g_2(ll)).*M_pwr.*k_2_cpx(ll).^2;
PW42=2.*k_w(ll).*k_2_cpx(ll).*sin(thetaI).*costheta2(ll);

```

```

PW13=-(1+g_s(ll)).*k_w(ll).*sin(thetaI);
PW23=2.*mu_x.*k_sw_cpx(ll).*k_w(ll).*sin(thetaI).*costhetaS(ll);
PW33=0;
PW43=(k_sw_cpx(ll).^2.*costhetaS(ll).^2)-...
    (k_w(ll).^2.*sin(thetaI).^2);
PW14=k_w(ll).*cos(thetaI);
PW24=omega_2(ll).*rho_f;
PW34=-omega_2(ll).*rho_f;
PW44=0;
PW=[PW11,PW12,PW13,PW14;PW21,PW22,PW23,PW24;...
    PW31,PW32,PW33,PW34;PW41,PW42,PW43,PW44];

I=1;
AM11=I.*k_w(ll).*cos(thetaI);
AM21=-omega_2(ll).*rho_f.*I;
AM31=omega_2(ll).*rho_f.*I;
AM41=0;
AM=[AM11;AM21;AM31;AM41];
CC=PW\AM; % this will find the coefficients A1, A2, C, and R.
A1=CC(1,1); %A1 coefficient
AA1=[AA1;A1];
A2=CC(2,1); %A2 coefficient
AA2=[AA2;A2];
C=CC(3,1); %C coefficient
AC=[AC;C];
R=CC(4,1); %R coefficient
RR=[RR;R];

end
end

% this code was edited to solve for costhetaS/1/2 per discussions with
% Steve on 9NOV. Since the angle thetaS/1/2 is never used by itself.

```

Adapted from Stoll and Kan (1981); Buchanan et al. (2004).

Figure 36. MATLAB Code—Plane Wave Reflection

```

% LCDR Laura-Michel DeHaan
% Assistance from Clyde Scandrett & Steve Baker
% Created: 05 June 2015
% Last Updated: 14 FEB 2019
% Thesis FEM Code
% Calculating the dilatational(compressional/fast and slow) and shear
% wave speeds. From Buchanan et al., Chapter 5, 2004.
%
% Parameters/Functions to define:
% a11, R/d, dimensionless, Buchanan, Chapter 5, page 230
% a12, Q/d, dimensionless, Buchanan, Chapter 5, page 230

```

```

% a22,  $(\lambda + 2\mu)/d$ , dimensionless, Buchanan, Chapter 5, page 230
% b, dissipation function (Pa), Buchanan, Chapter 5, equation 5.11,
% page 222
% B11,  $a_{11}p_{11} - a_{12}p_{12}$ , Buchanan, Chapter 5, page 230
% B12,  $-a_{12}p_{11} + a_{22}p_{12}$ , Buchanan, Chapter 5, page 230
% B21,  $a_{11}p_{12} - a_{12}p_{22}$ , Buchanan, Chapter 5, page 230
% B22,  $-a_{12}p_{12} + a_{22}p_{22}$ , Buchanan, Chapter 5, page 230
% B33,  $p_{11}p_{22} - p_{12}^2/\mu * p_{22}$ , Buchanan, Chapter 5, page 231
% beta1, Porosity, dimensionless parameter
% c_p_fast, wave speed for Dilatational Waves, Type I, Fast, (m/s),
% Buchanan, Chapter 5, page 232
% c_p_slow, wave speed for Dilatational Waves, Type II, Slow, (m/s),
% Buchanan, Chapter 5, page 232
% c_s, wave speed for Shear Waves, (m/s), Buchanan, Chapter 5, page 233
% d, (Pa), Buchanan, Chapter 5, page 230
% D, dissipation function (Pa), Buchanan, Chapter 5, equation 5.15,
% page 225
% eta, Viscosity of fluid, Poiseuille(Pa)  $1\text{PI} = 1\text{Pa}\cdot\text{s} = 1\text{kg/ms}$ 
% F, dimensionless, correction factor function, Stoll, page 14
% F_kappa, dimensionless, F evaluated for kappa, Stoll, page 14
% F_kappa_abs, dimensionless, absolute value of F evaluated for kappa,
% Stoll, page 14
% F_kappa_i, dimensionless, Imaginary part of F evaluated for kappa,
% Stoll, page 14
% F_kappa_r, dimensionless, Real part of F evaluated for kappa,
% Stoll, page 14
% freq1, frequency (Hz)
% gamma_p_fast, Attenuation for Dilatational Wave, Type I, Fast,
% (dB/wavelength), Buchanan, Chapter 5, equation 5.37, page 232
% gamma_p_slow, Attenuation for Dilatational Wave, Type II, Slow,
% (dB/wavelength), Buchanan, Chapter 5, equation 5.37, page 232
% gamma_shear, Attenuation for Shear Wave (dB/wavelength)
% Buchanan, Chapter 5, page 233
% ii, used in for loop
% junk, used in for loop
% K_b, Bulk Modulus (Pa=kg/ms)
% K_bi, Imaginary part of Bulk Modulus of the skeletal frame (Pa)
% K_br, Real part of Bulk Modulus of the skeletal frame (Pa)
% K_f, Bulk Modulus of the pore fluid (Pa)
% k_p_fast, Wave number for Dilatational Wave, Type I, Fast, (1/m)),
% Buchanan, Chapter 5, equation 5.36, page 232
% k_p_slow, Wave number for Dilatational Wave, Type II, Slow, (1/m)
% Buchanan, Chapter 5, equation 5.36, page 232
% k_s, Wave number for Shear Wave (1/m), Buchanan, Chapter 5,
% equation 5.38, page 232
% kappa, dimensionless, Argument of T and F
% kappa_r, dimensionless, real part of argument of T and F
% lambda, Lamé coefficient (Pa), Buchanan, Chapter 5, Equation 5.14,
% page 224
% m, Mass (kg)
% mu_x, Shear Modulus of skeletal frame (Pa)
% mu_i, Imaginary part of Shear Modulus of skeletal frame (Pa)

```

```

% mu_r, Real part of Shear Modulus of skeletal frame (Pa)
% nn, used in for loop
% nu, dimensionless, Buchanan, Chapter 5, page 232
% omega, angular frequency (rads/s)
% omega_2, angular frequency squared (rads^2/s^2)
% p11, pressure of the frame (Pa)
% p12, pressure of the frame-fluid interaction (Pa)
% p22, pressure of the fluid (Pa)
% perma, Permability (m^2)
% Q, (Pa), Buchanan, Chapter 5, page 224
% R, (Pa), Buchanan, Chapter 5, page 224
% rho, Density (kg/m^3)
% rho_11, density of the frame (kg/m^3)
% rho_12, density of the frame-fluid interaction (kg/m^3)
% rho_22, density of the fluid (kg/m^3)
% rho_f, Density of the fluid (kg/m^3)
% rho_r, Density of the grains/sediment (kg/m^3)
% script_a, Pore-size parameter (m)
% tau, Structure factor (Tortousity), dimensionless, using tau
% alpha already in use in the MATLAB toolbox
% T, dimensionless, computing the bessel functions, Stoll, page 14
% tt1, used in for loop
% tt2, used in for loop

% Parameters from Sediment file (loaded at begining of script)
% alpha, Structure factor (Tortousity), dimensionless
% beta1, Porosity, dimensionless parameter
% eta, Viscosity of fluid, Poiseuille(PI) 1PI = 1Pa*s = 1kg/ms
% freq1, frequency (Hz)
% K_bi, Imaginary part of Bulk Modulus of the skeletal frame (Pa)
% K_br, Real part of Bulk Modulus of the skeletal frame (Pa)
% K_f, Bulk Modulus of the pore fluid (Pa)
% K_r, Bulk Modulus of the sediment grains (Pa)
% mu_i, Imaginary part of Shear Modulus of skeletal frame (Pa)
% mu_r, Real part of Shear Modulus of skeletal frame (Pa)
% perma, Permability (m^2)
% rho_f, Density of the fluid (kg/m^3)
% rho_r, Density of the grains/sediment (kg/m^3)
% script_a, Pore-size parameter (m)
% d_grain, Diameter of the grains (m)
%
% NOTE: Negative sign added to attenuation equations due to choice of sign,
% from meeting with Steve Baker on 01JULY15.
% -----
format long

% Chapter_5_Buchanan_Coarse_Sand_Fine_Gravel_Parameters_22JUL17 %load test
% values to get the input values
% Chapter_5_Buchanan_Fine_Sand_Parameters_22JUL17 %load test parameter
% values to get the input values
% Chapter_5_Buchanan_Coarse_Sand_Parameters_22JUL17 %load test parameter
% values to get the input values

```

```

% Sand_Stoll_Test_11NOV15_LOGDEC %load test parameter values to get
% the input values
% COMSOL_Parameters_22JUL17 %load test parameter values to get the
% input values
% this code uses script_a as is, vice taking (1/4)d_grain=script_a,
% from Steve Baker
% freq1 contained in files above

% mu, real and imaginary parts given, need to put back together to solve
% Buchanan, Chapter 5, equations on page 225-231
mu_x=mu_r+(1i*mu_i);

% K_b, real and imaginary parts given, need to put back together to solve
% Buchanan, Chapter 5, equations on page 225-231
K_b=K_br+(1i*K_bi);

omega=freq1*2*pi; % converting from Hz to angular frequency
omega_2=omega.^2; % computing omega squared

% Computing mass, m
m=(tau.*rho_f)./beta1; % Buchanan, Chapter 5, page 225
c_f=sqrt(K_f/rho_f); %Clyde Scandrett addition, consistency of equations

% calculating densities, Buchanan, Chapter 5, page 226
rho_11=(1-beta1).*rho_r-beta1.*(rho_f-m.*beta1);
rho_12=beta1.*(rho_f-m.*beta1);
rho_22=m.*beta1.^2;
rho=(1-beta1)*rho_r+beta1*rho_f; %Clyde Scandrett edit, average density

% Calculating F_kappa using input from Clyde Scandrett on coding
% Bessel functions
kappa=script_a.*sqrt(((omega.*rho_f)./eta));
T=@(qq)-besselj(1,qq*exp(3*1i*pi/4))*exp(3*1i*pi/4)...
    ./besselj(0,qq*exp(3*1i*pi/4));
F=@(qq)(1/4)*qq.*T(qq)./(1-2*T(qq)./(1i*qq));
F_kappa=F(kappa);
F_kappa_r=real(F_kappa);
F_kappa_i=imag(F_kappa);
F_kappa_abs=abs(F_kappa);
kappa_r=real(kappa);

% Calculating b, Buchanan, Chapter 5, Equation 5.11, page 222,
% using kappa in place of psi
b=(F_kappa.*(beta1.^2).*eta)/perma;

% Solving for D, Buchanan, Chapter 5, Equation 5.15, page 225
D=K_r.*(1+(beta1.*((K_r./K_f)-1)));

% Solving for lambda, Buchanan, Chapter 5, Equation 5.14, page 224
lambda=K_b-(((2/3).* mu_x)+((((K_r-K_b).^2)-(2.*beta1.*K_r.*(K_r-K_b))...
    +((beta1.^2).*(K_r.^2)))./(D - K_b));

```

```

% Solving for R, Buchanan, Chapter 5, page 225
R=((beta1.^2).*(K_r.^2))./(D - K_b);

% Solving for Q, Buchanan, Chapter 5, page 225
Q=(beta1.*K_r.*((1-beta1).*K_r)-K_b))./(D - K_b);

% Solving for d, Buchanan, Chapter 5, page 230
d=(R.*(lambda+(2.*mu_x)))-(Q.^2);

% Solving for p11, p12, and p22, Buchanan, Chapter 5,
% equation 5.25, page 229
p11=(omega_2.*rho_11)-(1i.*omega.*b);
p12=(omega_2.*rho_12)+(1i.*omega.*b);
p22=(omega_2.*rho_22)-(1i.*omega.*b);

% solving for a11, a12, and a22, Buchanan, Chapter 5, page 230
a11=R./d;
a12=Q./d;
a22=(lambda+(2.*mu_x))./d;

% Solving for B11, B12, B21, and B22, Buchanan, Chapter 5, page 230
B11=(a11.*p11)-(a12.*p12);
B12=(-a12.*p11)+(a22.*p12);
B21=(a11.*p12)-(a12.*p22);
B22=(-a12.*p12)+(a22.*p22);
B33=(p11./mu_x)-((p12.^2)./(p22.*mu_x));

% Solving for the compressional wave speeds (m/s) and
% attenuation coefficients (dB/m)
% Fast Wave (Type I), positive sign in square root of Buchanan,
% Chapter 5, equation 5.36, page 232
% Slow Wave (Type II), negative sign in square root of Buchanan,
% Chapter 5, equation 5.36, page 232
tt1=sqrt((B11+B22+(sqrt(((B11-B22).^2)+(4.*B12.*B21)))))./2);
tt2=sqrt((B11+B22-(sqrt(((B11-B22).^2)+(4.*B12.*B21)))))./2);
[junk,nn]=size(freq1);
for ii=1:nn
    if real(tt1(ii)) < real(tt2(ii)), k_p_fast(ii)=tt1(ii);...
        k_p_slow(ii)=tt2(ii);
    else k_p_fast(ii)=tt2(ii); k_p_slow(ii)=tt1(ii);
    end
end

% Solving for c_p_fast (m/s), Buchanan, Chapter 5, equation 5.37, page 232
c_p_fast=omega./(abs(real(k_p_fast)));
c_p_fast_cpx=omega./k_p_fast; % complex values for use in Plane Wave
% Reflection computations

% Solving for c_p_slow (m/s), Buchanan, Chapter 5, equation 5.37, page 232
c_p_slow=omega./(abs(real(k_p_slow)));
c_p_slow_cpx=omega./k_p_slow; % complex values for use in Plane Wave
% Reflection computations

```

```

% Defining nu
nu=log(10)./(40.*pi);

% Solving for gamma_p_fast (dB/wavelength), Buchanan, Chapter 5,
% equation 5.37, page 232
gamma_p_fast=- (imag(k_p_fast))./(nu.*(real(k_p_fast)));

% Solving for gamma_p_slow (dB/wavelength), Buchanan, Chapter 5,
% equation 5.37, page 232
gamma_p_slow=- (imag(k_p_slow))./(nu.*(real(k_p_slow)));

% Solving for the shear wave speeds (m/s) and
% attenuation coefficients (dB/m), Buchanan, Chapter 5,
% equation 5.38, page 232
k_s=sqrt(B33);

% Solving for c_s (m/s)
c_s=omega./(abs(real(k_s)));
c_s_cpx=omega./k_s; % complex values for use in Plane Wave
% Reflection computations

% Solving for gamma_s (dB/wavelength), Buchanan, Chapter 5,
% page 233
gamma_shear=- (imag(k_s))./(nu .* (real(k_s)));

% Run Chapter_5_Buchanan_Plots file to make plots

```

Adapted from Stoll and Kan (1981); Buchanan et al. (2004).

Figure 37. MATLAB Code—Wave Speed and Attenuation

```

% Coarse Sand
% LCDR Laura-Michel DeHaan
% 05 June 2015
% Thesis
% Parameter Values for testing of Chapter_5_Buchanan_Parameters_19JUNE15.m
% Test Parameter Values from Buchanan, Ch 5, Table 5.2, pages 226-7 & 233
% Last edited: 22 JULY 2017
%
% Parameters to input into Chapter_5_Buchanan_Wave_Speed_and_Attenuation...
% _11NOV15.m:
% tau, Structure factor (Tortuosity), dimensionless parameter; using tau
% (alpha is already in use in the MATLAB toolbox)
% beta1, Porosity, dimensionless parameter
% d_grain, Diameter of the grains, m
% eta, Viscosity of pore fluid, Poiseuille(PI) 1PI = 1Pa*s = 1kg/ms
% freq1, Frequency, in Hz
% K_bi, Imaginary part of Bulk Modulus of the skeletal frame, in Pa=kg/ms

```

```

% K_br, Real part of Bulk Modulus of the skeletal frame, in Pa=kg/ms
% K_f, Bulk Modulus of the pore fluid, in Pa=kg/ms
% K_r, Bulk Modulus of the sediment grains, in Pa=kg/ms
% mu_i, Imaginary part of Shear Modulus of skeletal frame, in Pa=kg/ms
% mu_r, Real part of Shear Modulus of skeletal frame, in Pa=kg/ms
% perma, Permeability
% rho_f, Density of the fluid, kg/m^3
% rho_r, Density of the grains (sediment), kg/m^3
% script_a, Pore-size parameter, m
%-----
tau = 1.25; % Structure factor (Tortousity), dimensionless parameter
beta1 = 0.38; % Porosity, dimensionless parameter
d_grain = 62.8e-6; % Diameter of the grains, m
eta = 1.01e-3; % Viscosity of pore fluid, Poiseuille(PI) 1PI=1Pa*s=1kg/ms
freq1=[10 100 1000 10000]; %to match COMSOL plots
K_bi = 7.4e5; % Bulk modulus of skeletal frame, imaginary, in Pa=kg/ms
K_br = 5.3e7; % Bulk modulus of skeletal frame, real, in Pa=kg/ms
K_f = 2.4e9; % Bulk modulus of pore fluid, in Pa=kg/ms
K_r = 5.6e10; % Bulk Modulus of grains, in Pa=kg/ms
mu_i = 4.7e6; % Shear modulus of skeletal frame, imaginary, in Pa=kg/ms
mu_r = 7.4e7; % Shear modulus of skeletal frame, real, in Pa=kg/ms
perma = 7.5e-11; % Permeability, m^2
rho_f = 1000; % Density of pore fluid, kg/m^3
rho_r = 2710; % Density of grains, kg/m^3
script_a = 6.28e-5; % Pore-size parameter,m
sed='CS'; %added for labeling of plots

```

Adapted from Stoll and Kan (1981); Buchanan et al. (2004).

Figure 38. MATLAB Code—Coarse Sand Parameters

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