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Seismic velocities contain information about depth, lithology, fluid content, and microstructure

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SEISMIC VELOCITIES CONTAIN INFORMATION ABOUT DEPTH, LITHOLOGY, FLUID CONTENT, AND MICROSTRUCTURE

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Abstract

Recent advances in field and laboratory methods for measuring elastic wave velocities provide incentive and opportunity for improving interpretation of geophysical data for engineering and environmental applications. Advancing the state-of-the-art of seismic imaging requires developing petrophysical relationships between measured velocities and the hydrogeology parameters and lithology. Our approach uses laboratory data and rock physics methods. Compressional (Vp) and shear (Vs) wave velocities, Vp/Vs ratios, and relative wave amplitudes show systematic changes related to composition, saturation, applied stress (analogous to depth), and distribution of clay for laboratory ultrasonic measurements on soils. The artificial soils were mixtures of Ottawa sand and a second phase, either Wyoming bentonite or peat moss used to represent clay or organic components found in natural soils. Compressional and shear wave velocities were measured for dry, saturated, and partially-saturated conditions, for applied stresses between about 7 and 100 kPa, representing approximately the top 5 m of the subsurface. Analysis of the results using rock physics methods shows the link between microstructure and wave propagation, and implications for future advances in seismic data interpretation. For example, we found that Vp in dry sand-clay mixtures initially increases as clay cements the sand grains and fills porosity, but then Vp decreases when the clay content is high enough that the clay matrix controls the elastic response of the material. Vs decreases monotonically with increasing clay content. This provides a method for using Vp/Vs ratios to estimate clay content in a dry soil.

Introduction

Recent advances in methods for recording seismic surveys (e.g., Bachrach et al., 1998; Baker et al., 1999; Carr et al., 1998; Steeples et al., 1999) have provided ways to image shallow structure in highly attenuating soils and near-surface rock. Generally the data in the literature have been interpreted for first-order structural features such as using surface wave methods to find subsurface cavities, using reflection techniques to find the water table or faults, and using refraction techniques to find variations in lithology that manifest as variations in velocity structure. New laboratory measurements of ultrasonic velocities in soils at low pressures (e.g., Bonner et al., 2001; Zimmer et al., 2001) point the way for developing next-generation interpretation methods (e.g., Bertete-Aguirre and Berge, 2001; Bertete-Aguirre et al., 2002) that may allow seismologists to obtain more information from their data in the future.

Such new interpretation methods require finding relationships between measured geophysical properties and parameters of interest, including porosity, saturation, fluid and clay distribution, lithology, and depth. In this paper we apply rock physics theories to laboratory data for soils to investigate the connections between compressional (P) and shear (S) wave velocities and lithology, fluid content, and microstructure.

Methods

Laboratory Data

In this paper, we use compressional-wave velocity (Vp) and shear-wave velocity (Vs) data for artificial soils at low pressures. The data (**Figure 1, Figure 2, Figure 3, and Figure 4**) were collected using a recently-developed technique (Bonner et al., 1999a) for uniaxial measurements of ultrasonic velocities for dry, saturated, and partially-saturated soils at pressures below approximately 0.1 MPa (Trombino, 1998, Aracne-Ruddle et al., 1999; Berge et al., 1999; Bonner et al., 1999b, 2001, Zimmer et al., 2001). The laboratory measurements were made at pressures between 0 and about 0.1 MPa (about 16 psi) in pressure increments of about 0.01 MPa (about 1.5 psi), and represent the top few meters of the subsurface. The soil samples were made by combining various amounts of Ottawa sand and a second phase, Wyoming bentonite (a Na montmorillonite) or peat moss, to represent silty sands and sandy soils with organic components. Accuracy for velocity measurements was limited to 20% at the lowest stresses near 7 kPa, but improved with signal amplitude to about 3% for Vp and 10% for Vs at higher stresses. Precision in timing the arrivals was about 1% for P and 2 to 5% for S arrivals in most cases. Sample construction and laboratory measurement techniques are described in detail in Trombino (1998) and Aracne-Ruddle et al. (1999).

Rock Physics Models

Effective medium theories (e.g., see Berryman, 1995 for a review) can be used to estimate the elastic properties of a composite material from the known properties of component grains and fluids. Such theories as the self-consistent (SC) effective medium theory (Berryman, 1980) and the differential effective medium (DEM) theory (e.g., Berge et al., 1992) make explicit use of the elastic constants and relative volumes of the component solids and fluids. They also contain implicit assumptions about microstructure that must be compatible with the material being modeled (Berge et al., 1993). For our purposes, the key microstructure assumption in the DEM theory is that a composite is made up of a solid host material containing isolated inclusions. The SC theory does not assign a host, but instead treats all solids and fluids equivalently, and may be more appropriate for unconsolidated materials. Neither theory explicitly incorporates effects of cementation between grains. These theories also do not include pressure effects explicitly. See Berryman (1995) for the DEM and SC mathematical expressions that provide the estimated Vp and Vs values for the composite material, given the velocities and densities of the component solids and fluids.

Solid-fluid mixtures can be modeled as linear poroelastic media described by the Biot-Gassmann relations (Gassmann, 1951; Biot, 1956; see Berryman, 1995 for a review). The material is assumed to have finite permeability and to be microhomogeneous. Properties of a saturated or partially-saturated material can be estimated from the properties of the dry, porous material using Gassmann's formulas. Note that these are static results and may not apply to data collected at ultrasonic frequencies. If the material is partially-saturated and pores do not all contain the same relative mixture of liquid and gas, the material has patchy saturation (e.g., Endres and Knight, 1989) and Gassmann's relations apply locally but not globally. The Gassmann formulas can be applied to each region and the results are averaged over the material, for the patchy saturation model. Berryman et al. (2000, 2002) have developed a new method for plotting functions of Vp and Vs to determine if a material behaves as a

Gassmann material with homogeneous saturation or if it follows the patchy saturation model. This method does not require density or saturation information, only velocities.

Results

Pressure Effects

In **Figure 1** we see the effects of pressure on Vp for dry sand and sand-clay samples. Most empirical fits to data for unconsolidated materials at low pressures find that Vp varies with depth or applied pressure raised to the 1/6 or 1/3 power (e.g., Brandt, 1955; Zimmer et al., 2001). We find an intermediate value, about 0.22, in our power-law fit to Vp vs. pressure for a loosely-packed Ottawa sand sample (**Figure 1a**). Nonlinearity depends on the details of grain arrangement. Small movements and rotations increase the velocity by increasing the coordination number (number of contacts per grain). Note that efficient packing reduces or removes the nonlinearity. The packing effects are most important at pressures up to about 6-8 psi (about the top 2 m of the subsurface), and much less significant at pressures near 16 psi (about 5 m depth). This has important implications for receiver locations for shallow seismic field experiments. Also note that refraction experiments using hammer sources may have packing effects after several blows change the shallow structure just below the source plate.

The effect of clay on the load dependence of Vp can be seen in sand-clay data from Toffelmier et al. (2001), in **Figure 1b**. The Ottawa sand sample has a gradient, and the sample containing about 1% clay (a Ca montmorillonite from Texas) has a small gradient at the lowest pressures. (These samples were dry but the clay was equilibrated with 100% humidity air, causing some swelling.) Further addition of clay produces samples with no significant gradient. Clay acts to cement the sand, increasing Vp while reducing nonlinearity. In field seismic data, a lack of velocity increase with depth in the shallow subsurface could be a useful indicator of clay in unconsolidated sands.

Compositional Effects

Velocities for dry sand-peat mixtures are shown in **Figure 2a and Figure 2b**. Since pressure gradients in the shallow subsurface are about 1 psi per foot, these lab measurements are compared to field seismic velocity data (Crouse et al., 1993; Taylor and Wilson, 1997) for about the top 5 m in peat. Vp and Vs both increase with pressure (depth) because grain-grain contacts improve. (Porosity decrease with pressure is negligible at these low pressures.) Vs decreases with increasing clay content mainly due to density effects as soft peat replaces air in pore spaces. Vp behaves in a more complicated manner as peat fills some pores and behaves as a soft cement, eventually filling all pore space and then finally replaces and separates quartz grains. Theoretical models (**Figure 2c**) must use compatible microstructural assumptions.

To model the sand-peat mixtures, we assume the material is made up of agglomerated spheres with the properties of pure sand and pure peat. These end-member materials account for the porosity implicitly. Using quartz and peat minerals as the end-member materials (e.g., Berge et al., 1999) would not achieve useful results because the behavior of unconsolidated materials at low pressures is controlled by grain contacts and these are not explicitly accounted for, in the effective medium theories. By using unconsolidated sand and peat as the end-member materials we can implicitly include some of these effects in our modeling.

The DEM theory is inappropriate for the sand-peat mixtures except at very low inclusion concentrations, and we will not apply it here. The SC theory can provide useful estimates for Vs at very low concentrations of peat (below 30%) and at very high concentrations (approaching 100%). It is less successful for intermediate values, because it does not include the influence of grain-grain contacts in the sample having a continuous network of sand grains and all pores filled with peat. Similarly, the SC theory provides reasonable Vp estimates at low and very high peat concentrations, but cannot predict Vp for samples having peat concentrations of about 60 to 70% because it ignores grain-grain contact effects. To separate pressure effects from compositional effects, we examine velocities for sand-clay samples for the highest pressures only, near 16 psi (about 0.1 MPa), where packing effects are less significant (**Figure 3a**). We see that Vs decreases monotonically with increasing clay content, whereas Vp follows the same pattern as seen in the sand-peat samples. Clearly, Vp/Vs ratio could be an important discriminator for clay content in silty sands in the shallow subsurface.

Since we do not have reliable properties for an end-member "pure clay" material, we approximate that material by letting the shear modulus drop to about 2 orders of magnitude lower than the modulus for the sand, and drop the bulk modulus by a factor of 4. These assumptions allow us to qualitatively examine effective medium theory predictions for velocities in sand-clay mixtures. The DEM theory assumes the material is a sand pack containing isolated spheres of porous clay (**Figure 3b**). It provides excellent estimates of Vs, implying that this is a reasonable model of the true microstructure for shear properties. The Vp estimates are not as useful, again because the DEM theory cannot account for grain-grain contacts that stiffen the sand-clay mixture at intermediate clay concentrations. An empirical fit of a second-order polynomial yields a relationship for Vp as a function of clay content.

Fluid Effects

We examine effects of partial saturation and fluid distribution for velocities in unconsolidated materials, in **Figure 4**. Our Ottawa sand sample with uniaxial stress of about 0.04 MPa (6 psi) has homogeneous saturation (**Figure 4a**) and shows typical Gassmann (1951) behavior. Vs decreases slightly as density increases with saturation. Vp remains almost constant until full saturation, where it increases dramatically. Similar behavior is seen for Ottawa sand at about 10 MPa (**Figure 4b**), from the classic paper by Domenico (1977). There may be some patchy saturation at saturation levels above 90%, for that sample, due to difficulties in achieving full saturation using the flow technique. In contrast, patchy saturation effects (i.e., linear increase of Vp with saturation) can be seen in data for Domenico's glass-bead samples (**Figure 4c**) at high pressure, while homogeneous saturation and Gassmann behavior are seen for his glass-bead samples saturated using imbibition (**Figure 4d**).

In field examples we would have Vp and Vs available but we would not have saturation information available. It is still possible to find evidence of homogeneous or patchy saturation behavior, by plotting functions of Vp and Vs using the new method of Berryman et al. (2000, 2002). We plot the ratio of the Lamé parameters λ and μ vs. the ratio of the density and μ, which is simply $(Vp/Vs)^2 - 2$ vs. $(1/Vs)^2$. The density varies systematically with saturation and the shear modulus varies slowly (if at all) with saturation. Thus, the ρ/μ ratio is a good indicator of saturation. The effects of fluids on the elastic behavior should be indicated mainly by the λ parameter, which is scaled by μ in the plot. The λ plots for the materials of **Figure 4** are shown in **Figure 5**.

We see that the homogeneous saturation for our Ottawa sand at low pressures is shown clearly by the behavior in **Figure 5a**, and the effects of homogeneous vs. patchy saturation can be seen in **Figure 5c** by comparing the flow and imbibition data. The tendency for departure from homogeneous saturation behavior for the high-pressure Ottawa sand samples with saturation above 90% is seen in **Figure 5b**. These results show that it is likely we could use Vp and Vs values from shallow seismic data sets to obtain information about the amount and distribution of fluids in shallow soils.

Discussion and Conclusions

These new laboratory velocity measurements for unconsolidated soils at low stresses confirm recent field observations of extremely low seismic velocities of a few hundred m/s in shallow soils (e.g., Bachrach et al., 1998; Carr et al., 1998; Steeples et al., 1999). We note that some of the Vp values measured in the laboratory are extremely low, below the speed of sound in air. Field seismic studies also have observed very low Vp values, e.g. 130 m/s in the upper few cm of soil and 180 m/s in the next few tens of cm (Baker et al., 1999) and 150 to 170 m/s in the top m (Bachrach et al., 1998). Such low Vp values are consistent with effective medium theories since an unconsolidated porous material can have an effective bulk modulus that is much closer to the bulk modulus of the component fluid than the bulk modulus of a mineral component, while having a density that is not much lower than the mineral density. This correspondence between state-of-the-art laboratory and field velocity values gives us confidence that laboratory measurements can be used to understand field results.

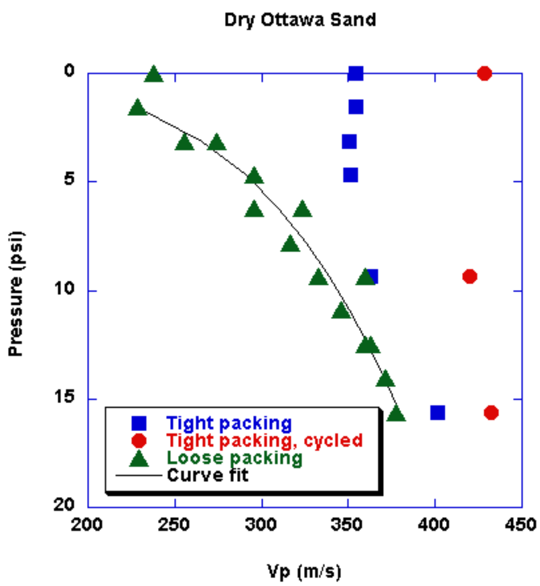
In addition we know that the laboratory velocities for sand samples, collected at frequencies of about 100 kHz, behave as predicted by Gassmann's static result, and thus laboratory ultrasonic results can be used as analogues for seismic frequencies in the field.

Shallow sands have very steep gradients for Vp, particularly for pressures equivalent to the top 2 to 3 m. This has important implications for processing seismic field data using ray-tracing codes. Packing effects could cause problems in shallow surveys using hammer sources because properties below the plate could change after repeated blows. The presence of clay reduces the nonlinearity, and this may be apparent in seismic field data.

For sandy soils containing relatively low concentrations of clays or organic materials (i.e., below about 20% clay or peat), effective medium theories such as the DEM and SC can be used to estimate Vp and Vs and clay or organic content. But for higher concentrations of clay or peat, these theories will not produce high enough velocities, particularly for Vp, because they ignore grain-grain contact effects. Future work will investigate how grain contact theories and cementation theories may be applied to these unconsolidated materials.

If both Vp and Vs are available they can be used to make λ plots that provide information about saturation and whether fluid distribution is homogeneous or patchy. This technique could be applied to investigate fluid distribution in the vadose zone.

Figures



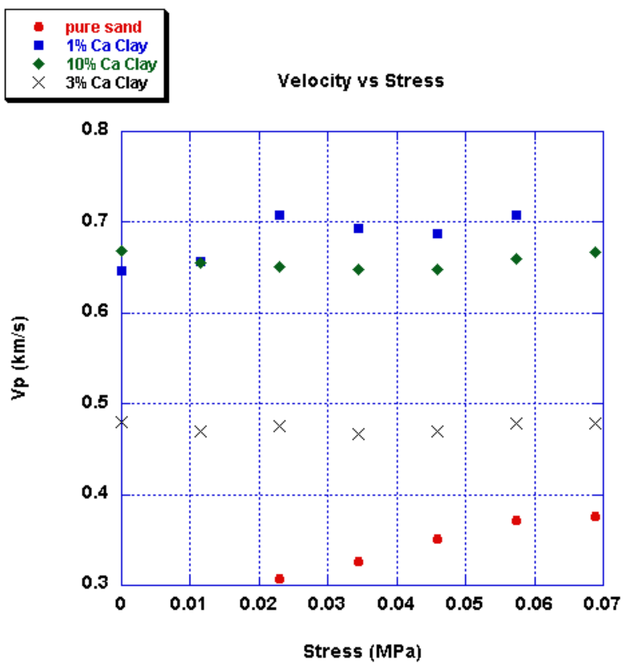
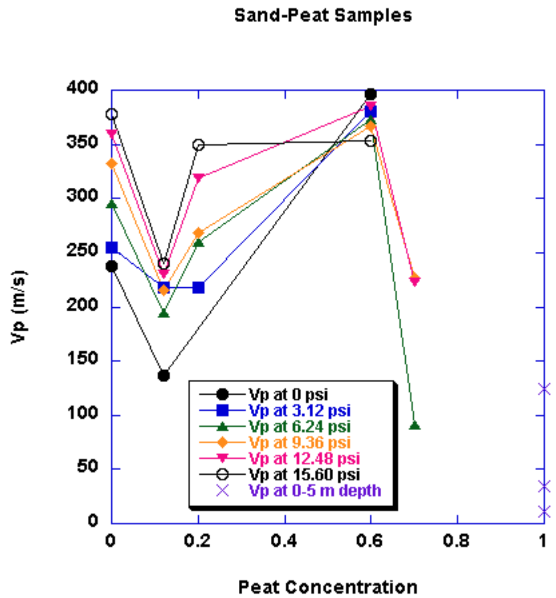
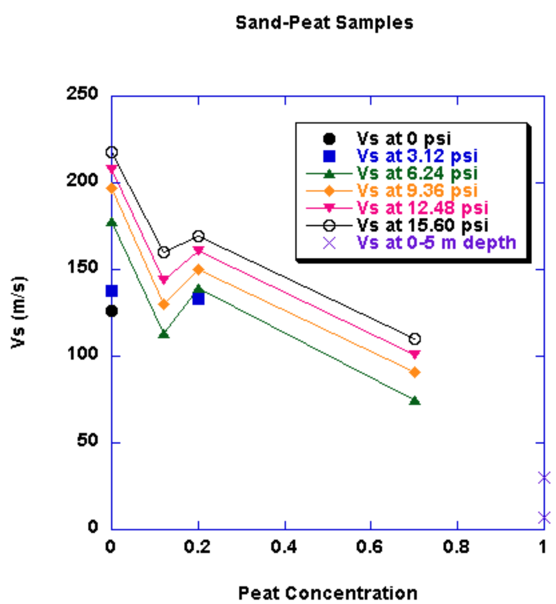


Figure 1a and Figure 1b – Pressure effects on Vp. (a) Effects of sample packing on Vp for pure Ottawa sand samples from Aracne-Ruddle et al. (1999) and Bonner et al. (1999b, 2001). (b) Ottawa sand and Texas swelling clay samples from Toffelmier et al. (2001).


Sand-Peat Samples
Vp (m/s)
Peat Concentration
0
50
100
150
200
250
300
350
400
0
0.2
0.4
0.6
0.8
1
Vp at 0 psi
Vp at 3.12 psi
Vp at 6.24 psi
Vp at 9.36 psi
Vp at 12.48 psi
Vp at 15.60 psi
Vp at 0-5 m depth


Sand-Peat Samples
Vs (m/s)
Peat Concentration
0
50
100
150
200
250
0
0.2
0.4
0.6
0.8
1
Vs at 0 psi
Vs at 3.12 psi
Vs at 6.24 psi
Vs at 9.36 psi
Vs at 12.48 psi
Vs at 15.60 psi
Vs at 0-5 m depth

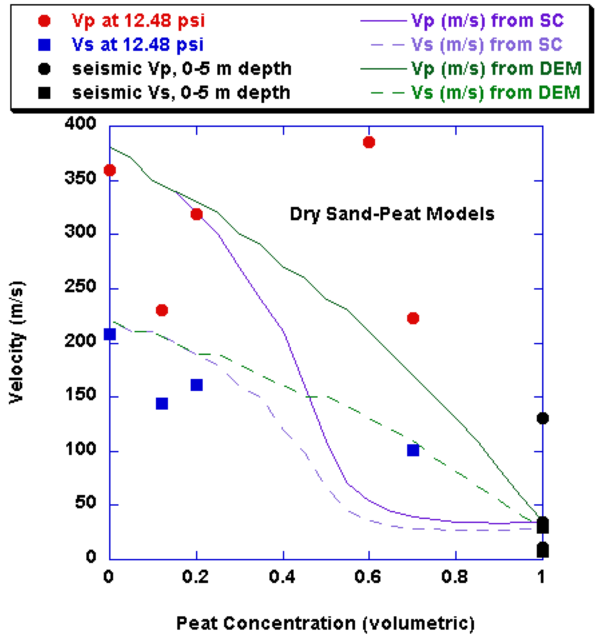
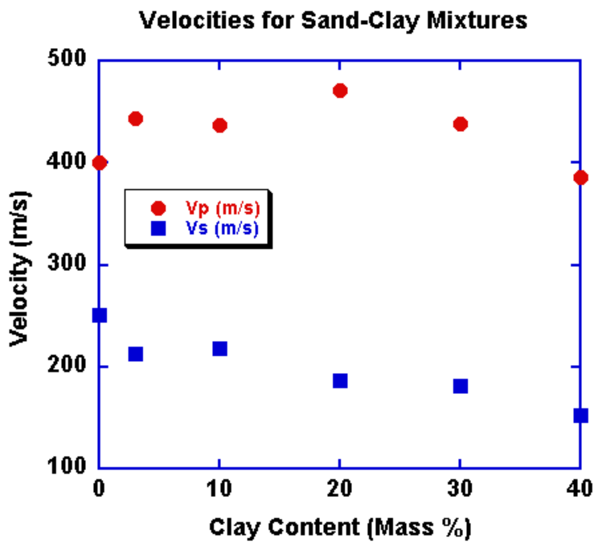


Figure 2a, Figure 2b, and Figure 2c – Velocity vs. peat content and pressure, for sand-peat mixtures. The lab measurements for (a) Vp and (b) Vs from Trombino (1998) and Berge et al. (1999) can be compared to field seismic velocity data for about the top 5 m (e.g., Crouse et al., 1993; Taylor and Wilson, 1997, shown by purple x symbols) and to (c) theoretical models.



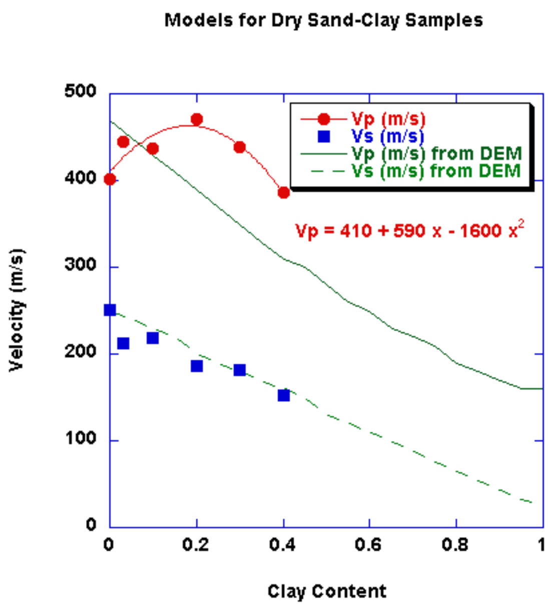
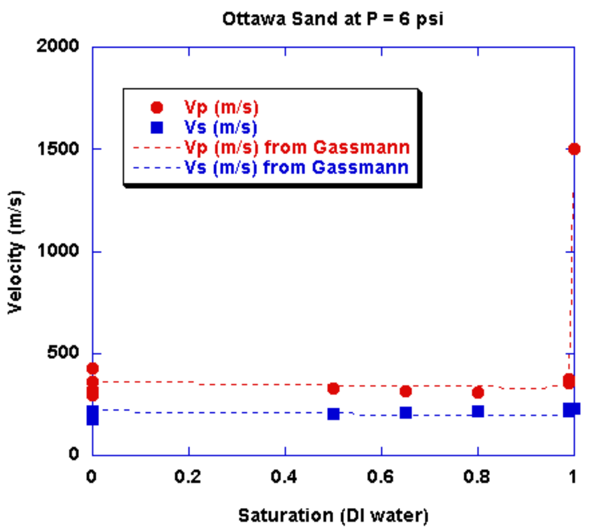
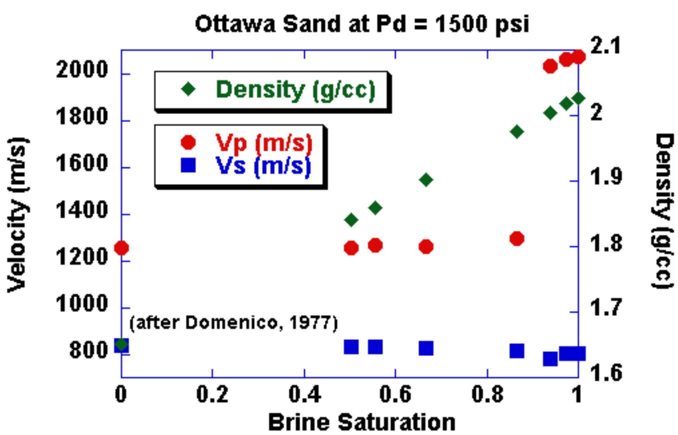
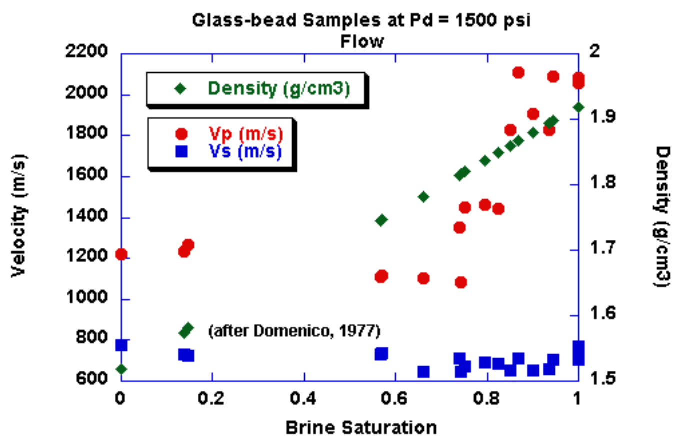


Figure 3a and Figure 3b – Velocity vs. clay content and pressure, for sand-clay mixtures. (a) Lab measurements from Aracne-Ruddle et al. (1999) and Bonner et al. (1999b, 2001). (b) Velocity modeling results compared to lab data.


Ottawa Sand at P = 6 psi
2000
1500
1000
500
0
Velocity (m/s)
Vp (m/s)
Vs (m/s)
Vp (m/s) from Gassmann
Vs (m/s) from Gassmann
0
0.2
0.4
0.6
0.8
1
Saturation (DI water)


Ottawa Sand at Pd = 1500 psi
2000
1800
1600
1400
1200
1000
800
Velocity (m/s)
Density (g/cc)
Vp (m/s)
Vs (m/s)
(after Domenico, 1977)
2.1
2
1.9
1.8
1.7
1.6
Density (g/cc)
0
0.2
0.4
0.6
0.8
1
Brine Saturation



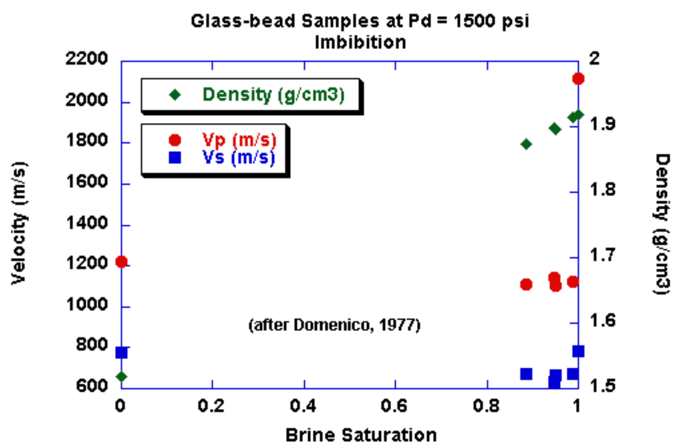


Figure 4a, Figure 4b, Figure 4c, and Figure 4d – Effects of partial saturation and fluid distribution for unconsolidated samples. Velocities for Ottawa sand with (a) data from Bonner et al. (2001) for uniaxial stress of about 0.04 MPa (6 psi) and (b) data from Domenico for 10 MPa. Velocities for Domenico's glass-bead samples at 10 MPa for (c) samples saturated using flow technique and (b) samples saturated using imbibition technique.

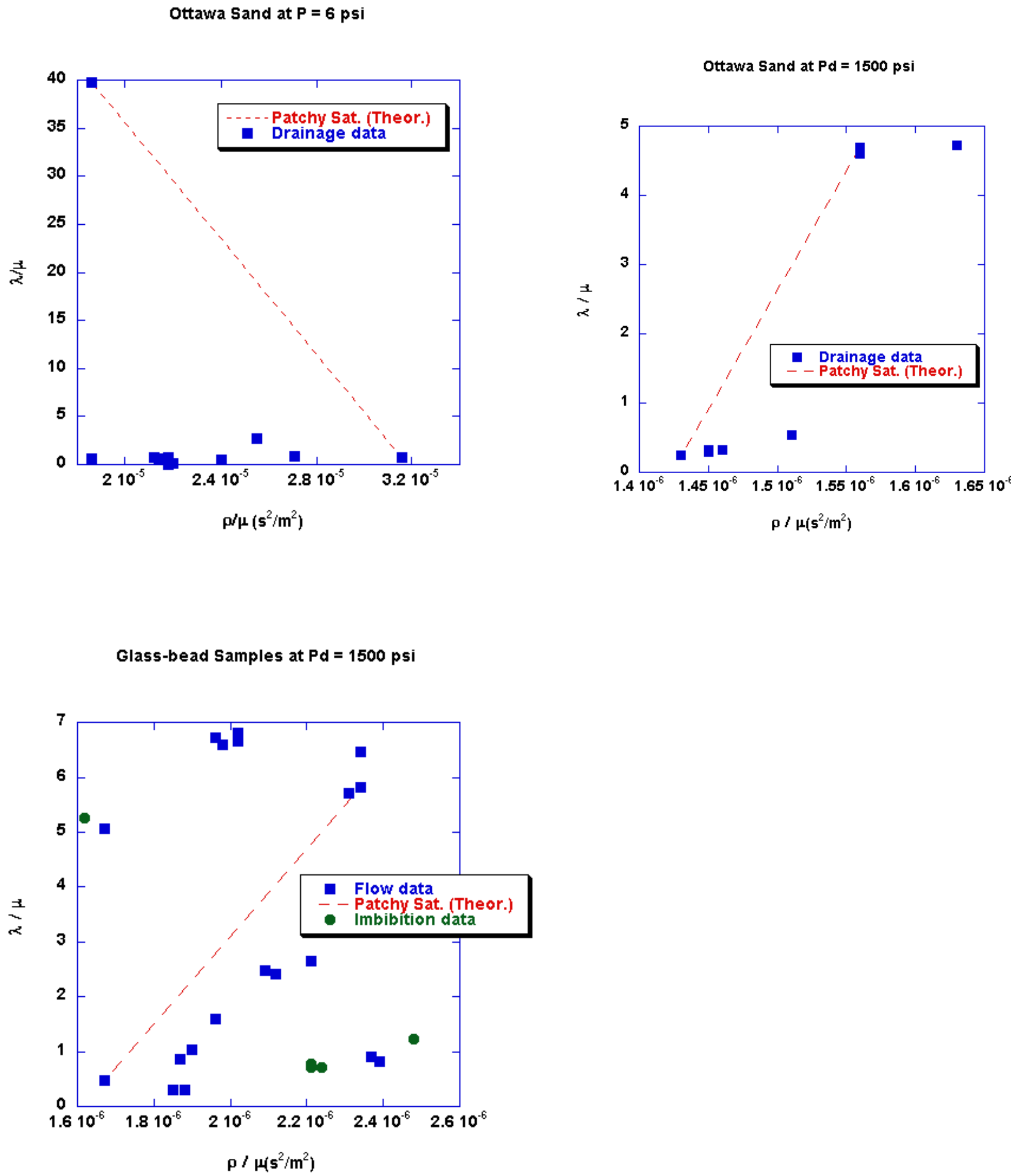


Figure 5a, Figure 5b, and Figure 5c – Fluid distribution effects on velocities. Recently developed methods (Berryman et al., 2000; 2002) for analyzing velocity data for partially-saturated materials have been applied to the Ottawa sand samples at (a) low and (b) high pressures and the glass-bead data (c).

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