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THE COMPRESSIONAL TO SHEAR-WAVE VELOCITY RATIO FOR SURFACE SOILS AND SHALLOW SEDIMENTS

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ABSTRACT

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The compressional to shear-wave velocity ratio, or velocity ratio (V_P/V_S), is an effective parameter in describing various physical parameters and lithological attributes of porous media, as well as the nature and kind of saturant filling the pores. In this study, V_P/V_S was obtained for surface soils and glacially originated shallow sediments (northern Germany), using in-situ seismic refraction measurements. For the whole column of the soils and sediments investigated, V_P/V_S lies in a general range of 1.28-3.19, with an average value of 2.42. The V_P/V_S shows considerable variations for the direct waves propagating through the surface soils saturated with air, and for the waves refracted from the underlying sediments that are partially or totally saturated with water. The V_P/V_S-value of 2 is remarkable in discriminating between the surface soils and the partially saturated sediments, and the V_P/V_S-value of 2.5 is remarkable in discriminating between the partially and totally saturated sediments. The heterogeneity of the soils and sediments, vertically and laterally, and the variations in porosity, mineralogical composition, grain size, degree of saturation and kind of saturant (air or water) are primary factors responsible for the V_P/V_S-variations. Direct relationships between V_P/V_S, on the one hand, and the compressional wave velocity and the shear wave velocity, on the other, and an inverse relationship between V_P/V_S and porosity, were obtained with coefficients of correlation ranging from 0.87 to 0.92.

KEY WORDS: compressional to shear-wave velocity ratio, seismic refraction measurements, surface soils and shallow sediments, porosity, lithology, air and water saturations.

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INTRODUCTION

The compressional to shear-wave velocity ratio, or simply velocity ratio (V_P/V_S), is an important parameter in interpreting field and laboratory seismic and sonic measurements, and in understanding the propagation's mechanism of the compressional (P) and shear (S) seismic waves through porous media. The V_P/V_S has been widely and effectively used in investigating site engineering, sea-floor sediments, and groundwater- and hydrocarbon-bearing formations. For these purposes, V_P/V_S has proved to be effective in providing good evaluation and modelling of lithological properties and petrophysical parameters of sediments and rocks. The variations of V_P/V_S with porosity, lithology, mineralogy, consolidation and fluid saturation are attributed to variations of the elastic moduli that govern the P- and S-waves' propagation.

Any relative variations between any two elastic moduli can be related to variations in V_P/V_S. The presence of clays or the increase of clay content, and the increase of water saturation tend to increase the value of V_P/V_S for porous media.

Mavko and Mukerji (1998) pointed out that V_P/V_S is a key parameter in lithology determination. For different lithologies, Pickett (1960, 1963) obtained the following V_P/V_S-ranges: 1.65-1.75 for sandstones, 1.75-1.85 for dolomites, and 1.85-1.95 for limestones. Benzing (1978) and Benzing et al. (1983) used V_P/V_S to indicate variations in lithology and porosity, and concluded that the presence of mud or shale in carbonates and sandstones causes an increase in V_P/V_S. For sea-floor muds, Hamilton (1979) obtained extremely high V_P/V_S-values, ranging from 13 to 46. For heterogeneous consolidated formations, Salem (1993) observed that the zones enriched with shales (clays) exhibit greater values of V_P/V_S than the zones of lesser amounts of shales or the zones that are composed of other kinds of lithology, such as sandstones, carbonates or conglomerates.

The V_P/V_S has also been successfully used in identifying the kind of fluid saturating porous media (Gardner and Harris, 1968; Gregory, 1976, 1977; Domenico, 1976, 1977; Tatham and Stoffa, 1976; Tatham, 1982; Salem, 1993; Mavko and Mukerji, 1998). For example, Gardner and Harris (1968) obtained V_P/V_S-values of < 2 for unconsolidated sediments saturated with gas or air, and values of > 2 for unconsolidated sediments saturated with oil or water. Gregory (1977) obtained V_P/V_S-values of around 1.5 for gas-saturated sandstone, a range of 1.62-2.02 for oil-saturated sandstone, and a range of 1.63-2.18 for brine-saturated sandstone. Tatham (1982) also obtained a value of 1.5 for gas-saturated sediments. Salem (1993) obtained V_P/V_S-values ranging from 1.78 to 2.4, corresponding to highly heterogeneous shaly sandstone reservoirs saturated with multi-phase fluids (oil, gas and brine). Salem (1993) observed that V_P/V_S is lower for the gas-saturated formations than that for the oil- or brine-saturated formations. The V_P/V_S-variations with the kind of saturant are due to variations in the saturant's nature (being compressible or incompressible) and density.

Researchers have also investigated the influence of water saturation and clay content on V_P/V_S for sediments and rocks, and showed that V_P/V_S is an increasing function of both influences (Eastwood and Castagna, 1983; Robertson, 1983; Stuempel et al., 1984; Meissner et al., 1985; Han et al., 1986; Zimmerman and King, 1986). For example, Eastwood and Castagna (1983) used binary and ternary mixtures of quartz, clay and water, and showed that V_P/V_S is highly sensitive to, and variable with water saturation and lithology. Eastwood and Castagna (1983) obtained a V_P/V_S-value of 1.8 for quartz-rich rocks, and values of > 5 for loose, water-saturated sediments. Stuempel et al. (1984) and Meissner et al. (1985) obtained V_P/V_S-values of up to 9, corresponding to water-saturated sediments having clays.

The V_P/V_S has also been used to indicate the shape and size of grains composing porous media. Castagna et al. (1985) obtained a V_P/V_S-value of 1.45 for quartz spheres, suggesting that the velocity ratio decreases with increasing the degree of sphericity of grains (or increases with increasing the degree of angularity of grains). Tatham (1985) pointed out that silts, with similar grain shapes as sands, exhibit greater values of V_P/V_S than sands, even though both silts and sands have the same porosity.

V_P/V_S AND OTHER PARAMETERS

The velocity ratio has a strong dependence on several parameters that influence the propagation of seismic waves or acoustic signals in porous media. These parameters include length and frequency of the waves and signals, elastic moduli and the Poisson's ratio.

The V_P/V_S can be expressed in terms of wavelength of the compressional wave (λ_P) and that of the shear wave (λ_S), along with frequency of the compressional wave (f_P) and that of the shear wave (f_S):

$$V_P/V_S = (\lambda_P/\lambda_S)/(f_S/f_P) \quad . \tag{1}$$

The velocity ratio can also be expressed in terms of the bulk modulus (K) and shear modulus (μ) or their ratio (K/μ):

$$V_P/V_S = [\{K + (4\mu/3)\}/\mu]^{1/2} \quad , \tag{2}$$

leads to:

$$(V_P/V_S)^2 = (K/\mu) + (4/3) \quad . \tag{3}$$

The velocity ratio can also be related to the Poisson's ratio (σ), which is defined as the ratio of the transverse strain or contraction to the longitudinal strain or extension, resulting from a change in normal stress under compression or dilatation. The σ can be expressed in terms of the bulk and shear moduli (Eq. 4), which can be used to obtain the velocity ratio (Eq. 5):

$$\sigma = (3K - 2\mu)/(6K - 2\mu) \ , \qquad (4)$$

and

$$V_P/V_S = [2(1 - \sigma)/(1 - 2\sigma)]^{1/2} \ . \qquad (5)$$

STUDY AREA

The study area is located in Schleswig-Holstein, northern Germany. The sediments of the area, similar to other glacial deposits in northern Europe, were glacially originated during Pleistocene (Einsele and Schulz, 1973). The Glacial deposits are characterized by a high degree of heterogeneity (laterally and vertically). They generally consist of silts, sands and gravels, with variable amounts of clays, and a variety of grain sizes and shapes. Large quantities of the sands and gravels were laid down as outwash material, swept out from the melting glaciers by melt water streams and also as moraines, deposited in front of the glaciers.

The area of investigation receives annual precipitation of about 800 mm/yr, distributed as: 500-mm evaporation, 60-mm runoff, and 240-mm infiltration recharging the aquifer system. The aquifer (totally saturated sediments) is overlain by the aeration zone (partially saturated sediments) which is overlain by the weathering zone (surface soils), and is underlain by an aquiclude composed of glacial clays (till), known as "Geschiebemergel". Electric measurements carried out for the same area (Salem, 1999) showed that the aquifer's thickness ranges from $\approx$ 30 to 70 m, depending on the water-table level. The water table is located at about 5 to 10 m below the surface, and at about 20 m below the surface of higher altitudes. The permeability of the aquifer ranges from 7.51×10^{-5} to 2.87×10^{-3} m/s (with an average value of 8.7×10^{-4} m/s) (Salem, 1999).

In the present study, surface seismic measurements were carried out to determine the compressional to shear wave-velocity ratio for the surface soils, the partially saturated sediments, and the totally saturated sediments. Relationships among the velocity ratio (V_P/V_S), compressional wave velocity (V_P), shear wave velocity (V_S) and porosity (ϕ) were obtained.

METHODOLOGY

For this study, seismic refraction measurements were carried out to record compressional and shear waves. A 24-channel digital recording system and forward and reverse shooting, as well as a sledge hammer and a plate (energy source) were used.

The waves were recorded with detectors (geophones) of a linear response of up to 100 Hz and a resonance frequency ranging from 10 to 50 Hz. The detector groups were arranged in an inline-split spread configuration, using a detector spacing of 2 m. The forward and reverse shot points were located at a 1-m spacing off the first and last detectors in each spread. The signals were sampled at 1000 or 2000 samples per second and recorded on digital cassettes that were copied on magnetic tapes to be processed.

The seismograms (field data) were digitized to pick the travel times of the direct and refracted waves. The observed travel times of the compressional and shear waves were plotted against the distance between the shot points and the detectors. The V_P and V_S of the direct and refracted waves were obtained as the reciprocal of the slopes of the regression lines of each segment of the relationship between the travel time and the distance. The V_P and V_S of the direct and refracted waves were then used to obtain the velocity ratio (V_P/V_S).

V_P/V_S-VARIATIONS

The results indicate wide variations of V_P/V_S, due to variations in V_P, V_S or both. These variations are attributed to several influences, including lithology and mineralogical composition, sizes and shapes of the grains, degree of saturation and kind of saturant (air or water), porosity and depth. The depth predicted from the compressional and shear waves for the three horizons lies in a general range of $\approx$ 1-12 m. The depth differences predicted from both kinds of the waves for the same horizon are generally small.

The results indicate that V_P/V_S generally varies from 1.28 to 3.19, with an average value of 2.42 (231 readings), representing the surface soils, the partially saturated sediments and the totally saturated sediments (Table 1; Fig. 1). The surface soils exhibit a V_P/V_S-range of 1.28-2.11 (average = 1.74; 46 readings); the partially saturated sediments exhibit a range of 1.97-2.65 (average = 2.31; 70 readings); and the totally saturated sediments exhibit a range of 2.36-3.19 (average = 2.75; 115 readings) (Table 1; Fig. 1). The V_P/V_S-variations, laterally and vertically, are attributed to the high degree of heterogeneity of the soils and the sediments investigated.

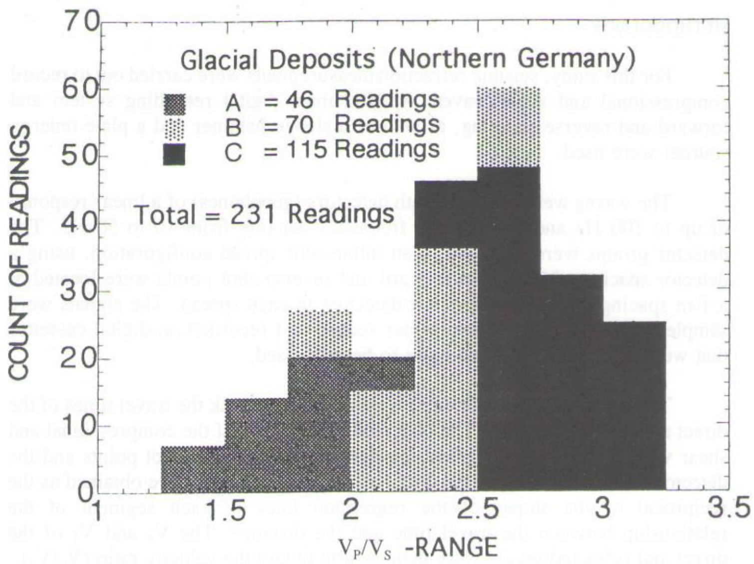

Fig. 1. Histogram showing the range and count of the compressional to shear wave-velocity ratio (V_P/V_S) for the surface soils (A = 46 readings), partially saturated sediments (B = 70 readings) and totally saturated sediments (C = 115 readings); total = 231 readings.

Fig. 1 also shows overlapping in the V_P/V_S-values for the range of between ≈ 1.75 and 2.25 (corresponding to the surface soils and the partially saturated sediments), and for the range of between ≈ 2.25 and 2.75 (corresponding to the partially and totally saturated sediments). The overlapping in both cases can be attributed to the pores that are filled with both air and water, and to the presence of the same material at different depths, as a result of the lens configuration characterizing the glacial deposits.

V_P/V_S AND COMPRESSIONAL WAVE VELOCITY

Fig. 2 (Eq. (6)) shows an increasing relationship between V_P/V_S and V_P with a coefficient of correlation (R_c) = 0.89.

$$V_P/V_S = 1.6113 + 0.00071\ V_P\ . \tag{6}$$

The general range of V_P/V_S (1.28-3.19; average = 2.42) corresponds to a general range of V_P of between 134 and 2060 m/s (average = 1134 m/s) for the whole column of the soils and sediments investigated (Table 1; Fig. 2). In spite of the overlapping in some of the values of V_P/V_S and V_P for the surface soils, partially saturated sediments, and totally saturated sediments (Table 1), clear distinctions can be observed among the three horizons at the V_P/V_S-values of 2 and 2.5 (Fig. 2).

The V_P/V_S-value of 2, corresponding to the V_P-value of ≈ 550 m/s (Fig. 2; Eq. (6)), can be considered as a discriminating value between the surface soils and the partially saturated sediments. The V_P/V_S-value of 2.5, corresponding to the V_P-value of ≈ 1250 m/s (Fig. 2; Eq. (6)), can be considered as a discriminating value between the partially saturated sediments and the totally saturated sediments.

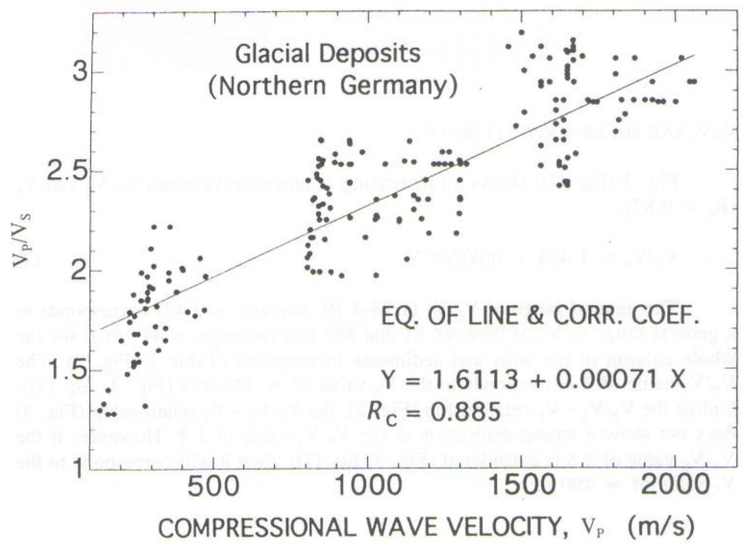

Fig. 2. Relationship between the compressional to shear wave-velocity ratio (V_P/V_S) and compressional wave velocity (V_P, in m/s) for the surface soils, partially saturated sediments and totally saturated sediments (231 readings).

Table 1. Ranges and average values (given in brackets) of the compressional wave velocity (V_P, in m/s), shear wave velocity (V_S, in m/s), compressional to shear wave-velocity ratio (V_P/V_S), and porosity (ϕ, in %) for the surface soils (46 readings), partially saturated sediments (70 readings), and totally saturated sediments (115 readings), as well as the overall ranges and average values of all parameters for the whole column of the soils and sediments investigated (231 readings).

	V_P (m/s)	V_S (m/s)	V_P/V_S	ϕ (%)
Surface soils	134-474 (291)	81-245 (155)	1.28-2.11 (1.74)	45.7-65.9 (55.4)
Partially saturated sediments	307-1300 (970)	161-518 (398)	1.97-2.65 (2.31)	35.1-42.2 (39.0)
Totally saturated sediments	828-2060 (1571)	354-863 (597)	2.36-3.19 (2.75)	28.8-33.5 (31.7)
Overall range and average	134-2060 (1134)	81-863 (449)	1.28-3.19 (2.42)	28.8-65.9 (39.5)

V_P/V_S AND SHEAR WAVE VELOCITY

Fig. 3 (Eq. (7)) shows an increasing relationship between V_P/V_S and V_S (R_c = 0.87).

$$V_P/V_S = 1.498 + 0.00205\ V_S\ . \tag{7}$$

The general range of V_P/V_S (1.28-3.19; average = 2.42) corresponds to a general range of V_S of between 81 and 863 m/s (average = 449 m/s) for the whole column of the soils and sediments investigated (Table 1; Fig. 3). The V_P/V_S-value of 2 corresponds to the V_S-value of $\approx$ 245 m/s (Fig. 3; Eq. (7)). Unlike the V_P/V_S - V_P relationship (Fig. 2), the V_P/V_S - V_S relationship (Fig. 3) does not show a strong distinction at the V_P/V_S-value of 2.5. However, if the V_P/V_S-value of 2.5 is considered (Fig. 3; Eq. (7)), then it will correspond to the V_S-value of $\approx$ 490 m/s.

V_P/V_S AND POROSITY

The porosity (ϕ) was obtained by using the following equation given by Watkins et al. (1972):

$$\phi = -0.175\ \ln(V_P) + 1.56\ . \tag{8}$$

The Watkins et al. (1972) equation, with $R_c = 0.94$, was obtained for shallow sediments of different mineralogical and lithological composition. It correlates between a range of fractional porosity of $\approx$ 0.2 - 0.8 (obtained experimentally) and a range of compressional wave velocity of $\approx$ 80 - 2700 m/s (obtained from in-situ seismic refraction measurements).

As shown in Table 1, the surface soils exhibit the lowest values of V_P/V_S and the highest values of ϕ, meanwhile the totally saturated sediments exhibit the highest values of V_P/V_S and the lowest values of ϕ. The partially saturated sediments, sandwiched between the surface soils and the totally saturated sediments, exhibit intermediate values of both V_P/V_S and ϕ. These results indicate that V_P/V_S increases with depth, whereby ϕ tends to decrease. The inverse relationship between the velocity ratio and porosity, in % (Fig. 4), is expressed in the following equation ($R_c = 0.92$):

$$V_P/V_S = 4.0665 - 0.042617\phi \ . \tag{9}$$

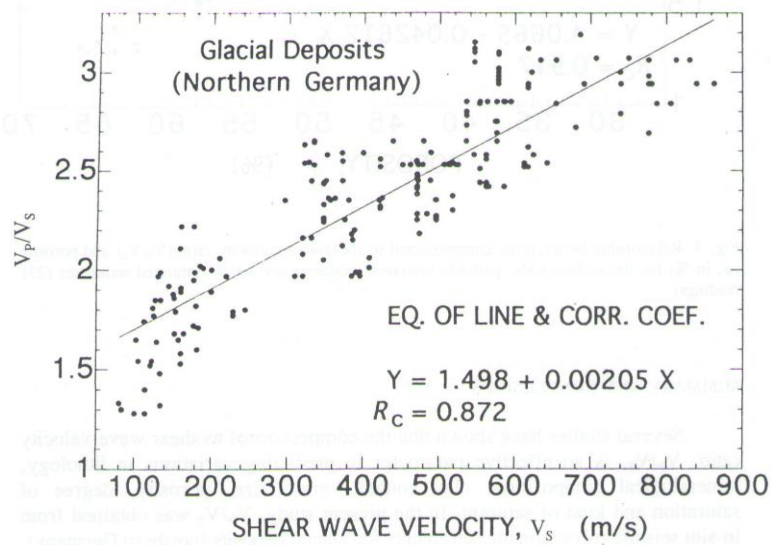

Fig. 3. Relationship between the compressional to shear-wave velocity ratio (V_P/V_S) and shear wave velocity (V_S in m/s) for the surface soils, partially saturated sediments and totally saturated sediments (231 readings).

At the V_P/V_S-value of 2, ϕ is $\approx$ 49%, and at the V_P/V_S-value of 2.5, ϕ is $\approx$ 37% (Fig. 4; Eq. (9)).

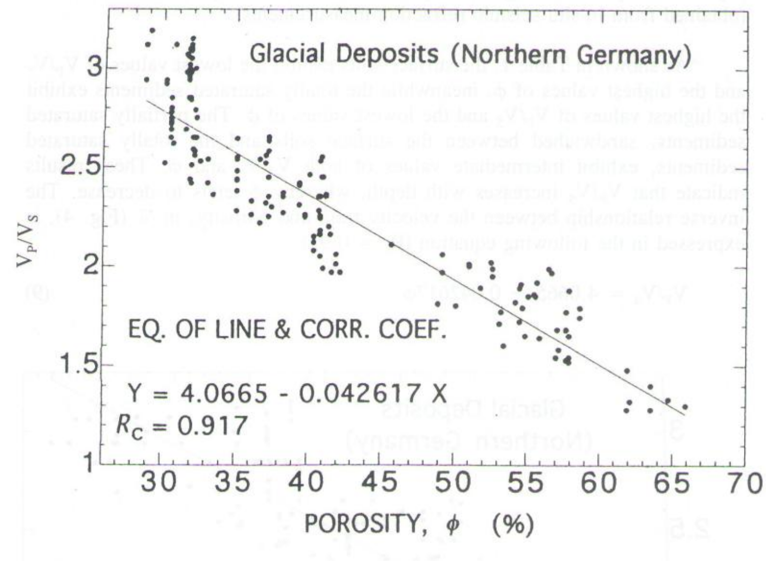

Fig. 4. Relationship between the compressional to shear-wave velocity ratio (V_P/V_S) and porosity (ϕ, in %) for the surface soils, partially saturated sediments and totally saturated sediments (231 readings).

SUMMARY AND CONCLUSIONS

Several studies have shown that the compressional to shear wave-velocity ratio, V_P/V_S, is an effective parameter in predicting variations in lithology, mineralogical composition, clay content, grain size, porosity, degree of saturation and kind of saturant. In the present study, V_P/V_S was obtained from in-situ seismic refraction measurements for glacial deposits (northern Germany), and was correlated to the compressional wave velocity, V_P, shear wave velocity, V_S, and porosity, ϕ.

For the surface soils and the partially and totally saturated sediments, V_P exhibits a general range of 134-2060 m/s (average = 1134 m/s), and V_S exhibits a general range of 81-863 (average = 449 m/s). These ranges correspond to a general V_P/V_S-range of between 1.28 and 3.19 (average = 2.42). The results indicate that V_P/V_S increases with increasing the compressional and shear wave velocities, and decreases with increasing the porosity that exhibits a general range of ≈ 29-66% (average ≈ 40%). Also, the velocity ratio increases with depth, where a change in the kind of saturant (from air to water) and an increase in the degree of saturation are expected. The size degradation from coarser to finer grains, the increase in water saturation, and the presence of a small fraction of clays in the sediments (Salem, 1999, 2000) are contributing factors to the increase of the velocity ratio with depth.

The V_P/V_S-value of 2 is remarkable in discriminating between the surface (dry) soils and the underlying sediments that are partially saturated with water (as observed from the correlations of V_P/V_S with both V_P and V_S). The V_P/V_S-value of 2.5 is remarkable in discriminating between the partially and totally saturated sediments (as observed from the correlation of V_P/V_S with V_P only). When $V_P/V_S = 2$, the value of V_S is approximately half the value of V_P, and when $V_P/V_S = 2.5$, the value of V_S is approximately 40% of the value of V_P. At the V_P/V_S-value of 2, the wavelength of both compressional and shear waves is approximately the same. When V_P/V_S exceeds 2, the wavelength of the shear wave is shorter than that of the compressional wave.

By increasing the degree of water saturation at the expense of air saturation, the fluid compressibility tends to decrease (increase in bulk modulus, and thus, increase in V_P), which results in an increase in the velocity ratio. The overlapping in the ranges of V_P/V_S (between the surface soils and the partially saturated sediments, and between the partially and totally saturated sediments) is attributed to several factors, including the pore spaces that are filled with both air and water, the lens configuration, and the heterogeneity characterizing the glacial deposits, both horizontally and vertically.

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