

**Estimation of water saturation in a sand dune using
electrical conductivity and seismic methods**

BY

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In

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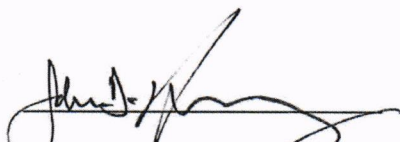
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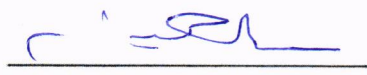
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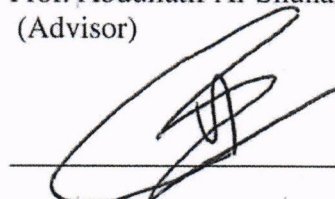

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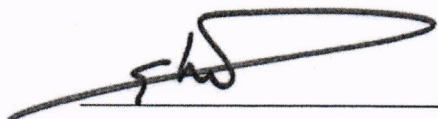
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Dedication

I would like to dedicate this Master's thesis to my Sheikh, My Family, and my friends. Their unwavering support and encouragement have been instrumental in the successful completion of this research work.

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LIST OF ABBREVIATIONS

a : radius of the grain contact area (m)

C_a : conductivity (mS/m) of the Albite of the matrix

C_{air} : conductivity (mS/m) of the air of the matrix

C_c : conductivity (mS/m) of the Calcite of the matrix

C_g : conductivity (mS/m) of the Gypsum of the matrix

C_i : conductivity (mS/m) of the i^{th} mineral of the matrix

C_{mc} : conductivity (mS/m) of the Microcline of the matrix

C_n : conductivity (mS/m) of the Anorthite of the matrix

C_o : conductivity (mS/m) of the Oligoclase of the matrix

C_q : conductivity (mS/m) of the Quartz of the matrix

C_w : pore-water conductivity (mS/m)

C_m : conductivity of the matrix (mS/m)

$CRIM$: complex refractive index method

C_s : conductivity of saturated sand

D : the maximum penetration depth of the diving direct wave

ERT : electrical resistivity tomography

f : factor proposed by Hanafy et al. (2020) to account for grain nonsphericity

g : gravitational acceleration (m/s^2)

G_d : effective shear modulus of dry sand (N/m^2)

G_e : effective shear modulus of saturated sand (N/m^2)

G_i : shear modulus of the i^{th} mineral phase of the matrix (N/m^2)

G_m : effective shear modulus of a sand matrix (N/m^2)

K_a : bulk modulus of pore air (N/m^2)

K_d : effective bulk modulus of dry sand (N/m^2)

K_e : effective bulk modulus of saturated sand (N/m^2)

K_f : effective bulk modulus of pore fluid (N/m^2)

K_i : bulk modulus of the i^{th} mineral phase of the matrix (N/m^2)

K_m : effective bulk of sand matrix (N/m^2)

K_w : bulk modulus of pore water (N/m^2)

N : coordination number (average number of grain contacts per grain)

P : lithostatic pressure exerted on the grains (N/m^2)

p_i : volume fraction of the i^{th} mineral phase of the matrix

PPT : total dissolved solids (TDS) (parts per thousand)

R : average radius of the spherical grains (m)

S_n : Normal Stiffness (m^2/N)

S_t : tangential stiffness (m^2/N)

S_w : water saturation

t : traveltime (s)

VES : vertical electric sounding

ν_m : Poisson's ratio of the sand matrix

V_P : P-wave velocity (m/s)

V_{pc} : calculated P-wave velocity (m/s)

V_{pm} : calculated P-wave velocity (m/s)

W_C : Water content

x : offset (m)

z : sand thickness (m)

φ : porosity

ρ_a : density of air (kg/m^3)

ρ_d : density of dry sand (kg/m^3)

ρ_e : effective density of saturated sand (kg/m^3)

ρ_i : density of the i^{th} mineral phase of the matrix (kg/m³)

ρ_m : density of sand matrix (kg/m³)

ρ_w : pore-water density (kg/m³)

ABSTRACT

Full Name : [Omar Tarchi]
Thesis Title : [Estimation of Water Saturation in a Sand Dune using Electrical Conductivity and Seismic Methods]
Major Field : [Master of Science in Geophysics]
Date of Degree : [November 2023]

Determination of water saturation (S_w) in sand dunes is essential for any human activity, particularly in desert areas where this resource is difficult to investigate. The objective of this study is to use joint inversion of seismic and conductivity (C) measurements to characterize the water saturation in sand dunes in dry areas during the dry season. A procedure for inverting S_w from measurements of electric conductivity and seismic P-wave velocities (V_p) will be presented. The process of inversion employs the complex refractive index method (*CRIM*) model, which relates the conductivity of a sand to its saturation, matrix, and pore-fluid properties. For the seismic P-wave velocity, the Gassmann-Hertz-Mindlin model will be used for sands with porosity values similar to their respective critical porosities. The inversion procedure was tested on 10 couples of C - V_p measurements acquired in a sand dune located near Dammam Airport in eastern Saudi Arabia. The results show for S_w a minimum of 0.04566, a maximum of 0.09945 and a median of 0.05142. In the meanwhile, the experiment shows for S_w a minimum of 0.01389, a maximum of 0.11198 and a median of 0.04571. Both of inverted and measured water saturation values S_w show a dry sand dune, these results are enough in most applications.

ملخص الرسالة

الاسم الكامل: عمر طرشي

عنوان الرسالة: تقدير تشبع المياه في الكثبان الرملية باستخدام الناقلية الكهربائية والموجة الزلزالية الأولية المباشرة

التخصص: الماجستير في علوم الجيوفيزياء

تاريخ الدرجة العلمية: ديسمبر 2023

يعد تحديد تشبع المياه في الكثبان الرملية أمرًا ضروريًا لأي نشاط بشري، لا سيما في المناطق الصحراوية حيث يصعب التحقيق في وجود هذا المورد الطبيعي. الهدف من هذه الدراسة هو استخدام الانعكاس المشترك لسرعة الموجة P الزلزالية وقياسات الموصلية (C) لتوصيف تشبع الماء في الكثبان الرملية في المناطق الجافة خلال موسم الجفاف. سيتم تقديم إجراء لعكس تشبع الماء S_W من قياسات الموصلية الكهربائية وسرعات الموجات P الزلزالية. تستخدم عملية الانعكاس نموذج معامل الانكسار المعقد ($CRIM$) الذي يربط موصلية نوع من الرمال بتشبعها ومصفوفة التربة وخصائص سائل المسام. بالنسبة لسرعة الموجة P الزلزالية، سيتم استخدام نموذج Gassmann-Biot للتربة ذات قيم مسامية مماثلة للمسامير الحرجة لكل منها. تم اختبار إجراء الانعكاس على 10 أزواج من قياسات $C-Vp$ تم الحصول عليها في كثبان رملية تقع بالقرب من مطار الدمام في شرق المملكة العربية السعودية. تظهر النتائج لقيم S_W بحد أدنى 0.04566، بحد أقصى 0.09945 ومتوسط 0.05142. في غضون ذلك، تظهر التجربة لـ S_W ما لا يقل عن 0.01389، بحد أقصى 0.11198 ومتوسط 0.04571. تظهر كل من قيم المياه المقلوقة والمقاسة S_W كثبانًا رمليًا جافًا، وهذه النتائج كافية في معظم التطبيقات.

CHAPTER 1

INTRODUCTION

Sand dunes are very challenging in terms of natural resource exploration and production. These challenges are targets for geoscientists to solve. For many sustainability reasons, water content needs to be determined and estimated in desert areas. Water availability in these areas is one of the most challenging tasks that needs to be solved due to the variability of water content and sand characteristics in space and time. Different geophysical methods and tools have been used in the past to explore water in deserts. Conductivity is used in water exploration, but it offers a large range of values that might be difficult to interpret. Refraction seismic has been used before to detect refractions from saturated formations. However, this method cannot be used to explore water in formations with low to medium saturations.

I use an inversion technique similar to that of Al-Shuhail (2017) to estimate water saturation in sand dunes. The main objective of this study is to determine the degree of saturation, but it is not to estimate the exact values of the water saturations. Therefore, to drill a well for water exploitation, people are not interested in the exact value of water saturation but more for the degree of saturation (low or high).

The inversion procedure uses seismic and conductivity data to estimate the degree of water saturation in subsurface rocks. In this study, I applied this method to estimate the degree of water saturation in a dune from seismic and conductivity data acquired on a barchan

sand dune near Dammam Airport in eastern Saudi Arabia. The results will be compared to true saturation data measured in the laboratory using sand samples acquired from the dune at various depths. Furthermore, the results will be compared to real saturation data published in the literature measured in sands of desert areas with similar dry conditions to the studied area.

1.1 Water in Sand Dunes

Water in sand dunes is a very important resource in desert areas. The presence of this rare resource is fundamental for natural and industrial processes, particularly during the dry season in semiarid and arid areas (Scheidt et al., 2010). In recent years, the demand for water has increased, and water exploration and investigation have increased considerably using different scientific tools. It is important to investigate the moisture in such sparse sand at different depths as well as the relationship between water content and geophysical response.

Dincer et al., (1974) conducted a study on sand dunes in Saudi Arabia, utilizing stable isotopes and thermonuclear tritium to measure the water content within the sand dune. The findings revealed a minimum water content of 0.0118, a maximum of 0.0443, and a median value of 0.0244.

Al-Sanad et al., (1993) studied the properties of dune sands in four different sand dune sites in Kuwait using geotechnical lab tools. The minimum recorded water content is 0.0011, the maximum is 0.0045, and the median is 0.0022.

Zuo et al., (2008) studied the properties of the soil in sand dunes in northern China under restoration and grazing. The results show that the median water content is 0.0218, with a

minimum of 0.0055 and a maximum of 0.0493. Pan and Wang (2009) studied the spatial variability of water content and the controlling factors in the Tengger Desert in northern China. The soil moisture in this study area varies between a minimum of 0.0122 and a maximum of 0.1529, with a median of 0.0744. Liu et al., (2011) studied the effect of sand properties on plant germination in a moving sand dune in the Gurbantunggut desert in China using direct in situ measurements. The values of water content are between a minimum of 0.0140 and a maximum of 0.2328 with a median of 0.0225. Fu et al., (2018) studied the distribution of soil moisture in three different types of sand dunes in a sandy transition area between the Chinese Plateau and the northwestern desert. Lab measurements were performed to evaluate the water content in that area. The results show that the soil moisture changes between a minimum of 0.0206 and a maximum of 0.2328 with a median of 0.0436.

Considering all of the above studies, the median water content is 0.0343, the minimum is 0.0011, and the maximum is 0.2328. Figure 1 and Table 1 show all the extracted values of water content.

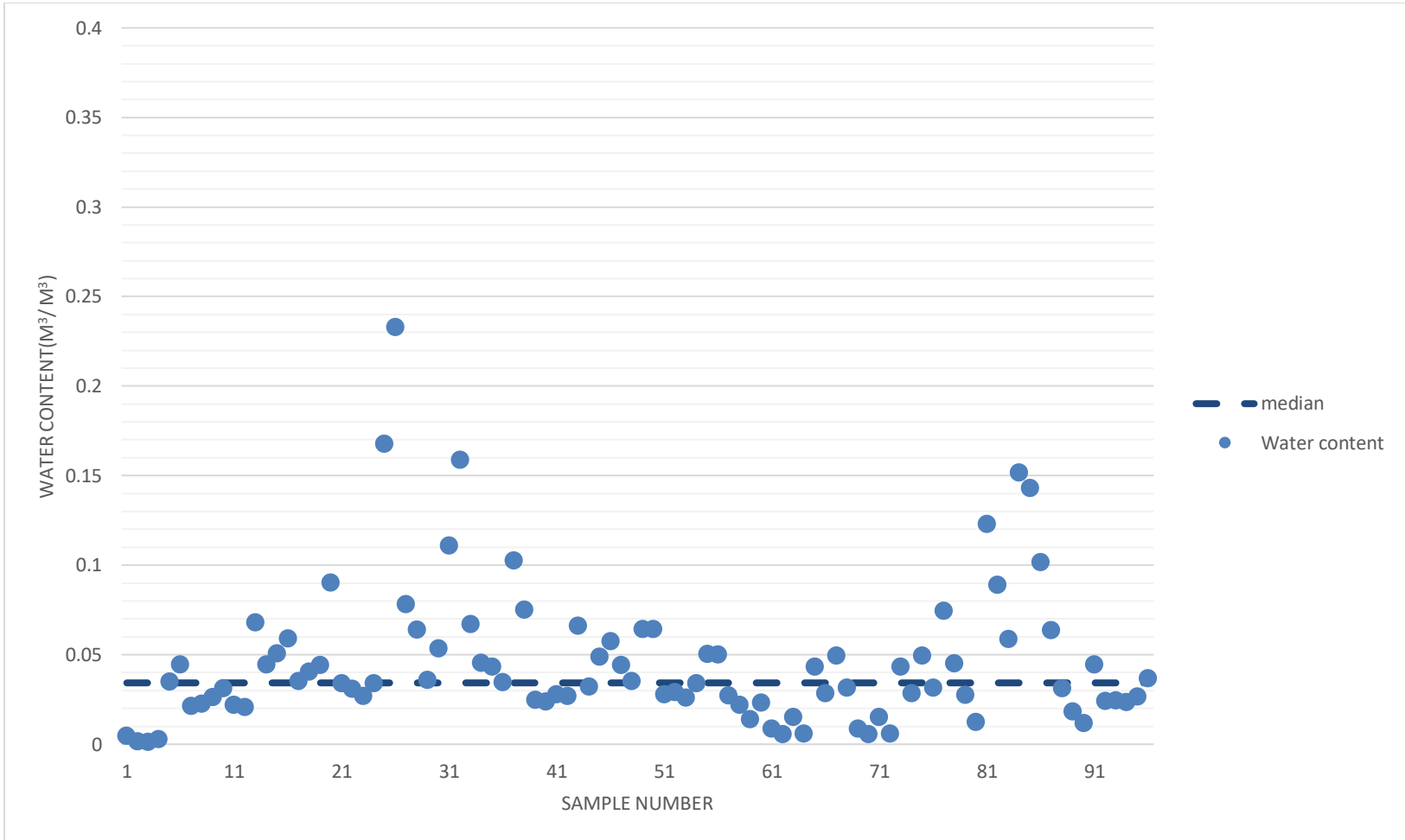


Figure 1: Water content in sand dunes from different locations in the world.

Table 1: Water content in sand dunes from the literature

Sample number	Water content (m ³ / m ³)	Reference
1	0.0045	Al-Sanad et al., (1993)
2	0.0015	
3	0.0011	
4	0.0029	
5	0.0350	
6	0.0444	Fu et al., (2018)
7	0.0214	
8	0.0224	
9	0.0262	
10	0.0311	
11	0.0219	
12	0.0206	
13	0.0679	
14	0.0443	
15	0.0507	
16	0.0590	
17	0.0351	
18	0.0405	
19	0.0442	
20	0.0902	
21	0.0340	
22	0.0308	
23	0.0268	
24	0.0338	
25	0.1678	
26	0.2328	
27	0.0782	
28	0.0640	
29	0.0357	
30	0.0534	
31	0.1108	
32	0.1586	
33	0.0671	
34	0.0454	
35	0.0431	
36	0.0345	
37	0.1024	
38	0.0749	
39	0.0248	
40	0.0237	

41	0.0278	
42	0.0268	
43	0.0662	
44	0.0322	
45	0.0487	
46	0.0574	
47	0.0440	
48	0.0353	
49	0.0641	
50	0.0643	
51	0.0277	
52	0.0289	
53	0.0258	
54	0.0338	
55	0.0503	
56	0.0501	
57	0.0270	Liu et al., (2011)
58	0.0220	
59	0.0140	
60	0.0230	
61	0.0086	Zuo et al., (2008)
62	0.0055	
63	0.0151	
64	0.0058	
65	0.0432	
66	0.0285	
67	0.0493	
68	0.0314	
69	0.0086	Pan and Wang (2009)
70	0.0055	
71	0.0151	
72	0.0058	
73	0.0432	
74	0.0285	
75	0.0493	
76	0.0314	
77	0.0744	
78	0.0450	
79	0.0275	
80	0.0122	
81	0.1230	
82	0.0890	
83	0.0588	

84	0.1515	
85	0.1430	
86	0.1015	
87	0.0636	
88	0.0311	
89	0.0182	
90	0.0118	Dincer et al., (1974)
91	0.0443	
92	0.0241	
93	0.0244	
94	0.0235	
95	0.0264	
96	0.0367	
Minimum	0.0011	
Maximum	0.2328	
Mean	0.0456	
Median	0.0343	
Standard deviation	0.0390	

1.2 Resistivity methods in water exploration

Many authors have used resistivity methods in water exploration in some areas with similar conditions. Araffa et al., (2021) used the vertical electric sounding (VES) method in the northwestern desert in Egypt for hydrogeophysical purposes. They used this method coupled with well logging data to study the subsurface stratigraphy and to explore the geo-electrical units. The authors have successfully revealed the number and lithology of the stratigraphic layers and their vertical and lateral extension. Khalfi et al., (2021) used geoelectrical studies integrated with hydrogeological data and hydrochemical measurements in the Chott of Djerid, South Tunisia, to evaluate brine encroachment. They succeeded in imaging the shape and extension of the salt brine encroachment ‘structure’ and established a conceptual model for this phenomenon. Mohammed et al., (2022) used electrical resistivity tomography (*ERT*) and electromagnetic induction for soil assessment

and monitoring in Al-Ahsa, Saudi Arabia. They studied the relationship between the salinity and the soil texture and hydrogeological conditions. Benaafi et al., (2020) used the ERT method to study the water content in a sand dune in the eastern province of Saudi Arabia. They mapped the dune into several vertical zones based on their water content and salinity.

1.3 Seismic for water exploration

Some geophysicists have used seismic activity in water exploration in places with different geological settings. Al-Shuhail and Al-Shaibani (2009) used seismic refraction to investigate two coastal sabkhas in eastern Saudi Arabia. The authors used this method to determine the velocities and thicknesses of the upper layers in the studied sabkhas. They revealed and characterized the existing layers in terms of number and velocities.

Al-Shuhail and Al-Shaibani (2013) used seismic refraction profiling for the characterization of the sabkha called Jayb Uwayyid in Eastern Saudi Arabia. They used this method to characterize the sabkha in terms of stratigraphy, number of layers, velocities and water table. Brixová et al., (2018) used case studies of shallow seismic refraction measurements in the western Carpathians in Slovakia for many purposes, including water exploration. In the case of groundwater exploration, the authors determined the water level below the surface. Xayavong et al., (2020) used a seismic refraction method for groundwater exploration in Vietnam Province in Laos. The main objective of this study was the delineation of groundwater potential zones. The analysis of seismic velocities

revealed the existence of different lithological layers with different velocities and helped particularly in the delineation of potential zones.

CHAPTER 2

METHODOLOGY

2.1 Complex refractive index model (CRIM)

Water saturation (S_w), porosity (ϕ) and conductivities of the matrix and pore fluids are the main factors influencing the effective conductivity (C_s) in porous sand. Some models have been developed to explain the relationship between C_s and S_w and ϕ . These models are of two types: empirical equations and semiempirical mixing formulas. A part of the semiempirical mixing formulas is the complex refractive index method (*CRIM*) (Loeffler and Bano, 2004), which is used in this study.

The *CRIM* equation for the conductivity of saturated sand (in units of milli Siemens/meter, mS/m) is:

$$C_s = [(1 - \phi)\sqrt{C_m} + \phi\{\sqrt{C_w} * S_w + \sqrt{C_a} * (1 - S_w)\}]^2, \quad (1)$$

where C_w is the pore-water conductivity given as (Annan, 2001):

$$C_w (\text{mS/m}) = 0.15 * PPT. \quad (2)$$

The conductivity of the matrix C_m (mS/m) is given as:

$$C_m = [\sum_i (p_i * \sqrt{C_i})]^2. \quad (3)$$

Since I need to compare the obtained results with data from the literature, I use the values of the estimated porosity φ to convert the obtained S_w values to W_c values using the following formula:

$$W_c = \varphi * S_w. \quad (4)$$

The value of the estimated porosity will not be used for the inversion itself, but only to convert from water saturation values to water content values. Figure 2 shows conductivity change with water saturation for a sand with properties given in Table 2.

2.2 Gassmann and Hertz–Mindlin models

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). In this model, the effective bulk and shear elastic constants of the sediment are expressed in terms of those of the matrix, dry sediment, and fluid as follows:

$$\frac{K_e}{K_m - K_e} = \frac{K_d}{K_m - K_d} + \frac{K_f}{\varphi(K_m - K_f)}, \quad (5a)$$

$$G_e = G_d. \quad (5b)$$

For a multimineral matrix, matrix moduli K_m and G_m can be calculated from Hill's averages of the Voigt and Ross moduli as follows:

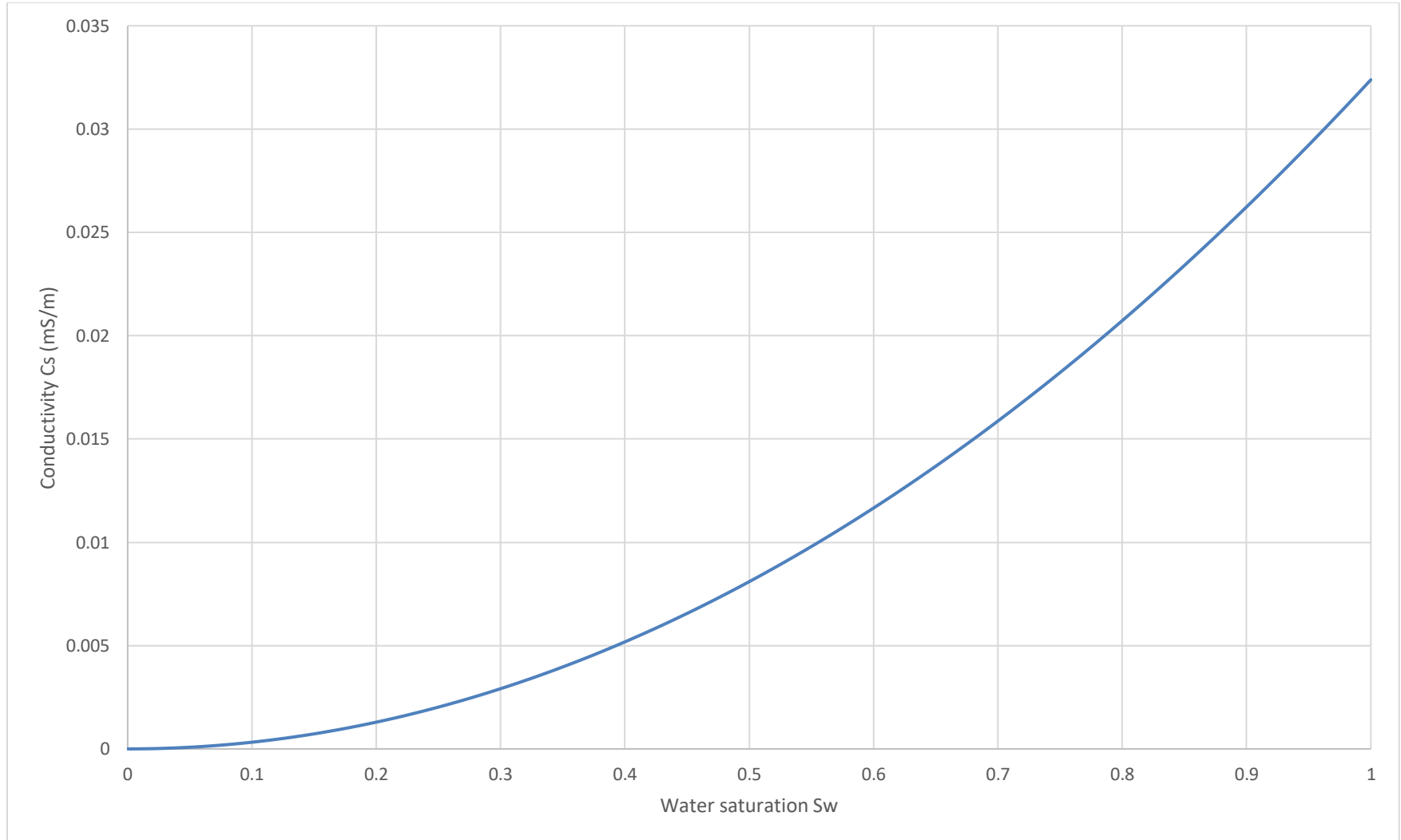


Figure 2: Conductivity change with water saturation.

$$K_m = \frac{1}{2} \times \left[\sum_i (p_i \times K_i) + \left\{ \sum_i \left(\frac{p_i}{K_i} \right) \right\}^{-1} \right], \quad (6a)$$

$$G_m = \frac{1}{2} \times \left[\sum_i (p_i \times G_i) + \left\{ \sum_i \left(\frac{p_i}{G_i} \right) \right\}^{-1} \right]. \quad (6b)$$

The fluid modulus K_f is calculated from the bulk moduli of the air and water from Wood's equation as Mavko et al. (2020):

$$K_f = \left(\frac{S_w}{K_w} + \frac{1-S_w}{K_a} \right)^{-1}. \quad (7)$$

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

$$K_d = \frac{N(1-\varphi)}{12\pi R} S_n \quad (8a)$$

$$G_d = \frac{N(1-\varphi)}{20\pi R} (S_n + 1.5S_t). \quad (8b)$$

The normal and tangential stiffnesses are calculated as:

$$S_n = \frac{4aG_m}{1-\nu_m} \quad (9a)$$

$$S_t = \frac{8aG_m}{2-\nu_m}. \quad (9b)$$

The matrix Poisson's ratio is calculated as:

$$\nu_m = \frac{3K_m - 2G_m}{6K_m + 2G_m}. \quad (9c)$$

The radius of the grain contact area is given as:

$$a = \left(\frac{1}{f}\right) \left[\frac{3\pi(1-\nu_m)}{2N(1-\varphi)G_m} P \right]^{\frac{1}{3}}. \quad (10)$$

The lithostatic pressure exerted on the grains is calculated as:

$$P = \rho_d g z. \quad (11a)$$

The density of the dry matrix is calculated as:

$$\rho_d = \varphi \rho_a + (1 - \varphi) \rho_m. \quad (11b)$$

The factor f in equation (9) is a factor proposed by Hanafy *et al.* (2020) to account for grain nonsphericity.

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

$$V_p = \sqrt{\frac{K_e + \frac{4}{3}G_e}{\rho_e}}. \quad (12a)$$

The effective density of the saturated sediment is calculated as:

$$\rho_e = (1 - \varphi) \rho_m + \varphi [(1 - S_w) \rho_a + S_w \rho_w]. \quad (12b)$$

For a multimineral matrix, the matrix density can be calculated as:

$$\rho_m = \sum_i (p_i * \rho_i). \quad (12c)$$

To summarize, the steps to calculate V_p are as follows:

1. Substitute equation (11b) into equation (11a) to calculate P .
2. Substitute equations (11a) and (9c) into equation (10) to calculate a .

3. Equations (9c) and (10) are substituted into equations (9a) and (9b) to calculate S_n and S_t , respectively.
4. Substitute equations (9a) and (9b) into equations (8a) and (8b) to calculate K_d and G_d , respectively.
5. Equation (8b) is substituted into equation (5b) to calculate G_e .
6. Solve equation (5a) for K_e and substitute K_d from equation (8a) and K_f from equation (7).
7. Substitute K_e from equation (5a), G_e from equation (5b), and ρ_e from equation (12b) into equation (12a) to calculate V_p .

The general form of V_p is too long to reproduce here neatly. However, for a sediment composed of uniform spherical quartz grains (Table 2), $V_p(z, S_w)$ in ($m \cdot s^{-1}$) becomes:

$$V_p(z, S_w) = \sqrt{\frac{-3.91552 \times 10^{23} + (-1.95967 \times 10^{26} + 1.95959 \times 10^{26} S_w) z^{1/3} + 1.3087 \times 10^{18} z^{2/3}}{(4.92736 + 1. S_w)(-4.79174 \times 10^{20} + 4.7915 \times 10^{20} S_w + 4.83412 \times 10^{12} z^{1/3})}} \quad (14)$$

Figures 3 and 4 show plots of $V_p(z = 5m, S_w)$ and $V_p(z, S_w = 0.3)$, respectively. The plot of $V_p(z, S_w = 0.3)$ shows the sharp increase in P-wave velocity with depth at shallow depths that is expected by previous studies (Al-Shuhail, 2002; Al-Shuhail, 2006; Gassmann, 1951). Similarly, the plot of $V_p(z = 5m, S_w)$ shows a slight decrease in velocity with increasing S_w between 0 and approximately 0.9, and then it increases sharply until it reaches the velocity in saturated sand.

Determining partial saturation solely based on P-wave velocity can be challenging due to the minimal variation in P-wave velocity between completely dry and 99% saturation conditions. As the water content increases in the pore spaces, the total density increases,

while the elastic moduli remain relatively constant. Consequently, this leads to a decrease in P-wave velocity. However, once full saturation is attained, the bulk modulus experiences a significant increase, while the density only slightly increases. As a result, the P-wave velocity exhibits a sharp increase (Dvorkin et al., 2014).

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

Property	Value
C_{air} (S/cm)	0.0
C_a (S/cm)	$2.08 \cdot 10^{-9}$
C_c (S/cm)	$1.1 \cdot 10^{-14}$
C_g (S/cm)	$9.524 \cdot 10^{-12}$
C_{mc} (S/cm)	$5.56 \cdot 10^{-12}$
C_n (S/cm)	$1.3 \cdot 10^{-10}$
C_o (S/cm)	$1 \cdot 10^{-9}$
C_q (S/cm)	$5 \cdot 10^{-15}$
C_w (S/cm)	0.15*PPT
Φ	0.35
Km (GPa)	37
Gm (GPa)	45
ρ_m (kg/m ³)	2650
Ka (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
n	6

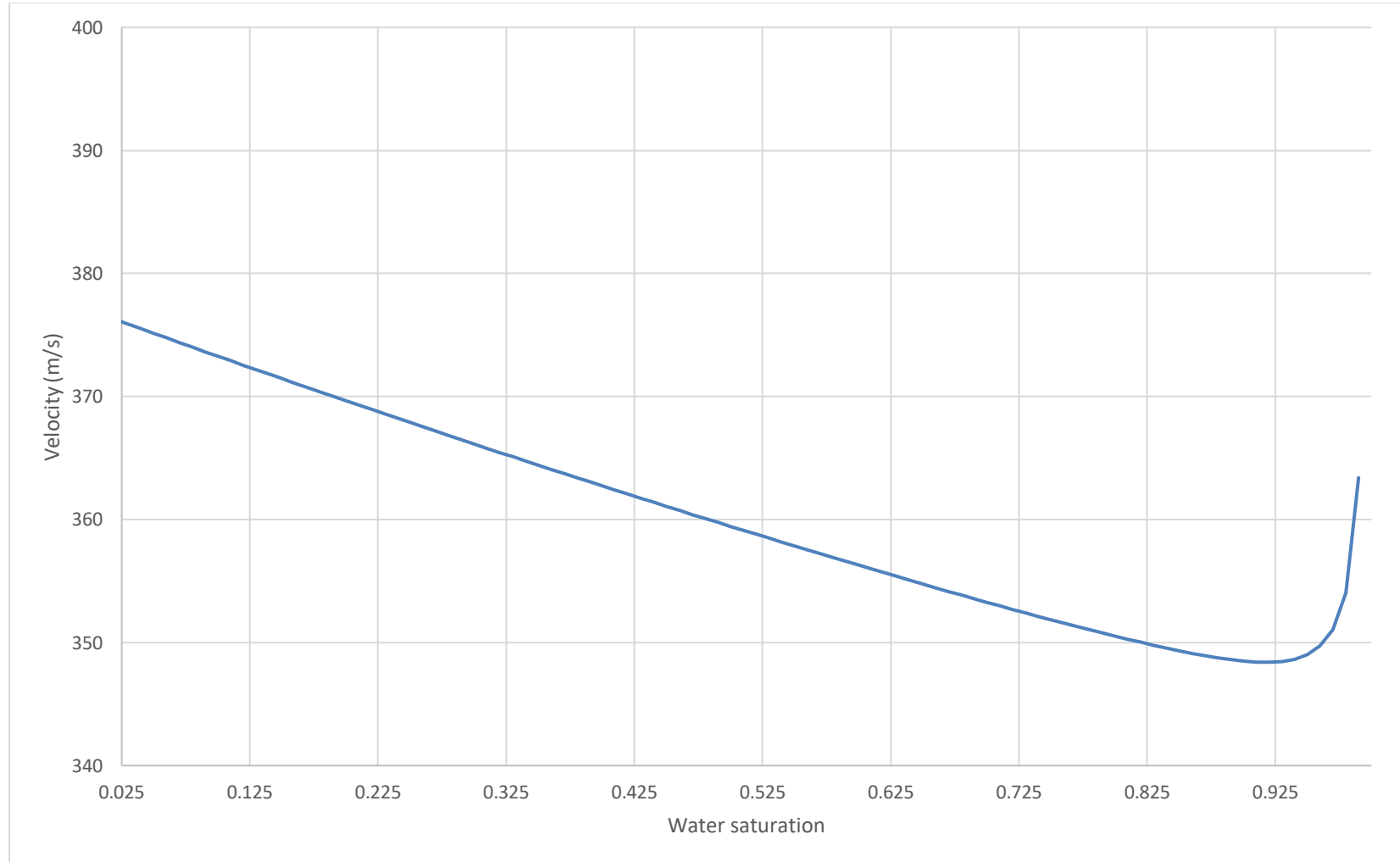


Figure 3: P-wave velocity change with water saturation (at a constant depth $z=5$ m)

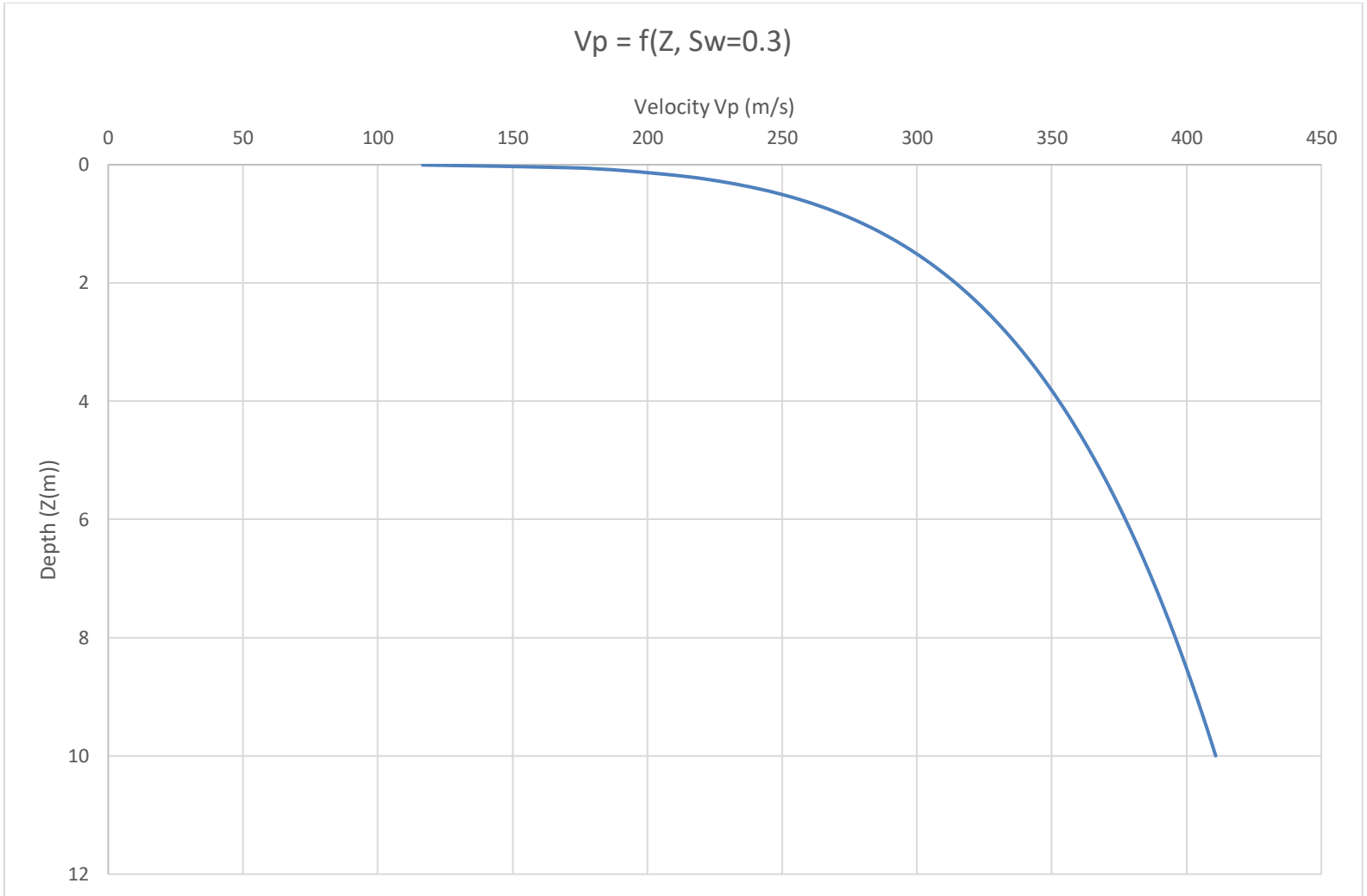


Figure 4: P-wave velocity change with depth z (at constant water saturation $S_w=0.3$)

2.3. The inversion procedure for S_w

This study aims to explore the feasibility of determining S_w in loose sand with saturation levels ranging from 0 to 0.9. Traditional shallow seismic techniques, as demonstrated by (Sheriff and Geldart, 1995), can effectively observe and analyze the refraction from fully saturated sand. Therefore, this investigation focuses on saturation levels up to $S_w=0.9$. However, it is important to note that the velocity change between saturation levels of 0 and 0.9 is not easily discernible using conventional methods. Despite this, it is crucial to understand the significant impact that highly saturated sand (e.g., $S_w=0.9$) and dry sand have on desert-dwelling humans, animals, and plants.

The following steps are proposed to invert $S_w(D)$ as a function of the maximum penetration depth of the diving direct wave at every observed P-wave velocity and conductivity C_s :

1. Solving *CRIM* (Eq. 1) for the porosity ϕ to obtain $\phi (C_s, S_w)$. This step has the advantage of eliminating the dependence of the proposed inversion method on porosity.
2. Putting $\phi (C_s, S_w)$ into $V_P (\phi, S_w)$ to obtain $V_P (C_s, S_w)$.
3. Minimize the relative absolute error between the calculated $V_P (C_s, S_w)$ and observed V_P for S_w at each measured depth.

The relative absolute error is described as follows:

$$RAE = \left[\frac{\{V_{pm} - V_{pc}\}}{V_{pm}} \right]^2 \quad (13)$$

Where:

RAE: Relative Absolute Error

V_{pm} : Measured P-wave velocity

V_{pc} : Calculated P-wave velocity

There is a possibility of trapping the algorithm at a local value of minimum near the starting search point since most minimization algorithms depend on a starting search point. To avoid these cases, it is recommended to apply *RAE* minimization several times using a wide range of starting search points that cover all expected S_w values in the study area. In case there are no local minima, the minimization algorithm should return the S_w value that gives the overall *RAE* minimum, regardless of the starting point of the search. However, for different reasons (e.g., noise, measurement errors, etc.), there may be local *RAE* minima that prompt the algorithm to return multiple S_w values close to various starting search points. The S_w value that is associated with the global minimum *RAE* value should be selected in these circumstances.

2.4. The minimization process

The objective of function minimization is to identify either the local or global minima (Dahlquist et al., 2008; Cheney et al., 2012). Mathematica employs built-in functions such as FindMinimum and Minimize, along with other functions, to provide a local and global minimum for a given function, respectively. Variable localization and numerical evaluation of the results are carried out by the FindMinimum function. In contrast, the Minimize function aims to find the smallest values within given constraints, often referred to as the best fit or configuration. It is crucial to remember that there is no guarantee of finding the global minimum when a function has multiple local minima. The solution is to experiment with various starting points, and the smallest local minimum is the global minimum

(Dahlquist et al., 2008). Any logical combination (e.g., equations, inequalities, region specification) can be used to constrain the FindMinimum algorithm in Mathematica. Furthermore, it utilizes the given restrictions and then aims for a local minimum, avoiding the use of derivatives (Wolfram Research, 2021).

In this study, I used 10 starting search points (0, 0.1, 0.2 ..., 0.9) for every depth. Therefore, at every depth, I end up with 10 minima; of which the selected S_w value is the one occurring at the smallest minimum.

CHAPTER 3

DATA ACQUISITION

3.1 Study Area

The data used for the study were acquired in a Barchan sand dune in Dammam, Eastern Saudi Arabia (Hanafy et al., 2020). Sand dunes are found in the coastal area of the Eastern Province in Saudi Arabia, particularly in Al Jafurah dune field (Edgell, 2006). The dune field is situated south of Qatif. Aeolian sand in the Eastern Province was deposited during the Quaternary Period and originated from the Bitlis-Zagros thrust belt (Anton, 1983a). This sand was derived from the Tigris-Euphrates paleo-river system. The consistently high speeds of the Shamal, the prevailing northerly wind, sands were transported during the Pleistocene Period, resulting in the formation of barchanoid dunes (Fryberger et al., 1984; Garzanti et al., 2013a). It is worth noting that the sand dunes in the Al Jafurah Desert are relatively young compared to other dunes in the Arabian region, with their accumulation occurring approximately 4000 years ago (Anton and Vincent, 1986). Previous studies have shown that the sand dunes in the Eastern Province of Saudi Arabia exhibit variations in texture and composition, which are influenced by their geographical location (Benaafi and Abdullatif, 2015; Edgell, 2006).

The grain size and sorting of these dunes range from fine to coarse and poorly sorted to very well sorted, respectively (Anton, 1983b; Benaafi and Abdullatif, 2015). In terms of mineral composition, early research indicated that the sand dunes near the Arabian Gulf coastal area primarily consist of quartz, along with significant amounts of feldspars and

carbonate minerals (Garzanti et al., 2013b). However, investigations on the water content profile of sand dunes in the Eastern Province of Saudi Arabia are very scarce ((Benaafi et al., 2020). Furthermore, earlier studies focused on the properties of sand dunes based on samples collected from the surface, which may not accurately represent the overall characteristics of the dunes (Benaafi et al., 2020). In this study, I use seismic and electrical resistivity data acquired over a sand dune located approximately 30 km east of Dhahran city in the Eastern Province of Saudi Arabia (Figure 1). More details about the seismic and electrical resistivity data used in this study can be found in Hanafy et al. (2020) and Benaafi et al. (2020), respectively.



Figure 5: Location of the studied sand dune

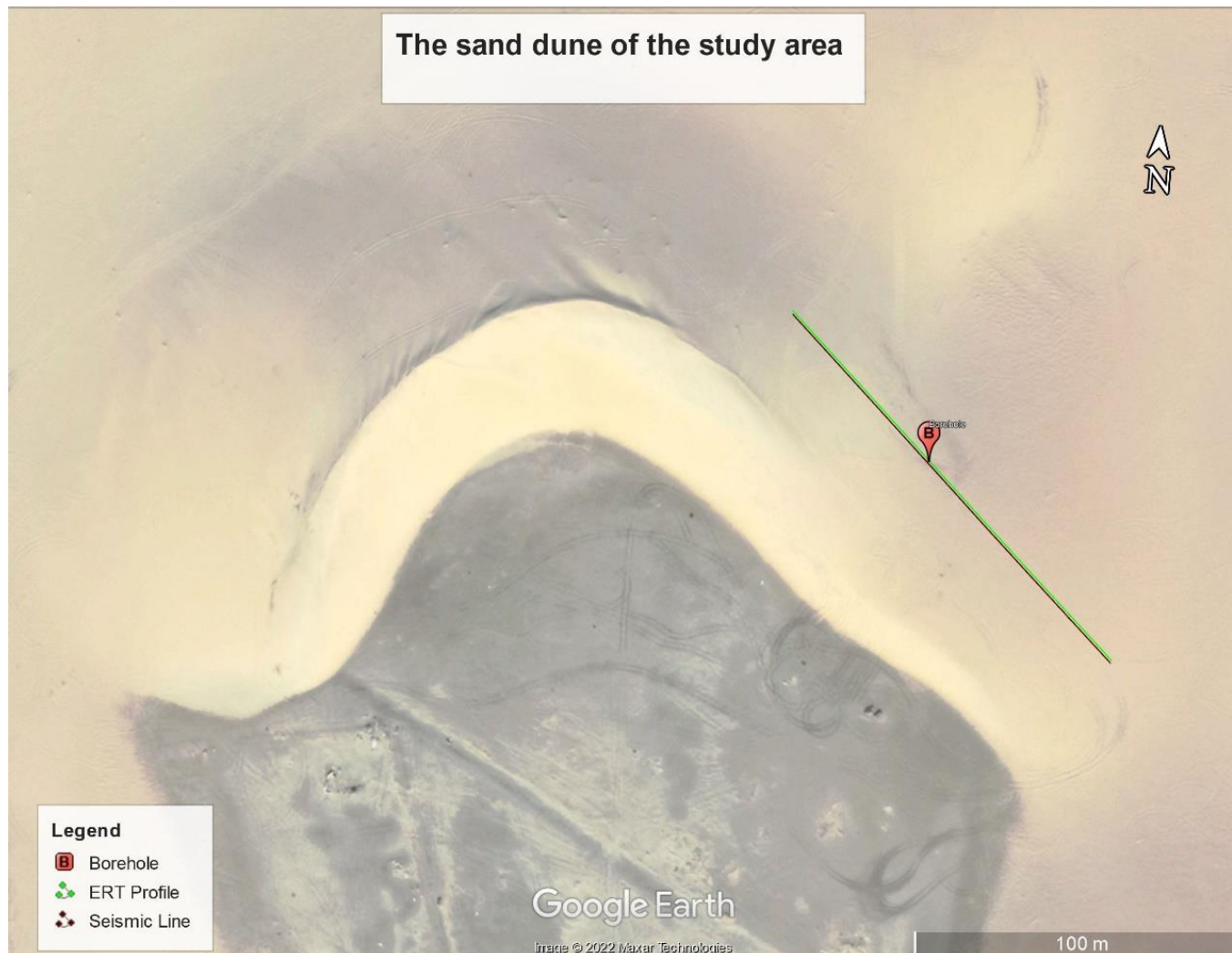


Figure 6: The studied sand dune in Dammam.

3.2 Data Acquisition and Processing

3.2.1 Seismic Data

A comprehensive seismic investigation utilizing both conventional (low resolution) and high-resolution surveys was carried out to acquire a P-wave velocity profile in the sand dune of the study area (S. M. Hanafy et al., 2020). In the conventional seismic survey, a sledgehammer weighing 8 kg and a plate measuring 20 x 20 x 4 cm were employed as the seismic source. A total of 73 shot gathers were recorded, with each shot being spaced at 1 m intervals. Figure 6 presents a sample shot gather with three the direct, head, and surface arrivals indicated. Within each shot gather, the first arrivals were manually picked (S. M. Hanafy et al., 2020).

For the high-resolution seismic acquisition, a smaller sledgehammer with a 0.7 kg weight and plate was utilized as the seismic source. This survey utilized 31 geophones, which were activated with each shot. The geophones were spaced as follows: 1-12 were placed at 0.1 m intervals, 12-23 were placed at 0.2 m intervals, and 23-31 were placed at 0.25 m intervals. Consequently, the total length of the receiver line amounted to 5.4 m (Hanafy et al., 2020).

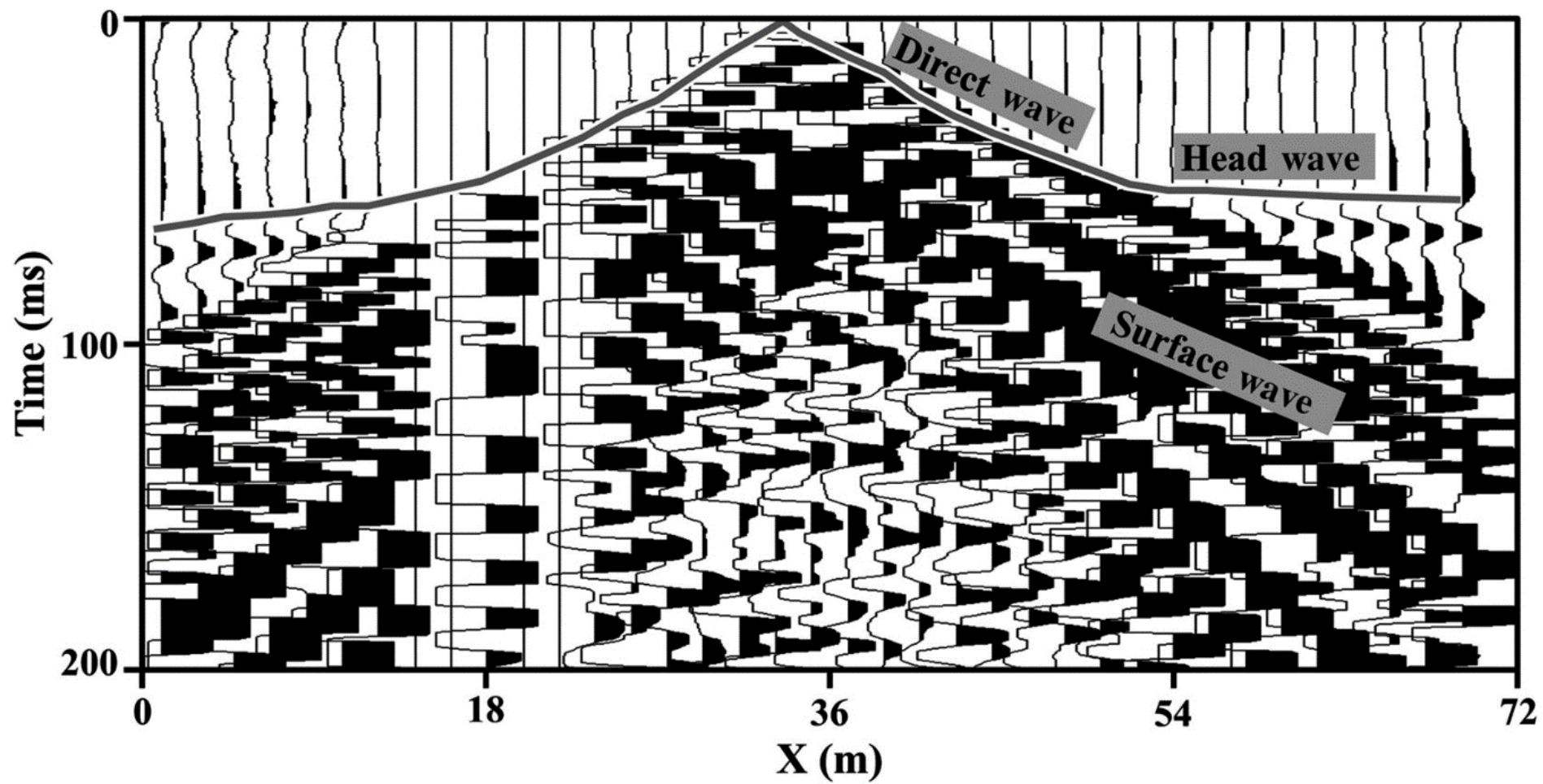


Figure 7: Example of a shot gather for conventional seismic (Hanafy et al., 2020)

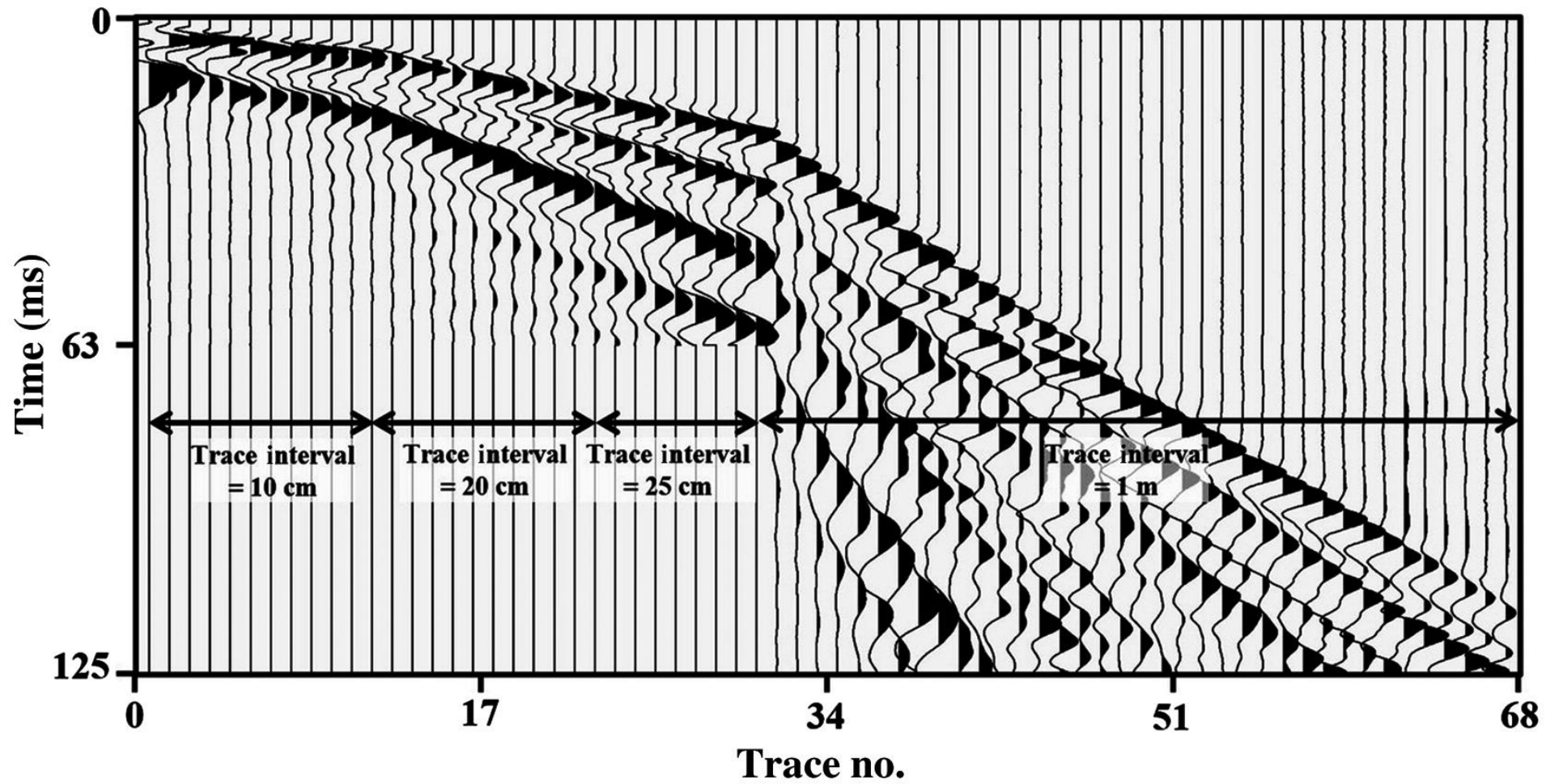


Figure 8: Example of the recorded high-resolution data (Traces 1-31) and conventional data (Traces 32-68) (Hanafy et al., 2020)

The maximum depth of investigation ($z_{\max}$) of the diving direct P-wave was determined from the offset (x) by the following formula (Hanafy et al., 2020):

$$z_{\max} = \frac{8x}{15\pi} \approx \frac{x}{5.89} . \quad (14)$$

The velocity of the diving direct P-wave (V_p) at $z_{\max}$ is derived from the offset and picked traveltime (t) of the diving direct P-wave as follows:

$$V_p = \frac{x}{t} . \quad (15)$$

From these two surveys, ten offsets were picked, corresponding to the depths at which the sand samples were collected in a borehole drilled using a dry drilling method. Subsequently, the water content of these samples was measured in the laboratory, as indicated in Table 3 and Figure 9 (Benaafi et al., 2020).

Table 3: Measured water saturation (Benaafi et al., 2020)

Depth (m)	Measured S_w
0.1	0.0139
0.35	0.1120
0.85	0.0394
1.6	0.0617
2.425	0.0446
3.25	0.0538
4.9	0.0371
5.5	0.0380
5.775	0.0469
6.4	0.0655

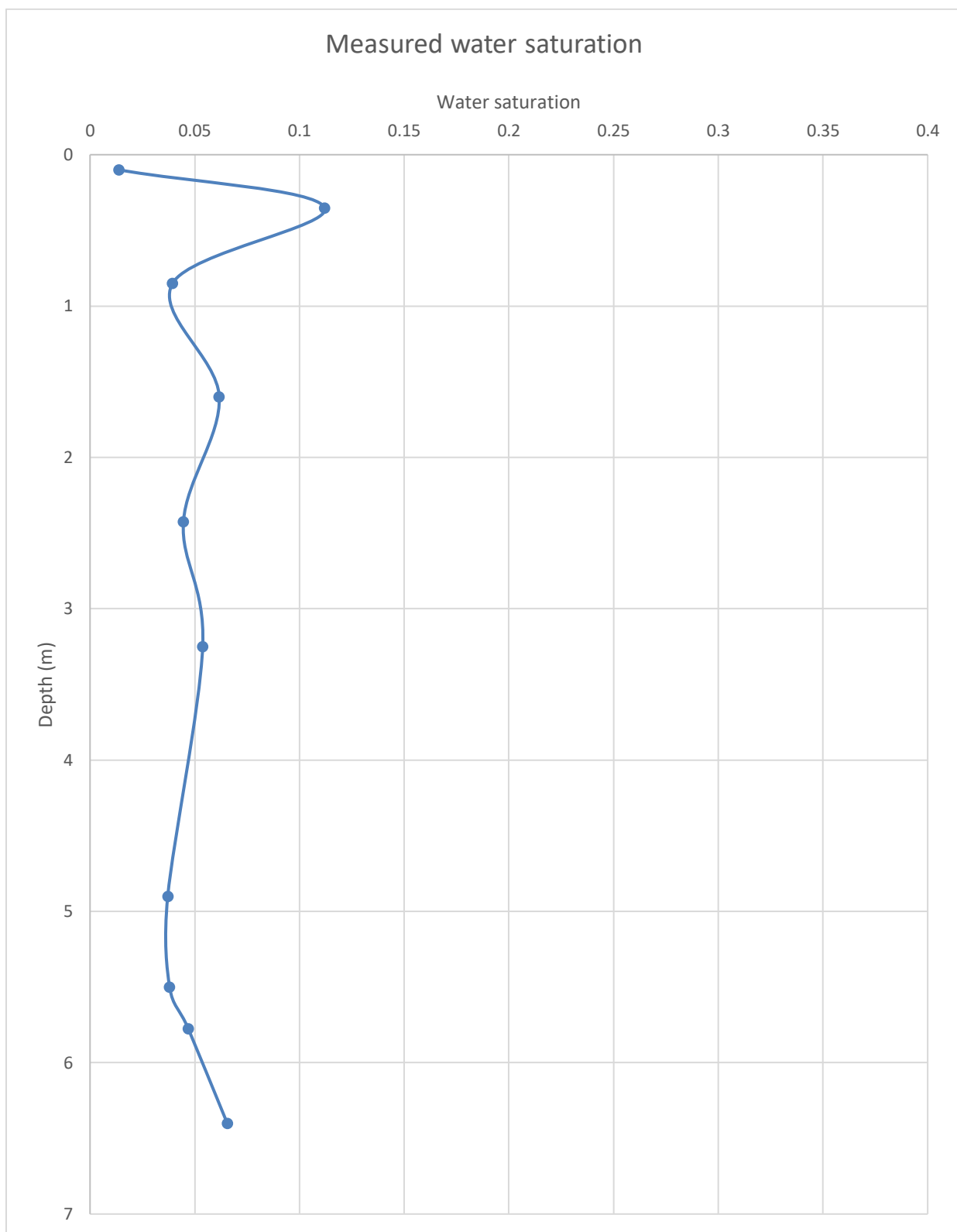


Figure 9: Measured water saturation (Benaafi et al., 2020)

Table 4: Measured seismic velocity versus depth

Depth (m)	Measured P-wave velocity (m/s)
0.1	208.853
0.35	257.117
0.85	297.964
1.6	331.01
2.425	354.716
3.25	372.426
4.9	398.761
5.5	406.502
5.775	409.816
6.4	416.886

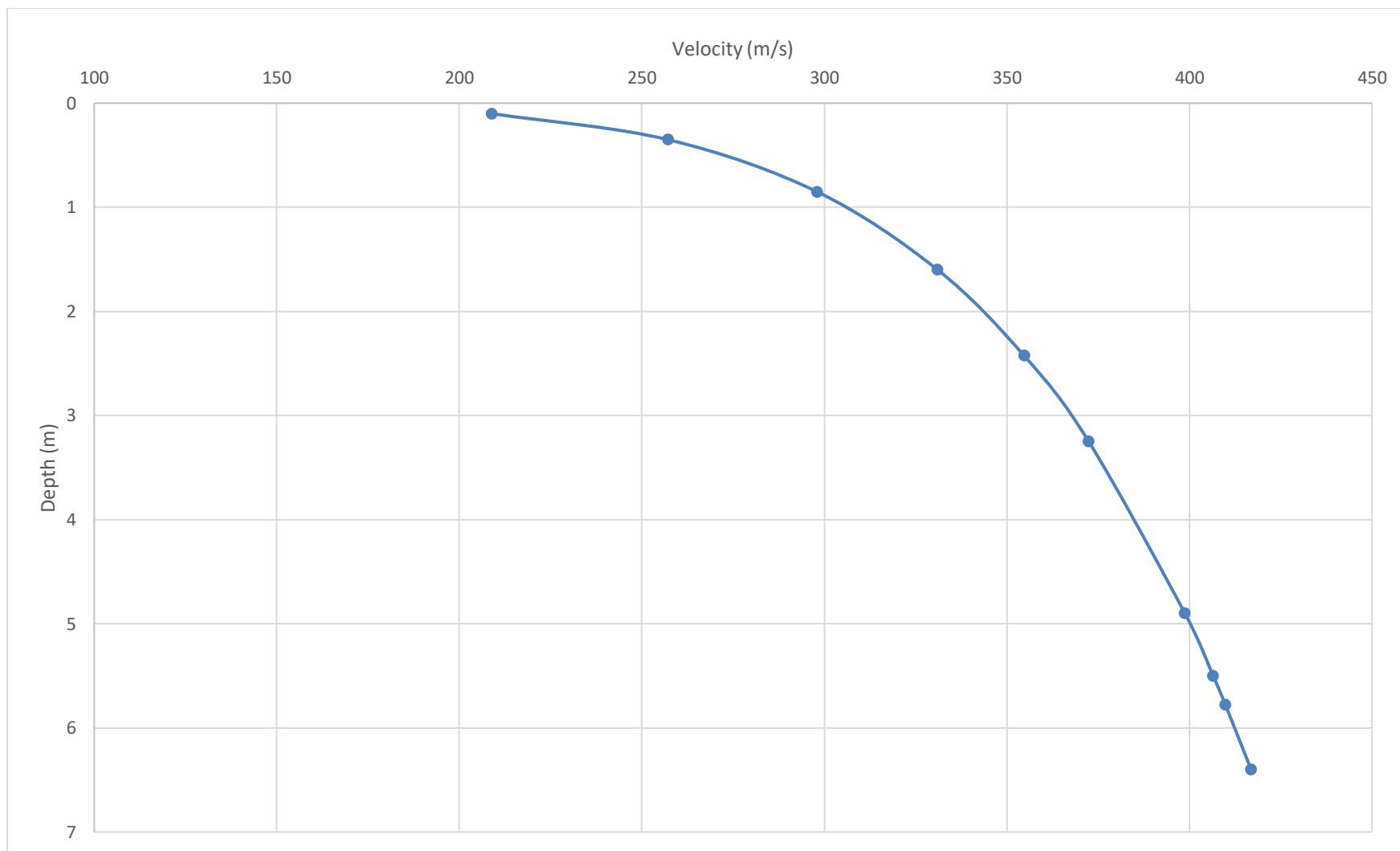


Figure 10: Measured seismic velocity versus depth

3.2.2 Electric Data

The electric resistivity method is widely used geophysical in various fields, such as geology, engineering, archaeology, mining, environment, and groundwater applications. It is sometimes also employed in hydrocarbon exploration (Loke et al., 2013). This method involves measuring the variations in subsurface resistivity from the surface of the ground by varying the separation between electrodes (Hanafy, 2015). Subsequently, the true resistivity of the subsurface can be calculated based on the depth.

To analyze resistivity changes in both the vertical and horizontal directions along the survey line, the electrical resistivity tomography (*ERT*) technique, a two-dimensional (2-D) modeling approach, is used (Loke et al., 2013). It is assumed that the resistivity remains constant perpendicular to the survey line, which is a valid assumption in many geological scenarios. For field measurements, four electrodes are necessary. Two of these electrodes (referred to as *C1* and *C2*) are responsible for injecting the current (*I*) into the subsurface, while the other two electrodes (*P1* and *P2*) measure the potential difference (ΔV). The apparent resistivity (ρ_a) is then calculated in Ohm-m using the following formula (Hanafy et al., 2014):

$$\rho_a = k \Delta V / I. \quad (16)$$

where *k* is a geometric factor measured in meters that depends on the electrode spread.

In this study, the *ERT* profile was conducted by employing 96 electrodes with intervals of 0.75 m, arranged on top of the sand dune at the side of the limb. All electrodes were connected to the measuring unit using a multicore cable, and an electric switching unit was employed to automatically select the relevant four electrodes for each measuring point. The

recorded apparent resistivity was then inverted to determine the true resistivity as a function of depth. From the inverted true data, I obtain the conductivity by reciprocating the resistivity. Table 5 and Figure 10 show the measured conductivities at the depths where the sand samples were collected in the borehole. I use linear interpolation to estimate conductivity at depths that were not sampled by the resistivity survey.

Table 5: Measured conductivity versus depth

Depth (m)	Measured Conductivity mS/cm)
0.1	17.404
0.35	21.946
0.85	65.634
1.6	40.177
2.425	46.066
3.25	8.091
4.9	7.684
5.5	7.921
5.775	8.518
6.4	15.638

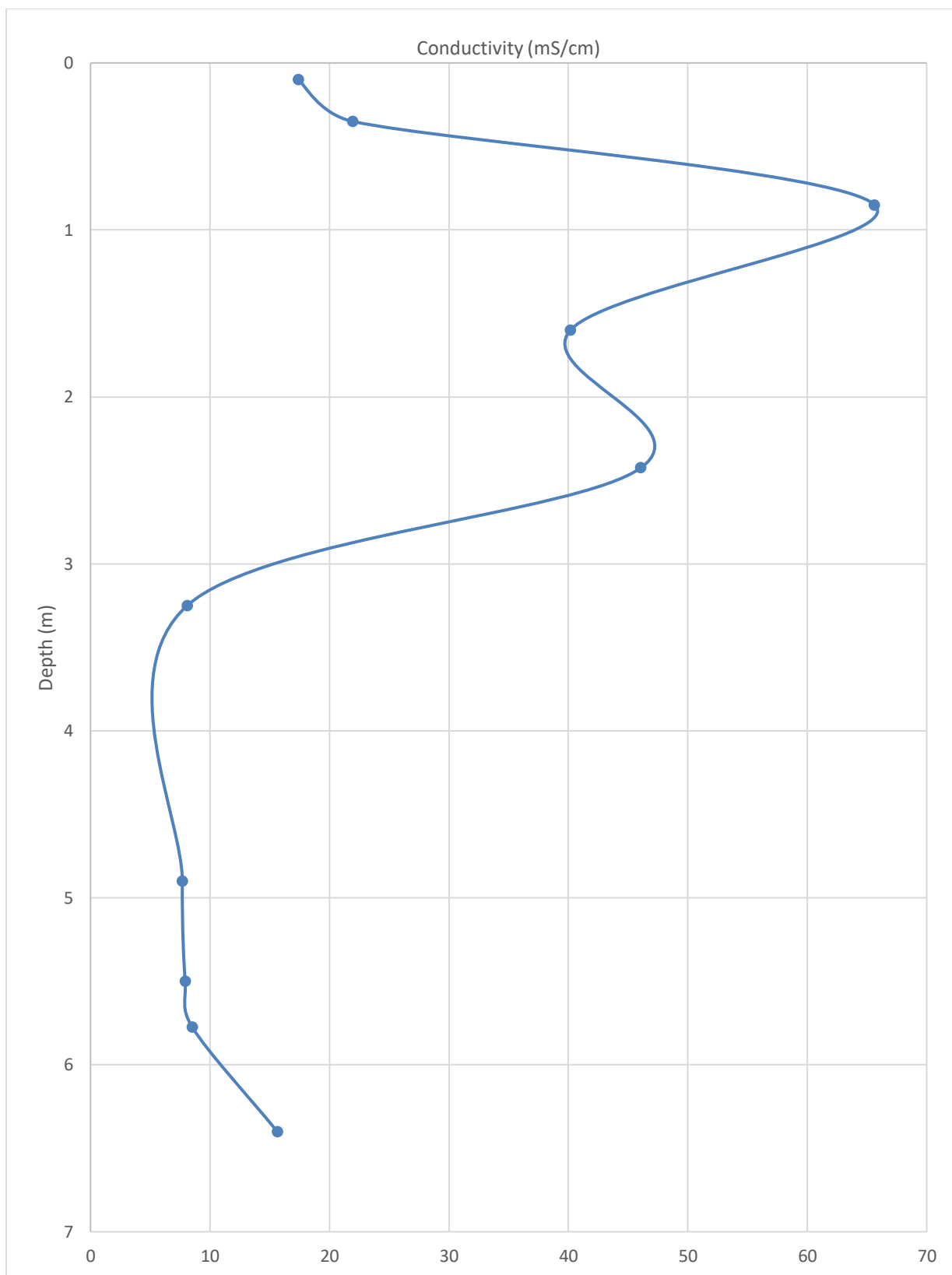


Figure 11: Measured conductivity versus depth

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Results

In this study, I applied the inversion procedure described in section (2.3) on 10 C_S and V_P measurements in a sand dune near Dammam Airport in eastern Saudi Arabia (Tables 4 and 5). I assumed the matrix and fluid properties listed in Table 2. The inverted S_W values are shown in Table 6 and Figure 12.

To facilitate comparison with data from other publications, I convert the inverted water saturation values S_W to water content W_C using the assumed porosity value (Table 2) in the dune as indicated in section (2.1) in equation (4). Furthermore, I convert the measured S_W values using a constant porosity of 0.35, which corresponds to the average critical porosity in loose sands (Nur et al., 1998). The converted values of water content are shown in Table 7 and Figure 13. The median water content of the inverted values is 0.018, while the median of the measured values is 0.016. Both medians indicate a very dry sand dune. Despite considerable differences between the individual values of the inverted and measured water contents, their means and the medians indicate a very low water saturation (Table 8 and Figure 14).

4.2. Discussion

The produced results show differences between the inverted and the measured water saturation values, especially at shallow depths. This difference might be due to the quantity of water added during the operation of planting of the electrodes into the sand during the resistivity survey. This might also explain the general increase in the inverted S_w values compared to the measured values.

Table 6: Inverted and measured water saturation (S_w) versus depth

Depth	Inverted S_w	Measured S_w
0.1	0.0612	0.0139
0.35	0.0674	0.1120
0.85	0.0994	0.0394
1.6	0.0926	0.0617
2.425	0.0521	0.0446
3.25	0.0458	0.0538
4.9	0.0457	0.0371
5.5	0.0459	0.0380
5.775	0.0470	0.0469
6.4	0.0507	0.0655
Minimum	0.0457	0.0139
Maximum	0.0994	0.1120
Mean	0.0608	0.05129
Median	0.0514	0.04575
Standard deviation	0.0199	0.0257

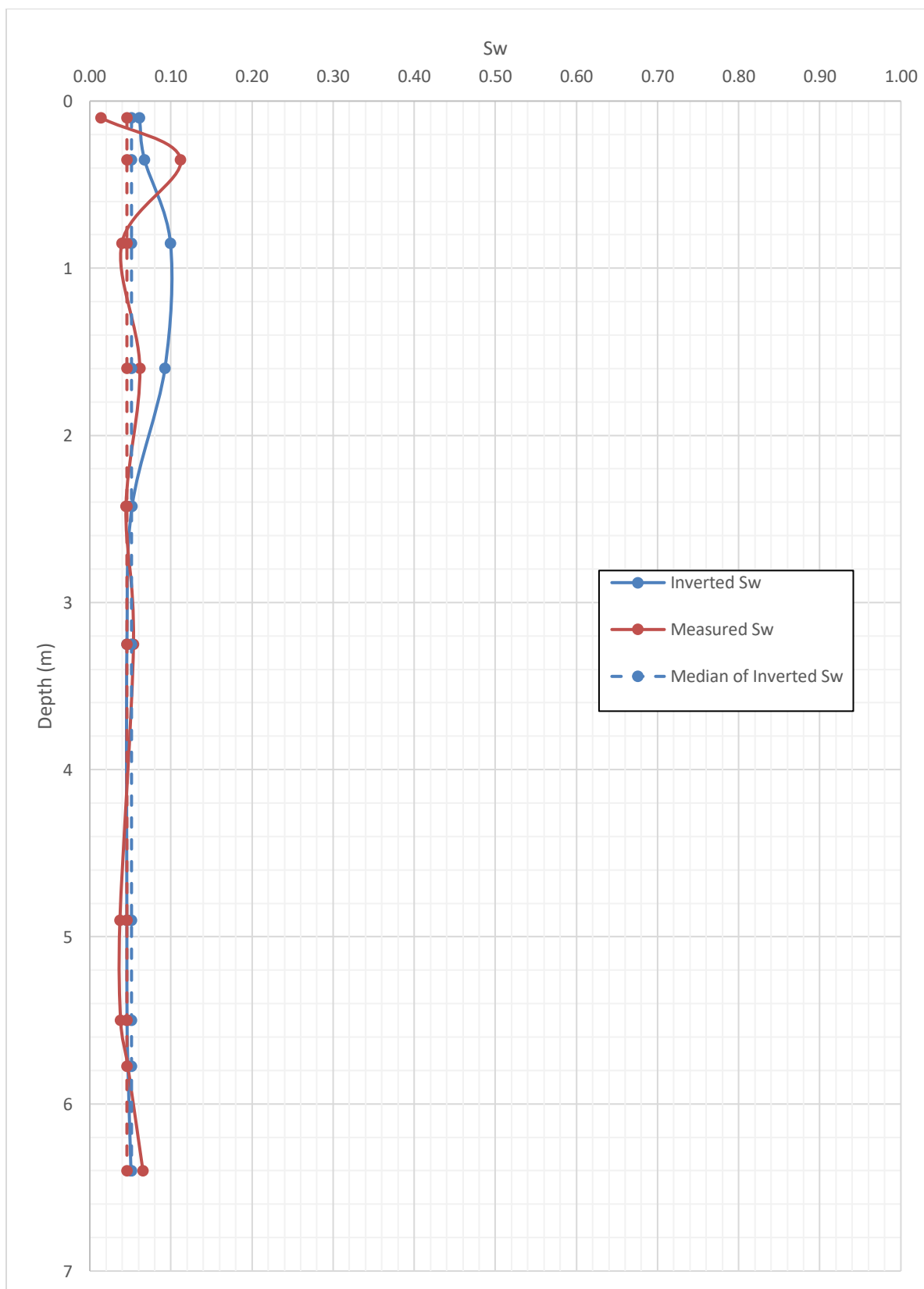


Figure 12: Inverted and measured water saturation versus depth Table 7: Inverted and measured water contents versus depth

Depth	Measured W_C	Inverted W_C
0.100	0.0049	0.0214
0.350	0.0392	0.0236
0.850	0.0138	0.0348
1.600	0.0216	0.0324
2.425	0.0156	0.0182
3.250	0.0188	0.0160
4.900	0.0130	0.0160
5.500	0.0133	0.0161
5.775	0.0164	0.0164
6.400	0.0229	0.0178
Minimum	0.0049	0.0160
Maximum	0.0392	0.0348
Mean	0.0179	0.0213
Median	0.0160	0.0180
Standard deviation	0.0090	0.0070

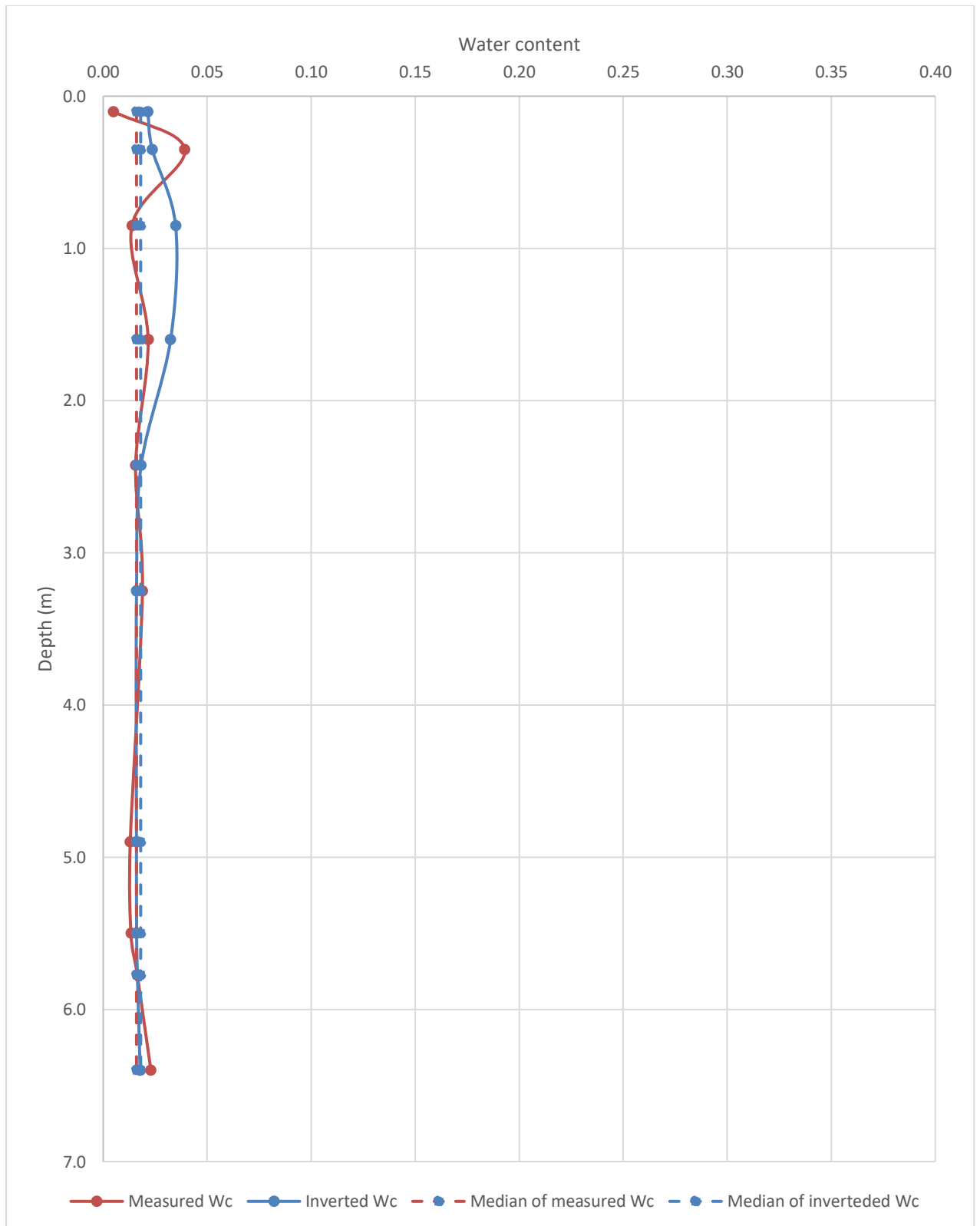


Figure 13: Inverted and measured water contents versus depth
Table 8: Error between measured and inverted values of water content W_C

Depth (m)	Error (%)
0.02143	77.3
0.02360	66.1
0.03481	60.4
0.03240	33.4
0.01824	14.5
0.01601	17.6
0.01598	18.7
0.01607	17.1
0.01643	0.2
0.01775	29.0
Minimum	0.2
Maximum	77.3
Mean	33.4
Median	23.9
STD	25.7

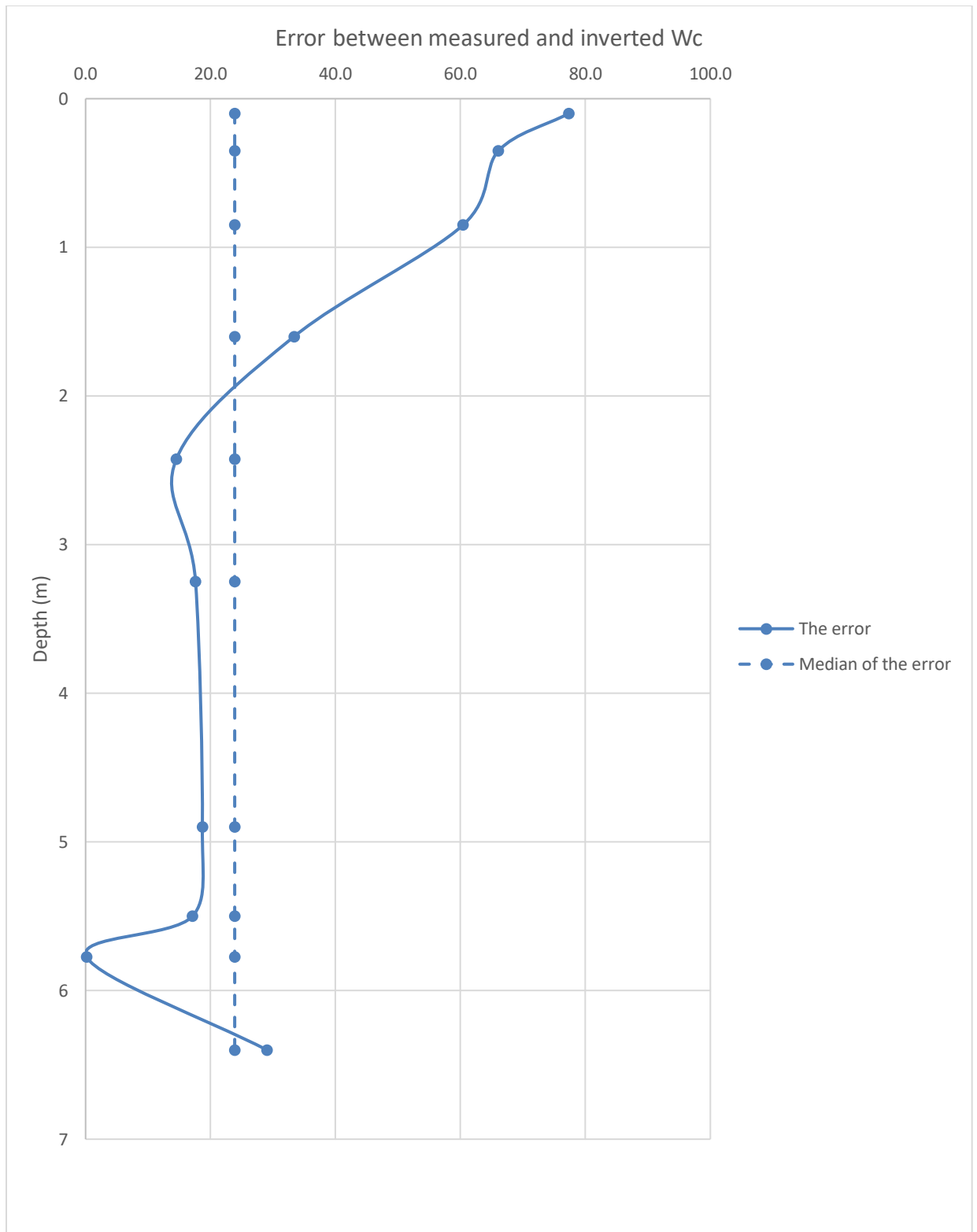


Figure 14: Error between measured and inverted values of water content WC

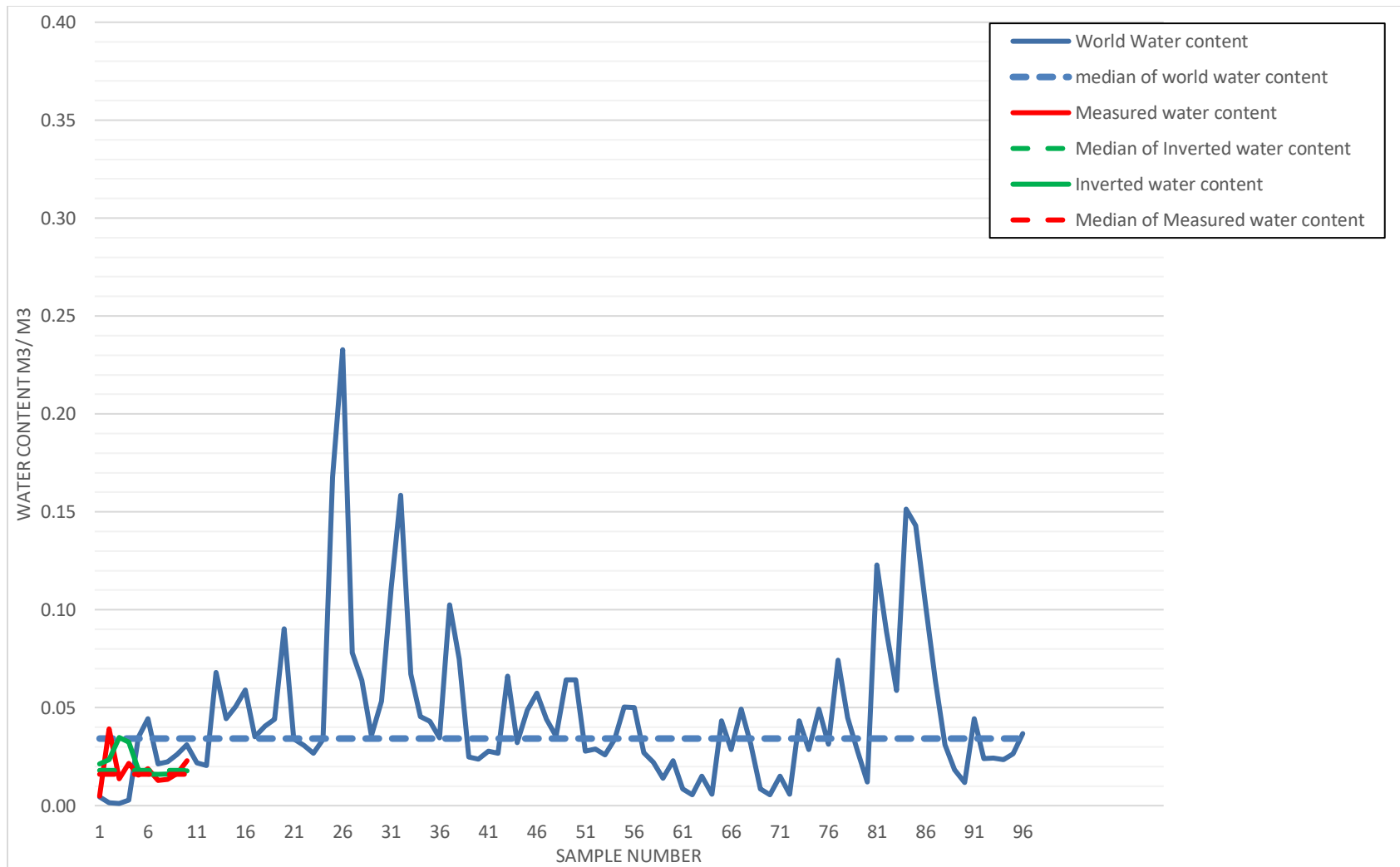


Figure 15: Water content values: inverted (green), measured (red) in the studied dune and measured in world dunes (blue). Colored dashed line represents the median of each data set.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

In this study, I propose a joint inversion method to estimate water saturation in near-surface layers from seismic and resistivity measurements. The proposed method is important for water exploration, and is relatively less costly than drilling. This study utilized diving direct P-waves and electrical conductivity to estimate water saturation (S_w) in partially saturated unconsolidated sediments. The relationship between the P-wave velocity (V_p), electrical conductivity (C) and water saturation (S_w) was established using the Complex Refractive Index Model (*CRIM*) and the Gassmann and Hertz–Mindlin models, as well as the properties of the matrix and pore fluid. This resulted in a relation, $V_p(C_s, S_w)$, which served as an objective function based on the measured and calculated V_p and C_s to estimate S_w at each depth. One of the advantages of this method is the elimination of the dependence on porosity.

To test the proposed relation, real data were used to invert S_w as a function of the maximum penetration depth (z_{max}) of the diving direct wave calculated from the observed offsets. The proposed method was applied to 10 samples from a sand dune in Eastern Province, Saudi Arabia. S_w values were inverted at different depths assuming a pure quartz matrix in the dune. The results from the inverted water content values show a median of 0.018 while the median of measured water contents is 0.016 with both indicating a very dry sand dune.

Although the inverted W_C values of individual samples differed from the measured values, both indicated a dry sand dune. Furthermore, the observed water content values in the studied dune were similar to values reported in dunes under similar conditions in different parts of the world. This proves that the method works well in low-saturated media.

I assumed 100% quartz matrix although the dune matrix contained small amounts of other minerals (Benaafi et al., 2020). However, this assumption is essential to make the proposed method practical. It is also a reasonable assumption since most dunes in the eastern province of Saudi Arabia have a quartz-rich matrix. For similar reasons, I assumed a constant porosity of 0.35 in the dune to convert S_w to W_C values which corresponds to the average critical porosity in loose sands (Nur et al., 1998). These porosity values were not used in the inversion of saturation but only to convert S_w to W_C values in order to facilitate comparison of my inverted W_C values to those from other deserts of the world. Furthermore, although I used the *CRIM* and Gassmann-Hertz–Mindlin models, other models may be more relevant in other environments.

5.2. Recommendations

For future work, I recommend the following:

1. Trying different models other the *CRIM* and Gassmann-Hertz–Mindlin models.
2. Trying the same method on other soils (e.g., sabkha).
3. Trying other global minimization techniques.

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