

**ESTIMATION OF WATER SATURATION IN
A SAND DUNE FROM DIVING DIRECT
SEISMIC P-WAVES**

BY

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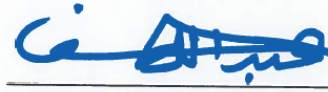
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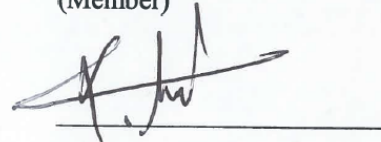
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I dedicate this work to my family.

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LIST OF ABBREVIATIONS

S_w : Water Saturation

V_p : P-wave Velocity

ABSTRACT

Full Name : [Abdullah Sadiq Al Sahwan]
Thesis Title : [Estimation of Water Saturation in a Sand Dune from Diving Direct Seismic P-waves]
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Seismic P-wave velocity (V_P) in an unconsolidated sediment slightly decreases with water saturation (S_W) until full saturation, where V_P value suddenly jumps in the saturated sediment. In this study, I propose a method to estimate S_W in partially saturated unconsolidated sediments using diving direct P-waves. I utilize the velocity profile observed and predicted in these sediments by Gassmann and Hertz-Mindlin models to construct a V_P (S_W) relation using available information about other matrix and pore-fluid properties. S_W is estimated by minimizing the normalized squared error between the observed and calculated travel times of the diving direct arrival.

Testing the proposed method on synthetic data in sandy dunes with S_W ranging between 0 and 0.9 led to estimating the correct S_W values within 2% error. Moreover, this method was also tested using direct arrivals in a sand dune in eastern Saudi Arabia, where S_W values were measured in the laboratory for 10 samples from different depths. Despite considerable differences between the individual inverted and measured values at each depth, both measured and inverted S_W values collectively indicate a dry dune. In addition, medians of both measured and inverted S_W values are comparable to medians of S_W values commonly reported in dry sand dunes across the world.

ملخص الرسالة

الاسم الكامل: عبدالله بن صادق آل سهوان

عنوان الرسالة: تقدير تشبع المياه في الكثبان الرملية باستخدام الموجة الزلزالية الأولية المباشرة

التخصص: الماجستير في علوم الجيوفيزياء

تاريخ الدرجة العلمية: يوليو 2023

تتخضع سرعة الموجة الزلزالية الأولية في الرواسب غير المجمعة بشكل طفيف مع ارتفاع تشبع الماء فيها، ثم ترتفع سرعتها بشكل مفاجئ وسريع عند تشبعها بالكامل بالماء. تهدف هذه الدراسة إلى معرفة مقدار تشبع المياه جزئياً في الرواسب غير المجمعة باستخدام الموجة الزلزالية الأولية المباشرة. باستخدام نماذج (قاسمان وهيرتز- ميندلين) وملف السرعة الملاحظ والمقدر من خلال هذه النماذج، سيتم بناء علاقة رياضية بين السرعة الزلزالية الأولية ومقدار تشبع المياه في الرواسب غير المجمعة باستخدام خواص المسامية للسوائل والمصفوفة للصخور. كمية تشبع المياه سيتم تقديرها باستخدام تقليل الخطأ التربيعي بين الوقت الملاحظ للموجة الزلزالية الأولية والوقت المقدر باستخدام العلاقة الرياضية المقترحة في هذه الدراسة. اختبرت العلاقة الرياضية بين السرعة الزلزالية ومقدار تشبع المياه على بيانات اصطناعية في تربة رملية وكان مقدار تشبع المياه فيها يتراوح بين (0-0.9)، وكانت النتائج تعطي القيم الصحيحة لتشبع المياه بنسبة خطأ 2%. علاوة على ذلك تم اختبار الطريقة المشار إليها في كثبان رملية في شرق المملكة العربية السعودية، ومقارنتها بالقيم المقاسة من العينات المأخوذة في المختبر والتي أشارت إلى كثبان رملية جافة. رغم اختلاف القيم الطفيف بين القيم المقاسة في المختبر والقيم المقدرة باستخدام العلاقة الرياضية المشار إليها، تشير النتائج إلى أن الكثيب الرملي جاف بشكل عام. استخدمت العلاقة أيضاً في المقارنة مع قيم مختلفة لتشبع المياه في الكثبان الرملية مأخوذة من دراسات لمناطق مختلفة حول العالم عند نفس الظروف.

CHAPTER 1

INTRODUCTION

Deserts span enormous areas of the world and pose a variety of issues, including desertification and water scarcity, due to extremely low precipitation. Although many people think of deserts as empty and lifeless, they can be a home for many animals and plants. Moreover, humans have lived in and adapted to the harsh environment of deserts. All living creatures in deserts are in a continuous and eternal search for water to survive. Approximately 35% of the total area of Saudi Arabia is covered by the sandy desert (Alaamer, 2012). Saudi Arabia has three big deserts which are Rub Al-Khali, An-Nafud and Ad-Dahna deserts as seen in Figure (1) (Alaamer, 2012). In general, deserts are widespread and arid due to dry weather, low precipitation, and high evaporation rate (Warner, 2004). For example, the precipitation over the Rub Al-Khali (the empty quarter) desert in eastern and southeastern Saudi Arabia is lower than that 60 mm annually reported by (Hasanean et al., 2015). Saudi Arabia is considered one of the most water scarce countries, with no running rivers and only non-perennial wadies that flow only seasonally (Edgell, 2006). However, the main water resources in Saudi Arabia are surface water, groundwater, and seawater desalination (World Bank, 2005). In general, desert-dwelling plants, animals, and humans depend on groundwater stored in the soil, such as sand dunes, due to its easy access and use. For most desert projects, it is sufficient for a particular water exploration method to determine the general conditions of

saturation in soil (i.e., low/high) even if the method does not accurately determine the exact water saturation (S_w) value.



Figure 1 Major deserts in Saudi Arabia (Alaamer, 2012)

1.1 Water in Dunes

The saturation in the dunes is estimated using a variety of methodologies from a variety of scientific disciplines. One of these methods is the gravimetric soil moisture method, which involves drying soil samples in an oven and then weighing them, where the difference between the two samples represents the weight of the soil moisture (Novák et al., 2019). Another method is to place soil-moisture probes in the subsurface to continuously estimate the water content (Novák et al., 2019). Sand dunes can be a reliable source of water due to rainfall in the wet season or recharge from the subsurface aquifer underlying the sand dunes (Hugenholtz et al., 2013; Scheidt et al., 2010). (Dincer et al., 1974), studied sand dunes in Saudi Arabia using stable isotopes and thermonuclear tritium and measured the water content in the sand dune. (Gad et al., 2012) conducted a study to investigate the mechanism of how natural vegetation adapts to adverse environments in sand dunes in northern Sinai, Egypt. They measured the soil moisture content for six different sand dunes in the dry season. (Rouhipour, 2006) studied the seasonal fluctuations in soil moisture content and condensation processes in Khuzestan sand dunes in Iran. For this study, three different locations of the sand dune (windward, dune crest, and leeward) were chosen, and the water content was measured. The study concluded that there must be a source of water to carry plants through extended periods of dry weather.

In China's Gurbantonggut desert, a study was conducted to determine the characteristics of macrobiotic crust occurrence and their environmental significance on dune surfaces by (Chen et al., 2007). They conducted an analysis of the physiochemical properties of the soil at different dunes, including the water content. (Al-Agely et al., 1995) examined the relationship

between initial soil depth, water content, and pH on the formation of vesicular-arbuscular mycorrhizae. Thirteen samples were taken from Colorado's north Sandhills sand dunes and the water content was determined. Table (1) is a compilation of water contents and their corresponding depths for these studies as well as the minimum, maximum and median water content of each study (Figure (2)). The last row in Table (1) shows the minimum (0.00132), maximum (0.044), and median (0.006) water content of all studies.

Table 1 List of water content measured in samples in dry dunes in various locations of the world, as well as the minimum, maximum and median values for each study and for all studies.

Study	Country	Location	Depth (m)	Water content (M ³ /M ³)	Min	Max	Median
Gad et al. (2012)	Egypt	Elsabha, 1 st year	0.002	0.218	0.132	1.045	0.315
			0.4	0.266			
		Elsabha, 2 nd year	0.002	0.132			
			0.4	0.162			
		Zuwied, 1 st year	0.002	0.346			
			0.4	0.422			
		Zuwied, 2 nd year	0.002	0.855			
			0.4	1.045			
		Abu-Asab, 1 st year	0.002	0.222			
			0.4	0.272			
		Abu-Asab, 2 nd year	0.002	0.426			
			0.4	0.52			
		El-Hauol, 1 st year	0.002	0.283			
			0.4	0.345			
		El-Hauol, 2 nd year	0.002	0.341			
			0.4	0.417			
		El-Gapher, 1 st year	0.002	0.261			
			0.4	0.319			
		El-Gapher, 2 nd year	0.002	0.323			
			0.4	0.395			
		Magaria, 1 st year	0.002	0.255			
			0.4	0.311			
			0.002	0.248			

		Magaria, 2 nd year	0.4	0.304			
Rouhipour, (2006)	Iran	Sand dune Windward	0.2	0.0031	0.003	0.024	0.0108
			0.4	0.0164			
			0.6	0.0108			
			0.8	0.021			
			1	0.0215			
		Sand Dune Crest	0.2	0.0037			
			0.4	0.0053			
			0.6	0.01			
			0.8	0.0217			
			1	0.024			
		Sand Dune Leeward	0.2	0.003			
			0.4	0.0057			
			0.6	0.01			
			0.8	0.018			
			1	0.0182			
Chen et al., (2007)	China	Upper side of Sand Dune	0.02	0.006	0.005	0.0325	0.015
			0.05	0.008			
			0.1	0.016			
			0.2	0.0162			
		Mid of Sand Dune	0.02	0.005			
			0.05	0.021			
			0.1	0.0325			
			0.2	0.021			
			0.02	0.006			

		Lower side of Sand dune	0.05	0.0252			
			0.1	0.009			
			0.2	0.014			
Dincer et al., (1974)	Saudi Arabia	Riyadh Sand dune	0.2	0.0118	0.018	0.0443	0.0244
			0.5	0.0443			
			1	0.0241			
			1.5	0.0244			
			2	0.0235			
			2.5	0.0264			
			3	0.0367			
Al-Agely et al., (1995)	USA	Colorado Sand dune	0.1	1.02	0.0102	0.0182	0.0155
			0.2	1.34			
			0.3	1.55			
			0.4	1.7			
			0.5	1.82			
All studies					0.00132	0.044	0.006

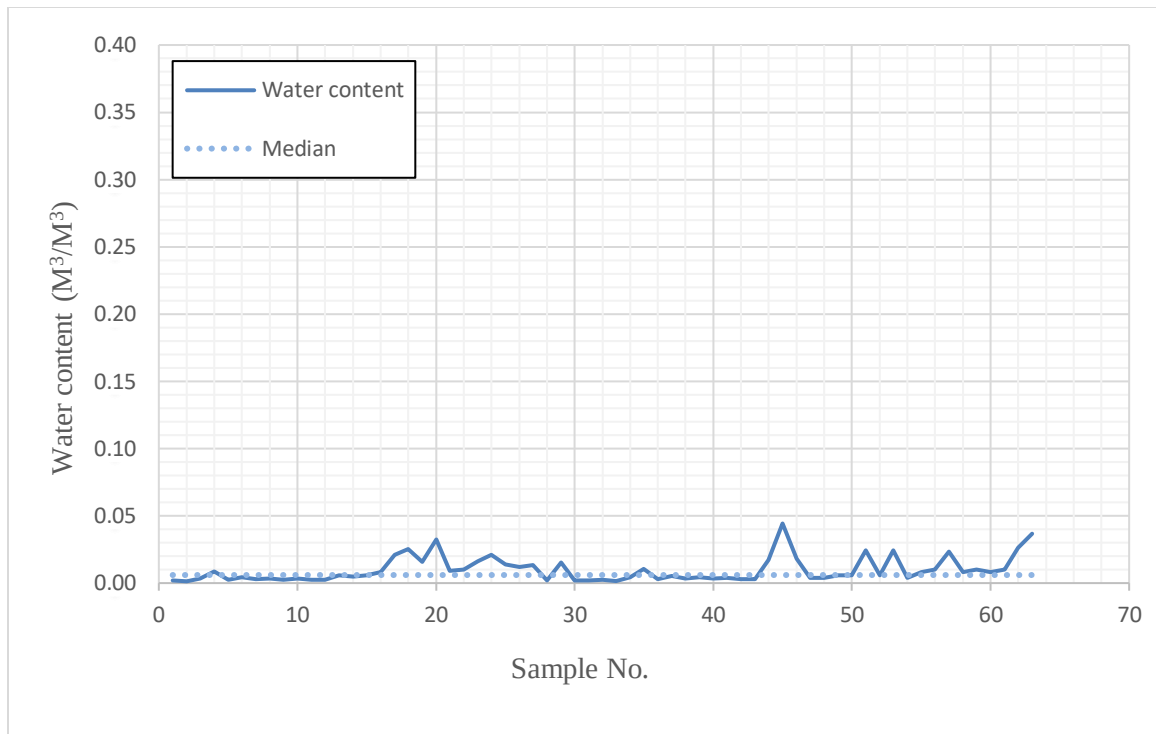


Figure 2 Water contents measured from different dry sand dunes of the world.

1.2 Water Content Estimation Using Geophysical Methods

Estimation of water content in the subsurface at large scale can be impractical and costly if direct measurements were used like the soil moisture probes which only cover few centimeters around the sensor. However, geophysical techniques are suitable for larger scale and higher depth in the subsurface (Fan et al., 2015). A study in north Stradbroke Island in Australia used a 2D surface electrical resistivity tomography (ERT) and 1D spatial time domain reflectometry (TDR) to estimate the water content in the sand dune (Fan et al., 2015). Integration between both methods has shown the potential of monitoring and estimation of water content in shallow depths of the sand dune. Another study conducted in a sand dune in the southern part of Vietnam used magnetic resonance sounding (MRS) to investigate the subsurface hydrology and propose a spot for monitoring groundwater (Giang et al., 2012). The interpretation of MRS sounding revealed that the water content is between 3- 9.5% which is confirmed by borehole data. However, a study from Gurbantünggüt desert in China used ground penetrating radar (GPR) survey to determine the water content in a sand dune in the desert (Qin et al., 2013). For water content measurements, both GPR and TDR data have followed the same trend in general with slight increases in GPR measurements. In addition, GPR survey and combined penetrometer moisture probe (CPMP) were used to evaluate the spatial distribution of the soil moisture in Hokkaido, Japan (Iwasaki et al., 2020). The resulting data from this study revealed that the combination of both GPR survey and CPMP probes are helpful for evaluating spatial distribution of groundwater in costal sand dunes.

Furthermore, modelling of GPR waves has been used to estimate the water content in a sand dune in Tchad desert in Chad (Bano, 2004). In this study, the complex refractive index method (CRIM) formula has been used and estimated a water content in the range of (4-5.5%). However, a study conducted in the desert of Abu Dhabi in the United Arab Emirates used surface and borehole nuclear magnetic resonance (NMR) data to estimate partial water content in the subsurface (Yaramanci et al., 2009). The surface NMR inverted data has reconstructed the subsurface very well compared to borehole NMR data and allowed for confident estimation of water content. (Lambot et al., 2004) conducted a controlled experiment on a tank filled with two layers of sandy soil to analyze the relation between the accuracy of the forward model and inversely estimated parameter using GPR and TDR. The results showed perfect agreement between GPR and TDR data especially for values ranging from (0.04-0.12 M³/M³) in terms of water content, whereas lower water content values showed slight differences. (Van Giang, 2010) used different geophysical methods in Binh Thuan sand dunes in Vietnam to understand the hydrological conditions of the study area. The interpretation of magneto telluric data and transient electromagnetic method have shown the amount of water content in the shallow aquifer to be 3.6%, whereas 9.8% for the deeper aquifer. However, another study was held in South Africa used seismic method to detect the water table in a sand dune (van Zijl, 1971). The water table was marked by a seismic discontinuity, which match exactly the findings from borehole data in the same area. (Woodward et al., 1991) used uphole data from hydrocarbon exploration seismic surveys to investigate groundwater in sand dunes in Abu Dhabi (UAE). Although, the uphole seismic surveys were conducted for hydrocarbon exploration, they can be used for shallow groundwater exploration. The measured water

table in the area coincided completely with the extracted one from the interpretation from the seismic uphole surveys.

1.3 Water Exploration by Seismic Methods

The seismic refraction method has been used effectively for shallow groundwater exploration and detecting the water table in the subsurface (Abdullahi et al., 2011; Moustafa et al., 2012). (Abdelrahman et al., 2017) used seismic refraction tomography based on velocity changes gradually or discretely. Their study area is situated in Wadi Al-Showat in the southern part of Saudi Arabia. The results show three main seismic layers, where the second one represents the host of shallow groundwater aquifer with velocity averaging between 900 - 1800 m/s and depth varying from 1 - 12 m. Furthermore, because full saturation yields a significant increase in seismic velocity, the seismic refraction approach provides immediate information on the depth of the water table for a homogeneous lithology (Alhassan et al., 2018). Additionally, a seismic refraction survey was carried out in the southern part of Paiko, Nigeria, to investigate and delineate the subsurface groundwater potential in the area. The study concluded that seven-shot points were considered for aquifer potentials with depth to refractor ranging from 13 - 18 m (Alhassan et al., 2018). Moreover, the seismic refraction method was used in Brunei Darussalam (Azhar et al., 2019). The P-wave velocity for water-saturated strata of the surveyed area ranged from 1200 to 1800 m/s. A seismic refraction experiment was carried out in Abuja, Nigeria, to delineate the fracture zones and bedrock depth. Three seismic layers were discovered, with the second layer representing the aquifer zone with a velocity of 1572 m/s (Maunde et al., 2017). Another study was carried out in Vientiane province

(Laos) to investigate for groundwater potential (Viengthong et al., 2020). The objective of this study is to map the aquifer and to delineate the water table. The results revealed that the seismic velocity for the targeted layer is 1750 m/s. Al-Shuhail and Al-Shaibani (2009, 2013) used this method to determine the depth and thickness of the saturated zone in several sabkhas located in eastern Saudi Arabia. The seismic refraction method can identify fully saturated layers in the subsurface. However, it fails to specify partial amounts of water in the subsurface. In this study, diving direct P-wave arrivals are used to estimate partial water saturation in sand dunes and apply the proposed method on synthetic data and real data at a site on a dune near Dammam Airport in eastern Saudi Arabia.

CHAPTER 2

METHODOLOGY

2.1 Gassmann Assumptions

Seismic P-wave velocity increases with depth in the subsurface due to the increase in elastic constants caused by increasing pressure with depth (Dvorkin et al., 2014). This observation is more evident in unconsolidated and loosely consolidated sediments where cementation plays a negligible role. One of the most commonly used models proposed to explain this observation is by Gassmann (1951). Basically, it is commonly known that Gassmann's equations are used for seismic velocity prediction caused by different pore-fluid saturations (Han et al., 2004). Several assumptions were made in the derivation of Gassmann's equations. A Porous medium is an isotropic and homogenous, closed medium system with pore fluid movement and no chemical interaction between the fluid and the porous medium (Berryman, 1999; Han et al., 2004). In this model, the effective bulk (K_e) and shear (G_e) elastic constants of the sediment are expressed in terms of those of the matrix (K_m and G_m), dry sediment (K_d and G_d), and fluid (K_f) as follows:

$$\frac{K_e}{K_m - K_e} = \frac{K_d}{K_m - K_d} + \frac{K_f}{\varphi(K_m - K_f)}, \quad (2.1)$$

$$G_e = G_d, \quad (2.2)$$

where φ is the sediment's porosity. K_m and G_m for a multimineral matrix can be calculated from Hill's averages of Voigt and Ross moduli as follows:

$$K_m = \frac{1}{2} \times \left[\sum_i (p_i \times K_i) + \sum_i \left(\frac{p_i}{K_i} \right) \right] \quad (2.3)$$

$$G_m = \frac{1}{2} \times \left[\sum_i (p_i \times G_i) + \sum_i \left(\frac{p_i}{G_i} \right) \right] \quad (2.4)$$

where p_i , K_i , and G_i are the fractional volume, bulk, and shear moduli of the i^{th} mineral phase of the matrix. K_f of an air-water mixture is calculated from the bulk moduli of the air and water (K_a and K_w) as:

$$\frac{1}{K_f} = \frac{S_w}{K_w} + \frac{1-S_w}{K_a} \quad (2.5)$$

where S_w is the water saturation (Mavko et al., 2009).

The bulk and shear moduli of the dry sediment are calculated from Hertz-Mindlin contact theory (Mindlin, 1949) as follows:

$$K_d = \frac{C(1-\varphi)}{12\pi R} S_n, \quad (2.6)$$

$$G_d = \frac{C(1-\varphi)}{20\pi R} (S_n + 1.5S_t), \quad (2.7)$$

where C is the coordination number indicating the average number of grain contacts per grain and R is the average radius of the uniform spherical grains. S_n and S_t are the normal and tangential stiffnesses calculated as:

$$S_n = \frac{4aG_m}{1-\nu}, \quad (2.8)$$

$$S_t = \frac{8aG_m}{2-\nu}, \quad (2.9)$$

where ν is the grains Poisson's ratio and a is the radius of the grain's contact area given as:

$$a = \left(\frac{1}{f}\right) \left[\frac{3\pi(1-\nu)}{2C(1-\varphi)G_m} P \right]^{1/3}. \quad (2.10)$$

P is the hydrostatic pressure exerted on the grains calculated as:

$$P = \rho_d g z, \quad (2.11)$$

where g is the gravitational acceleration, z is the sediment thickness, and ρ_d is the density of the dry matrix calculated as:

$$\rho_d = \varphi \rho_a + (1 - \varphi) \rho_m, \quad (2.12)$$

where ρ_a and ρ_m are the densities of air and matrix, respectively. The factor f in equation (2.10) is a factor proposed by Hanafy et al. (2020) to account for grain non-sphericity.

The P-wave velocity of the saturated sediment is calculated as:

$$V_P = \sqrt{\frac{K_e + \frac{4}{3}G_e}{\rho_e}}, \quad (2.13)$$

where ρ_e is the effective density of the sediment calculated as:

$$\rho_e = (1 - \varphi) \rho_m + \varphi [(1 - S_w) \rho_a + S_w \rho_w], \quad (2.14)$$

where ρ_w is the pore-water density. To summarize, the steps to calculate V_P are as follows:

1. Equation (2.12) is substituted into equation (2.11) to calculate P .
2. Equation (2.11) is substituted into equation (2.10) to calculate a .
3. Equations (2.10) and (2.4) are substituted into equations (2.8) and (2.9) to calculate S_n and S_t , respectively.

4. Equations (2.8) and (2.9) are substituted into equations (2.6) and (2.7) to calculate K_d and G_d , respectively.
5. Equation (2.7) is substituted into equation (2.2) to calculate G_d .
6. Equation (2.5) is solved for K_f .
7. Equation (2.1) is solved for K_e and substitute K_d .
8. K_e from equation (2.1), G_e from equation (2.2), and ρ_e from equation (2.14) are substituted into equation (2.13) to calculate V_p .

For a sediment made up of uniform spherical quartz grains (Table 2), $V_p(z, S_w)$ becomes:

$$V_p(z, S_w) = 0.568 \sqrt{\frac{-3.763 \times 10^{24} + (1.88325 \times 10^{27} S_w - 1.88316 \times 10^{27}) z^{1/3} + 1.258 \times 10^{19} z^{2/3}}{(4.927 + S_w)(-1.48544 \times 10^{21} + 1.48537 \times 10^{21} S_w + 1.5 \times 10^{13} z^{1/3})}} \quad (2.15)$$

Figures (3) and (4) show plots of $V_p(z, S_w = 0.3)$ and $V_p(z = 5 \text{ m}, S_w)$ respectively. The plot of $V_p(z, S_w = 0.3)$ shows a sharp increase in P-wave velocity versus depth at shallow depths, which is expected by previous studies (e.g., Al-Shuhail, 2002; Al-Shuhail, 2006). On the other hand, the plot of $V_p(z = 5 \text{ m}, S_w)$ shows a slight decrease in velocity with increasing S_w between 0 and approximately 0.9, then it increases sharply until it reaches the velocity of the saturated sand. Due to low variation in P-wave velocity between totally dry and 99% saturation, partial saturation is very difficult to determine using only P-wave velocity. As the amount of water increases in the pore spaces, the total density will increase, while the elastic moduli stay almost fixed, which in turn decreases the P-wave velocity (V_p). However, when full saturation is achieved, the Bulk modulus increases considerably while density increases only slightly causing the P-wave velocity to increase sharply (Dvorkin et al., 2014).

Table 2 Matrix and pore-fluid properties (Dvorkin et al., 2014).

Property	Value
ϕ	0.35
K_m (GPa)	37
G_m (GPa)	45
ρ_m (kg/m ³)	2650
K_a (GPa)	0.000131
ρ_a (kg/m ³)	1.19
K_w (GPa)	2.225
ρ_w (kg/m ³)	1000
R	1
f	3.1

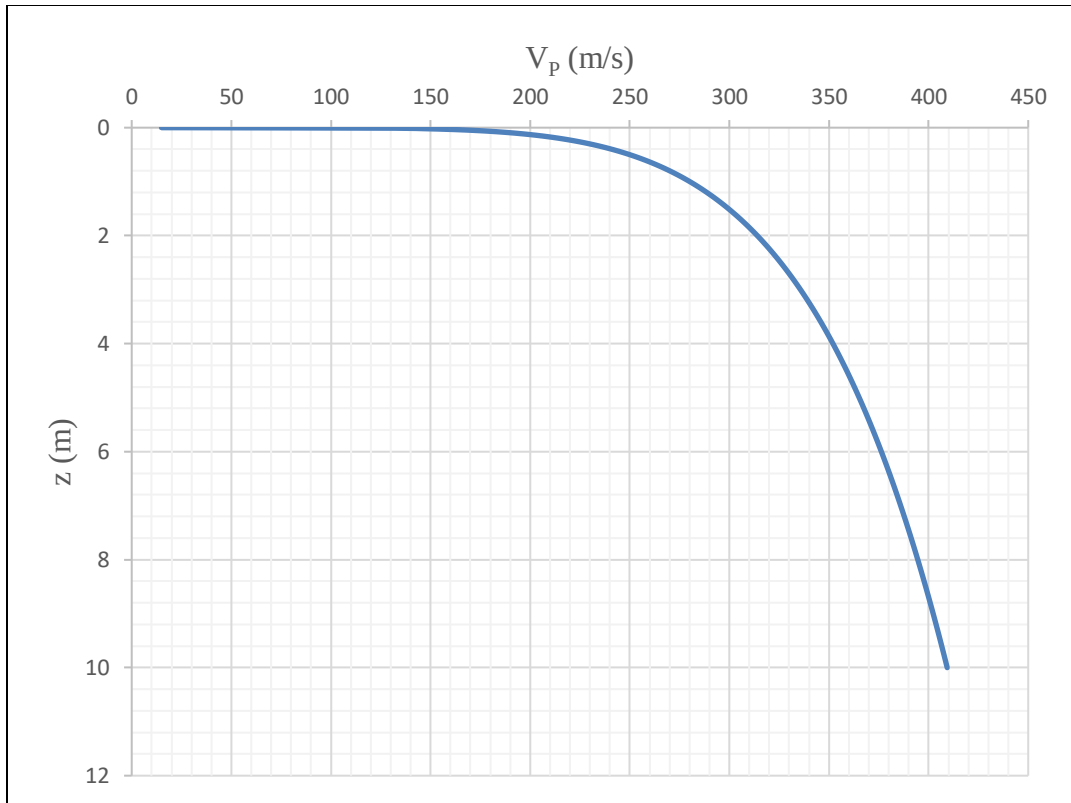


Figure 3 P-wave velocity as a function of depth, $V_p(z, S_w = 0.3)$ using equation (2.15).

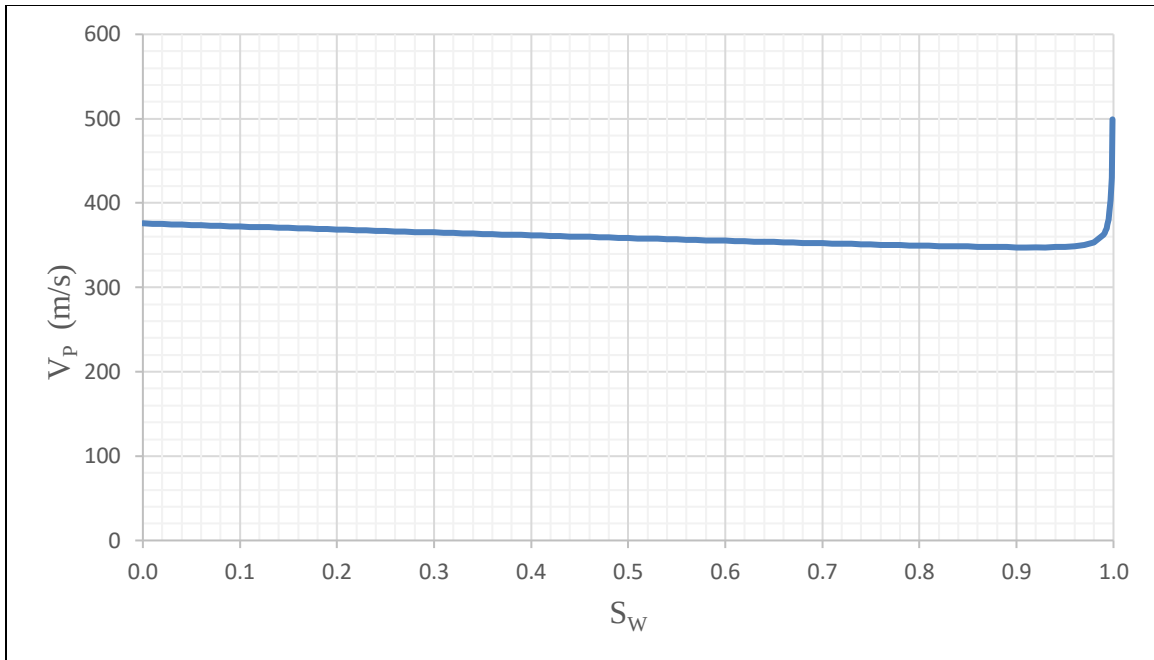


Figure 4 P-wave velocity as a function of S_w , V_p ($z = 5$ m, S_w) using equation (2.15).

2.2 Diving Direct Arrivals

In a medium with an increasing velocity with depth such as the one given by equation (2.15), direct waves will become diving waves, and offset (X) and two-way time (T) are calculated by the following parametric equations (e.g., Sheriff et al., 1995):

$$X = 2 \int_0^h \frac{V_P(z)}{V_P(h) \sqrt{1 - [V_P(z)/V_P(h)]^2}} dz \quad (2.16)$$

$$T = 2 \int_0^h \frac{dz}{V_P(z) \sqrt{1 - [V_P(z)/V_P(h)]^2}} \quad (2.17)$$

where h is the maximum depth of penetration of the diving direct wave that corresponds to this (X, T) pair. The maximum depth of penetration of the diving direct wave can be found from the observed offset (X_0) proposed by Hanafy et al. (2020) as follows:

$$h = \frac{X_0}{5.89}. \quad (2.18)$$

In general, equations (2.16) and (2.17) cannot be integrated analytically due to the algebraic complexity of $V_P(z)$. Therefore, they are commonly integrated using numerical methods.

2.3 Water Saturation Inversion (S_w)

This study investigates the possibility of inverting S_w in loose sand with saturation between (0 and 0.9). Because the refraction from fully saturated sand can be observed and analyzed using conventional shallow seismic techniques (e.g., Sheriff et al., 1995), I stopped at ($S_w = 0.9$). However, velocity change between (0 and 0.9) saturation is much less evident to observe by conventional methods despite the significant difference in impact on desert-dwelling humans, animals, and plants between highly saturated sand (e.g., $S_w = 0.9$) and dry sand.

The following steps are proposed to invert $S_w(h)$ as a function of the maximum penetration depth of the diving direct wave at every observed offset:

1. Equation (2.18) is used to calculate the maximum penetration depth of the diving direct wave corresponding to the observed offset.
2. Calculate $V_P(z, S_w)$ by equation (2.15) using the steps detailed in the previous section.
3. Minimize the normalized squared error (NSE) between the observed (T_0) and calculated arrival times of the diving direct wave arriving at X_0 for S_w .

The NSE is defined as follows:

$$NSE = \left[\frac{\left\{ T_0 - 2 \int_0^h \frac{dz}{V_P(z, S_w) \sqrt{1 - [V_P(z, S_w) / V_P(h, S_w)]^2}} \right\}}{T_0} \right]^2 \quad (2.19)$$

The integral in equation (2.19) can be calculated numerically using any available numerical integration method as well as the minimization method of the NSE (e.g., Press et al., 2007).

Since most minimization algorithms depend on a starting search point; there is a possibility of algorithm entrapment at a local minimum value near the starting search point. To avoid these cases, it is recommended to apply NSE minimization multiple times using a range of starting search points that span all expected S_w values in the investigated area (ideally 0, 0.1, ..., 0.9). Regardless of the starting search point, the minimization algorithm should ideally return the same S_w value producing the global NSE minimum if no local minima exist. However, due to several reasons (e.g., noise, measurement errors, etc.), there could be local NSE minima leading the algorithm to return multiple S_w values close to various attempted

starting search points. The S_w value associated with the global minimum NSE value should be chosen in such circumstances.

2.4 Numerical Integration

Numerical integration as opposed to indefinite integration has been utilized when the analytical techniques fail (Davis et al., 1984). Also, it can be defined as the study of finding the numerical value of an integral. Indefinite integration or antiderivative is simply the integration without limits which can be solved by different methods including integration by parts, integration by substitution, and many others (Hastings, 1999). Numerical integration is also called quadrature which has an extended history back to the invention of calculus (Press et al., 2007). In simple words, numerical integration provides an alternative choice to find the numerical value of an integral. Many methods have been developed including approximate integration, infinite series, differential equations, and many others (Davis et al., 1984). In this study numerical integration has been utilized to invert for S_w value.

Similarly, Mathematica built-in codes offer different methods for numerical integration. NIntegrate is a numerical integrator function that deals with wide a range of one-dimensional or multidimensional integrals. In addition, it can deal with integrands over finite or infinite regions. Basically, Mathematica algorithms can simplify the integrals by symbolic pre-processing and automatically choose the best integral method. In general, computational effort is being addressed to integrand discontinuity or singularity by different adaptive strategies. Furthermore, it continuously divides the integration region using adaptive algorithms until the minimum error has been reached. Integration strategies can be defined as algorithms that attempt to compute integral estimates and are classified based on integration sampling region.

The most commonly used strategies are “global adaptive”, “local adaptive”, and “monte carlo” (Wolfram Research, 2014b).

2.5 Minimization Method

The purpose of minimizing a function is to find either the local or global minima (Dahlquist et al., 2008; Cheney et al., 2012). Mathematica uses FindMinimum and Minimize built-in functions, in addition to other functions, which return a local and global minimum for a function, respectively. The FindMinimum function localizes the values of all variables then evaluates the results numerically. On the other hand, the Minimize function seeks the smallest values under the provided constraints, which is also referred to as the best fit or configuration. However, there is no guarantee that the global minimum will be found for a function that has several local minima. A solution for that is to try different starting points and the smallest local minimum corresponds to the global minimum (Dahlquist et al., 2008). In Mathematica, the constraints of FindMinimum algorithm can take any type of logical combinations (e.g., equations, inequalities, region specification). In addition, it uses the given constraints and then searches for local minimum avoiding use of derivatives (Wolfram Research, 2014a).

CHAPTER 3

Data

3.1 Study Area

The data used in this study are from a Barchan dune in Dammam in Saudi Arabia (Hanafy et al., 2020). The dunes in the eastern province belong to Al Jafurah dune field which is mostly comprised of transverse dunes (Edgell, 2006). The accumulation of the aeolian sand in the area was during Quaternary period and originated from Bitlis Zagros thrust belt (Anton, 1983). However, Barchanoid dunes were formed due to northerly high-speed winds during Pleistocene period (Fryberger et al., 1984). The mineral composition of the sand dunes in the study area consists of mainly quartz, feldspar, and carbonate minerals (Garzanti et al., 2013). The study area receives about 54 - 138 mm annual rainfall with an average of 84 mm (General Authority for Statistics, 2015) which is quite higher than the average of Rub Al-Khali desert which is less than that 60 mm (Hasanean et al., 2015; Edgell, 2006). A complete core was taken from a shallow 10 m borehole drilled in the mid-slope of the dune, where the borehole fully penetrated the dune and the upper part of the underlying sabkha. Figure (5) shows the studied area which is 30 km east of Dhahran city in the eastern province of Saudi Arabia. The dune is composed mostly of quartz, with minor quantities of feldspar and calcite. The underlying sabkha contained quartz, feldspar, calcite, with increased amounts of halite and gypsum. The sabkha is composed of fine to medium grain sizes in the top 2.5 m, whereas the underlying 0.5 m is mainly muddy sand with fine grains. The drilled part showed that there

was a partially saturated zone up to 7.6 m deep mostly within the dune, while the deeper 2.4 m is fully water saturated and fully in the sabkha (Hanafy et al., 2020).

3.2 Data Acquisition

2D seismic survey using conventional (low resolution) and high-resolution methods to obtain a P-wave velocity profile for the shallow part of the sand dune were conducted in the study area (Hanafy et al., 2020). For the conventional seismic survey, an 8 kg sledgehammer and 20 x 20 x 4 cm³ plate were used as a source, and a total of 73 shot gathers spaced at 1 m intervals and 37 receivers spaced at 1 m intervals were recorded with each shot. For the high-resolution seismic acquisition, a smaller sledgehammer and plate were used as a source. There were 31 geophones activated with each shot in this survey spaced as follows: 0.1 m spacing for the first 12 geophones, 0.2 m spacing for geophones 12 to 23, and 0.25 m for geophones 23 to 31, resulting in 5.4 m as the total length of the receiver line. Ten offsets were picked from these two surveys that correspond to the depth at which the sand samples were collected, and the water content was measured in the laboratory as seen in Table (3) (Benaafi et al., 2020).

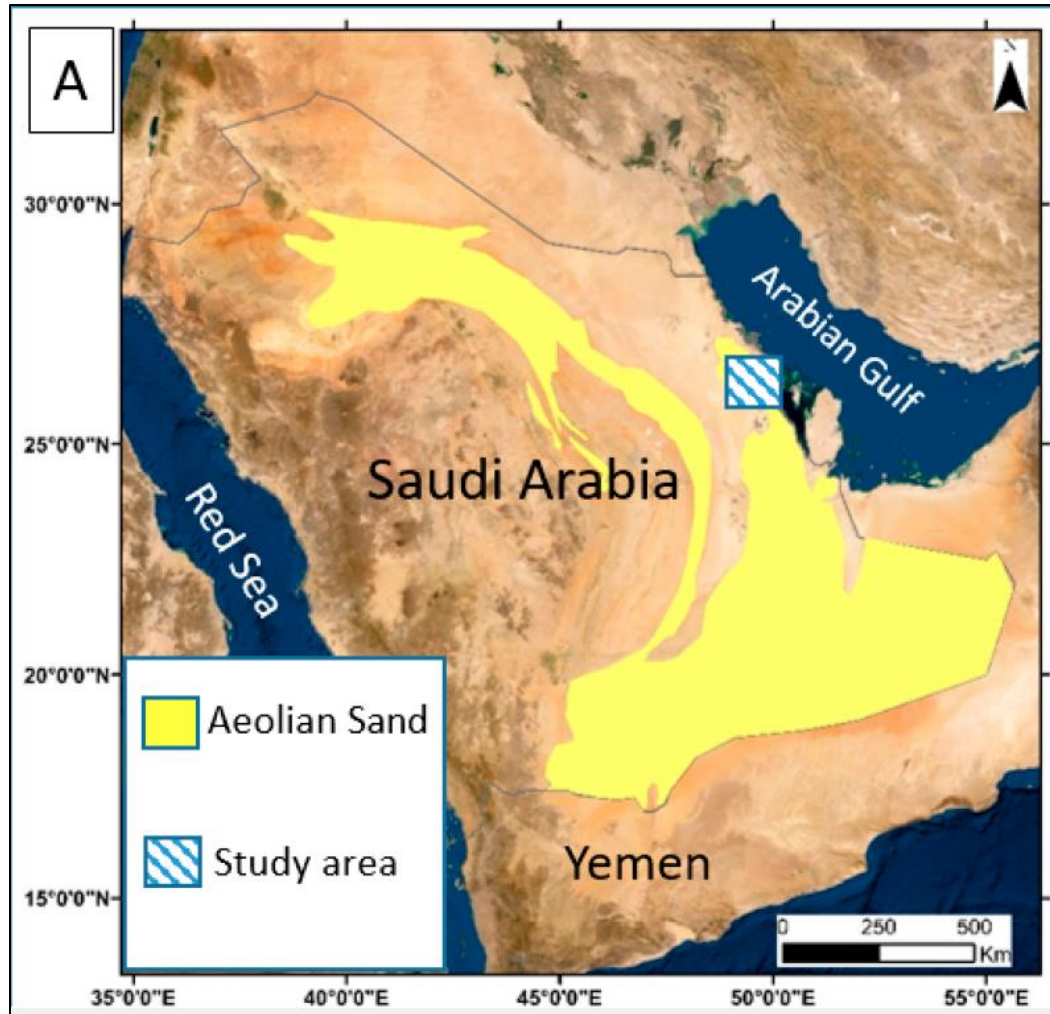


Figure 5 Distribution of aeolian sand and study area in eastern Saudi Arabia (after Benaafi et al., 2020).

3.3 Matrix and pore-fluid data

Mineral composition and porosity were measured in the lab (Benaafi et al., 2020). The dune properties for each sample are listed in Table (3). Basically, water content is equal to water saturation multiplied by porosity. To make the proposed method more practical, a few assumptions were made. The dune is assumed to have a pure quartz matrix, and a constant average critical porosity of 35%. Additionally, a value of 3.1 for the non-sphericity factor (f) was used as determined from $X_0 - T_0$ data in the studied dune (Hanafy et al., 2020).

Table 3 Water content and saturation, porosity and matrix mineralogy measured in the laboratory for the 10 sand samples acquired at various depths from the studied dune.

Sample no.	Depth (m)	Quartz	Calcite	Albite	Microcline	Anorthite	Oligoclase	Gypsum	Measured porosity	Measured water content	Measured water saturation
1	0.1	0.834	0.036	0.079	0.039	0.000	0.000	0.012	0.36	0.0050	0.0139
2	0.35	0.787	0.037	0.095	0.069	0.000	0.000	0.012	0.3438	0.0385	0.112
3	0.85	0.854	0.027	0.000	0.044	0.000	0.065	0.010	0.3429	0.0135	0.0394
4	1.6	0.835	0.030	0.000	0.030	0.094	0.000	0.011	0.3	0.0185	0.0617
5	2.425	0.806	0.024	0.000	0.043	0.118	0.000	0.009	0.303	0.0135	0.0446
6	3.25	0.824	0.031	0.000	0.051	0.000	0.082	0.012	0.3438	0.0185	0.0538
7	4.9	0.838	0.020	0.000	0.032	0.105	0.000	0.005	0.3636	0.0135	0.0371
8	5.5	0.812	0.021	0.092	0.067	0.000	0.000	0.008	0.3548	0.0135	0.038
9	5.775	0.805	0.021	0.116	0.051	0.000	0.000	0.007	0.3947	0.0185	0.0469
10	6.4	0.876	0.020	0.046	0.046	0.000	0.000	0.012	0.359	0.0235	0.0655
Min	0.1	0.7870	0.0200	0.0000	0.030	0.0000	0.0000	0.0050	0.3	0.005	0.0139
Max	6.4	0.8760	0.0370	0.1160	0.069	0.1180	0.0820	0.0120	0.3947	0.0385	0.112
Mean	3.115	0.8271	0.0267	0.0428	0.047	0.0317	0.0147	0.0098	0.34656	0.01765	0.05129
Media	2.837	0.8290	0.0255	0.0230	0.045	0.0000	0.0000	0.0105	0.3493	0.016	0.04575
SD	2.389	0.0261	0.0065	0.0483	0.013	0.0514	0.0312	0.0025	0.0280	0.00881	0.0257

CHAPTER 4

Results and Discussion

4.1 Introduction

The following steps are used to invert the measured time-offset data:

1. The sample depths were used to calculate the corresponding offsets by equation (2.18).
2. The closest measured offsets (X_0) from Hanafy et al. (2020) were selected.
3. The corresponding measured (manually picked) times (T_0) of the diving direct wave arrivals to these offsets are selected from Hanafy et al. (2020).
4. A dune with a pure quartz matrix and properties given in Table (2) is assumed to establish $V_P(z, S_w)$ in equation (2.15).
5. $V_P(z, S_w)$ is used in S_w inversion by equation (2.19).

4.2 Synthetic data

To test this method, simulated data were used from a dune with a quartz matrix and the properties given in Table (2). Water saturation in this dune increases with depth according to Table (4). These depths and saturations are used to calculate the corresponding observed times T_0 in Table (4) using equation (2.17). The water saturation S_w value at each depth and corresponding time in Table (4) are inverted using equation (2.19). The minimization at each offset is carried out 10 times corresponding to 10 S_w starting search points (namely, 0, 0.1, ..., 0.9). Although 10 starting search points were tested for each offset, the minimization was

able to return the inverted S_w with the lowest error. As a result, the proposed method was able to invert all assumed S_w values within 2% error and a median error of approximately 0%, The inverted S_w values associated with the global NSE minimum at each T_0 pick are shown in Table (4) and Figure (6). These results show that the proposed method is capable of estimating the water saturation between 0 and 0.9 with marginal error.

Table 4 Inversion results for the synthetic data along with their respective minimum, maximum, mean, median, and standard deviation (SD) values.

Sample no.	h (m)	Assumed S_w	Calculated T_0 (s)	Inverted S_w	Error (%)
1	0.017	0	0.0008	0.0224	N/A
2	0.137	0.1	0.0047	0.0999	0.10
3	0.307	0.2	0.0093	0.2000	0.00
4	0.546	0.3	0.0152	0.3000	0.00
5	0.836	0.4	0.0220	0.4000	0.00
6	1.705	0.5	0.0401	0.5000	0.00
7	2.899	0.6	0.0631	0.6000	0.00
8	4.096	0.7	0.0848	0.7011	0.16
9	5.300	0.8	0.1061	0.8000	0.00
10	6.536	0.9	0.1273	0.8808	2.13
Min	0.017	0	0.0008	0.0224	0
Max	6.53	0.9	0.127	0.880	2.13
Mean	2.23	0.45	0.0473	0.450	0.265
Median	1.270	0.45	0.0310	0.45	0
SD	2.355	0.302	0.0455	0.296	0.701

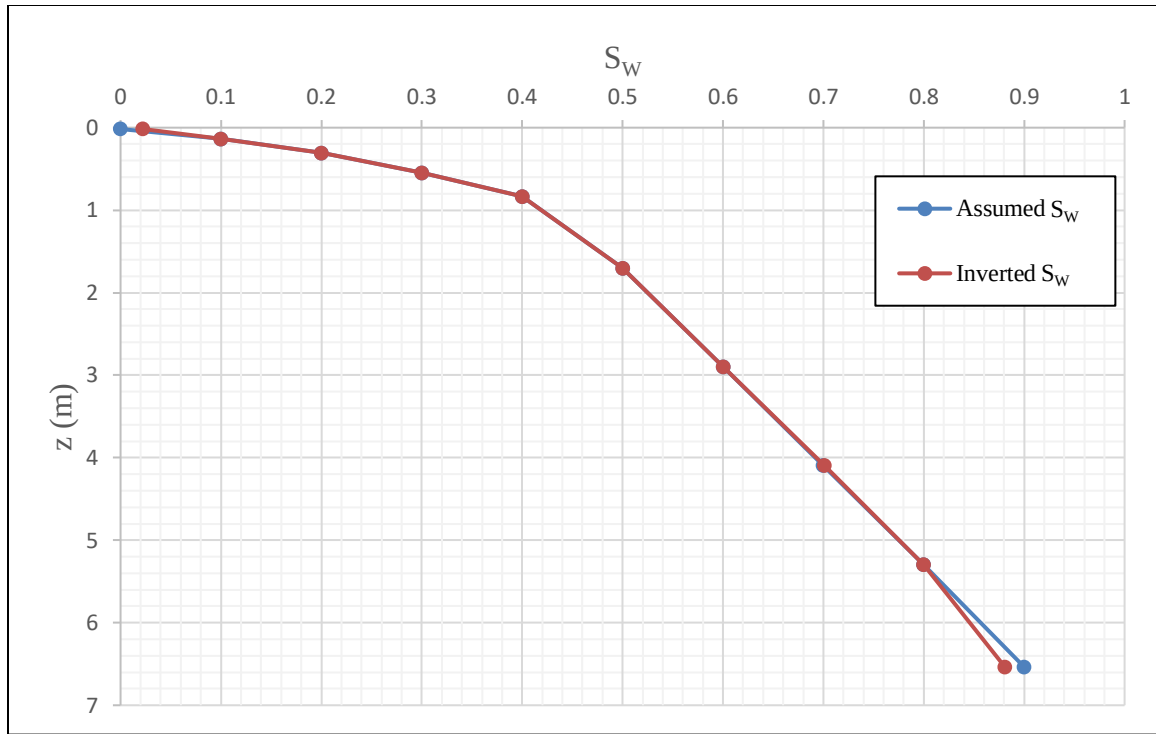


Figure 6 Assumed and inverted S_w as functions of depth for the synthetic data.

4.3 Real data

Although 68 different offsets were acquired by Hanafy et al. (2020), I only use those 10 offsets that corresponded to depths at which sand samples were extracted and their properties are measured in the laboratory (Benaafi et al., 2020). I apply the method described in section 4.1 to the real picks assuming a dune with a pure quartz matrix and properties given in Table (2). Table (5) shows the inputs and outputs of the proposed S_w inversion method when applied to the real dataset. The measured water content values are within a range of (0.005-0.0385) with a median of (0.016); while the inverted water content values fall within the range of (0.0001365-0.004816) and have a median of (0.0009748). Although there is an apparent considerable difference between the individual values of the inverted and measured water contents, both indicate a dune with very low water saturation (Figure 7).

To see the effect of assuming a pure quartz matrix and a constant porosity of 0.35, I use the matrix and porosity values measured in the laboratory to derive the corresponding $V_p(z, S_w)$ and use it to invert the water content at the measured depths (Figure 8). Comparison of Figures (7) and (8) shows that my assumptions did not affect the main conclusion that the dune is generally very dry.

Comparison of the measured and inverted water contents values in the studied dune with those measured in other dunes across the world as seen in Figure (9), we can see that both inverted and measured water content values are within the range of world water content values. Furthermore, there is a general trend in the study area toward higher measured and lower inverted water content values than world dune values.

Table 5 Measured sample depth, corresponding offset, and arrival time of the diving direct wave. Measured water contents and corresponding saturations S_w values were reported by Benaafi et al. (2020) for these sand samples. The inverted S_w and its corresponding water content using the proposed method are also listed. Water saturation is calculated from water content and vice versa using the measured porosity values in Table (2). Also shown are the respective minimum, maximum, mean, median, and standard deviation (SD) values for each column.

Sample no.	Sample depth (m)	Corresponding measured offset X_0 (m)	Measured (picked) time T_0 (s)	Measured water saturation	Measured water content	Inverted water saturation	Inverted water content
1	0.10	0.6	0.0028	0.0139	0.0050	0.00582	0.002037
2	0.34	2	0.00746	0.112	0.0385	0.00222	0.000777
3	0.83	4.9	0.01655	0.0394	0.0135	0.00648	0.002268
4	1.53	9	0.02755	0.0617	0.0185	0.00307	0.0010745
5	2.38	14	0.03973	0.0446	0.0135	0.01376	0.004816
6	3.23	19	0.05094	0.0538	0.0185	0.00039	0.0001365
7	4.92	29	0.07248	0.0371	0.0135	0.00269	0.0009415
8	5.43	32	0.07819	0.038	0.0135	0.00039	0.0001365
9	5.77	34	0.08251	0.0469	0.0185	0.00288	0.001008
10	6.45	38	0.09038	0.0655	0.0235	0.00265	0.0009275
Min	0.1	0.6	0.0028	0.0139	0.0050	0.00039	0.0001365
Max	6.45	38	0.09038	0.112	0.0385	0.01376	0.004816
Mean	3.098	18.25	0.046859	0.05129	0.0179515	0.004035	0.0014123
Median	2.805	16.5	0.045335	0.04575	0.0160125	0.002785	0.0009748
SD	2.40054	14.14506	0.03275	0.02578	0.00902	0.00394	0.0013784

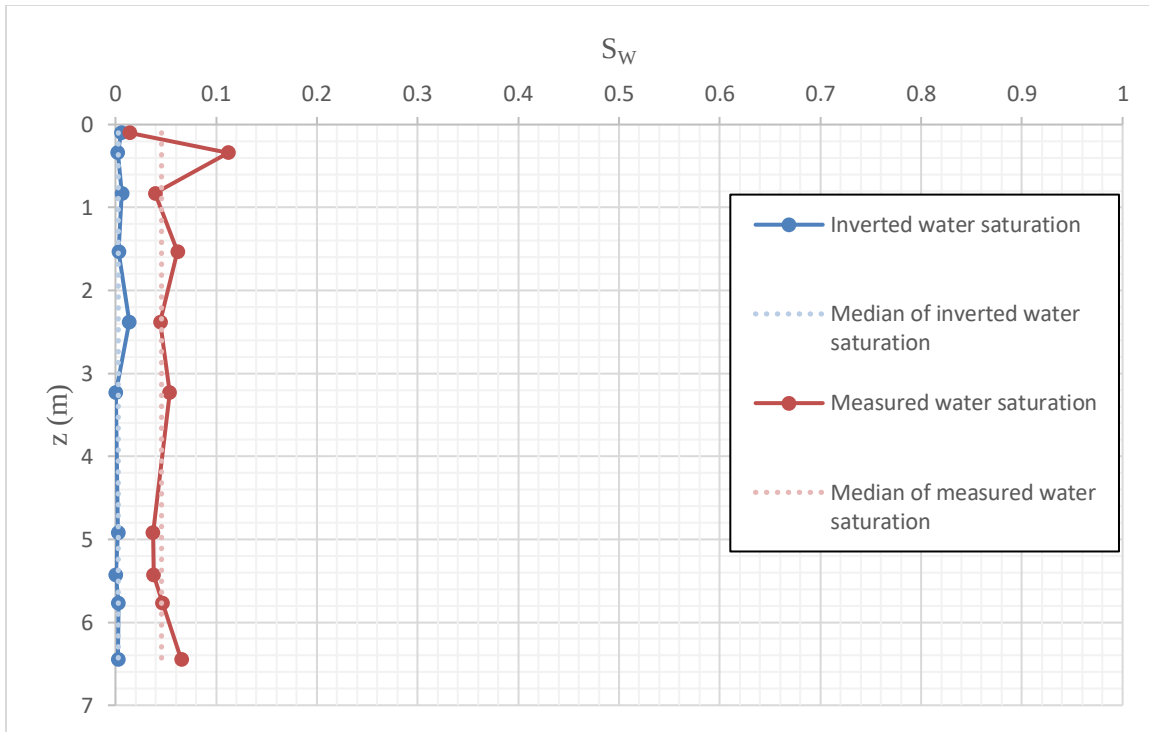


Figure 7 Measured and inverted water saturation values for the real data.

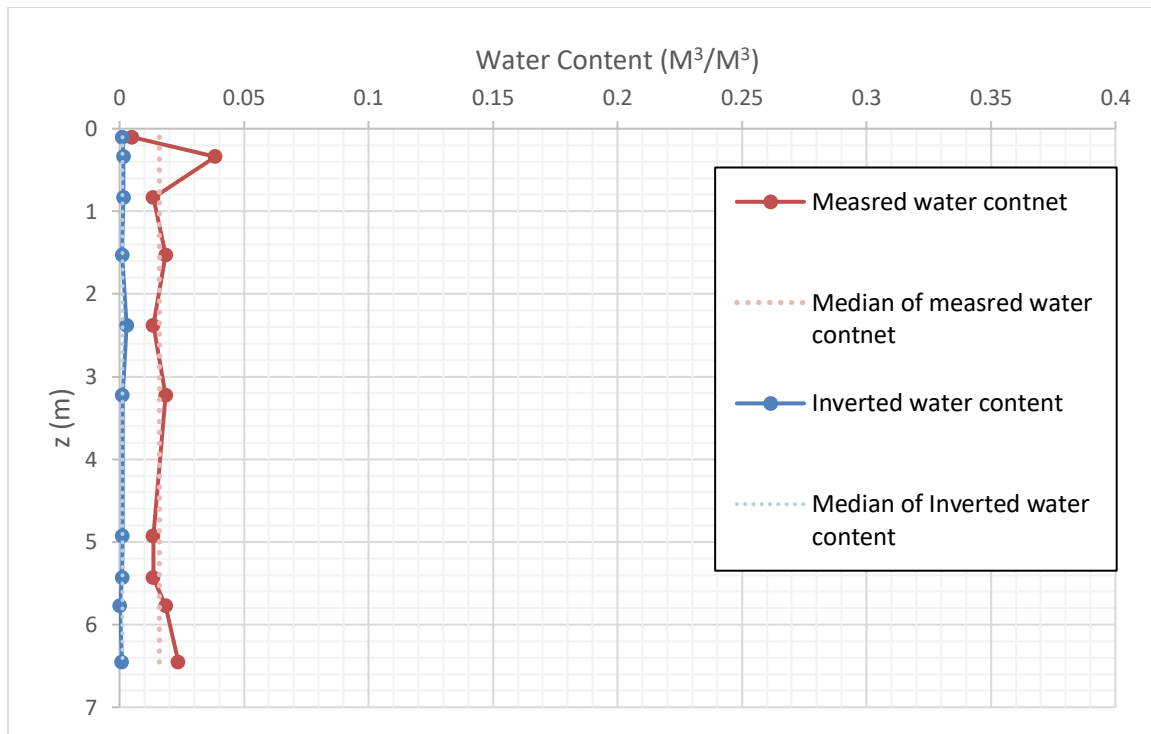


Figure 8 Inverted (blue) and measured (red) water content values using the matrix and porosity values measured in the laboratory (Benaafi et al., 2020).

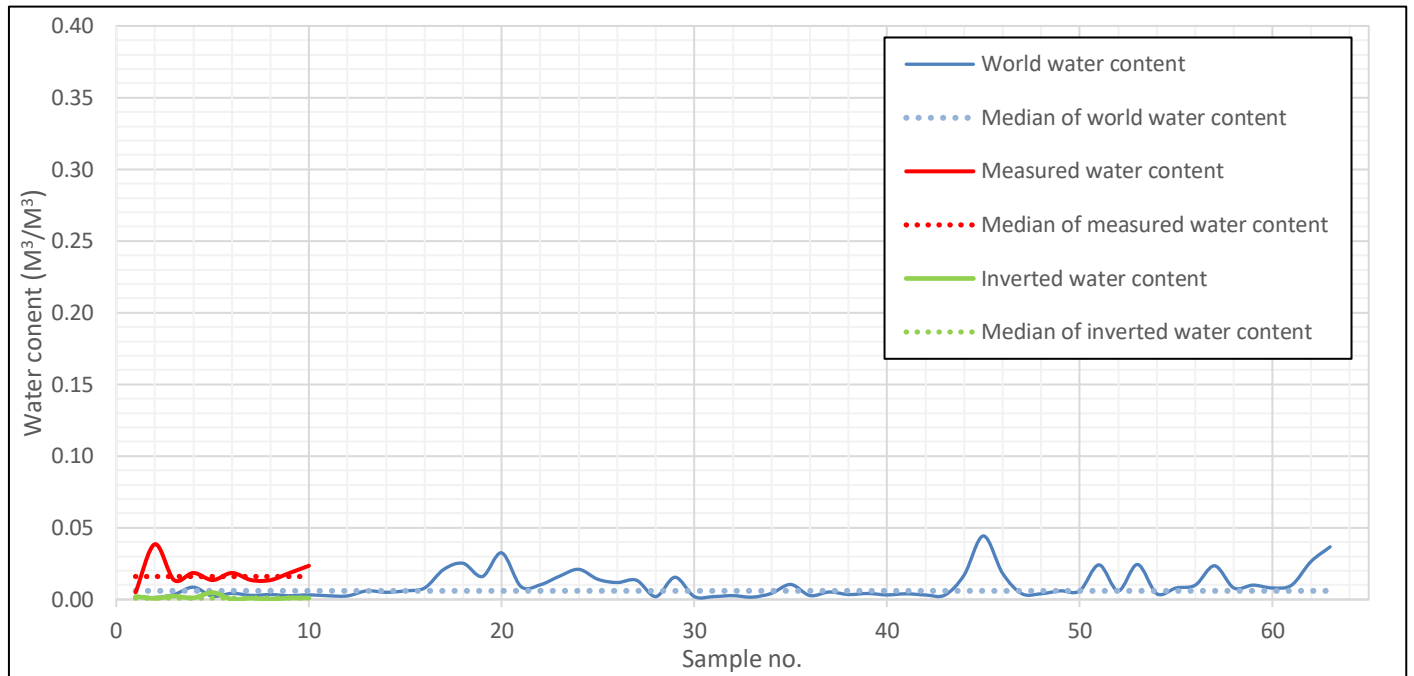


Figure 9 Comparison of water content values inverted (green) and measured (red) in the studied dune with those measured in world dunes (blue). Dashed lines show their respective medians.

CHAPTER 5

Conclusion and Recommendations

5.1 Conclusion

In this study, diving direct P-waves were utilized to estimate the water saturation S_w in partially saturated unconsolidated sediments. Gassmann and Hertz-Mindlin models and matrix and pore fluid properties were used to construct a relation of $V_p(z, S_w)$. The resulting relation was used to establish an objective function in terms of the measured and calculated travel times of the diving direct P-wave at each offset (depth). The proposed relation was tested to estimate the water saturation in synthetic data by inverting $S_w(h)$ as a function of the maximum penetration depth of the diving direct wave at every observed offset. The proposed method showed a negligible maximum error of about 2% between the assumed (0,0.1, ..,0.9) and inverted S_w values.

In addition, the proposed method was also tested on 10 samples from a sand dune in Dammam, Saudi Arabia, where S_w was measured at various depths assuming pure quartz matrix and a porosity of 0.35. Although the inverted S_w values of individual samples were different from the measured values, ranges of both inverted and measured S_w values indicate a dry sand dune. Using the measured matrix and porosity values did not considerably affect the statistics of the inverted S_w values. Furthermore, I observe that the measured and inverted water content values in the studied dune were comparable to water content values collected in dunes under similar conditions from different parts of the world.

5.2 Recommendations

As seen in this study, the proposed method utilizes the P-wave velocity and minimization technique for S_w inversion. The assumptions made for this method are completely valid assumptions and were suitable for the Dammam sand dune. I recommend the following:

1. Putting extra effort into generalizing this method taking into consideration different matrix (e.g., clay-rich) and pore fluid (e.g., high saturation) properties.
2. Since the total travel time of the diving wave is used for S_w inversion, it means that the inverted S_w indicates an average saturation value along the curved raypath. The proposed method should be improved to work on inverting the interval S_w .
3. Since this method was used on very dry sand dunes, I recommend to test it on highly saturated sand dune.

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