

**Estimation of Water Content Using GPR and
Seismic Data in a Sand Dune in Eastern Saudi
Arabia**

BY

Ali Ahmed Alkhunaizi

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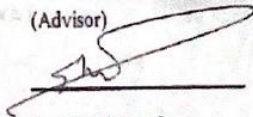
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This thesis, written by **Ali Ahmed Alkhunaizi** under the direction of his thesis supervisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **Master of Science in Geophysics**



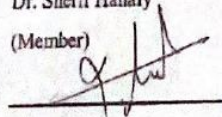
Prof. Abdullatif Al-Shuhail

(Advisor)



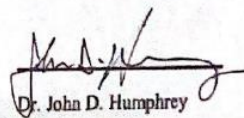
Dr. Sherif Hanafy

(Member)



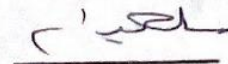
Dr. Mohammed Benaafi

(Member)



Dr. John D. Humphrey

Department Chairman



Prof. Soliman S. Al-Homidan

Dean of Graduate Studies

01/10/2024

Date



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I Dedicate this work to my family and friends

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LIST OF ABBREVIATIONS

S_w : Water Saturation

V_P : P-wave velocity

V_G : GPR velocity

WC: Water content

φ : Porosity

ABSTRACT

Full Name : [Ali Ahmed Alkhunaizi]

Thesis Title : [Estimation of Water Content Using GPR and Seismic Data in a Sand Dune in Eastern Saudi Arabia]

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In many environmental, engineering, and petroleum applications, water saturation (S_w) and porosity (ϕ) of near-surface materials are critical parameters. In this study, I propose a method to estimate S_w in partially saturated unconsolidated sediments using seismic P-wave velocities alongside GPR velocities. Utilizing Gassmann and Hertz-Mindlin models (P-wave) and CRIM model (GPR), I construct $V_P(z, S_w)$ & $V_G(\phi, S_w)$ relations using available information about other matrix and pore-fluid properties. S_w is then estimated by minimizing the normalized squared error between the $V_P(S_w, V_G)$ and the V_P value measured at the maximum penetration depth of the diving direct P-wave corresponding to each offset. I validated S_w values estimated from the measured V_P and V_G through comparison with those measured from sand samples analyzed in the lab.

The proposed inversion method was tested on real data in a sand dune in eastern Saudi Arabia, where S_w values were measured in the laboratory for 4 samples from different depths. Error between individual inverted and measured S_w values ranged from (26.8% - 131.813%). Nevertheless, both sets had a common mean value of ~ 0.07 with an error of less than 1% indicating a collective conclusion of a dry dune environment. Furthermore, means of both measured and inverted S_w sets are close to the mean of S_w values commonly reported in dry sand dunes across the globe (~ 0.06).

ملخص الرسالة

الاسم الكامل: علي بن أحمد الخنيزي

عنوان الرسالة: تقدير تشبع المياه في الكتبان الرملية باستخدام الموجة الزلزالية والموجة الكهرومغناطيسية

التخصص: الماجستير في علوم الجيوفيزياء

تاريخ الدرجة العلمية: يناير 2024

في العديد من التطبيقات البيئية والهندسية والبتروولية، يعد تشبع الماء (S_w) والمسامية (ϕ) للمواد القريبة من السطح من العوامل الحاسمة. في هذه الدراسة، أقترح طريقة لتقدير تشبع الماء في الرواسب غير المجمعة المشبعة جزئياً باستخدام سرعات الموجة الزلزالية إلى جانب سرعات الموجة الكهرومغناطيسية. باستخدام نماذج (قاسمان وهيرتز - ميندلين) ونموذج (كرم)، سيتم بناء علاقة رياضية بين السرعة الزلزالية والسرعة الكهرومغناطيسية ومقدار تشبع المياه في الرواسب غير المجمعة باستخدام خواص المسامية للسوائل والمصفوفة للصخور. يتم بعد ذلك تقدير تشبع الماء عن طريق تقليل الخطأ التربيعي بين العلاقة الرياضية المبينة سابقاً للسرعة الزلزالية والسرعة الكهرومغناطيسية وقيمة السرعة الزلزالية المقاسة عند كل مستوى عمق. بعد النتائج، أقوم بالتحقق من صحة قيم تشبع الماء المقدرة من العلاقة الرياضية المقاسة من خلال المقارنة مع تلك المقاسة من عينات الرمل التي تم تحليلها في المختبر.

تم اختبار طريقة الانعكاس المقترحة على بيانات حقيقية في الكتبان الرملية في شرق المملكة العربية السعودية، حيث تم قياس قيم تشبع الماء في المختبر لـ 4 عينات من أعماق مختلفة. وتراوحت نسبة الخطأ بين قيم تشبع الماء الفردية المقدرة من العلاقة الرياضية والمقاسة في المختبر من (26.8% - 131.813%). ومع ذلك، كان لكلا المجموعتين قيمة متوسطة مشتركة تبلغ ~0.07 مع وجود خطأ أقل من 1% يشير إلى استنتاج جماعي لبيئة الكتبان الجافة. علاوة على ذلك، فإن القيم المتوسطة لتشبع الماء المقاس والمقدر قريبة من القيمة المتوسطة لتشبع الماء التي يتم الإبلاغ عنها بشكل شائع في الكتبان الرملية الجافة في جميع أنحاء العالم (~0.06).

CHAPTER 1

INTRODUCTION

Deserts pose several critical problems due to low precipitation rates, which lead to desertification and water scarcity. Contrary to what many people believe, deserts are not as empty and lifeless as they may seem, as they can host many living organisms in plants, animals, or even humans who have adapted to such extreme environments throughout history. Understanding deserts and their environments is essential, as they make up almost 35% of our planet's surface area. They can be defined as barren areas of landscape where little precipitation occurs (less than 250 mm/year), making living conditions hostile for plants, animals, or even humans (Harris, 2003). Figure 1 shows the global distribution of deserts and their classification in terms of aridity. It is clear that the Arabian Peninsula has a large coverage percentage of deserts (CSUS, 2007). Zooming on a smaller scale, almost the same global desert land surface percentage covers Saudi Arabia's surface area, 35% (Alaamer, 2012). Saudi Arabia has 3 enormous main deserts in Rub Al-Khali (Empty Quarter), An-Nafud, and Ad-Dahna, as seen in Figure 2 (Alaamer, 2012). Deserts in Saudi Arabia are highly arid due to dry weather, low precipitation rates, and high evaporation rates. For instance, the precipitation rate in the Rub Al-Khali Desert, one of the largest deserts in the world, is approximately 60 mm/year (Hasanean et al., 2015), which is much less than the 250 mm/year threshold. Water resources can vary depending on the desert, including rainfall, rivers, lakes, oases, groundwater, metabolic water (in the case of animals), fog, dew, and water vapor (Gurera and Bhushan, 2020). According to the World Bank in 2005, Saudi Arabia's water resources mainly

depend on surface water, groundwater, and seawater desalination, as it is considered a water-scarce country due to its lack of natural water bodies. All living creatures, especially those in deserts, are in continuous search of water resources. Those resources in deserts are mainly found in accessible and easily used areas such as soils or sand dunes. In areas where water is not highly accumulated and available, such as deserts and dunes, it is essential to study and investigate the quantity and resources of the existing water content. For most purposes, it is sufficient to establish the general state of the soil or dune in terms of saturation (i.e., high/low), regardless of the accurate water saturation (S_w) value.

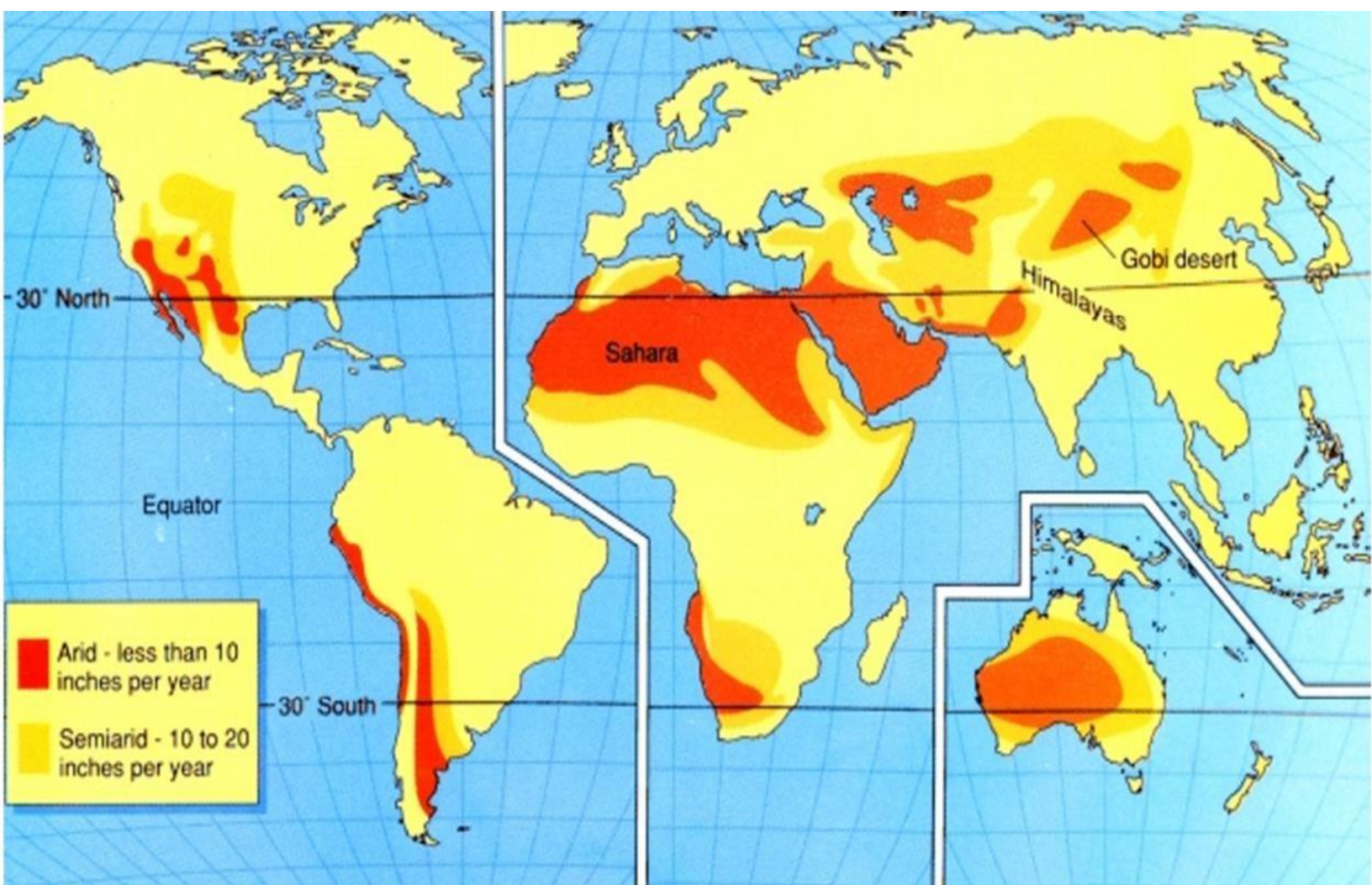


Figure 1 Global distribution of deserts (California State University, 2007).



Figure 2 Deserts in Saudi Arabia (Alaamer, 2012)

1.1. Literature Review

In any water-scarce zone, determining the water content is of great value (Munoth et al., 2016). Throughout history, farmers used to estimate water content based on its effect on plants; water was needed whenever the plant was wilting. However, irrigation and water content are not uniformly distributed. Therefore, different methods from a variety of scientific disciplines are needed to estimate such an important quantity (Rasheed et al., 2022). The basic method of understanding the water content in any soil or unconsolidated sample is to simply weigh it before any water is lost, dry it in the oven, and then weigh it again (Pask et al., 2012). The difference in its weight is a direct measurement of its soil water content (Evelt, 2008). Another standard method is to use soil moisture probes to continuously measure the moisture content, nutrients and pH of the soil ((Ferrarezi et al., 2015). A different method was used by Dincer et al. (1974) in a sand dune in Saudi Arabia, where the water content was estimated using stable isotopes and thermonuclear tritium. Mertzaniides et al. (2020) conducted a study in northern Greece to provide a regional evaluation of spatiotemporal variations in soil moisture content in a complex clayey field. The study was conducted from June to October and resulted in identifying changes in soil moisture resistivity, whether temporally or spatially, easily, and efficiently. Another study to identify fluctuations in soil moisture content took place in Khuzestan sand dunes in Iran (Rouhipour, 2006). Water content was measured in three different locations from the sand dune in this study, and it was concluded that a source of water must be present to carry plants through dry weather times.

In northern China, a study was conducted to measure the soil water content in Horqin Sandy Land (Yao et al., 2018). The study's aim was to characterize the changes in soil water content in a fixed dune and how it responds to rainfall to understand the spatiotemporal variations in

soil water content. The study concluded that different levels of soil are affected in a distinct manner. The soil water content was lowest in the surface layer (0-10 cm), followed by the deepest layer (90-150 cm), and highest in the shallow layer (10-90 cm). The level of soil water content was significantly different among the three layers.

Table 1 below shows a compilation of water content values from the literature and their corresponding study locations, alongside the minimum, maximum, and mean values. Figure 3 is a visual representation of the points gathered from the literature review. The minimum, maximum, and mean water content values of all reviewed studies are: 0.003, 0.266 and 0.04, respectively.

Study	Country	Location	Water Content	Min	Max	Mean
Yao et al. (2018)	China	Horqin Sandy Land	0.0146	0.0146	0.0396	0.0292
			0.0309			
			0.0396			
			0.0374			
			0.0308			
			0.0269			
			0.026			
			0.0275			
Bashtian et al. (2019)	Iran	Arid alluvial fan located in Khorasan Razavi province	0.0056	0.0048	0.032	0.0143
			0.0048			
			0.008			
			0.008			
			0.021			
			0.025			
			0.016			
			0.032			
			0.009			
Ensign et al. (2006)	Canada	Pinery Provincial Park, Ontario	0.1	0.038	0.16	0.0748
			0.09			
			0.08			
			0.07			
			0.06			
			0.05			
			0.04			
			0.16			
			0.038			
			0.08			
			0.07			
			0.06			
Al-Mugrin et al. (1974)	Saudi Arabia	Riyadh Sand dune	0.0118	0.0118	0.0443	0.0273
			0.0443			
			0.0241			
			0.0244			
			0.0235			
			0.0264			
			0.0367			
Al-Agely & Reeves (1994)	USA	Colorado Sand dune	0.0102	0.0102	0.0182	0.01486
			0.0134			
			0.0155			
			0.017			
			0.0182			
Rouhipour, (2006)	Iran	Khuzestan Sand Dunes	0.0031	0.003	0.024	0.0108
			0.0164			
			0.0108			
			0.021			
			0.0215			
			0.0037			
			0.0053			
			0.01			
			0.0217			

			0.024			
			0.003			
			0.0057			
			0.01			
			0.018			
			0.0182			
Dincer et al., (1974)	Saudi Arabia	Riyadh Sand dune	0.0118	0.018	0.0443	0.0244
			0.0443			
			0.0241			
			0.0244			
			0.0235			
			0.0264			
			0.0367			
Gad et al. (2012)	Egypt	Elsahba, 1 st year	0.218	0.132	0.266	0.1945
			0.266			
		Elsahba, 2 nd year	0.132			
			0.162			
All studies				0.266	0.003	0.04

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 mean values for each study.

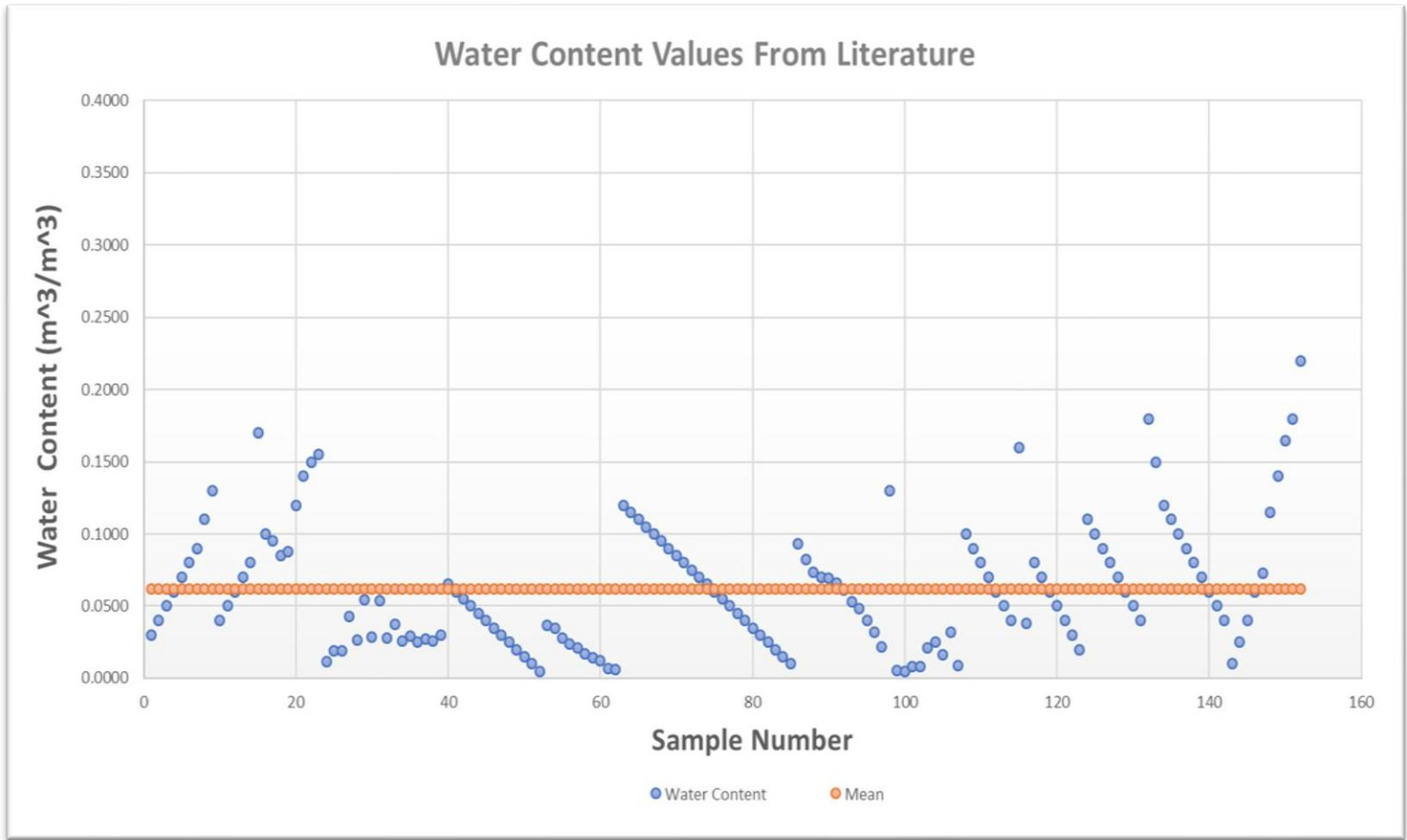


Figure 3 Water content measured from different dry sand dunes worldwide.

1.2. Water Content Estimation Using Geophysical Methods

Estimating water content using standard methodologies such as weighing samples or by using soil moisture probes can be inefficient and impractical, especially for large-scale studies since these standard methods only cover a few centimeters in a one-dimensional domain. Vereecken et al. (2008) categorized water content estimation methods into two groups: contact-based and contact-free methods. The standard methods mentioned earlier illustrate the contact-based group, while geophysical methods illustrate the latter. Therefore, geophysical methods can be very effective and helpful in larger-scale studies, providing spatial information as well as deeper depth of penetration. Mertzanides et al. (2020) conducted a study to measure the soil water content in northern Greece using surface 2D electrical resistivity tomography (ERT). The inversion revealed spatial and temporal changes in soil resistivity that reflected the inhomogeneities of the soil profiles related to water content, which varied between 0.18 and 0.3. Using electrical methods can be of great help, as they are not intrusive and provide information about water content alongside the soil depth. A study was conducted in a shaley sandy soil in the Cevennes (southern France) to monitor the soil water content (Brunet et al., 2010). The results from ERT were compared with local measurements made using time domain reflectometry (TDR), and the match proved to be well correlated. Tian et al. (2013) used a nuclear magnetic resonance (NMR) based approach to analyze the soil water characteristics in the Yellow River Delta. The study concluded that NMR is very helpful in determining not only the water content, but also its distribution with the pore size distribution. They also used this approach to characterize the mitigation process of pore water in unsaturated soil.

Geophysical methods have been proven to be successful in shallow groundwater exploration and determining the depth of the water table, and the seismic method is no different. Seismic data can be effective in water exploration because seismic velocities in unconsolidated media are a function of porosity, density, and moisture content (Adamo et al., 2005). The same study analyzed the use of an acoustic method (seismic) to determine soil properties and characteristics. The produced results provide an encouraging motive to use seismic data for obtaining soil classification, moisture estimation, and fluid distribution. Another study that took place in northern Paiko, Nigeria, was performed to evaluate the groundwater potential (Alhassan et al., 2015). The study used the seismic method to determine the depth to the water table, which ended up being approximately 14 m. Gabr et al. (2012) combined the seismic refraction method with electrical resistivity to determine the depth to the groundwater table in the Al-Ain region in the UAE. The study showed ranging seismic velocities for the weathering layer between 590 m/s and 1400 m/s, and the joint inversion estimated a depth of approximately 13 m to the water table. Al-Shuhail and Al-Shaibani (2009, 2013) used the seismic refraction method to determine the depth and thickness of the saturated zone in multiple sabkhas in eastern Saudi Arabia. Despite working effectively in determining such parameters, the seismic method fails to determine partial saturation in the subsurface, as the change in velocities is insignificant until reaching full saturation ($S_w = 100\%$).

1.3. Water Exploration by Ground Penetrating Radar (GPR)

Ground-penetrating radar (GPR) has been used in many applications, such as detecting shallow anomalies and measuring soil moisture heterogeneities (Annan, 2005). Due to its high resolution and easy accessibility, GPR is a common geophysical method for groundwater exploration and soil moisture estimations. GPR waves are also sensitive to soil water content changes and can relate the change in soil permittivity to water content (Zhang et al., 2022). Cross-hole GPR is another technique to measure soil water content (Klotzsche et al., 2018). The study was conducted in sandy sediments at the Arrenæs field site in Denmark. A total of 21 measurements measured the seasonal water content change between 2004 and 2006 and estimated it to be approximately $0.05 \text{ m}^3/\text{m}^3$. Furthermore, another study using GPR for soil water content was performed in California (Grote et al., 2003). The study compared soil water content values from GPR and gravimetric measurements, which ranged between 0.09 and $0.3 \text{ m}^3/\text{m}^3$. The values from both measurements were similar and had a coefficient of correlation of 0.94, which clearly indicates the accuracy of GPR measurements in estimating the soil water content. For this reason, and the limitation in the seismic technique in determining partial saturation values as stated in the previous section, a non-seismic technique is needed in addition to the seismic technique for better shallow-subsurface high-resolution characterization and GPR is one of the most recommended methods alongside seismic methods. I opted to use GPR in this research over other common geophysical methods such as electrical resistivity method (ES) due to its common limitations. Zhu et al. (2011) stated that Roth et al. (2002) conducted an electrical resistivity survey in Northampton County and concluded that the electrical resistivity response is dependent on the survey line orientation; as it can appear as low resistivity in one direction but high in the perpendicular orientation. Due to this and other limitations related to the known challenges of emitting electrical signals in highly

conductive/resistive environments, GPR has been favored to be the optimal supporting method. In this study, GPR electromagnetic velocities alongside seismic velocities are jointly used to invert and estimate partial water saturation in sand dunes. The proposed method will be applied to real data gathered from a site on a dune near Dammam Airport in eastern Saudi Arabia.

1.4. Problem Statement

The water content in unconsolidated sediments plays a role in determining the seismic P-wave velocity (V_P) as well as the GPR velocity (V_G). The P-wave velocity decreases slightly with increasing water saturation due to increasing density until full saturation, where it jumps significantly. As a result, partial saturation in subsurface layers is difficult to determine using only P-wave velocity.

1.5. Research Objective

The objective of this research is to estimate water saturation in partially saturated unconsolidated sediments. I will construct a P-wave velocity function in terms of water saturation and GPR velocity $V_P(V_G, S_w)$. Knowing the measured P-wave and GPR velocities as well as available information about the matrix and pore-fluid properties, it is possible to jointly invert the new $V_P(V_G, S_w)$ relation for S_w . The proposed method will be applied to real seismic and GPR data sets from a sand dune in eastern Saudi Arabia.

CHAPTER 2

METHODOLOGY

2.1 Gassmann Assumptions

Seismic P-wave velocity generally increases with depth in the subsurface due to the increase in elastic constants caused mainly by increasing pressure with depth. 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). Han & Batzle (2004) state that Gassmann's equations are commonly used to predict seismic velocity changes due to different pore fluid saturations. To produce these equations and models, several assumptions have been made (Leong & Cheng, 2012):

- i) Homogeneous and isotropic medium
- ii) Interconnected pores
- iii) Pore fluid is frictionless.
- iv) Relative motion between solid and fluid during wave propagation is negligible.
- v) Pore fluid does not interact with the solid mineral matrix.

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:

$$\frac{K_e}{K_m - K_e} = \frac{K_d}{K_m - K_d} + \frac{K_f}{\phi(K_m - K_f)}, \quad (1a)$$

$$G_e = G_d. \quad (1b)$$

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

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

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

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 (K_a and K_w) of the air and water as (Mavko et al., 2020):

$$\frac{1}{K_f} = \frac{S_w}{K_w} + \frac{1-S_w}{K_a}. \quad (3)$$

The bulk and shear moduli of the dry sediment are calculated from Hertz–Mindlin contact theory as follows:

$$K_d = \frac{C(1-\varphi)}{12\pi R} S_n \quad (4a)$$

$$G_d = \frac{C(1-\varphi)}{20\pi R} (S_n + 1.5S_t), \quad (4b)$$

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

$$S_n = \frac{4aG_m}{1-\nu} \quad (5a)$$

$$S_t = \frac{8aG_m}{2-\nu}, \quad (5b)$$

where ν is the matrix Poisson's ratio calculated as:

$$\nu = \frac{3K_m - 2G_m}{6K_m + 2G_m}. \quad (5c)$$

The parameter a is the radius of the grains' contact area given as:

$$a = \left(\frac{1}{f}\right) \left[\frac{3\pi(1-\nu)}{2C(1-\varphi)G_m} P\right]^{\frac{1}{3}}. \quad (6)$$

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

$$P = \rho_d g z, \quad (7a)$$

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

$$\rho_d = \varphi \rho_a + (1 - \varphi) \rho_m, \quad (7b)$$

where ρ_a and ρ_m are the densities of the air and matrix, respectively. The parameter f was proposed by Hanafy et al. (2020) to account for grain non-sphericity. The P-wave velocity of the saturated sediment is calculated as:

$$V_P = \sqrt{\frac{K_e + \frac{4}{3}G_e}{\rho_e}}, \quad (8a)$$

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

$$\rho_e = (1 - \varphi) \rho_m + \varphi[(1 - S_w) \rho_a + S_w \rho_w], \quad (8b)$$

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

1. Substitute equation (7b) into equation (7a) to calculate P .
2. Substitute equation (7a) into equation (6) to calculate a .
3. Substitute equations (6) and (2b) into equations (5a) and (5b) to calculate S_n and S_t , respectively.
4. Substitute equations (5a) and (5b) into equations (4a) and (4b) to calculate K_d and G_d , respectively.
5. Equation (4b) is substituted into equation (1b) to calculate G_d .
6. Solve equation (3) for K_f .
7. Solve equation (1a) for K_e and substitute K_d from equation (4a), K_f from equation (3), and K_m from equation (2a).
8. Substitute K_e from equation (1a), G_e from equation (1b), and ρ_e from equation (8b) into equation (8a) to calculate V_P .

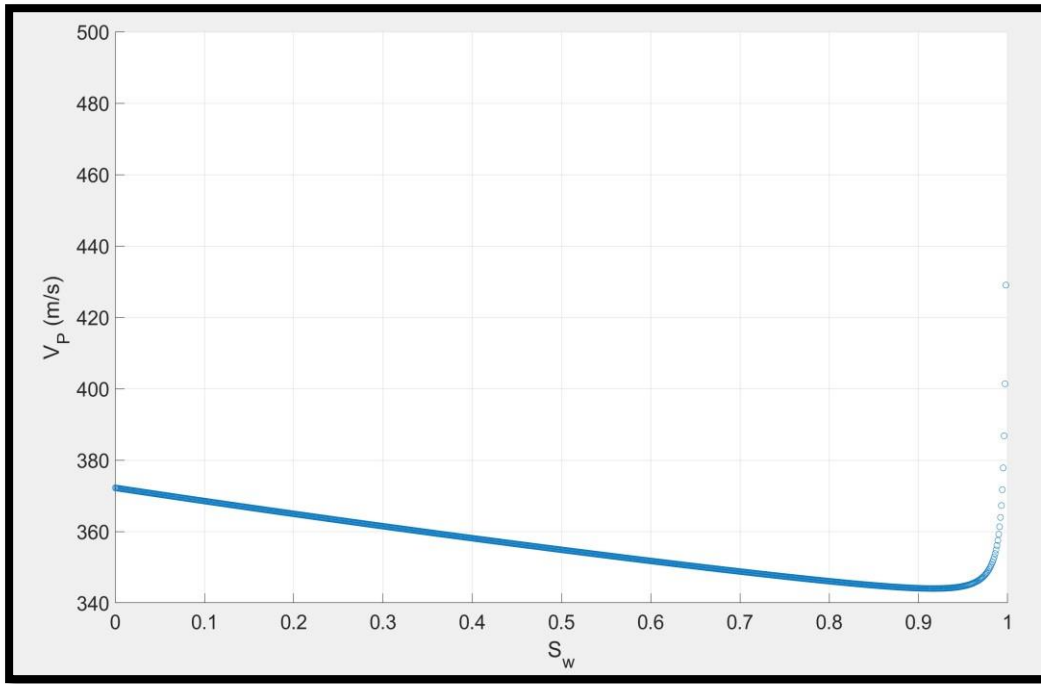
The general form of V_P is too long to reproduce here. For a sediment with properties as in Table 2, $V_P(z, S_w)$ becomes:

$$V_P(z, S_w) = \sqrt{\frac{-3.91552 \times 10^{23} + (-1.96034 \times 10^{26} + 1.96025 \times 10^{26} S_w) z^{1/3} + 1.30959 \times 10^{18} z^{2/3}}{(4.92736 + S_w)(-4.79174 \times 10^{20} + 4.7915 \times 10^{20} S_w + 4.83576 \times 10^{12} z^{1/3})}}. \quad (9)$$

Figures 4(a) and 4(b) show plots of $V_P(z, S_w = 0.3)$ and $V_P(z = 5m, S_w)$. $V_P(z)$ shows the sharp increase in P-wave velocity with depth at shallow depths that is expected by previous studies (e.g.,

Al-Shuhail, 2002; Al-Shuhail, 2006). Similarly, $V_P(S_w)$ shows a slight decrease in velocity with increasing S_w between 0 and approximately 0.9 because of increasing density; then, it increases sharply until it reaches the velocity in saturated sand at $S_w = 1.0$.

(a)



(b)

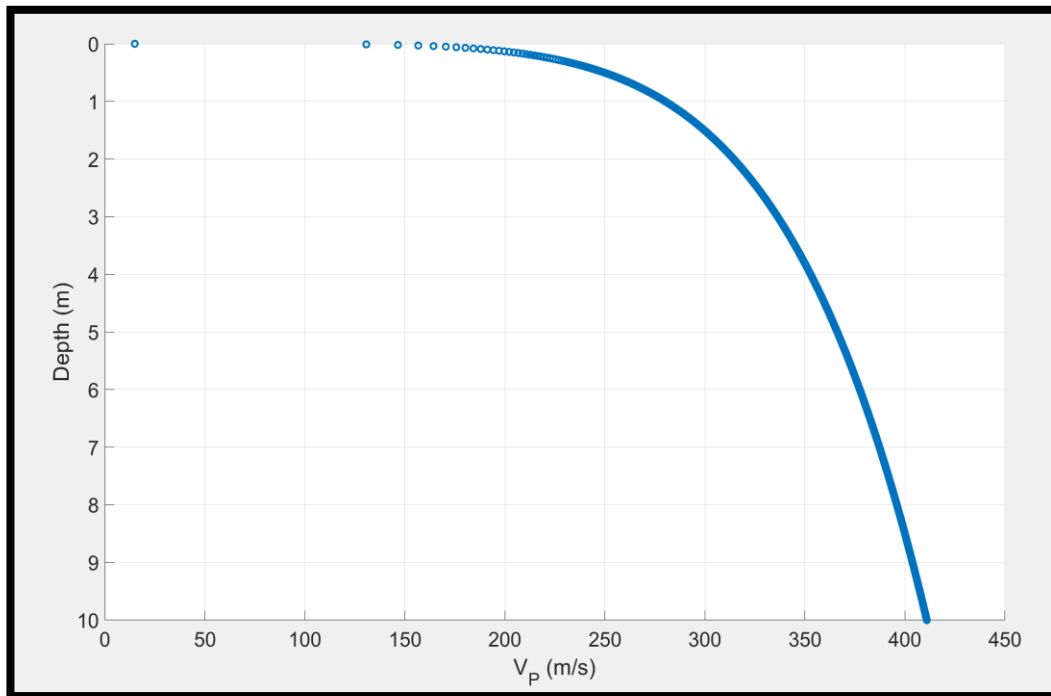


Figure 4 a) P-wave velocity as a function of S_w ($z = 5$ m, S_w) using equation (9).

b) P-wave as a function of depth V_P (z , $S_w=0.3$)

2.2 CRIM Model for GPR Velocities

In a nonconductive and nonmagnetic (i.e., low-loss) material, the velocity of a GPR wave depends on the material's dielectric constant (ϵ) as follows:

$$V_G = \frac{0.3}{\sqrt{\epsilon}}, \quad (10)$$

where V_G is measured in units of meters per nanosecond (m/ns) and ϵ is dimensionless. The dielectric constant of a fluid-filled porous material depends mainly on its water saturation and porosity. In addition, it is also dependent on the dielectric constants of the solid matrix and pore fluids in the material. To explain the relationship between V_G and ϕ and S_w in low-loss materials, several models have been proposed and tested. These models are divided into two types: empirical equations relating a material's dielectric constant to the volumetric water content WC ($\epsilon = \phi S_w$) or semi-empirical mixing formulas relating a material's dielectric constant to the dielectric constants of the solid matrix and pore fluids as well as ϕ and S_w . Topp et al. (1980) and Brisco et al. (1992) developed some of the empirical equations. On the other hand, the complex refractive index method (CRIM) and the Hanai-Bruggeman mixing formula (Bano, 2004) are part of the semi-empirical mixing formulas. Although the proposed inversion procedure can be used on other mixing formulas, the CRIM mixing formula is the one used in this study because of its common use in many similar studies. Hossain et al. (2021) utilized the CRIM approach to estimate the permittivity of heterogeneous concrete mixtures based on the permittivity of their components using GPR. Furthermore, Brovelli and Cassiani (2008) effectively used the CRIM model to monitor fluid saturation changes in porous media by linking the bulk electric properties of the porous media to their inner structure. Another study conducted by Cho et al. (2022) deployed the

CRIM analytic model to estimate the dielectric permittivity and hence define optimum Archie's parameters for water saturation estimation in shale formations.

For the material's dielectric constant, the CRIM equation offers the following formula:

$$\sqrt{\varepsilon} = (1 - \varphi)\sqrt{\varepsilon_m} + \varphi S_w \sqrt{\varepsilon_w} + \varphi(1 - S_w)\sqrt{\varepsilon_a} \quad (11)$$

where ε_m , ε_w , and ε_a are the dielectric constants of the solid matrix, water, and air in the material, respectively. Substituting Eq. (11) into (10) gives:

$$V_G(\varphi, S_w) = \frac{0.3}{(1-\varphi)\sqrt{\varepsilon_m} + \varphi S_w \sqrt{\varepsilon_w} + \varphi(1-S_w)\sqrt{\varepsilon_a}}. \quad (12)$$

In a sandy soil composed of a quartz matrix, $V_G(\varphi, S_w)$ takes the form (Table 2):

$$V_G(\varphi, S_w) = \frac{0.3}{4.5 + \varphi \{-4.75736 + 34.03529 S_w + \varphi [1.25736 + S_w (-17.9909 + 64.35561 S_w)]\}} \quad (13)$$

Figure 5 shows a plot of V_G in Eq. (13) as a function of S_w at $\varphi = 0.35$.

Property	Value
ϵ_a	1
ϵ_w	81
ϵ_m	4.5
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
g (m/s ²)	9.81

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

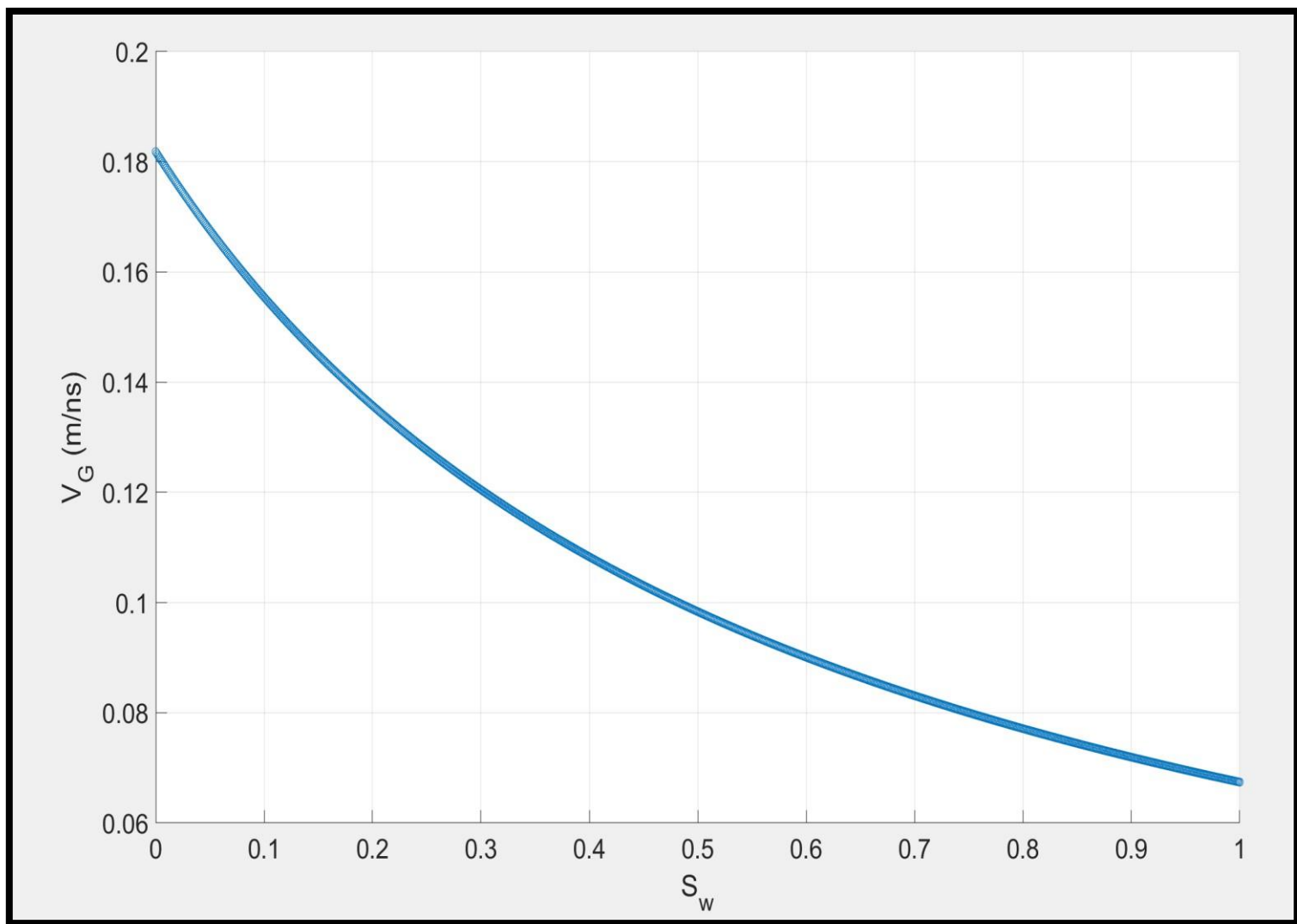


Figure 5 V_G as a function of S_w at $\phi = 0.35$.

2.3 Joint Inversion of GPR and Seismic Velocities

This methodology investigates the possibility of inverting S_w using V_G and V_P in loose sediments, with water saturation (S_w) ranging from 0 – 0.9. As stated in the previous sections, the conventional seismic refraction method can be well utilized in fully saturated sand ($S_w = 1.0$), so this analysis will be conducted on S_w values up to 0.9. However, despite the significant impact it has on life conditions in water-scarce deserts, seismic velocity changes are much less clear to observe in partial saturations ($S_w = 0 – 0.9$). Therefore, a joint inversion methodology is needed.

To invert S_w from V_P and V_G , I use the following procedure:

- (a) Solve equation (12) for φ . I obtain two solutions, of which the correct solution is:

$$\varphi = \frac{-0.3 + \sqrt{s_m} V_G}{V_G (\sqrt{s_m} - \sqrt{s_w} S_w + \sqrt{s_a} (S_w - 1))}. \quad (14)$$

- (b) Substitute φ from equation (14) in the general V_P formula. This results in a function $V_P(S_w, V_G)$, where V_G is the measured GPR velocity. The general $V_P(S_w, V_G)$ formula is too long to reproduce here.

- (c) The function $V_P(S_w, V_G)$ should be solved for S_w analytically whenever possible. However, due to its algebraic complexity, analytical solutions might take too long to obtain, and numerical solutions might be more feasible. One such solution is to try to find the S_w value that will minimize the normalized squared error (NSE) between $V_P(S_w, V_G)$ and the V_P value measured at a specific depth level defined as:

$$NSE = \left[\frac{\{V_P - V_P(S_w, V_G)\}}{V_P} \right]^2. \quad (15)$$

There is a possibility of algorithm entrapment at a local minimum value near the starting search point since most minimization algorithms depend on a starting search point. 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) to avoid such cases. The minimization algorithm should ideally return the same S_W value producing the global NSE minimum if no local minima exist regardless of the starting search point. Nevertheless, there could be local NSE minima leading the algorithm to return multiple S_W values close to various attempted starting search points for a variety of reasons (e.g., noise, error in data acquisition). In such instances, the S_W value associated with the global minimum NSE value should be selected.

2.4 Minimization Method

In many disciplines, optimization methods and techniques are applied to either minimize (e.g., applied in this study) or maximize the value of a given function (Eren, 2005). This study uses Mathematica software, which has several built-in minimization functions. These functions include Minimize, a function that finds the global minimum given certain constraints, also referred to as best fit. Moreover, given a function that has several local minima, a global minimum value may not be returned by the function. To solve such issues, different starting search points may be needed to locate the lowest local minimum that corresponds to the global minimum (Dahlquist et al., 2008). The function used in this study is FindMinimum. This function searches for a local minimum for a given function within a certain range, given certain constraints in regard to starting search points, without the use of derivatives (Wolfram Research, 2014a).

CHAPTER 3

DATA

3.1 Study Area

The investigated area is a sand dune overlaying a Sabkha layer near Dammam International Airport in eastern Saudi Arabia (Figure 6). The aeolian sand dunes that occurred in the coastal area of the Eastern Province in Saudi Arabia belong to the Al Jafurah dune field, which lies in the northern part of the Rub Al-Khali (Empty Quarter) desert (Edgell, 2006). These sand dunes accumulated during the Quaternary Period and were a result of the Bitlis-Zagros thrust belt (Anton, 1983). The northerly winds during the Pleistocene Period transported these sands and formed barchanoid dunes due to the high wind speed (Fryberger et al., 1984; Garzanti et al., 2013). The sand dunes of the studied area are generally younger than other dunes in Saudi Arabia (Anton et al., 1986). The early work on sand dunes in the Eastern Province of Saudi Arabia shows that the mineral composition consists of mainly quartz, feldspar and carbonate minerals (Garzanti et al., 2013). The underlying Sabkha sand contained quartz, feldspar, calcite and significant amounts of halite and gypsum (Hanafy et al., 2020).

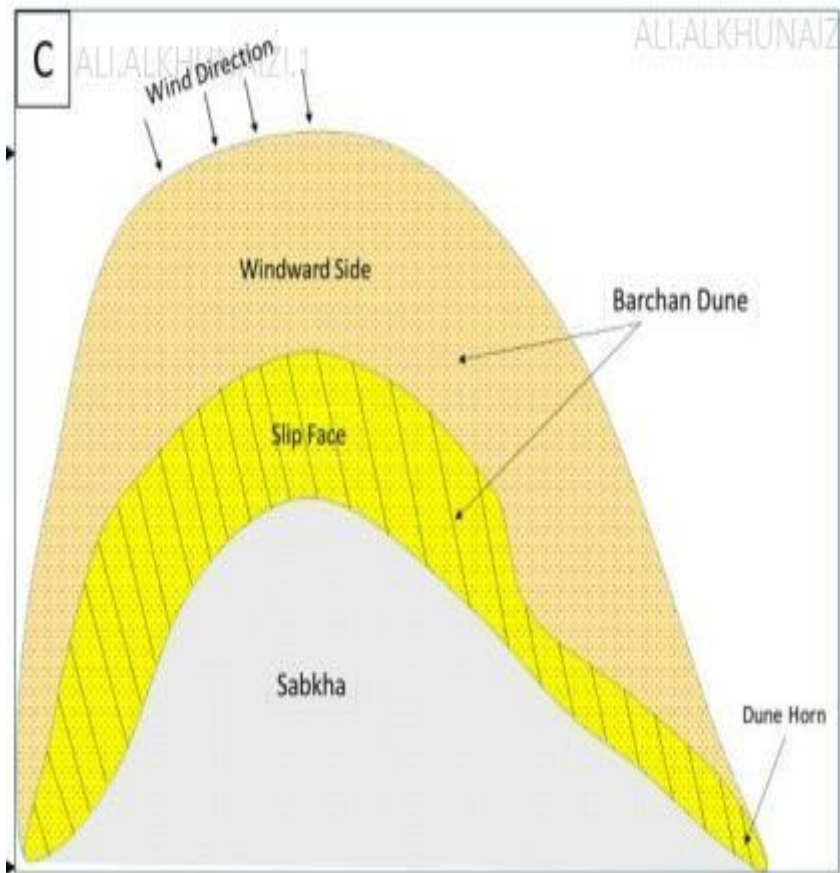
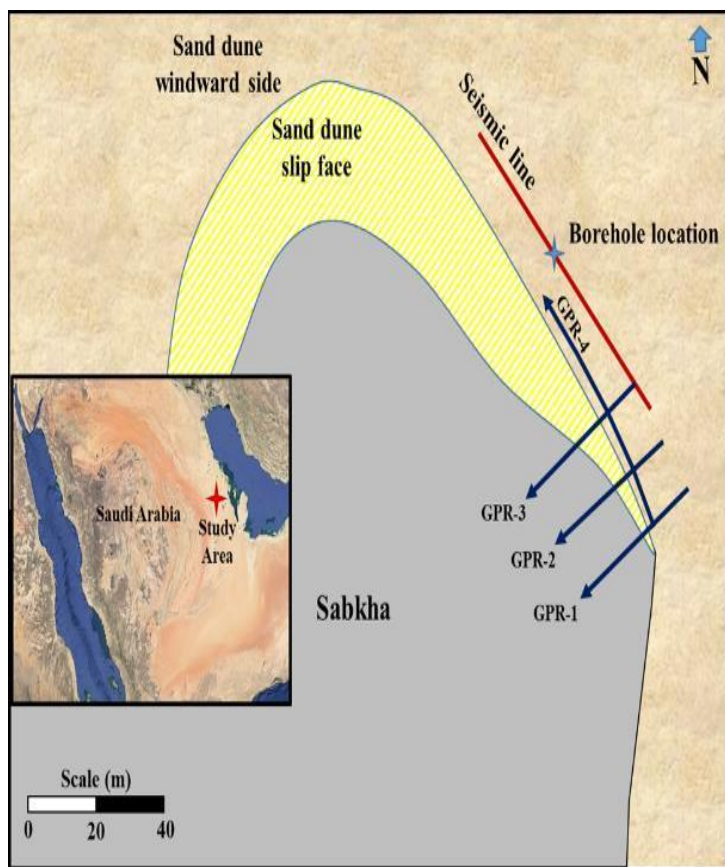


Figure 6 Study Area near Dammam Airport, Saudi Arabia (adapted from Benaafi et al., 2020)

3.2 Data Acquisition

3.2.1 GPR Acquisition

Four GPR profiles are recorded using a shielded 400 MHz antenna. Profiles P1, P2, and P3 run from NE to SW, starting on the dune and ending on the sabkha. The length of each of these profiles is approximately 40 m. Profile P4 runs almost perpendicular to the other three profiles and from SE to NW with a total length of 38 m (Figure 6).

To enhance the recorded GPR data, we apply the following processing steps:

1. **Bandpass filter.** To remove low- and high-frequency noise, we applied a bandpass filter with parameters of a low cut of 100 MHz and a high cut of 600 MHz.
2. **Automatic-gain control (AGC).** AGC is applied to the GPR data to enhance the later arrivals. The AGC window is 20 ns.
3. **2D running average.** This filter is used to decrease the random noise and smooth the data. The filter size is 5 traces by 8 ns.
4. **Moving-average subtraction.** In this filter, we calculate the moving average with the same window size as step 3 and then subtract the calculated value from the amplitude at the center of the window. Then, the window is shifted in the time direction and then in the spatial direction. Applying this filter will remove any horizontal events in the data and focus only on dipping events.
5. **Topographic correction.** The topographic correction is then applied to the recorded data to remove the effect of variable elevations along the profiles.

Figure 7 shows GPR profiles P1 to P4 after applying few processing steps only, while Figure 8 shows profiles P2-P4 after completing all the processing steps. The sand-sabkha contact can be observed in Figure 8 when the thickness of the sand is less than 40 ns (solid black lines in Figure 8). Beyond this time, the contact disappears due to the limited depth of penetration of the used GPR antenna (400 MHz).

One common midpoint (CMP) gather is recorded over the sand dune to calculate the GPR velocity to be used to convert the GPR vertical axis from the time to depth scale. The GPR CMP gather is conducted using a dual-unshielded 80 MHz antenna with a trace interval of 1 m and offsets ranging from 0 to 39 m. In this survey, the midpoint between the transmitter (Tx) and the receiver (Rx) was fixed and one trace is recorded, then the Tx 0.5 m was moved to the left of the midpoint and the Rx 0.5 m was moved to the right of the midpoint and recorded another trace. This process was repeated until the maximum offset of 39 m was reached. Figure 8a shows the recorded CMP gather. Here, the direct arrivals between the Tx and Rx form the first arrival event, which is followed by reflection from the ground surface. Then, the reflection from the bottom of the sand dune is received (marked as a solid blue line in Figure 9a). To calculate the GPR velocity, I picked the arrival times along this reflection event following the back-shifting method proposed by Booth et al. (2010). The study concludes that conventional velocity analysis on GPR CMP data can be misleading due to the nature of the GPR source wavelet. A non-minimum phase wavelet will have a zero amplitude from the first breaks and hence cannot deliver a semblance response. Instead, the semblance response will be generated from subsequent wavelet half-cycles, delayed from the first-break. Following this observation, I picked the second peak from the sabkha reflection instead of the first peak. After that, I plotted the $T^2 - X^2$ curve (Figure 9b), found the best-fit line to the $T^2 - X^2$ curve, and calculated its slope. The GPR velocity is then calculated

using the relation $V_G = \frac{1}{\sqrt{slope}}$. According to my calculations, V_G in this example is 0.1629 m/ns,

which is used to convert the time axis to the depth scale in all GPR profiles.

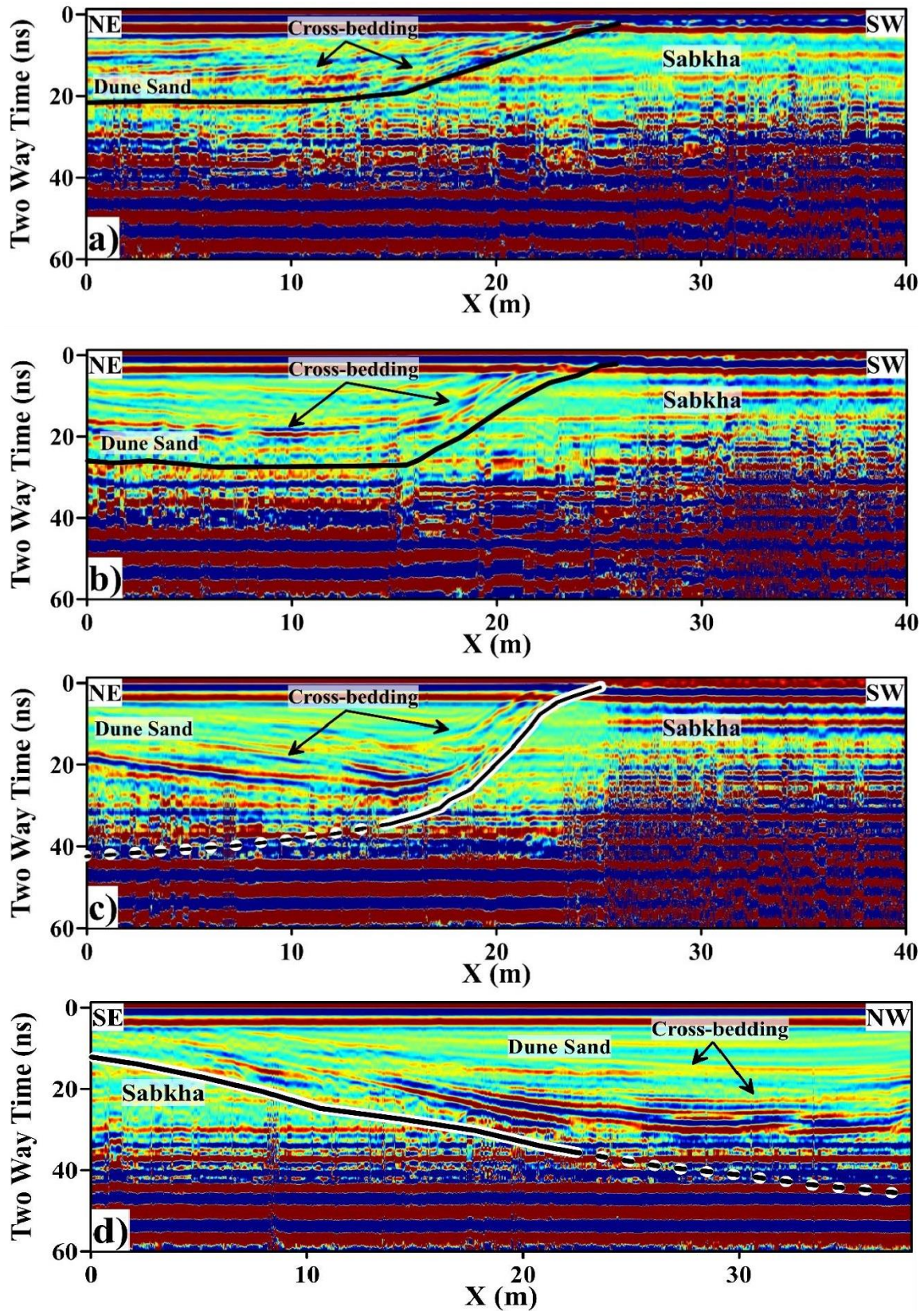


Figure 7 The GPR profiles P1 (a), P2 (b), P3 (c), and P4 (d) after band-pass, AGC, and 2D running average filters. The black solid lines show the sand-sabkha contact, while the black dashed lines

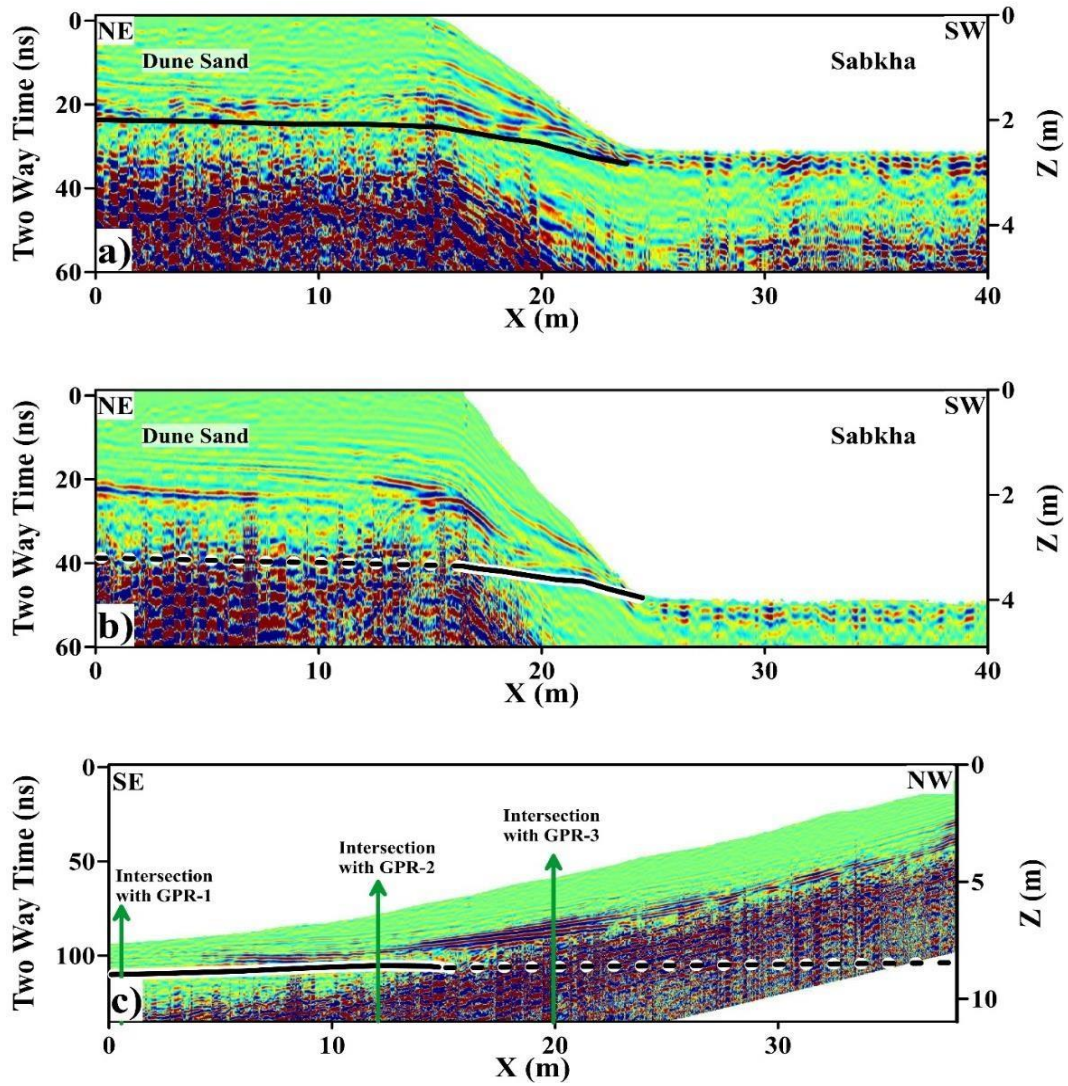


Figure 8 GPR profiles P2, P3, and P4 after all filters and topographic correction. The vertical axis is converted to depth scale using the GPR velocity 0.1629 m/ns as described in Figure 7. The black solid lines show the sand-sabkha contact, while the black dashed lines show its extrapolated location. Green lines indicate intersection points of profile P4 with profiles P1, P2, and P3.

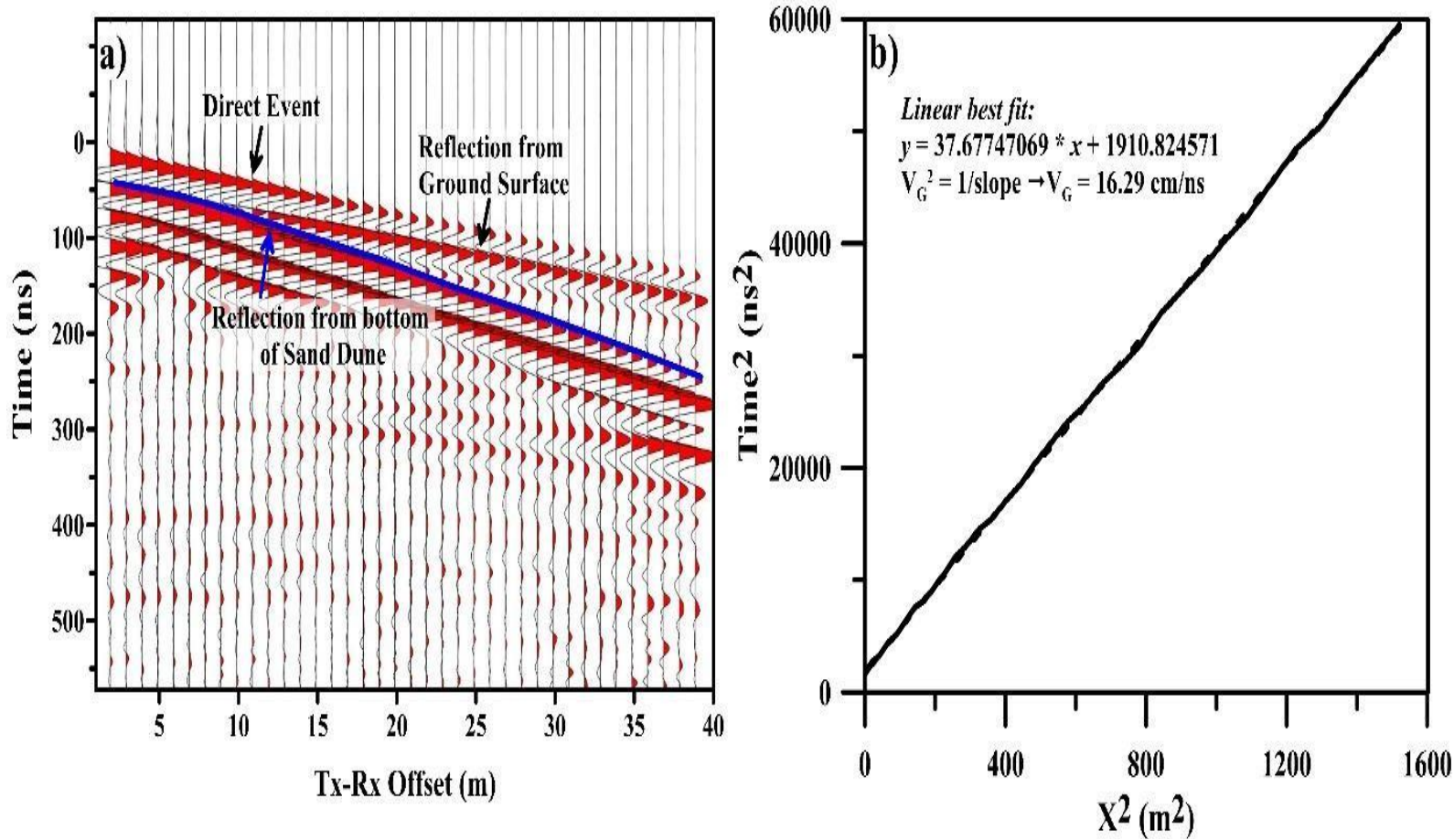


Figure 9 a) Common midpoint gather acquired near the borehole site. The direct event and reflection from the ground are indicated. The blue curve highlights the reflection from the bottom of the sand, which will be used to calculate the average GPR velocity value. b) The T^2-X^2 curve (solid curve). The best-fitting line (dashed line) and its equation are shown. The GPR velocity value is calculated to be 0.1629 m/ns.

3.2.2 Seismic Acquisition

Two seismic data sets are recorded on the same dune as described in detail by Hanafy et al. (2020). A conventional 2D data set that consists of 73 shot gathers at 1 m intervals and 37 receivers at 2 m intervals and recorded all receivers with each shot. The diving direct arrival times are then manually picked and used to estimate the velocity in the dune as a function of depth. The second seismic data set is high-resolution 2D seismic data, where the survey consisted of one shot gather and 30 receivers with variable spacings ranging between 0.1 m and 0.25 m with a total length of 5.4 m. Nine shots are fired at the same location (10 cm to the left of the first receiver) and stacked to improve the signal-to-noise ratio. The diving direct arrival times are also manually picked and used to calculate a high-resolution depth-velocity profile in the dune. The profile shows P-wave velocities ranging from 48 m/s at the top of the dune to 425 m/s at a depth of approximately 7 m. More details on the velocity profile are presented in Hanafy et al. (2020).

3.3 Matrix and Pore Fluid Data

Using a dry drilling technique, a borehole was drilled on the dune, and four sand samples were extracted at four known depths. The well penetrated the entire dune as well as the upper part of the Sabkha, as seen in Figures 9-10 (Hanafy et al., 2020). The sand samples were analyzed in the lab using the X-ray diffraction (XRD) technique to provide the mineral composition of the solid matrix. It consisted mainly of quartz with small amounts of calcite, albite, microcline, anorthite, oligoclase, and gypsum. Moreover, the porosity and water saturation of the sand samples were also measured in the laboratory and found to range between 0.304 and 0.359 for porosity and 0.05 and

0.11 for water saturation. Table 3 summarizes the XRD and petrophysical results from the sand samples (Benaafi et al., 2020).

Depth (m)	ϕ	S_w	Quartz	Calcite	Albite	Microcline	Anorthite	Oligoclase	Gypsum
0.35	0.3438	0.11	0.787	0.037	0.095	0.069	0.0	0.0	0.012
2.00	0.3015	0.05	0.8205	0.027	0.0	0.0365	0.106	0.0	0.012
3.25	0.3438	0.05	0.824	0.031	0.0	0.051	0.0	0.082	0.012
6.40	0.3590	0.07	0.876	0.020	0.046	0.046	0.0	0.0	0.012

Table 3 XRD and petrophysical analysis of the sand samples from lab measurements (Benaafi et al., 2020).

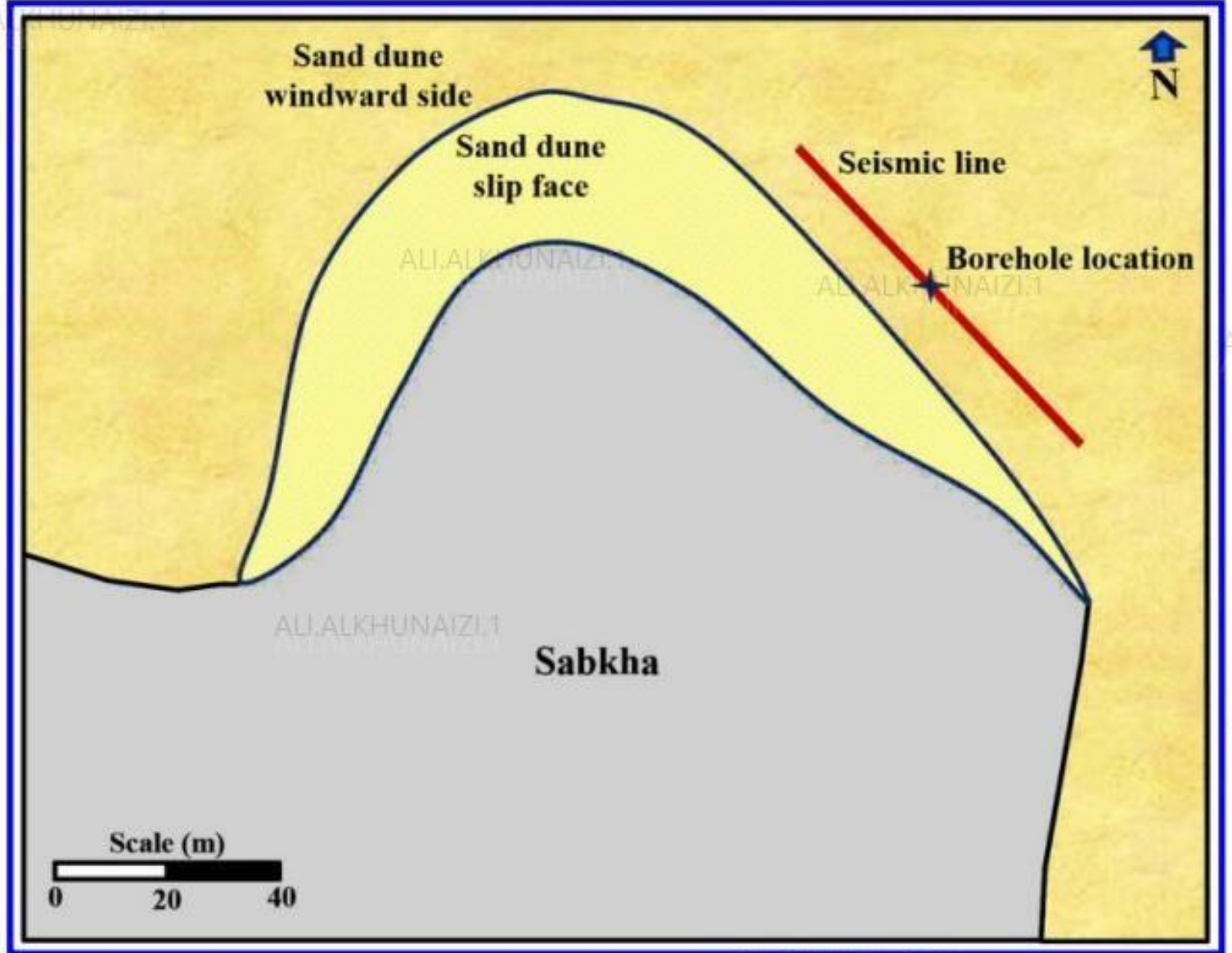


Figure 10 A sketch showing the sand dune, and sabkha, seismic line (red line), and drilling location as marked by the blue star (Hanafy et al. 2020)

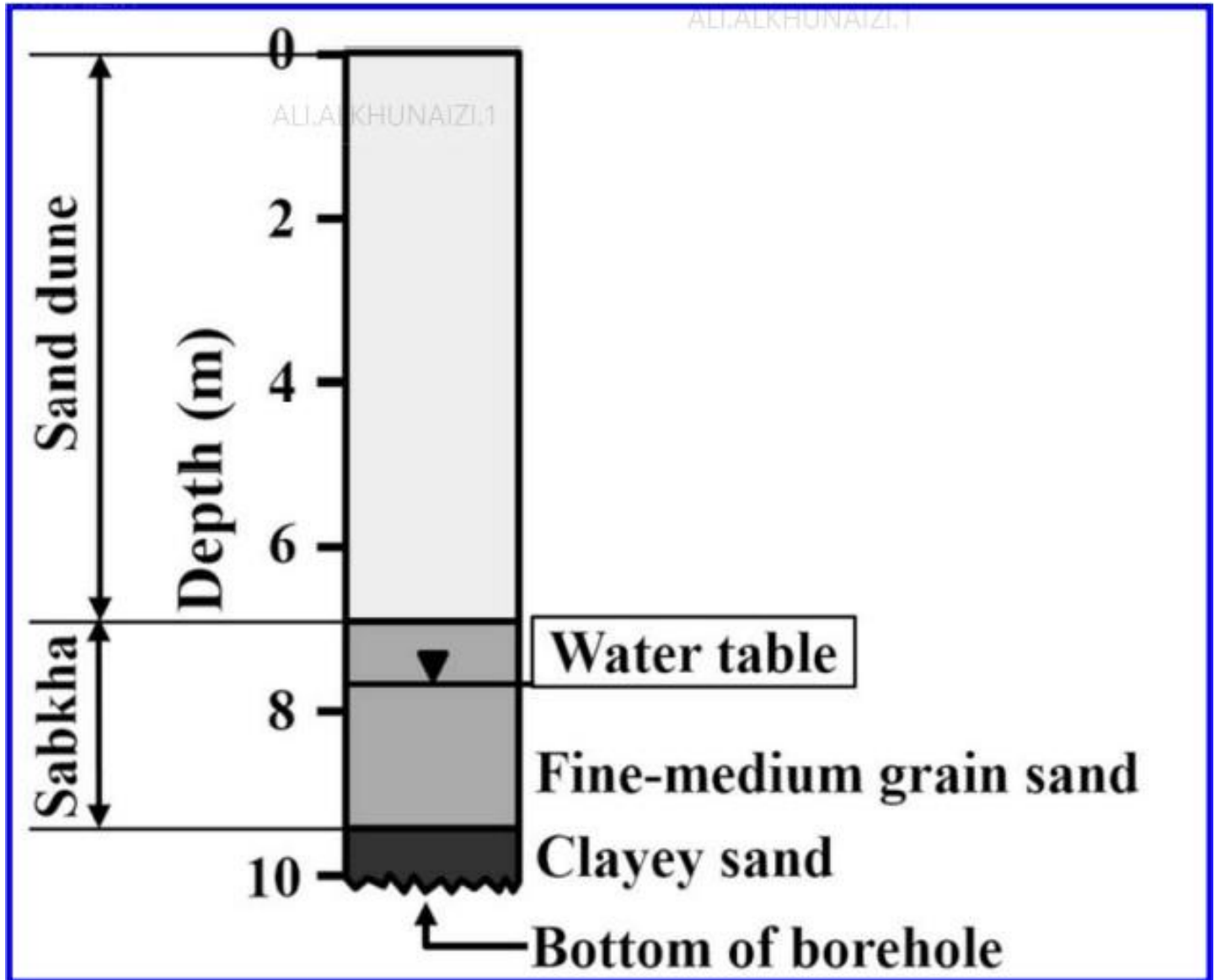


Figure 11 Stratigraphic column in a 10-m deep borehole (Hanafy et al. 2020)

CHAPTER 4

Results and Discussion

4.1 Introduction

To summarize and elaborate on what has been discussed in the previous sections, these are the steps to invert for S_w using V_P and V_G :

- 1- The dune thickness (Depth to Sabkha) was measured using differential GPS for profiles 1-3 in Figure 5.
- 2- Three GPR velocities were calculated by dividing the thickness of the sand dune by the one-way travel time of the reflection from the dune-sabkha contact, while the fourth velocity is the average for the dune obtained from the GPR CMP gather (Figure 7a). This velocity is used to convert from time to depth scale.
- 3- Seismic P-wave velocities at each depth are calculated (Table 2 of Hanafy et al., 2020) and are averaged over the analyzed depths corresponding to each GPR velocity.

Once the V_P and V_G velocities are obtained, with the assumption of a dune with a pure quartz matrix and properties given from Table 2, the steps discussed in section 2.3 are used to invert for S_w .

4.2 Inverted S_w Values

Although 68 different seismic P-wave velocities were obtained from Hanafy et al. (2020), this study is limited to depths where seismic and GPR velocities can be correlated and sand samples were extracted to analyze their properties in the laboratory (Benaafi et al., 2020). The method discussed in sections 2.3 and 4.1 is applied to both seismic and GPR velocities assuming a dune with a pure quartz matrix and properties given in Table 2.

The measured water saturation from laboratory analysis indicated a range of 0.05 – 0.11 with a mean of 0.07, while the inverted water saturation ranged from 2.35787×10^{-6} - 0.115907 with a mean of 0.0704241. The following equation was used to calculate the absolute percentage error between each measured and inverted S_w value:

$$\text{Percentage Absolute Error} = 100 \times \left| \frac{\text{Inverted } S_w - \text{Measured } S_w}{\text{Measured } S_w} \right|. \quad (20)$$

The error ranged from 26.8% - 131.813%; however, the error between the two mean values of the measured and inverted S_w does not exceed 1% and is calculated by equation 20 to be 0.605793%. Table 4 shows the input and output parameters and values of the proposed inversion method when applied to seismic P-wave and GPR velocities. Figure 12 shows how inverted S_w values are compared to measured S_w values from the lab analysis, while Figure 13 shows the corresponding water content, with both mean values presented. Table 4 also includes the corresponding water content values to facilitate comparison with water content values from the literature since water content is commonly used in engineering aspects ($WC = S_w * \phi$).

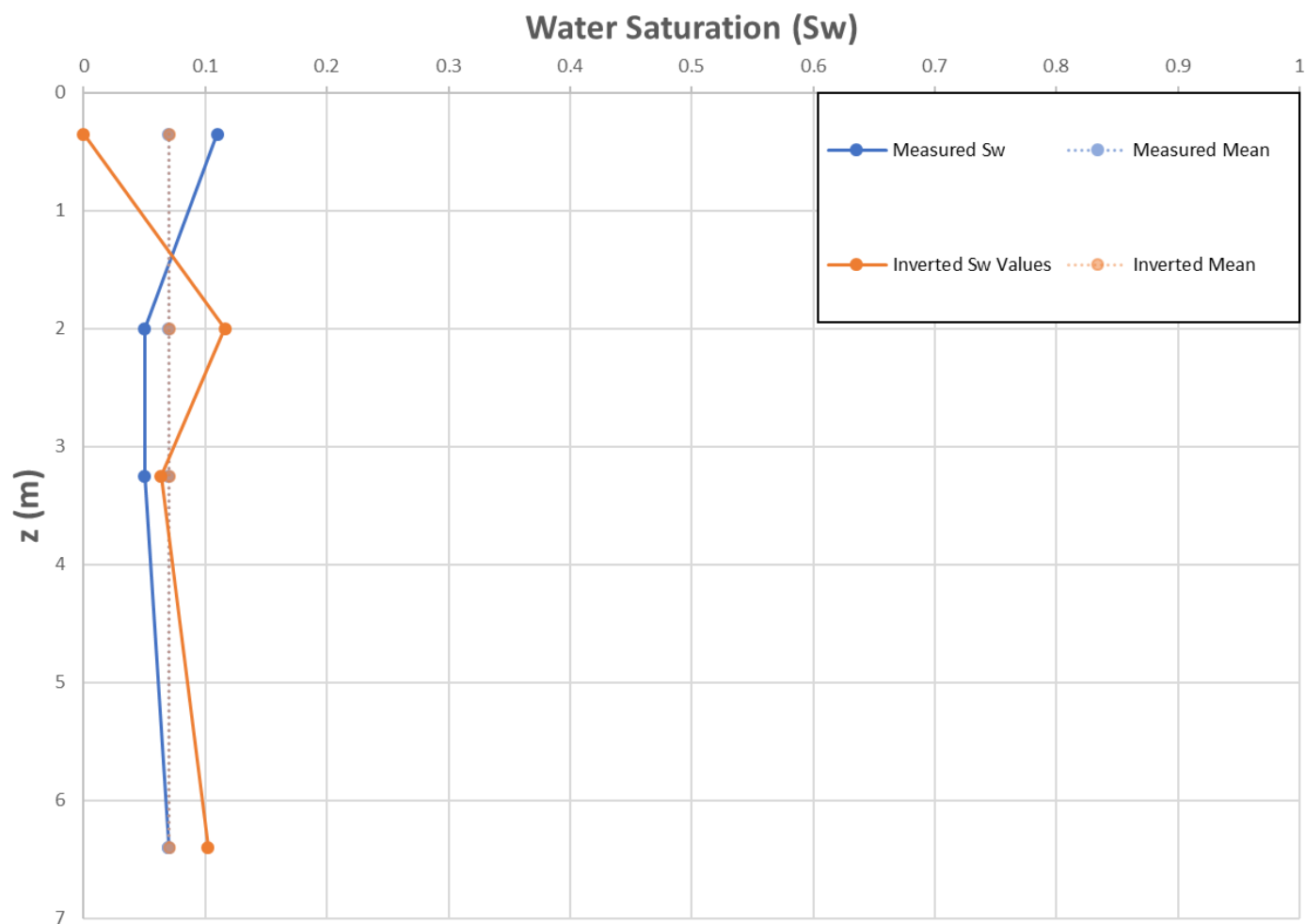


Figure 12 Measured and inverted water saturation values for the real data.

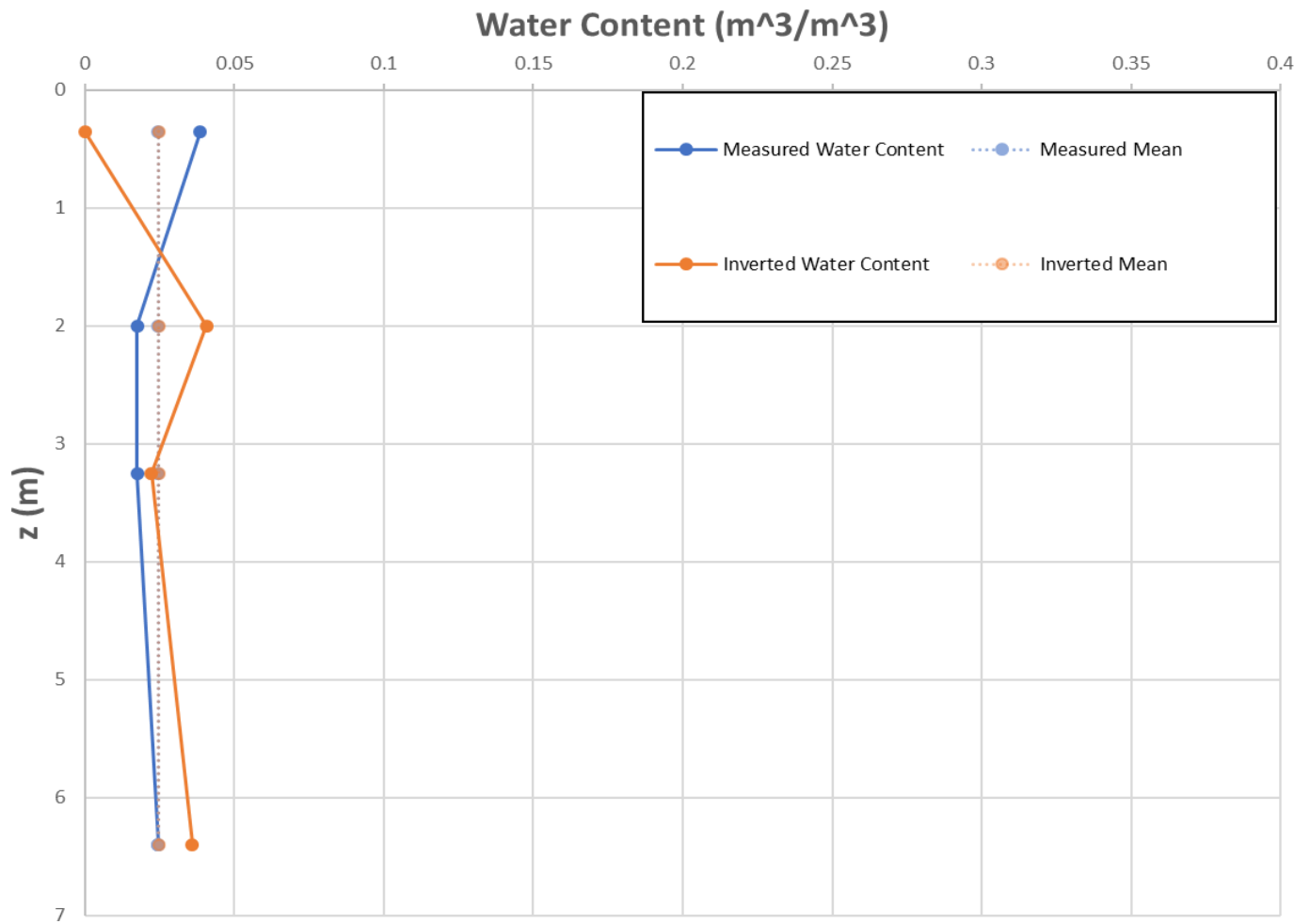


Figure 13 Measured and inverted water content values for the real data.

Sample no.	Sample depth (m)	V _P (m/s)	V _G (m/ns)	Measured water saturation	Measured water content	Inverted water saturation	Inverted water content
1	0.35	212	0.0738	0.11	0.0385	2.3519×10^{-6}	8.25255×10^{-7}
2	2.00	257	0.1544	0.05	0.0175	0.115907	0.04056745
3	3.25	271	0.1962	0.05	0.0175	0.0633784	0.02218244
4	6.40	317	0.1629	0.07	0.0245	0.102409	0.03584315
Min	0.35	212	0.0738	0.05	0.0175	2.3519×10^{-6}	8.25255×10^{-7}
Max	6.40	317	0.1962	0.11	0.0385	0.115907	0.04056745
Mean	3	264.25	0.146825	0.07	0.0245	0.070424189	0.024648466
Median	2.625	264	0.15865	0.06	0.021	0.0828937	0.029012795
SD	2.558971147	43.24638713	0.051917651	0.028284271	0.009899495	0.051963422	0.018187198

Table 4 Measured sample depth, corresponding P-wave and GPR velocities. Measured water contents and corresponding saturation 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.

4.3 Discussion

As illustrated in section 4.2, there is a considerable difference between the individual inverted and measured S_w values. Despite this, both individual values show a dune with very low water saturation. Moreover, the overall mean between the inverted and measured sets is almost identical, with an error of less than 1%, representing the reliability of the inversion algorithm used. Additionally, the aim of this study is to determine the overall state of saturation in the studied dune (very dry), regardless of the exact individual S_w values because of its practical importance in taking decisions for further development. Figure 14 shows how both the inverted and measured water content values compare with other measurements from different dunes across the world. Both data sets fall within the range of world water content values.

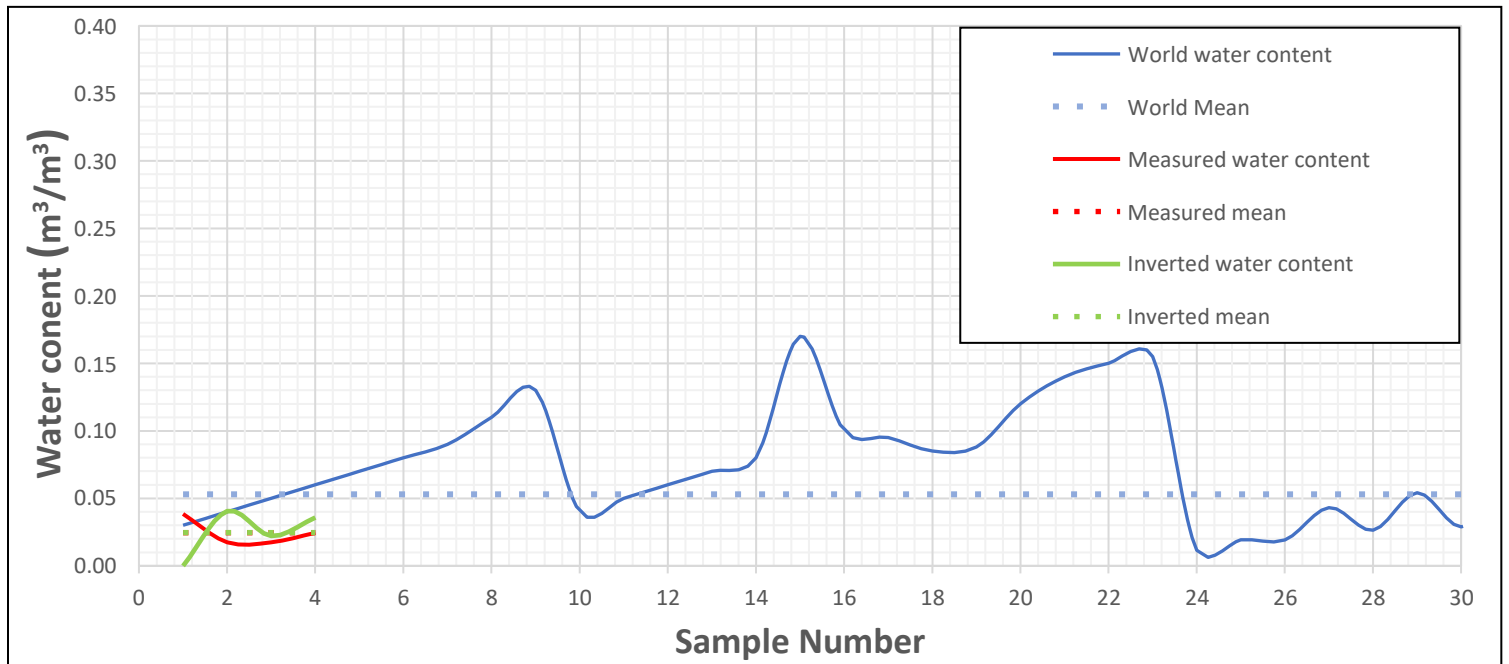


Figure 14 Comparison of inverted water content (green), measured from world dunes (blue) and measured from (Benaafi et al., 2020) (red), as well as the mean for each data set (dashed lines).

4.4 Sensitivity Analysis

In the proposed inversion method discussed earlier, several assumptions have been made that can be summarized in the following points:

- 1- Pure quartz matrix
- 2- Constant porosity of 35%
- 3- Sphericity factor of 3.1 (Hanafy et al., 2020)

To have confidence that these assumptions did not affect the inverted S_w values, I performed a simple sensitivity analysis to see how each parameter can affect the measurements. Starting with the first assumption, three tests were performed while alternating the quartz percentage in the sand sample (80% - 100%), with an arbitrary combination of the other minerals. Table 5 shows how the inverted S_w values vary with the variation in quartz percentage. The difference is quite negligible except for percentages of 85% and 80% where the inverted S_w values for depths 2m and 6.4 m are distinctly different. Further investigation is recommended regarding this observation.

Furthermore, I use the matrix and porosity values measured in the laboratory to derive the corresponding $V_p(z, S_w)$ and then invert for S_w to see the effect of assuming a pure quartz matrix and a constant porosity of 0.35. Comparing Figures 13 and 15 shows that both cases lead to the same conclusion: a very dry dune in general. Table 6 summarizes these results.

Quartz %	Inverted S_w Values			
	0.35 m	2 m	3.25 m	6.4 m
100	2.35787×10^{-6}	0.115907	0.063378	0.102409
95	2.43301×10^{-6}	0.11571	0.063275	0.102211
90	2.52773×10^{-6}	0.115517	0.063157	0.102004
85	1.08514×10^{-6}	2.41777×10^{-6}	0.064855	3.29254×10^{-6}
80	8.32456×10^{-7}	1.35342×10^{-6}	0.0653	2.1×10^{-6}

Table 5 Inverted S_w values with varying Quartz %.

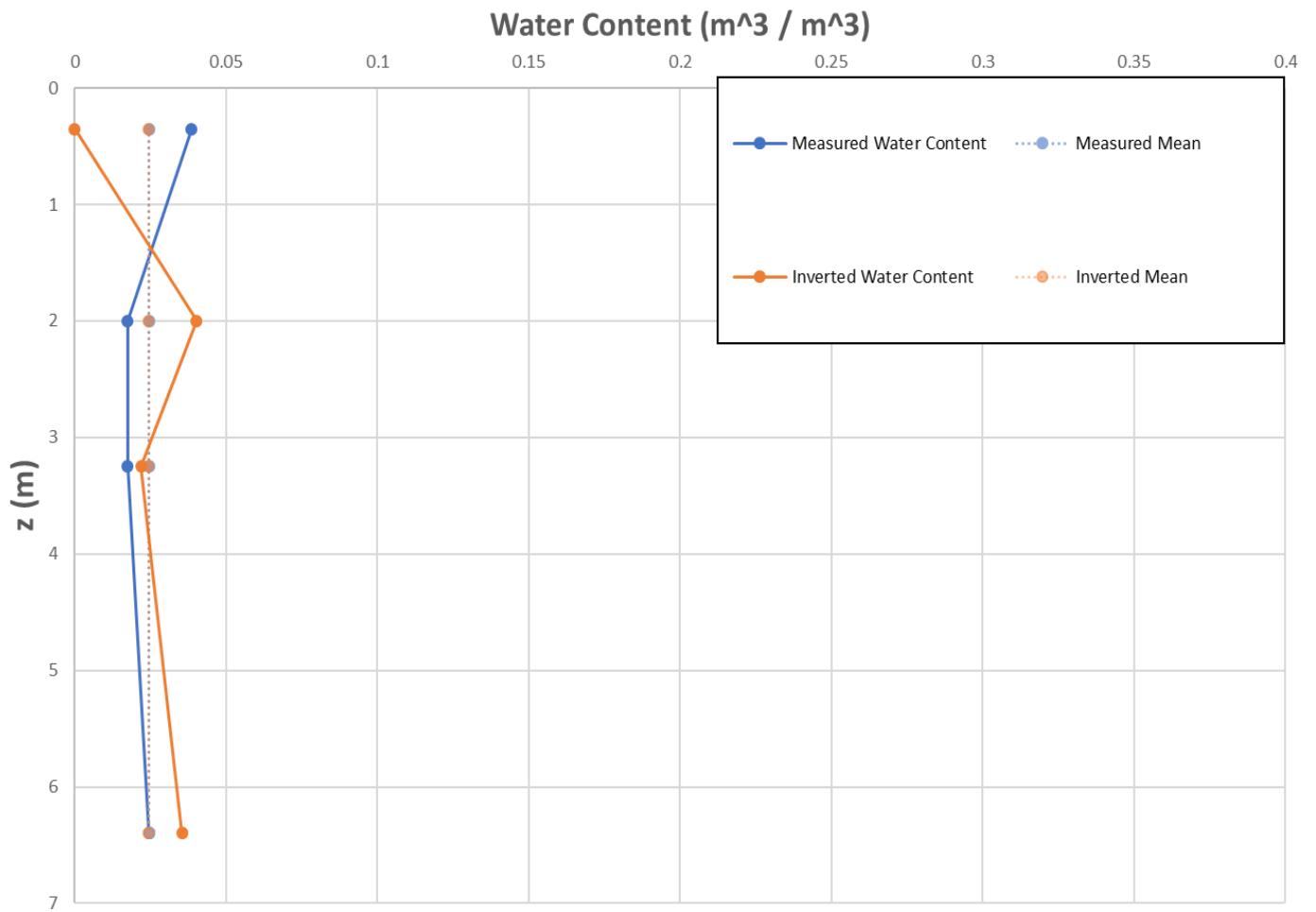


Figure 15 Measured and inverted water content values for the real data using true matrix parameters.

	Inverted S_w Values			
Depth	0.35 m	2 m	3.25 m	6.4 m
True Matrix Parameters	2.93849E-06	0.114884	0.062743	0.101304
Assumed Matrix Parameters	2.35787E-06	0.115907	0.063378	0.102409

Table 6 Comparison between inverted S_w values using true and assumed matrix parameters.

Moving on to the last assumption, sphericity factors of 1, 2, 3.1 and 4 have been assumed to see the effect it can have on the inverted S_w values. Figure 16 shows the comparison between the different sphericity factors, while Table 7 summarizes the results.

This analysis performed over the uncertain and assumed parameters shows that the assumptions had little to no effect on the inversion procedure. However, they can also be sources of error between the inverted and measured S_w values. The lab measurements and how accurate the measured S_w value might have a certain degree of uncertainty and can be another source of error.

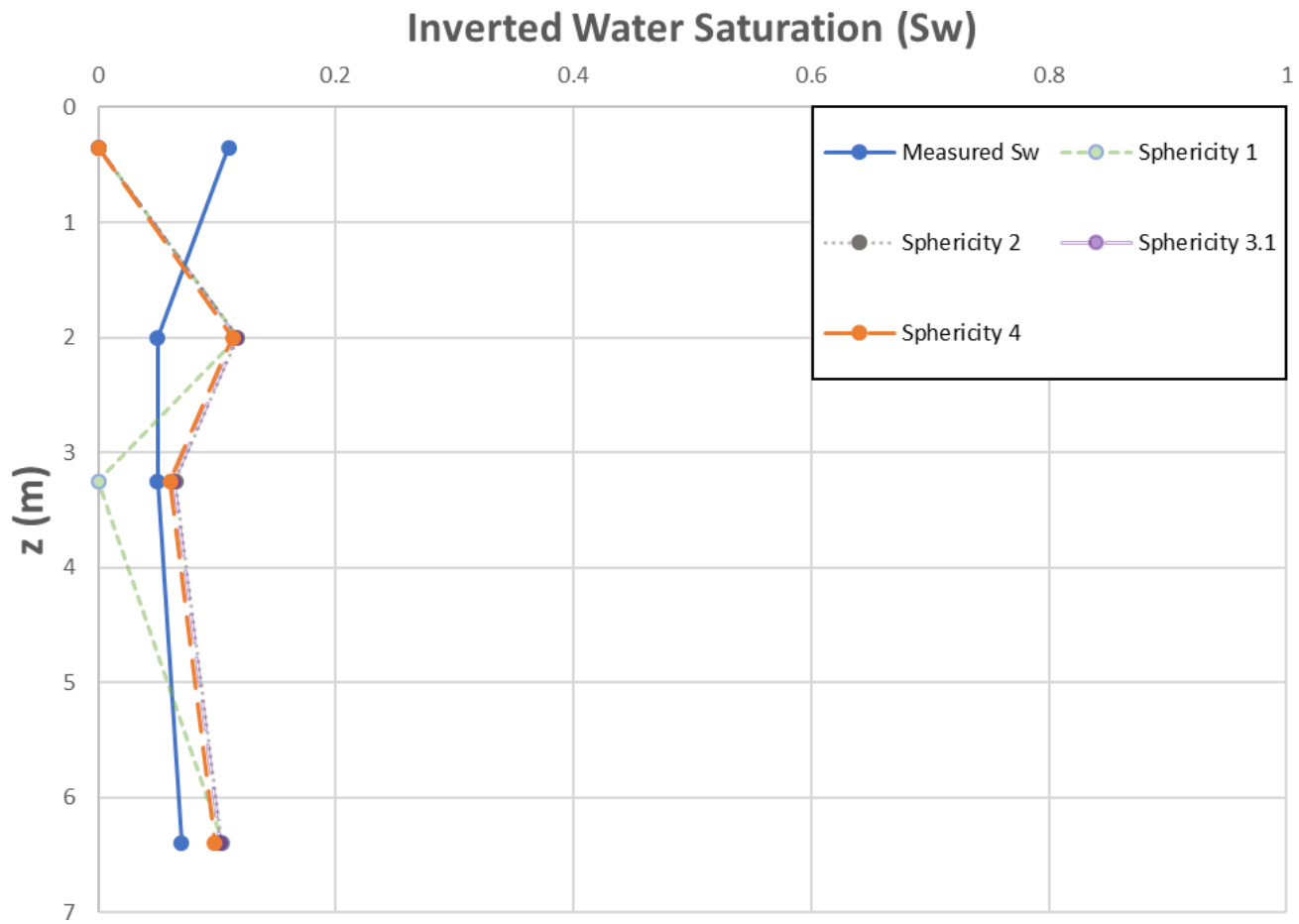


Figure 16 Effect of different sphericity factors on the inverted S_w value.

Sphericity Factor		Inverted S _w Values		
Depth	0.35 m	2 m	3.25 m	6.4 m
1	1.77017 x10 ⁻⁷	0.1173	0	0.104551
2	6.24771 x10 ⁻⁷	0.1169	0.064841	0.103929
3.1	2.35787 x10 ⁻⁶	0.1159	0.063378	0.102409
4	0.0000872	0.1134	0.060403	0.0981407

Table 7 Inverted S_w values with different sphericity factors.

CHAPTER 5

Conclusions & Recommendations

5.1 Conclusions

This study used a minimization approach to invert water saturation S_w from seismic P-wave and GPR wave velocities in partially saturated unconsolidated sediments. The inversion algorithm relates V_G and V_P to S_w through the CRIM and Gassmann-Hertz-Mindlin models, respectively. Lab analysis of sand samples from various depths in the dune provided the fractional volumes of the main matrix minerals. In addition, true porosity and water saturation values were measured in the laboratory and were used for comparison with estimated values. The seismic data were acquired using high-resolution and conventional surface seismic surveys, while GPR data were acquired via a zero-offset conventional GPR survey and a GPR CMP survey. The V_P and V_G measurements, pure quartz matrix, and pore-fluid properties were the input parameters of the inversion algorithm.

The proposed inversion method was tested on 4 samples acquired in a sand dune in Dammam, Saudi Arabia, where water saturation S_w was measured at various depths while holding the assumptions of a pure quartz matrix and a constant porosity of 35%. Despite the variation in individual S_w values between the measured and inverted sets, they shared a mean of $\sim 0.07\%$, and the error was less than 1%. Furthermore, the overall range of both measured and inverted sets indicates a dry sand dune. The assumed parameters shared the same inverted S_w statistics as when using true matrix and porosity values measured in the lab. A possible reason for the error in the

S_w values could be due to the averaging process I used to calculate both GPR and seismic velocities, as they yield an average water saturation value. However, S_w was measured in the lab using sand samples at specific depths, which might differ locally from its corresponding average. Nevertheless, both the measured and inverted water content values fall within the range of other water content values collected from different dunes under the same conditions across the globe.

5.2 Recommendations

As discussed in this study, the proposed method utilizes both the P-wave velocity and the GPR velocity to jointly invert S_w using a numerical minimization technique. Moreover, the assumptions made proved to be completely valid for this sand dune in Dammam, Saudi Arabia. However, more effort can be made to further improve the method, and hence, I recommend the following:

- 1- Expanding the method and generalizing it over different matrix and pore fluid properties. Moreover, it can be further expanded to invert for S_w alongside porosity at once.
- 2- The velocities used in this method (P-wave and GPR) are average velocities; hence, the inverted S_w is the average saturation for the given interval. The proposed method should be improved to invert the interval S_w for better comparison to lab-measured S_w .
- 3- The method was tested on a very dry sand dune. Further tests on saturated dunes should be performed to prove the robustness of the method.

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Vitae

Name : Ali Ahmed Alkhunaizi |

Nationality : Saudi |

Date of Birth : 3/29/1998 |

Email : alkhunaizi.ali@gmail.com |

Address : Al Majidiyah, Qatif 32632, Eastern Province, Kingdom of Saudi Arabia. |

Academic Background : **2021- Present:** Saudi Aramco

2016-2021: Bachelor's degree in Geophysics, King Fahd University of Petroleum & Minerals (KFUPM).