

**ESTIMATION OF WATER SATURATION IN SAND DUNES  
USING SOURCE-RECEIVER OFFSET**

BY

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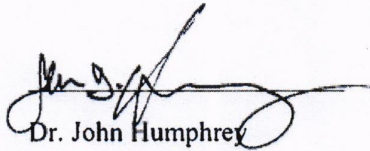
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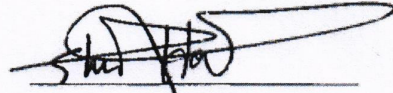
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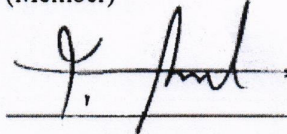
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## *Dedication*

*[To all who have helped me grow ]*

*If I have seen further, it is by standing on the shoulder of giants.*

- *Sir Isaac Newton*

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## LIST OF ABBREVIATIONS

|            |                                |
|------------|--------------------------------|
| <b>AM</b>  | Active Microwave               |
| <b>CP</b>  | Capacitance Probe              |
| <b>DDW</b> | Diving Direct P-wave           |
| <b>EM</b>  | Electromagnetic Induction      |
| <b>FDR</b> | Frequency-Domain Reflectometry |
| <b>GPR</b> | Ground-Penetrating Radar       |
| <b>NMR</b> | Nuclear Magnetic Resonance     |
| <b>NSE</b> | Normalized Squared Error       |
| <b>PM</b>  | Passive Microwave              |
| <b>TDR</b> | Time-Domain Reflectometry      |
| <b>VDF</b> | Velocity-Depth Function        |

## ABSTRACT

Full Name : OYEKAN, Hammed Ajiboye  
Thesis Title : Estimation of Water Saturation in Sand Dunes Using Source-Receiver Offset  
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Desertified lands constitute a significant portion of the global environment and make up about one-third of the earth's land surface. Hence, possessing knowledge on the proportion of water present within the pore spaces of the most prominent features found in this environment assumes utmost significance, given its pivotal role in many geological and environmental phenomena. The current study investigates the use of source-receiver offset to estimate the degree of water saturation in a sand dune providing an opportunity to estimate the water content level while seismic experiments are being carried out in this environment. I formulated a P-wave velocity depth function,  $V_p(z, S_w)$ , from established rock physics models and defined a suitable objective function aimed at minimizing the error between the observed offset and the offset calculated using ray tracing. I proposed steps to invert water saturation and tested the proposed steps on seismic data collected using a conventional and high-resolution method. The inverted water saturation values fall within the range of (0.0882 - 0.1514) and have a mean of 0.1035. Comparison with laboratory values of saturation collectively indicate a dry sand dune. Finally, I conducted sensitivity analyses to provide insights into how changes in assumed parameters including mineralogy, porosity, and sphericity factors affect the water saturation estimate derived from my inversion procedure.

## ملخص الرسالة

**عنوان الرسالة :** تقدير تشبع الماء في الكثبان الرملية باستخدام إزاحة المصدر والمستقبل  
**التخصص الرئيسي :** ماجستير العلوم في الجيوفيزياء  
**تاريخ الحصول على الدرجة :** 2024

تشكل الأراضي المتصحرة جزءًا كبيرًا من البيئة العالمية وتشكل حوالي ثلث مساحة اليابسة على الأرض. ومن هنا فإن معرفة نسبة المياه الموجودة ضمن المسامات من أبرز المعالم الموجودة في هذه البيئة تحظى بأهمية قصوى، نظرا لدورها المحوري في العديد من الظواهر الجيولوجية والبيئية. تبحث الدراسة في استخدام إزاحة المصدر والمستقبل لتقدير درجة التشبع المائي في الكثبان الرملية مما يوفر فرصة لتقدير مستوى المحتوى المائي أثناء إجراء التجربة من نموذج فيزياء الصخور ،  $P, V_p(z, S_w)$  الزلزالية في هذه البيئة. لقد قمت بصياغة دالة عمق سرعة الموجة المحدد وحددت دالة موضوعية مناسبة تهدف إلى تقليل الخطأ بين الإزاحة المرصودة والإزاحة المحسوبة باستخدام تتبع الشعاع. اقترحت خطوات لعكس تشبع الماء واختبرت الخطوات المقترحة على البيانات الزلزالية التي تم جمعها باستخدام طريقة تقليدية وعالية الدقة. وتقع قيم التشبع المائي المقلوب ضمن المدى (0.0882 – 0.1514) ومتوسطها تشير المقارنة مع قيم التشبع المخبرية مجتمعة إلى وجود الكثبان الرملية الجافة. أخيرًا، أجريت تحليلات 0.1035 حساسية لتقديم نظرة ثاقبة حول كيفية تأثير التغيرات في المعلمات، مثل أرقام التنسيق، على تقدير تشبع الماء المشتق من انعكاسي.

# **CHAPTER 1**

## **INTRODUCTION**

A significant portion of the Earth's surface is covered with unconsolidated sediments, which are deposited in diverse geological settings. Desertified lands constitute a significant portion of the global environment and make up about one-third of the earth's land surface. Consequently, a range of challenges have arisen, including the phenomenon of desertification and the issue of water scarcity, both of which exert a substantial influence on many ecosystems. Living organisms, including flora, fauna, and humans, residing within these habitats rely on subterranean water reserves found in the soil, such as dunes, to sustain their survival. Hence, possessing knowledge on the proportion of water present within the pore spaces of unconsolidated sediments assumes utmost significance, given its pivotal role in many geological and environmental phenomena. While there exist other approaches for assessing soil water saturation, including invasive procedures such as core samples and probes, geophysical exploration techniques are generally adequate for determining full water saturation in soil (i.e., groundwater table). Furthermore, some geophysical exploration methods are capable of determining the general degree of soil saturation (i.e., low, intermediate, high) without estimating an accurate water saturation value, which is generally sufficient for most human activities in deserts [2].

Sand dunes possess the potential to serve as a dependable water resource, mostly attributable to precipitation during the wet season or the replenishment of water from the

subsurface aquifers situated beneath the sand dunes [3]. The availability of water affects both their formation and evolution because the sand water content is crucial for determining the dune stability and shape [4]. Thus, understanding water saturation in sand dunes is pivotal to comprehending their response to changing environmental conditions. The saturation in the dunes is estimated using a variety of methodologies from a variety of scientific disciplines. One of these methods, and probably the most accurate method used in the laboratory, is the gravimetric method. The difference in weight before and after drying a core sample gives the water content, from which the water saturation can be estimated [5]. The neutron method is also a way of measuring the water content in dunes. This method basically uses a neutron source and a detector to measure the hydrogen content in the dunes. Because hydrogen atoms are present in water molecules, this method easily allows neutron probing to measure the water content [6]. Another method is to insert soil moisture probes into the subsurface. These portable devices measure soil moisture content using principles such as electrical resistance and dielectric measurements. Other methods include time domain and frequency domain reflectometry.

Several geophysical techniques have also been used effectively in groundwater exploration to provide information about the soil water content. The dielectric characteristics of sand dunes, for instance, affect the reflection of ground-penetrating radar (GPR) signals [7]. Alterations in these properties can serve as indicators of fluctuations in moisture levels inside the soil. [8] used radar reflections from a dry aeolian dune to estimate the water content using the wavelet modeling method. While seismic methods also offer valuable insights into the subsurface properties influencing water saturation in subsurface formations, including sand dunes, they are not primarily designed for direct water

saturation estimation. The complex relationship between seismic velocity and water saturation is influenced by factors such as lithology, compaction, and pore fluid characteristics. The seismic refraction method in particular has been extensively and effectively used for decades for groundwater exploration and detecting the water table in the subsurface [8] - [12]. Changes in seismic velocity are controlled by changes in the elastic properties of the formations. Thus, the higher the contrast in elastic properties, the more distinctively the characteristics of the formations and their boundaries can be defined. As the groundwater content in the subsurface reach full saturation, it yields a significant increase in the velocity of seismic P-waves. These outcomes can then be used to interpret the type, porosity, and water content of the materials. As a result, the seismic refraction approach provides immediate information on the depth of the water table for a homogeneous lithology [14]. [14] - [15] used this technique to delineate the depth and thickness of phreatic zone in several sabkhas at various locations in eastern province of Saudi Arabia.

## **1.1 Research Problem**

Generally, there exists some sort of relationship between seismic P-wave velocity and the water content of unconsolidated sediment. As the water content increases, P-wave velocity typically decreases. This is due to the increasing density of the sediment, while the elastic constants remain almost unaffected. However, as the formation approaches full saturation ( $S_w = 1.0$ ), the P-wave velocity jumps significantly [17]. As a result, determining partial saturation in subsurface layers using only the P-wave is challenging. [18] attempted to estimate water saturation in a sand dune using the travel times of the diving direct P-waves

(DDW). However, using traveltimes is prone to errors arising from inaccurate picking due to low data quality.

## **1.2 Research Objectives**

The objectives of this study are to:

1. Develop a function that relates seismic P-wave velocity to water saturation  $V_p(S_w)$  through the Digby's equation, Hertz–Mindlin equation, and Gassmann's fluid substitution models [17] and [18] to calculate the offset (X) of the DDW.
2. Estimate the water saturation at the maximum depths of rays corresponding to the offsets at which the DDW is received in the field.
3. Compare the results to water saturation values measured in the lab in sand samples obtained from the study area at the depths where the water saturation was inverted.
4. Perform sensitivity analysis to provide insights on how water saturation derived from my inversion is affected by changes in the mineralogical composition of the dunes, dune's porosity, and the sphericity of the sand grains.

## **1.3 Significance of the Study**

This study aims to estimate water saturation in unconsolidated sediments, such as sand dunes, using source-receiver offset measurements from a seismic survey. I use the offset, rather than time, of the diving direct P-wave to estimate water saturation at the depths corresponding to the measured offset because errors in offset measurement in the field are expected to be less than those associated with automatic or manual travel time picking during processing. Furthermore, I perform sensitivity analyses to provide insights on how

water saturation derived from my inversion is affected by several properties of the dune that are usually assumed.

## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1 Sand Dunes and Water Content**

Water content in the dunes is the amount of water present within the interstitial voids of the sand grains. This parameter is critical and holds significant importance within the field of hydrology due to its direct impact on a range of hydrological processes and phenomena. These include groundwater recharge, soil moisture levels, and plant growth within ecosystems, all of which depend on the properties of sediments and their grains. Water content also varies significantly due to precipitation, evaporation, and the dune's position relative to the water table. During precipitation events, water permeates the sand dune, increasing its content. The infiltrated water has the potential to trickle downwards, replenishing groundwater aquifers. These aquifers can then be utilized by humans for various purposes, such as domestic use, or they may undergo evaporation due to solar radiation. Additionally, the infiltrated water can be absorbed by plants, making a valuable contribution to the ecosystem of the dune. Therefore, it is crucial to know the water content in sand dunes to understand the availability of water resources in arid and semiarid regions where sand dunes are common.

Several studies have been carried out to accurately measure water content in various sand dunes worldwide, both in situ and in the laboratory. These studies aim to evaluate the sustainability of water resources and, recently, to study the effects of climate change and

land use on these fragile ecosystems, among other research objectives. A study by [19] investigates how vegetation growing on different sand dunes found in North Sinai, Egypt, adapts to the adverse conditions they are subjected to in the environment. They measured the water content in the dry and wet seasons across six sand dunes over a period of two years. In China, the relationship between cryptogamic crusts and environmental factors in the Gurbantonggut Desert was the subject of study by [20]. They analyzed the composition of surface material and applied various methods to measure the physiochemical properties, such as the soil moisture content. [20] used drying method to measure the water content across different parts of the dunes in the desert. The study also examines dune slope component variation and seasonal soil moisture content changes. In the Shapotou Region of northern China, [21] investigated sand dunes of this region to understand how revegetation affects water content in the Tengger Desert. The water content of the sand dunes was measured by the gravimetric approach. Due to the significant impact of water availability on microbial life, [21] provided the first quantitative evaluation of microbes and a detailed microbial characterization of barchan dunes from the hyper-arid Qatari desert, including moisture content analyses. They assessed the moisture content per gram of sand from two distinct depths at the base, middle, and crest of the barchan dune named Nadine, as well as from the adjacent desert floor, using the gravimetric method.

Because of climate and weather patterns throughout the year, dune moisture content can vary significantly with the season. [22] conducted research on three different types of Khuzestan Dunes in Iran to study seasonal fluctuations in soil water content and the condensation process. He measured the water content of the dunes in different locations of the dune. [23] also studied how soil water content varies during the growing season based

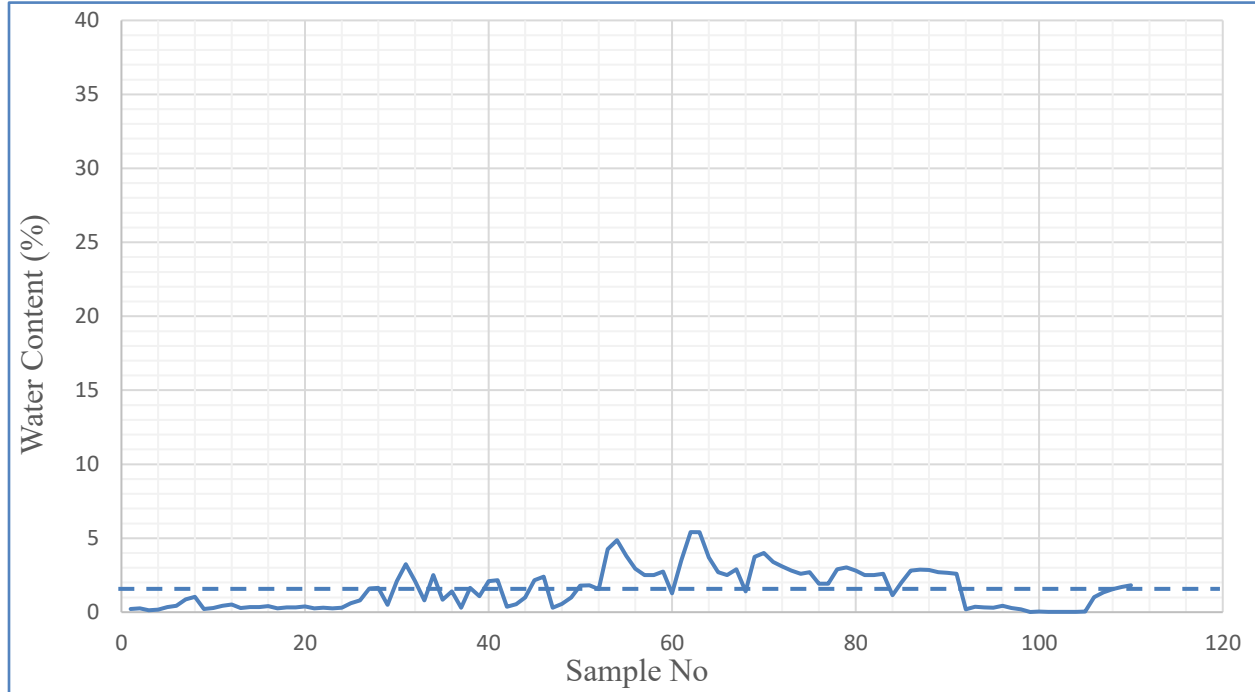
on monitoring data collected from May to September 2014 in the temperate semiarid region of the Horqin Sandy Land of northern China. [24] conducted research on the small-scale (microenvironmental variations) and seasonal changes in soil water content within the vadose zone of a sand dune system at Pinery Provincial Park in Canada. The study investigates the correlation between soil moisture and vegetation dynamics during various stages of stabilization in the dune environment. It provides insights into soil moisture dynamics in ecosystems, which could be crucial for conservation, land management, and ecological studies in the region. The moisture contents of sand dunes reported from all the studies reviewed above and other studies where the dune and weather conditions of the study area are similar to my study area have been collected, documented, and shown in Table 1 and Figure 1. The table shows their corresponding depths, the reported location and country for these studies, and descriptive statistics of the reported percentage water content values. The last row in Table 1 shows the minimum, maximum, and median water content of all studies reviewed.

**Table 1 Table of percentage water contents measured and reported from studies in various locations around the world with similar conditions to my study area.**

| Study             | Country | Location                     | Depth (cm) | Water content (%) | Method             | Min  | Max  | Median |
|-------------------|---------|------------------------------|------------|-------------------|--------------------|------|------|--------|
| Gad et al., 2012  | Egypt   | El-Ssabha First year         | 0 - 20     | 0.22              | Gravimetric method | 0.13 | 1.05 | 0.32   |
|                   |         |                              | 20 - 40    | 0.27              |                    |      |      |        |
|                   |         | El-Ssabha Second year        | 0 - 20     | 0.13              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.16              |                    |      |      |        |
|                   |         | El-Sheikh Zuwied First year  | 0 - 20     | 0.35              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.42              |                    |      |      |        |
|                   |         | El-Sheikh Zuwied Second year | 0 - 20     | 0.86              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 1.05              |                    |      |      |        |
|                   |         | Abu-Asab First year          | 0 - 20     | 0.22              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.27              |                    |      |      |        |
|                   |         | Abu-Asab Second year         | 0 - 20     | 0.43              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.52              |                    |      |      |        |
|                   |         | El-Hauol First year          | 0 - 20     | 0.28              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.35              |                    |      |      |        |
|                   |         | El-Hauol Second year         | 0 - 20     | 0.34              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.42              |                    |      |      |        |
|                   |         | El-Gapher First year         | 0 - 20     | 0.26              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.32              |                    |      |      |        |
|                   |         | El-Gapher Second year        | 0 - 20     | 0.32              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.40              |                    |      |      |        |
|                   |         | Magaria First year           | 0 - 20     | 0.26              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.31              |                    |      |      |        |
|                   |         | Magaria Second year          | 0 - 20     | 0.25              |                    |      |      |        |
|                   |         |                              | 20 - 40    | 0.30              |                    |      |      |        |
| Chen et al., 2007 | China   | Upper side of the dune       | 0 - 2      | 0.60              | Drying method      | 0.50 | 3.25 | 1.50   |
|                   |         |                              | 2 - 5      | 0.80              |                    |      |      |        |
|                   |         |                              | 5 - 10     | 1.60              |                    |      |      |        |
|                   |         |                              | 10 - 20    | 1.65              |                    |      |      |        |
|                   |         | Middle side of the dune      | 0 - 2      | 0.50              |                    |      |      |        |
|                   |         |                              | 2 - 5      | 2.10              |                    |      |      |        |
|                   |         |                              | 5 - 10     | 3.25              |                    |      |      |        |
|                   |         |                              | 10 - 20    | 2.10              |                    |      |      |        |
|                   |         | Lower side of the dune       | 0 - 2      | 0.80              |                    |      |      |        |
|                   |         |                              | 2 - 5      | 2.50              |                    |      |      |        |
|                   |         |                              | 5 - 10     | 0.85              |                    |      |      |        |
|                   |         |                              | 10 - 20    | 1.40              |                    |      |      |        |
| Rouhipour, 2006   | Iran    | windward slope               | 0 - 20     | 0.31              | Gravimetric method | 0.30 | 2.40 | 1.08   |
|                   |         |                              | 20 - 40    | 1.64              |                    |      |      |        |
|                   |         |                              | 40 - 60    | 1.08              |                    |      |      |        |

|                     |       |                      |              |      |                   |      |      |      |
|---------------------|-------|----------------------|--------------|------|-------------------|------|------|------|
|                     |       |                      | 60 – 80      | 2.10 |                   |      |      |      |
|                     |       |                      | 80 - 100     | 2.15 |                   |      |      |      |
|                     |       | Dune crest           | 0.0 - 20     | 0.37 |                   |      |      |      |
|                     |       |                      | 20 - 40      | 0.53 |                   |      |      |      |
|                     |       |                      | 40 - 60      | 1.00 |                   |      |      |      |
|                     |       |                      | 60 - 80      | 2.17 |                   |      |      |      |
|                     |       |                      | 80 - 100     | 2.40 |                   |      |      |      |
|                     |       | leeward slope        | 0.0 - 20     | 0.30 |                   |      |      |      |
|                     |       |                      | 20 - 40      | 0.57 |                   |      |      |      |
|                     |       |                      | 40 - 60      | 1.00 |                   |      |      |      |
|                     |       |                      | 60 - 80      | 1.80 |                   |      |      |      |
|                     |       |                      | 80 - 100     | 1.82 |                   |      |      |      |
| Yao et al.,<br>2018 | China | Horqin sandy<br>land | 0 - 10       | 1.56 | Neutron<br>probes | 1.14 | 5.41 | 2.78 |
|                     |       | May                  | 10 – 30      | 4.25 |                   |      |      |      |
|                     |       |                      | 30 - 50      | 4.87 |                   |      |      |      |
|                     |       |                      | 50 - 70      | 3.80 |                   |      |      |      |
|                     |       |                      | 70 - 90      | 2.95 |                   |      |      |      |
|                     |       |                      | 90 - 110     | 2.50 |                   |      |      |      |
|                     |       |                      | 110 –<br>130 | 2.50 |                   |      |      |      |
|                     |       |                      | 130 –<br>150 | 2.75 |                   |      |      |      |
|                     |       | June                 | 0 – 10       | 1.27 |                   |      |      |      |
|                     |       |                      | 10 – 30      | 3.50 |                   |      |      |      |
|                     |       |                      | 30 - 50      | 5.41 |                   |      |      |      |
|                     |       |                      | 50 - 70      | 5.40 |                   |      |      |      |
|                     |       |                      | 70 - 90      | 3.70 |                   |      |      |      |
|                     |       |                      | 90 - 110     | 2.70 |                   |      |      |      |
|                     |       |                      | 110 –<br>130 | 2.50 |                   |      |      |      |
|                     |       |                      | 130 –<br>150 | 2.90 |                   |      |      |      |
|                     |       | July                 | 0 – 10       | 1.40 |                   |      |      |      |
|                     |       |                      | 10 – 30      | 3.75 |                   |      |      |      |
|                     |       |                      | 30 - 50      | 3.99 |                   |      |      |      |
|                     |       |                      | 50 - 70      | 3.40 |                   |      |      |      |
|                     |       |                      | 70 - 90      | 3.10 |                   |      |      |      |
|                     |       |                      | 90 - 110     | 2.80 |                   |      |      |      |
|                     |       |                      | 110 –<br>130 | 2.60 |                   |      |      |      |
|                     |       |                      | 130 –<br>150 | 2.70 |                   |      |      |      |
|                     |       | August               | 0 – 10       | 1.92 |                   |      |      |      |
|                     |       |                      | 10 – 30      | 1.92 |                   |      |      |      |

|                          |                      |           |           |        |               |        |        |        |
|--------------------------|----------------------|-----------|-----------|--------|---------------|--------|--------|--------|
|                          |                      |           | 30 - 50   | 2.90   |               |        |        |        |
|                          |                      |           | 50 – 70   | 3.02   |               |        |        |        |
|                          |                      |           | 70 - 90   | 2.80   |               |        |        |        |
|                          |                      |           | 90 - 110  | 2.50   |               |        |        |        |
|                          |                      |           | 110 - 130 | 2.50   |               |        |        |        |
|                          |                      |           | 130 - 150 | 2.60   |               |        |        |        |
|                          |                      | September | 0 - 10    | 1.14   |               |        |        |        |
|                          |                      |           | 10 – 30   | 2.00   |               |        |        |        |
|                          |                      |           | 30 - 50   | 2.80   |               |        |        |        |
|                          |                      |           | 50 - 70   | 2.88   |               |        |        |        |
|                          |                      |           | 70 - 90   | 2.85   |               |        |        |        |
|                          |                      |           | 90 - 110  | 2.70   |               |        |        |        |
|                          |                      |           | 110 – 130 | 2.65   |               |        |        |        |
|                          |                      |           | 130 – 150 | 2.60   |               |        |        |        |
| Abdul Majid et al., 2016 | Qatari Barchan Dunes | Floor     | -         | 0.19   | Drying method | 0.19   | 0.42   | 0.29   |
|                          |                      | Base      | 0 – 5     | 0.37   |               |        |        |        |
|                          |                      |           | 15 – 20   | 0.32   |               |        |        |        |
|                          |                      | Mid       | 0 – 5     | 0.29   |               |        |        |        |
|                          |                      |           | 15 – 20   | 0.42   |               |        |        |        |
|                          |                      | Crest     | 0 – 5     | 0.28   |               |        |        |        |
| 15 – 20                  | 0.2                  |           |           |        |               |        |        |        |
| Dincer et al., 1974      | Riyadh Sand dune     |           | 0.2       | 0.0118 |               | 0.0118 | 0.0443 | 0.0244 |
|                          |                      |           | 0.5       | 0.0443 |               |        |        |        |
|                          |                      |           | 1         | 0.0241 |               |        |        |        |
|                          |                      |           | 1.5       | 0.0244 |               |        |        |        |
|                          |                      |           | 2         | 0.0235 |               |        |        |        |
|                          |                      |           | 2.5       | 0.0264 |               |        |        |        |
|                          |                      |           | 3         | 0.0367 |               |        |        |        |
| Al-Agely et al., 1995    | Colorado Sand dune   |           | 0.1       | 1.02   |               | 1.02   | 1.82   | 1.55   |
|                          |                      |           | 0.2       | 1.34   |               |        |        |        |
|                          |                      |           | 0.3       | 1.55   |               |        |        |        |
|                          |                      |           | 0.4       | 1.7    |               |        |        |        |
|                          |                      |           | 0.5       | 1.82   |               |        |        |        |
| All studies              |                      |           |           |        |               | 0.01   | 5.41   | 1.37   |



**Figure 1** Water contents measured from different dry sand dunes of the World. Dashed line indicates the median water content.

## **2.2 Studies on Water Content Measurement Using Geophysical Techniques**

Research on water content measurement using geophysical techniques focuses on developing methods to non-invasively assess the water content or saturation of rock formations. These studies aim to advance our understanding of hydrological processes, groundwater dynamics, distribution of soil water content, as well as environmental monitoring, all of which are crucial in groundwater resource management and assessing their environmental impacts. In recent years, geophysical techniques have emerged as

powerful tools for non-invasive and spatially extensive measurement of water content in the subsurface. Various geophysical methods have been adapted to measure the soil water content, including ground-penetrating radar (GPR), capacitance probes (CP), active microwaves (AM) or radar scatterometry, time and frequency domain reflectometry, passive microwaves (PM) remote sensing, electromagnetic induction (EMI), neutron moderation, magnetic resonance techniques (NMR), gamma ray attenuation, seismic method (SM) and electrical resistivity (ER) [25]. These techniques leverage the physical properties of soils and rocks, such as thermal properties, dielectric permittivity, electrical resistivity, and seismic wave velocities, to infer variations in water content. Due to the nature of the waves they use to propagate into the subsurface, several of these techniques, such as TDR, PM, EMI, GPR, CP, and AM, fall under the category of electromagnetic methods. Nonetheless, they differ from each other in principle, application, and field deployment. The fundamental principles of TDR and GPR are identical [26] and [27]. TDR involves inserting probes containing electromagnetic sensors into the subsurface, then sending radio frequency signals along the transmission line down the probes embedded in the soil. While GPR emits high-frequency electromagnetic pulses from a transmitting antenna into the subsurface, the receiver antenna records the reflected signals, making it well-suited for rapid bulk measurements over large areas. Both methods measure the travel time and amplitude of EM pulses, which are related to the dielectric properties of the soil and subsequently converted to soil water content. SM measures the propagation velocity of seismic waves through the subsurface. Changes in water content alter the velocities of these waves as they propagate through the subsurface, providing insight into subsurface water distribution and properties. Neutron thermalization basically relies on a radioactive

source emitting high-energy, epithermal neutrons that interact with hydrogen (H) nuclei in the soil. These interactions occur as the neutrons collide with H atoms, causing them to lose energy and thermalize. Since the mass of an H nucleus is similar to that of a neutron, they efficiently transfer energy during collisions. Since most H atoms in common soils are associated with water molecules, the thermalized neutrons that return to a detector provide a measure of the saturation of H atoms in the soil, closely related to volumetric water content, providing depth-specific estimates of the water content. This method is a crucial step in soil moisture measurement techniques such as neutron logging using the neutron depth probe.

[27] used ground-penetrating radar measurements to estimate the water content of partially saturated soil horizons found within the vadose zone of the superficial aquifer at the Gnangara Mound near Perth in Western Australia. The lateral water content distribution within the podzolic soil profile was successfully quantified using a pseudo-3D GPR dataset acquired as a series of 2D common-offset gathers, allowing for the estimation of moisture content variations within a layer of constant thickness within a homogeneous background. The calculated water content values agree with those reported in previous studies in the study area using gravimetric and neutron log water content measurements. [28] used an integrated geophysical approach to assess groundwater resources in the town of Gemas in southern Malaysia. Their research combines borehole logging, electrical resistivity, and induced polarization techniques to determine hydrogeological properties and identify the various resistive units in the volcano-sedimentary rocks of the study area in an effort to quantify the groundwater potential of the area. [29] combines GPR and geoelectrical measurements from a test site in Spandau, Germany, to estimate the water content and

porosity of the subsurface. It emphasizes the importance of combining geophysical methods to reduce ambiguity and provide a more precise description of the subsurface. [30], on the other hand, uses the two methods independently to estimate the volumetric water content in the vadose (unsaturated) zone and porosity in the saturated zone of a sandy formation from two different sites. The water content values in the vadose zone obtained from the techniques follow a similar trend, though the one from GPR measurement is slightly higher. The mean porosity measured in the saturated zone is consistent with known porosity values.

### **2.3 Water Saturation Inversion Using Seismic Methods**

In groundwater and hydrocarbon exploration, water saturation is perhaps the most challenging petrophysical calculation when trying to evaluate the property of a formation and is used to theoretically quantify the more important property, the seismic P-wave velocity. Complexities arise because there are several independent approaches using geophysical techniques such as the electrical resistivity method, ground penetrating radar (GPR), and even the seismic method that can be used to estimate the value of water saturation. The implication of these approaches is that they yield somewhat different  $S_w$  values, which unfortunately means that the value of the P-wave velocity would be inaccurately predicted.

The seismic refraction and reflection methods have been quite successful in groundwater exploration and mapping water tables in aquifers [32]. The seismic refraction method, for instance, has been used effectively for shallow groundwater exploration and detecting water tables in the subsurface. [14] utilized it to identify and characterize the subsurface

for the potential of groundwater in Nigeria, and [33] used refraction tomography in Wadi Showat in the southern part of Saudi Arabia to determine the depth of shallow groundwater. The seismic refraction method generally gives immediate information on the depth of the water table in homogeneous lithology because full water saturation below the water table causes a significant increase in seismic velocity [14]. This makes it ideal for groundwater exploration in fully saturated, unconsolidated sediments. However, determining the water saturation in partially saturated unconsolidated sediments using the seismic method is not very successful due to the low variation in velocity for water saturation below 100%. [34] carried out high-resolution, very shallow seismic reflection and refraction experiments to investigate the seismic response of groundwater level changes at Moss-Landing beach in sandy Monterey Bay, California. Using the first arrival signals coming from shallow depths, they directly inferred water saturation from the near-surface velocities. Their study suggests that reflected and refracted signals are influenced by partial saturation, which indicates that they are responsive to the history of water flow. This implies that these signals do not directly correspond to the water table but rather to the saturation profile. Basically, high-resolution seismic experiments are sufficient and effective to infer partial water saturation.

[18] also used data from high-resolution and conventional (low-frequency) seismic experiments collected by [1] to infer water saturation in a partially saturated dune. He minimizes the normalized squared error (NSE) between the travel times of direct arrivals and the calculated arrival times of the DDW. This method resulted in water saturation values that indicated a low-saturated dune similar to those measured in the studied dune. However, the utilization of traveltimes may present certain challenges because the travel

time of first arrivals still relies on picking, a process that is subjective and prone to potential errors.

[1] used the reciprocity condition as a rejection criterion in their study during data analysis, which rejects any time pick if the difference is greater than quarter of the wavelet's period between two arrivals when the positions of the source and receiver are interchanged. This means that some arrivals might be accepted with an error of as much as a quarter of the wavelet period, which is about 5 msec in their data. Although this error is tolerable for velocity studies, it is considered large for  $S_w$  inversion, especially in nearly dry sand dunes such as my studied dune. In comparison, offsets were calculated using coordinates from differential GPS field measurements resulting in a very high accuracy. Therefore, in this study, I use source-receiver offsets and their corresponding maximum depths of the direct diving P-waves to estimate water saturation in the same dune studied by [17] and [18] near Dammam Airport in eastern Saudi Arabia.

## **CHAPTER 3**

### **METHODOLOGY**

#### **3.1 Rock Physics Model Selection**

Rock physics establishes connections between a sediment's elastic properties, its overall physical properties (such as porosity and lithology), and its conditions (such as pore pressure and pore fluid) [35]. While rock physics establishes the connection between these properties, rock physics models establish the relationship between the physical properties of the rocks and their corresponding seismic response, such as velocity, attenuation, and amplitude measured during a seismic experiment. The physics behind these models encompasses the interaction of seismic waves with geological materials and the resultant properties observed in seismic data. These mathematical representations are therefore essential in the quantitative interpretation of seismic data and play a crucial role in estimating or inverting subsurface properties such as fluid saturation, porosity, or water content. [49] provides detailed explanations of some of these models, their assumptions, and limitations. Different rock physics models have been developed based on different geological settings, targeted fluids, and under different assumptions. Therefore, it is crucial to select a model with assumptions that are based on those observed in or relevant to the geological environment of the sand dunes.

### 3.1.1 Contact Model

Sand grains typically interact with each other through physical contact when they exhibit mechanical actions, such as the process of sand dunes formation, or when they are being transported by wind or water. So, to understand how stress, strain, and other mechanical properties propagate through rock formation, it is crucial to describe the contact interaction between mineral grains in a rock matrix. Such physical interactions are described by contact models. These mathematical models are particularly relevant for understanding the physics and for predicting the mechanical properties, such as effective moduli, of partially saturated or unsaturated (vadose) zone in an unconsolidated formation, such as sand dunes.

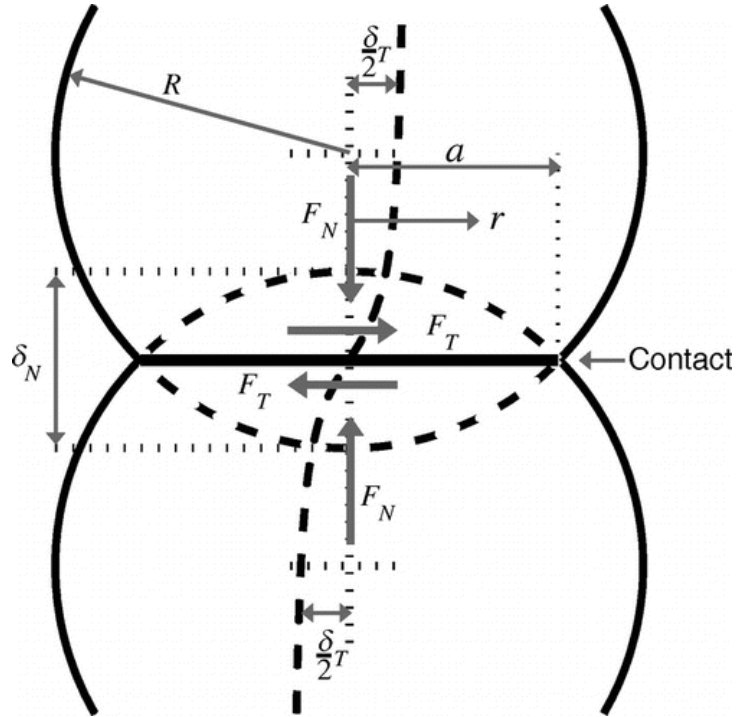


Figure 2: Illustration of Hertz-Mindlin contact mechanics between two identical spherical bodies with radius  $R$ , highlighting the normal force ( $F_N$ ), tangential force ( $F_T$ ), contact radius ( $a$ ), and the deformation components ( $\delta_N$  and  $\delta_T$ ) at the contact interface.

They help capture the effects of grain-to-grain contacts, pore pressure, and fluid distribution on the overall rock behavior. One of the models that explains the contact mechanics and the deformation behavior of elastic spheres is the Hertz-Mindlin Contact model. Implemented in an effective medium using a granular model which initially models a rock formation as a pack of grains, and then adds materials like different fluid phases into the model. In a sand grain packing where each grain is a sphere, the elastic properties of the packing of the sphere-shaped grains depend on two types of contact stiffness: normal and tangential. These stiffnesses are related to a two-particle combination in the packings [49] as shown in Figure 2. So, for these two elastic spheres in contact, this model assumes that the two spheres come into contact along a single point or a small contact area, and the contact can be represented as a series of elastic springs, the deformation or displacement of which is proportional to the applied normal ( $F$ ) or tangential ( $T$ ) forces. The amount of deformation induced by the respective forces depends on the respective stiffnesses of the contact bodies, defined as the ratio of the increment in force to the increment in displacement.

For a random packing of spheres, the bulk and shear modulus of a granular packing can be expressed by a combination of Digby's equations [37]:

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

$$\mu_{dry} = \frac{C(1-\varphi)}{20\pi R} (S_n + \frac{3}{2} S_t), \quad (2)$$

where  $C$  is the coordination number indicating the average number of contacts per grain of the sediment,  $R$  is the average radius of the spherical grains, and  $\varphi$  is the porosity of the

sediment.  $s_n$  and  $s_\tau$  are the normal and shear stiffnesses of a two spherical grain combination in contact [37]:

$$s_n = \frac{\Delta F}{\Delta \delta} = \frac{4a\mu}{1-\nu}, \quad (3)$$

$$s_\tau = \frac{\Delta T}{\Delta \tau} = \frac{8b\mu}{2-\nu}, \quad (4)$$

where  $a$  is the radius of the contact area and assuming  $a = b$  indicating no slippage (infinite-contact friction) along the contact area between the spheres.  $\Delta$  indicates is the increment in the applied forces or resulting displacement,  $\nu$  is Poisson's ratio of the mineral matrix and  $\mu$  is the shear modulus of the grain material.  $F$  and  $T$  are the normal and tangential forces, while  $\delta$  and  $\tau$  are the normal and tangential displacements.

Hertz theory [38] explains the behavior of the spheres under the action of a normal force which presses them together and gives the relationship between the radius of the contact area and the normal displacement caused by the force [49]:

$$\delta = \frac{a^2}{R}. \quad (5)$$

Therefore,

$$a \approx \sqrt{\delta R} = \sqrt[3]{\frac{3FR(1-\nu)}{8\mu}}. \quad (6)$$

Solving equation 6 for  $F$  results in a relationship between the normal force and the radius of the contact area governed by Hertzian contact theory, where higher normal forces result in greater deformation and spreading of the contact area, leading to a larger radius of contact:

$$F = \frac{8a^3\mu}{3R(1-\nu)}. \quad (7)$$

Differentiating equation 7 with respect to the normal displacement using the chain rule yields the normal stiffness:

$$s_n = \frac{\delta F}{\delta a} * \frac{\delta a}{\delta \delta} = \frac{\delta F}{\delta a} * \left(\frac{\delta \delta}{\delta a}\right)^{-1}. \quad (8)$$

If a hydrostatic pressure ( $P$ ) is applied to the solid portion of the packing, the normal force becomes

$$F = \frac{4\pi R^2 P}{C(1-\varphi)}. \quad (9)$$

Substituting equation 9 into equation 6 gives a new expression for the radius of the grain's contact area under the influence of a hydrostatic pressure:

$$a = \frac{R}{f} \sqrt[3]{\frac{3\pi(1-\nu)}{2C(1-\varphi)\mu} P}. \quad (10)$$

The factor  $f$  in equation 10 is called the sphericity factor proposed by [1] to account for the grain sphericity. A sphericity factor of 1 means the grain shape is a perfect sphere, and a factor greater than 1 implies deviation from a perfect sphere. The confining hydrostatic pressure exerted on the spherical grains packing is:

$$P = \rho_{dry} g z, \quad (11)$$

where  $g$  is the gravitational acceleration,  $z$  is the sediment's thickness above the grain contact, and  $\rho_{dry}$  is the density of the dry rock matrix calculated as:

$$\rho_{dry} = \varphi \rho_a + (1 - \varphi) \rho_m, \quad (12)$$

where  $\rho_a$  and  $\rho_m$  are the densities of air and rock matrix.

The dry effective bulk modulus for a random packing of spheres can be obtained by substituting equation 10 into equation 3 and subsequently adding the resulting equation into equation 1.

$$S_n = \frac{4\mu R}{f(1-\nu)} \sqrt[3]{\frac{3\pi(1-\nu)}{2C(1-\phi)\mu}} P, \quad (13)$$

$$k_{dry} = \frac{C(1-\phi)}{12\pi R} S_n = \sqrt[3]{\frac{C^2(1-\phi)^2\mu^2}{18\pi^2(1-\nu)^2}} P, \quad (14)$$

[39] expanded upon the Hertz's theory by introducing a minor tangential force,  $T$ , into the circular contact region between the two spheres that are initially subjected to a constant normal force [40]. [39] gave the tangential force displacement relation as:

$$T = \frac{4a\mu}{2-\nu} \tau. \quad (15)$$

At the boundary of the contact area between the two spheres, the distance from the center of the sphere over which the stress acts equal  $a$ . At this point, the shear stress becomes infinite. This condition occurs only when the coefficient of contact friction is infinite, implying that there is no partial slide within the contact area [40]. The tangential stiffness for such a boundary condition is given as:

$$s_\tau = 2 \left( \frac{\delta T}{\delta \tau} \right) = \frac{8a\mu}{2-\nu}. \quad (16)$$

By differentiating the tangential force with respect to tangential displacement, equation 16 will yield equation 4. Substitute equations 16, 10, and 3 into equation 2 to get the expression for the effective shear modulus for a random packing of spheres:

$$\mu_{dry} = \frac{(5-4\nu)R}{5(2-\nu)f} \sqrt{\frac{3C^2(1-\varphi)^2\mu^2}{2\pi^2(1-\nu)^2}} P. \quad (17)$$

The effective shear modulus can be rewritten in terms of the effective bulk modulus as:

$$\mu_{dry} = \frac{3(5-4\nu)}{5(2-\nu)} k_{dry}. \quad (18)$$

The Hertz-Mindlin model makes several assumptions to simplify the analysis of elastic contact between two solid bodies. It assumes that contacting bodies are linearly elastic, meaning the deformation of the bodies under stress obeys Hooke's law. The model also assumes that the contacting bodies have a spherical shape. This assumption simplifies the analysis by considering a single point of contact between the bodies. In reality, the contact area may have complex shapes, but the spherical approximation is often used for simplicity. It is for this reason that [18] introduced the sphericity factor,  $f$ , into the model to account for grain deviation from a spherical shape. The model also assumes identically homogenous, isotropic, elastic spherical grains. Finally, the model assumes small deformations at the contact interface, which is valid for small loads and elastic materials.

### 3.1.2 Fluid Substitution Model

The Hertz-Mindlin model assumes dry contacts, which means that there is no interstitial fluid lubricating the contact interface between particles. The model needs to be modified by incorporating a model that accounts for the effect of fluid on the elastic properties of the rock, as the presence of fluid can significantly alter the bulk modulus and shear modulus of the rock due to the differences in compressibility and density of the solid matrix and the fluid, and subsequently the velocity of seismic waves that propagate the rock. Figure 3 shows an illustration of the fluid substitution model showing rock samples with specific

pore geometry with no fluid (left) and pore spaces substituted with other fluids. The effect of saturation and pore fluids on seismic P-wave velocity is an old problem in rock physics and has been the subject of numerous theoretical ([8], [9], [10]), experimental ([12], [13], [14]), and field studies [31]. These studies confirmed that seismic velocity is sensitive to the presence of fluid in the porous space of sediments at any saturation level, but more pronounced around full saturation. For a porous elastic medium containing fluids, [42] and [43] derived the general linear stress–strain relations. Biot’s theory relates the elastic constants of saturated rocks to the properties of the materials as given by Gassmann’s equation [17]. The low-frequency Biot-Gassmann theory predicts the resulting increase in effective bulk modulus,  $k_{sat}$ , of the saturated rock. The equation, commonly known as Gassmann’s equation, allows for the prediction of bulk modulus changes resulting from fluid substitution or saturating fluid changes. It can also be used to predict seismic wave velocity caused by different pore-fluid saturations [46]. However, and most importantly, the equation is valid only at sufficiently low frequencies, where the induced pore pressures have enough time to equilibrate throughout the pore space [49]. Fluid-solid interactions occur quasi-statically, happening slowly enough compared to the time scale required for pore pressures to reach equilibrium. It also assumes that porous media are isotropic, homogeneous, closed systems with pore fluid movement and no chemical interaction ([47] and [48]), and that the minerals that make up the rock have the same elastic moduli. It also assumes that the shear modulus is independent of fluid content:

$$\mu_{sat} = \mu_{dry}, \quad (19)$$

where  $\mu_{dry}$  and  $\mu_{sat}$  are the effective shear moduli of the dry and saturated rock, respectively. The effective bulk modulus of the saturated rock ( $k_{sat}$ ) is expressed in terms of the bulk moduli of the matrix ( $k_m$ ), dry sediment ( $k_{dry}$ ), and fluid ( $k_{fluid}$ ):

$$\frac{k_{sat}}{k_m - k_{sat}} = \frac{k_{dry}}{k_m - k_{dry}} + \frac{k_{fluid}}{\varphi(k_m - k_{fluid})}, \quad (20)$$

where  $k_{dry}$  and  $k_{sat}$  is the effective bulk moduli of dry and saturated rock, respectively.  $\varphi$  is the porosity of the rock and  $k_{fluid}$  is the effective bulk modulus of the fluid(s) which can be computed using the iso-stress or Reuss average defined as:

$$\frac{1}{k_{fluid}} = \sum \frac{S_i}{k_i}, \quad (21)$$

where  $k_i$  and  $S_i$  are the bulk modulus and saturation of the  $i^{th}$  fluid phase. In my case,  $k_{fluid}$  can be calculated as the harmonic average of the air and water bulk moduli:

$$\frac{1}{k_{fluid}} = \frac{S_w}{k_w} + \frac{1 - S_w}{k_{air}}, \quad (22)$$

$k_m$  in equation 20 is the effective bulk modulus of the minerals material making up the rock. For a multimineral matrix, it can be calculated using the Voigt-Reuss-Hill (VRH) average, which is simply the arithmetic average of the Voigt upper bound and Reuss lower bound [48] expressed as:

$$M_{VRH} = \frac{M_V + M_R}{2}, \quad (23)$$

where  $M$  can be either the shear or bulk modulus. Therefore,

$$k_m = \frac{\sum_i^n p_i k_i + \sum_i^n \frac{p_i}{k_i}}{2}, \quad (24)$$

$$\mu_m = \frac{\sum_i^n p_i \mu_i + \sum_i^n \frac{p_i}{\mu_i}}{2}, \quad (25)$$

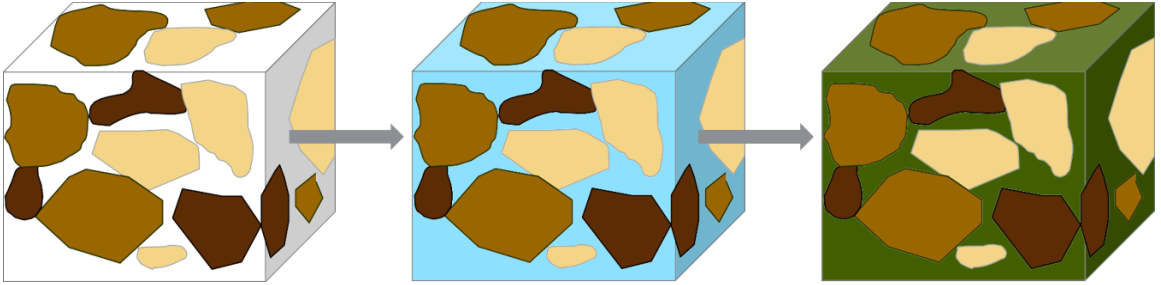
where:

$p_i$  = fractional volume of the  $i^{th}$  mineral phase of the matrix

$k_i$  = bulk modulus of the  $i^{th}$  mineral phase of the matrix

$\mu_i$  = shear modulus of the  $i^{th}$  mineral phase of the matrix.

$n$  represents the number of phases.



**Figure 3** Illustration of the fluid substitution model showing changes in pore fluid.

### 3.2 Velocity - Depth Function

The elastic wave equation is a fundamental concept in geophysics and rock mechanics, relating the elastic properties of a material to the velocities of seismic waves. Seismic velocity is a function of elastic constants, which describe how a rock responds to deformation under stress. Velocities of P- and S-waves are given respectively as:

$$V_P = \sqrt{\frac{k_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}}, \quad (26)$$

$$V_S = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}}, \quad (27)$$

where  $k_{sat}$  and  $\mu_{sat}$  are the bulk and shear moduli of the saturated material while  $\rho_{sat}$  is its density. The seismic P-wave velocity increases with depth in the subsurface due to the increase in elastic constants caused by increasing pressure with depth [49]. This observation is more evident in unconsolidated and loosely consolidated sediments, where cementation plays a negligible role. Realizing how seismic wave velocity changes with depth in the subsurface, I developed a mathematical function that relates the P-wave velocity in a fluid-saturated rock to the depth of wave propagation, the amount of water saturation, as well as the elastic constants of the rock and its fluid composition using the Hertz-Mindlin contact model and Gassmann's fluid substitution model described in section 3.1 above. The approach used to develop VDF is described below:

1. Start with Gassmann's equation (equation 20), which relates the bulk modulus of fluid-saturated rock,  $k_{sat}$ , to the bulk moduli of the dry rock, saturating fluid, and

mineral matrix, as well as the porosity of the rock. Equation 20 can be solved for  $k_{sat}$  as:

$$k_{sat} = k_{dry} + \frac{(1 - \frac{k_{dry}}{k_m})^2}{\frac{\varphi}{k_{fluid}} + \frac{1-\varphi}{k_m} + \frac{k_{dry}}{k_m^2}}. \quad (28)$$

The shear modulus of the fluid-saturated rock was given by equation 19.

2. Solve equation 22 for  $k_{fluid}$  and substitute it into equation 28.
3. Substitute  $k_{dry}$  given by Hertz's model in equation 14 into equation 28. Based on the conditions explained in Section 3.1,  $k_{dry}$  derived from Hertz's contact model can be used and is sufficient as the starting dry rock model in the Gassmann's equation (equation 28). I may also substitute equations 24 and 25 for  $k_m$  and  $\mu_m$ , respectively, into equation 28 if the volume percentage of each mineral making up the rock matrix is known. In my study, I begin by assuming a quartz-only mineralogy.
4. Substitute equation 12 into equation 11, and then the resulting equation into equation 28 after step 3. On the other hand, the shear modulus of the fluid-saturated rock is the same as that of the dry rock given by the Mindlin equation (equation 17) based on Gassmann's assumptions.
5. Poisson's ratio,  $\nu$ , in  $k_{sat}$  and  $\mu_{sat}$  in step 4 can be expressed as a function of the elastic moduli of the minerals that constitute the rock:

$$v = \frac{3k_m - 2\mu_m}{6k_m + 2\mu_m}. \quad (29)$$

6. Calculate the P-wave velocity in a fluid-saturated rock using equation 26 which can be rewritten as:

$$V_P = \sqrt{\frac{k_{sat} + \frac{4}{3}\mu_{sat}}{\rho_{sat}}} \quad (30)$$

where  $\rho_{sat}$  is the effective density of the fluid-saturated rock given by:

$$\rho_{sat} = \rho_{fluid} \varphi + \rho_m (1 - \varphi) \quad (31)$$

where  $\rho_m$  is the density of minerals that constitutes the rock.  $\rho_{fluid}$  is the density of the fluid(s) computed as the average fluid density weighted by the saturations of each fluid phase present in the rock. This approach accounts for the fact that different fluid phases (e.g., air and water) have different densities, and their contributions to the overall fluid density depend on their saturations within the rock.

Density of the fluid can be calculated as:

$$\rho_{fluid} = \sum_i S_i \rho_i, \quad (32)$$

where  $S_i$  and  $\rho_i$  are the saturation and density of the  $i^{th}$  fluid phase, respectively. For pores that are filled with only water and air,

$$\rho_{fluid} = S_w \rho_w + (1 - S_w) \rho_{air}. \quad (33)$$

$\rho_{sat}$  can be calculated as:

$$\rho_{sat} = \varphi[S_w\rho_w + (1 - S_w)\rho_{air}] + (1 - \varphi)\rho_m \quad (34)$$

7. Substitute the new version of equation 28 (bulk modulus) from step 5 above, equation 17 (shear modulus), and equation 34 (bulk density) into equation 30 to calculate the P-wave velocity.

These steps result in a long and complex algebraic equation for  $V_P$ , which is a function of depth of P-wave, water saturation, porosity, as well as the elastic properties of the air and water, and sand matrix. However, if I assume the sand dune is made up of quartz, water, and air with properties given in Table 2, then  $V_P$  reduced to equation 35 which is a function of  $z$  and  $S_w$ . The assumed matrix and pore-fluid properties in Table 2 are given by [49].

To make the method applicable in the field without the need for laboratory testing, I assume the following:

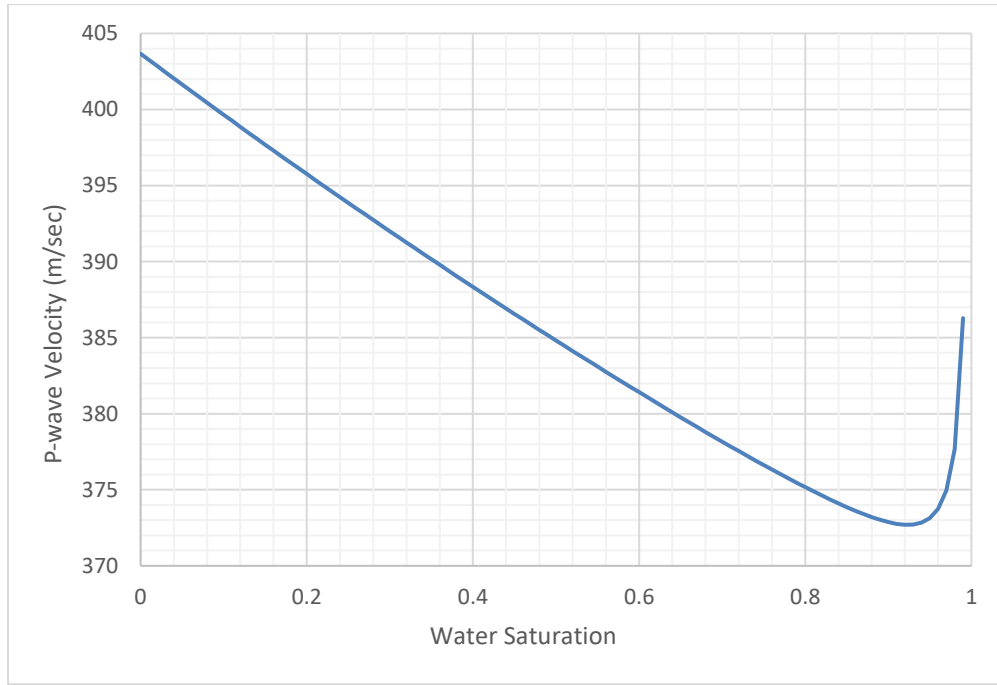
- Constant porosity of 0.35 because this is the average critical porosity in sands [49].
- $R$  is the normalized radius of the spherical grains and is assumed to be 1.
- The sphericity factor is assumed to be equal to 3.1 as estimated by [1].
- The coordination number  $C$  was estimated using a formula below that relates  $C$  to porosity (personal communication with A. Al-Shuhail):

$$C = 25.98 \varphi^2 - 43.76 \varphi + 21.67.$$

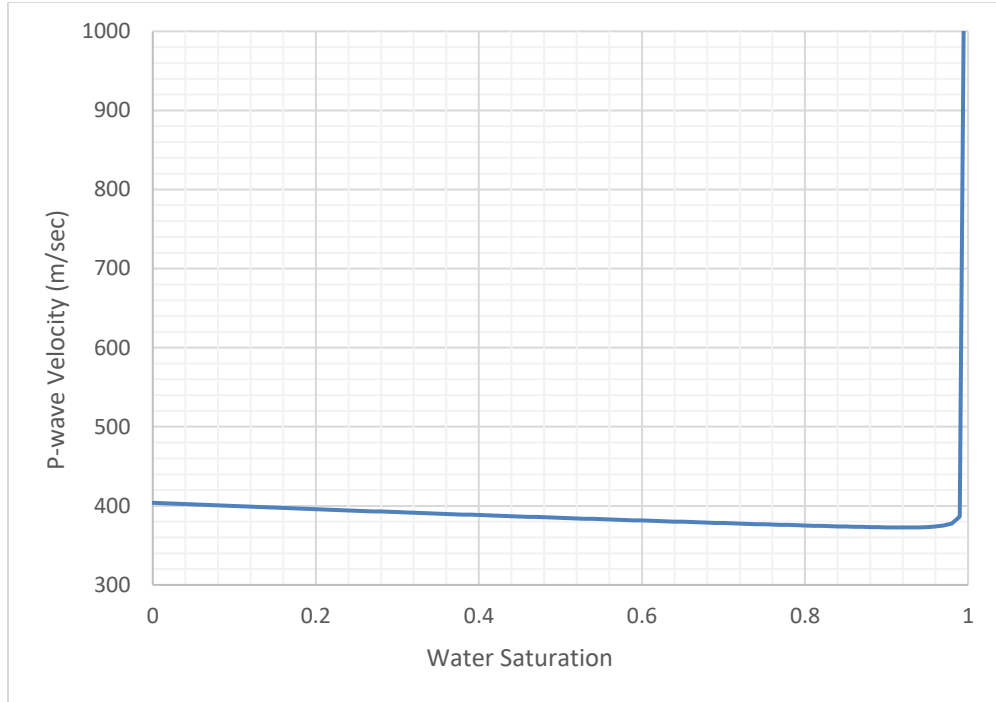
Inserting the values in Table 2 into the P-wave VDF equation, I get the following:

$$V_P(z, S_w) = \sqrt{\frac{-1144.3 + (-556274.06 + 556239.60 S_w) z^{1/3} - 0.0145962 z^{2/3}}{(4.92854 + S_w) (-1.00007 + S_w - 1.9615 \times 10^{-8} z^{1/3})}}. \quad (35)$$

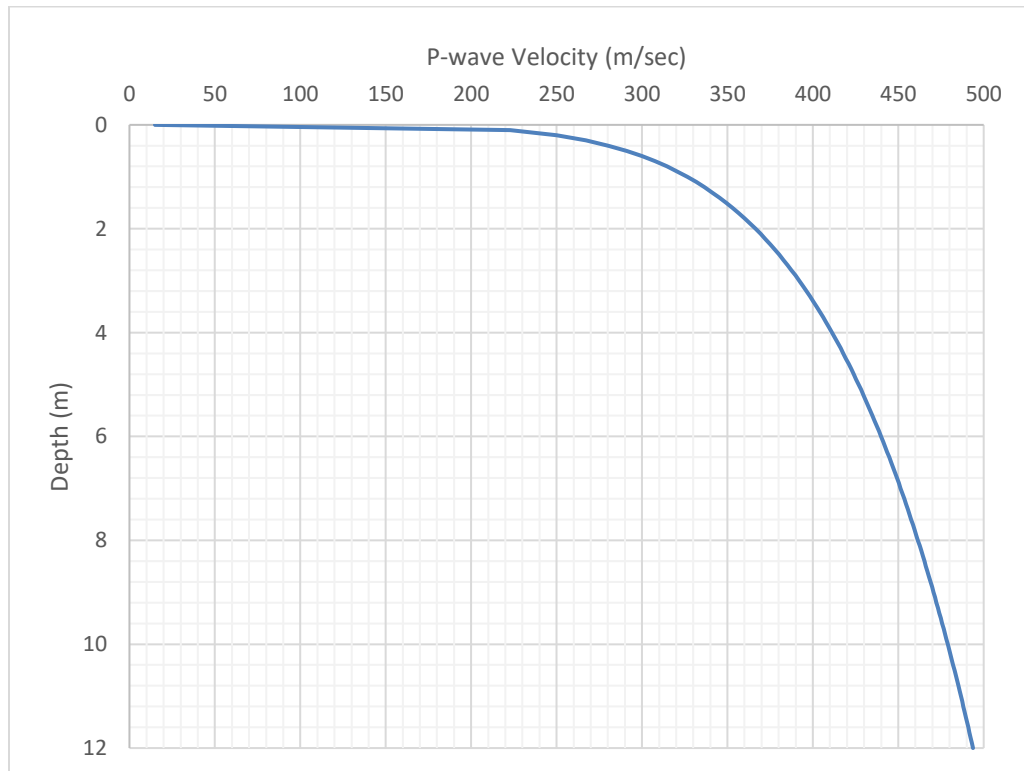
Figures 4 and 5 show the seismic P-wave velocity predicted by the Biot-Gassmann model (equation 35) for a range of water saturations. Figure 6 is a plot of  $V_P(z, S_w = 0.3)$  exhibiting the sharp increase in P-wave velocity versus depth at shallow depths, which was expected by previous studies [50]. On the other hand, plots of  $V_P(z = 5m, S_w)$  show a slight decrease in velocity with increasing  $S_w$  from 0% saturation to approximately 99% saturation (Figure 4); then, it increases sharply as it reaches 100% saturation (Figure 5) to reach the velocity of fully saturated sand. The sand density increases by about 20% as saturation increases from 0% to 99% while the shear modulus stays unchanged and the bulk modulus increase by only about 4%, which causes the highly saturated sand to have a P-wave velocity that is lower than the dry sand by about 8% [31]. Due to the low variation in P-wave velocity between dry and highly saturated sand, it has been always challenging to determine partial saturation using only P-wave velocity.



**Figure 4**  $V_P(z = 5m, S_w)$  over  $S_w = 0 - 0.99$ .

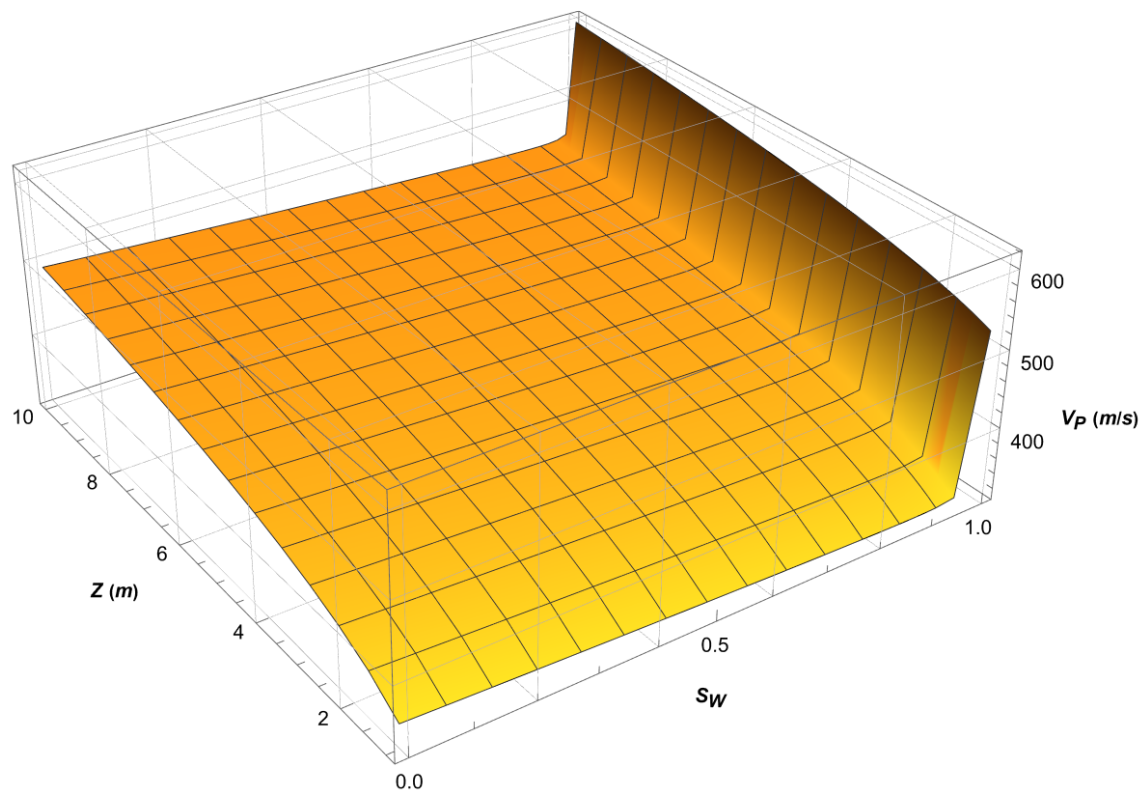


**Figure 5**  $V_P(z = 5m, S_w)$  over  $S_w = 0 - 1$ .



**Figure 6**  $V_P(z, S_w = 0.3)$  over  $z = 0 - 12$  m.

On the other hand, as the amount of water increases from 92% to 100%, the sand becomes stiffer and more resistant to deformation, which increases the bulk modulus sharply to become about 30 times its value at dry saturation while the shear modulus stays unchanged and the sand density increases by only about 1.5%, leading to a sharp increase in the P-wave velocity of the saturated sand by about 2.5 times its value at 92% saturation. Figure 7 shows the 3D plot of P-wave velocity (equation 35) as a function of depth and  $S_w$ . The depth ranges from 1 to 10 m and water saturation from 0 to 1.



**Figure 7 3D plot of P-wave velocity as a function of depth and water saturation.**

**Table 2** Matrix and pore-fluid properties assumed in the sand [49].

| Properties                        | Value  |
|-----------------------------------|--------|
| $\phi$                            | 0.35   |
| $k_m$ (GPa)                       | 36.6   |
| $\mu_m$ (GPa)                     | 45     |
| $\rho_m$ (kg/m <sup>3</sup> )     | 2650   |
| $k_{air}$ (GPa)                   | 0.0001 |
| $\rho_{air}$ (kg/m <sup>3</sup> ) | 1.2    |
| $k_w$ (GPa)                       | 2.25   |
| $\rho_w$ (kg/m <sup>3</sup> )     | 1000   |
| $R$                               | 1      |
| $f$                               | 3.1    |
| $C$                               | 9.5379 |

### 3.3 Diving Direct Arrivals

In a medium with an increasing velocity with depth, such as the one given by equation 35 and shown in Figure 4, direct waves will become diving waves. The offset and two-way travel time ( $T$ ) of the diving direct wave can be calculated by the following pair of parametric equations [51]:

$$X = 2 \int_0^h \left\{ \frac{V_P(z, S_w)}{V_P(h, S_w) \sqrt{1 - \left[ \frac{V_P(z, S_w)}{V_P(h, S_w)} \right]^2}} dz \right\}, \quad (36)$$

$$T = 2 \int_0^h \left\{ \frac{dz}{V_P(z, S_w) \sqrt{1 - \left[ \frac{V_P(z, S_w)}{V_P(h, S_w)} \right]^2}} \right\}, \quad (37)$$

where  $h$  is the maximum penetration depth of the ray that corresponds to this  $(X, T)$  pair. The maximum penetration depth of the DDW ray is found from the observed offset ( $X_{obs}$ ) as follows [1]:

$$h = \frac{8X_{obs}}{15\pi}. \quad (38)$$

In general, equations (36) and (37) cannot be integrated analytically due to the algebraic complexity of  $V_P(z)$ . Therefore, they are commonly integrated using numerical methods.

### 3.4 Water Saturation Inversion

The primary objective is to investigate the possibility of inverting  $S_w$  in loose unconsolidated sand when  $S_w$  is between 0 and 0.9. I stop at  $S_w = 0.9$  because the refraction from fully saturated sand can be observed and analyzed using conventional shallow seismic techniques. However, the velocity change between 0 and 0.9 saturation is much less evident by conventional methods despite the significant difference in impact on desert-dwelling humans, animals, and plants between highly saturated sand (e.g., with  $S_w = 0.9$ ) and dry sand.

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

1. Equation (38) is used to calculate the maximum penetration depth of the diving direct wave corresponding to the observed offset.
2. Calculate  $V_P(z, S_w)$  by equation (34) using the steps detailed in section 3.2.
3. Minimize the normalized squared error ( $NSE$ ) between the observed source-receiver offset,  $X_{obs}$ , and calculated offset of the diving direct wave arriving at  $X_{obs}$  for  $S_w$ . The  $NSE$  is defined as follows:

$$NSE = \left[ \frac{X_{obs} - 2 \int_0^h \frac{V_P(z, S_w)}{V_P(h, S_w) \sqrt{1 - \left[ \frac{V_P(z, S_w)}{V_P(h, S_w)} \right]^2}} dz}{X_{obs}} \right]^2 \quad (39)$$

The integral in equation (39) can be calculated numerically using any available numerical integration method as well as the minimization method of the  $NSE$  (see [22]).

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

points. The  $S_w$  value linked with the global minimum NSE value should be chosen in such circumstances.

### **3.5 Sensitivity Analysis**

The proposed inversion procedure's accuracy is dependent on a variety of factors, many of which are related to unknown or poorly constrained grain matrix properties like the sphericity factor, coordination number, etc., as well as pore fluid properties. These factors can have a significant impact on the reliability and accuracy of water saturation estimates derived from these methods. As a result, performing sensitivity analysis is critical for determining the impact of uncertain parameters on the inversion results. For this study, I conduct sensitivity analyses to provide insights into how changes in the following parameters affect the water saturation estimate derived from my inversion:

- mineralogical composition of the dune
- porosity of the dune
- sphericity of the dune grains.

## **CHAPTER 4**

### **APPLICATION TO SAND DUNES**

#### **4.1 Description of Study Area**

The study utilized data obtained from seismic experiments conducted over a barchan dune located in the vicinity of Dammam, Kingdom of Saudi Arabia (KSA). Barchan dunes are the most well-known aeolian features formed by erosion, transportation, and deposition of fine, loose sediment by wind that can be found in Arabia. The dune in my study area belongs to Al Jafurah desert (located north of Rub' al-Khali), one of Saudi Arabia's four major sand deserts, characterized by high linear and crescent dunes interspersed with gravel and gypsum plains [53]. Al Jafurah desert is located in the coastal lowlands along the Arabian Gulf [55] as seen in Figure 8. The aeolian dunes of this desert are relatively small in size when compared to Rub' al-Khali or the Great Nafud, consisting primarily of transverse dunes such as barchans, with associated barchanoid ridges, sand sheets, and parabolic and dome-like shield dunes with the horns pointed in the direction of the prevailing wind which can be attributed to Shamal (the northerly winds) [53], [54]. These winds constantly push sand grains up the gentle windward side of the dune and deposit them on the steeper leeward side, causing them to migrate while keeping their crescent shape [54] - [59]. The mineral composition of the sand dunes in the study area consists of mainly quartz, feldspar, and carbonate minerals [59]. The study area receives 54–80 mm

annual rainfall, which is quite higher than most of the Rub' al Khali, and lies in a high humidity belt [53].

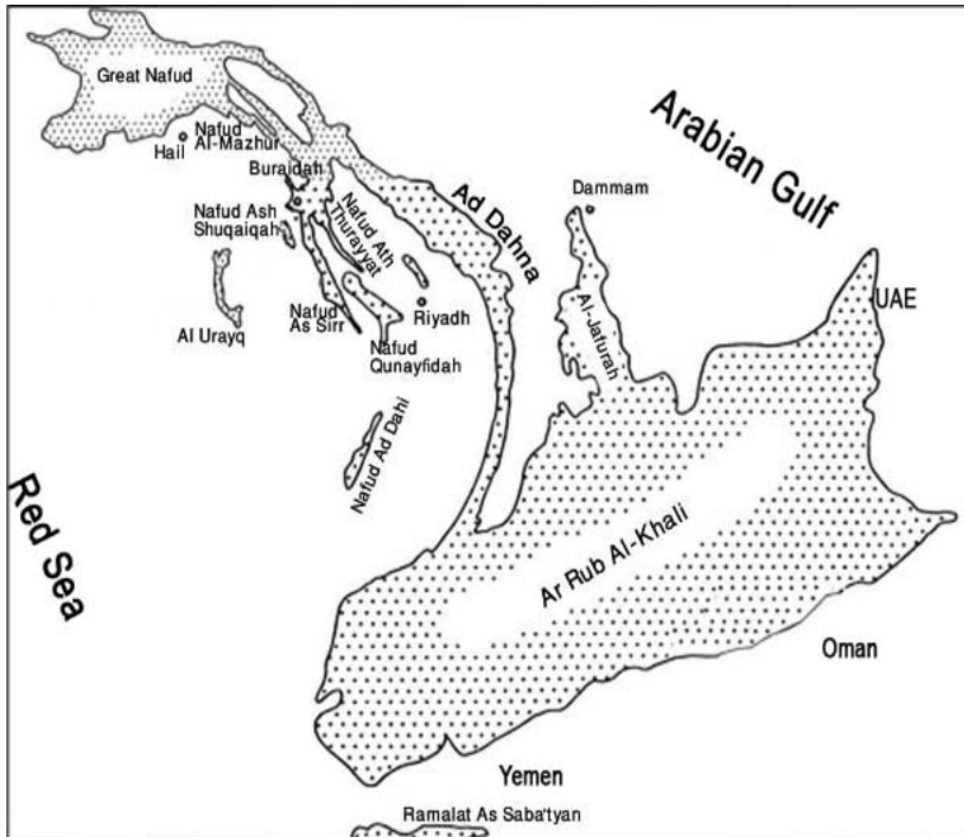
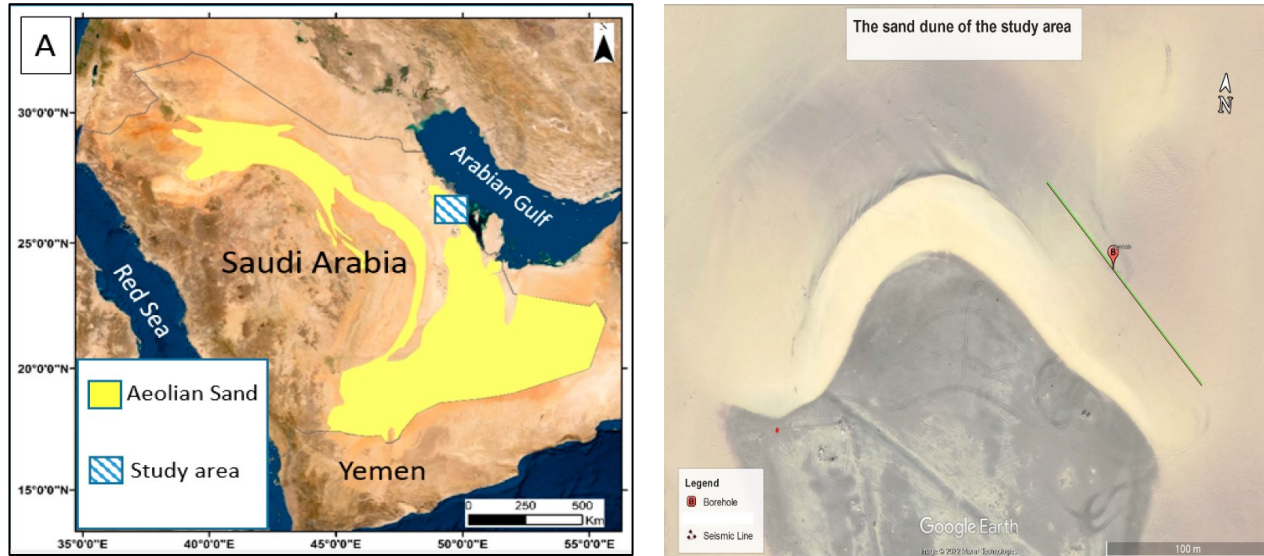


Figure 8 Location of major desert in Saudi Arabia [53].



**Figure 9 (A) Satellite image showing the Aeolian sand of Saudi Arabia [55] and (B) Sand dune in the study area showing the location of the seismic line and borehole.**

Using the dry percussion method, a 10-meter-deep vertical borehole was drilled at the limb side of the dune to characterize the dune's mineral composition, lithological properties, and pore-fluid content. Figure 9 shows the sand dune of the study area, the seismic line (red line) and the location of the borehole. A complete core was extracted from the top 3.5 m, and partial core samples were collected at an average of 1.5-m intervals up to a depth of 6.5 m. Figure 10 shows the lithology of the borehole and the position of the water table. The well penetrated the entirety of the dune (7 meters of medium-grained sand from the surface) as well as the uppermost 3 meters of the underlying sabkha. Mineralogy and chemical analysis show the dune contained about 83% quartz, 4% feldspars, 3% calcite, 1% gypsum, and minor amounts of other minerals (Figure 11). The dune is composed of fine to medium grain sizes. The drilled part showed that there was a partially saturated zone up to 7.6 m deep, mostly within the dune, while the deeper 2.4 m is a fully salt-water

saturated zone within the sabkha [18] and [56]. [55] provides a detailed description of the dune's lithology, grain size distribution, mineral composition, and water content of sand based on laboratory analyses of core samples.

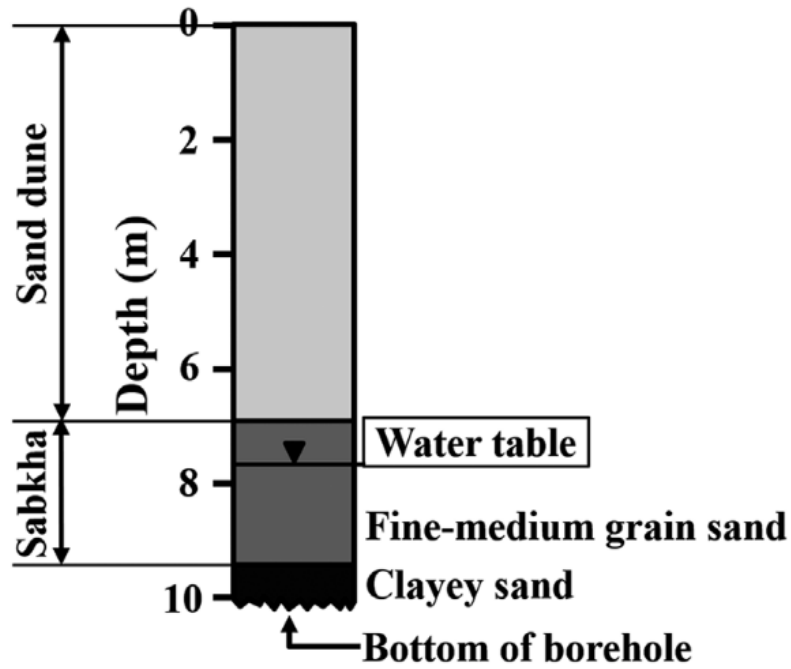


Figure 10: Lithology of the boreholes [1].

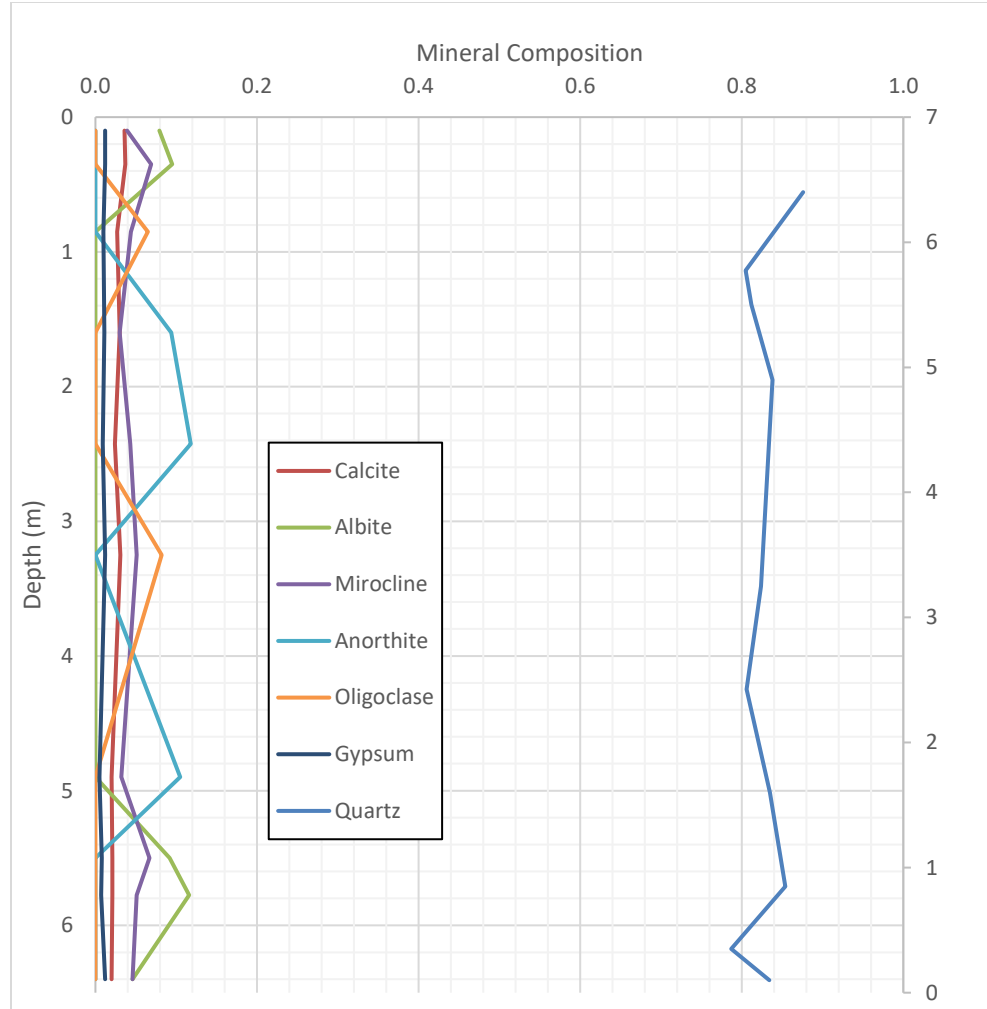


Figure 11 Measured mineralogy in 10 samples at different depths of the dune.

## 4.2 Data Acquisition and Processing

The experiments involved the use of both conventional and high-resolution seismic data acquisition techniques. For the conventional (low-resolution) seismic experiment, an 8-kg sledgehammer was used as the seismic source to generate an elastic wave by striking a metal plate. The produced seismic pulses penetrated the surface, facilitating the measurement of seismic velocity and subsurface properties. A total of 73 shot gathers were

recorded with each shot point spaced 1 meter apart. Each shot was recorded with 37 receivers spaced at a 2-meter interval.

For the high-resolution seismic experiment, seismic excitation was induced using a small 0.7-kg sledgehammer on a metal plate placed 0.1 m from the first receiver. Every shot gather was acquired using 31 geophones spaced as follows: 0.1 m spacing for the first 12 geophones, 0.2 m spacing for geophones 12 to 23, and 0.25 m spacing for geophones 23 to 31, resulting in a total receiver line length of 5.4 m. [1] gives a thorough account of the seismic experiments, including field acquisition, data processing, and analysis. Traces from these surveys were combined (Figure 12), and 10 offsets were picked from these two surveys that corresponded to the offset at which the sand samples were collected, after converting the sample depth to offset.

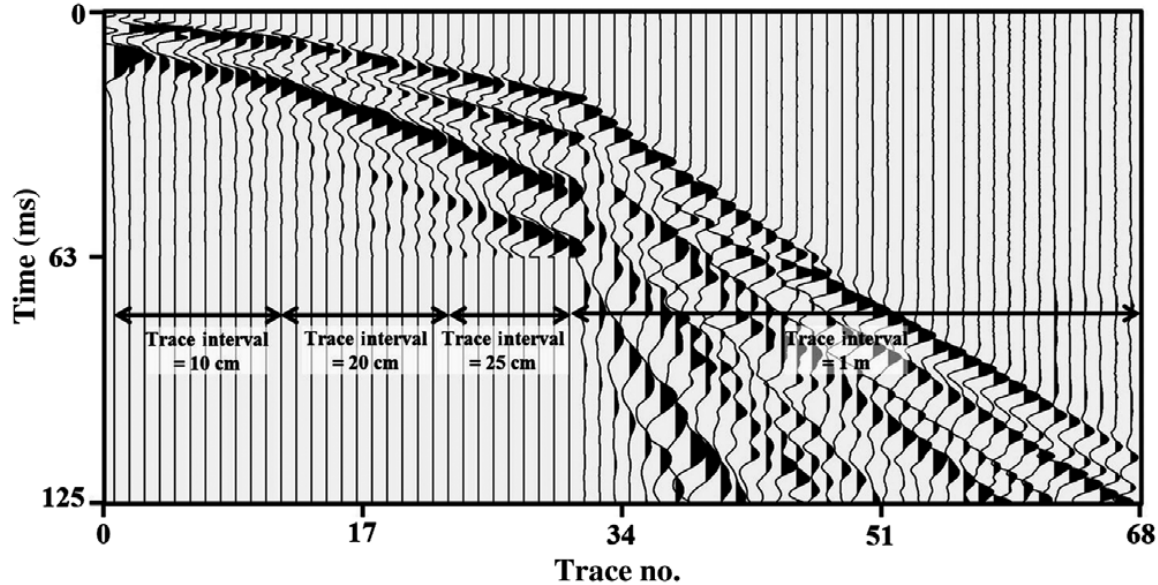


Figure 12 Stack display of traces from the conventional and high-resolution seismic experiments.

The water content was measured in the laboratory and indicated a low-saturated dune (Table 4). Porosity values in the depth profile ranged from 0.3 to 0.3947. Although there appears to be a slight variation with depth, there is no discernible trend from casual observation. The same holds true for water saturation and water content. Water saturation in Table 4 is calculated as the ratio of water content to measure porosity. Figure 13 shows the measured water saturation values with depth. Table 5 shows various descriptive statistics of the water content, water saturation, and porosity in the Barchan dune based on the laboratory measurements. These noticeable variations could be the result of localized changes in sediment composition, lithology, and grain size distribution, both laterally and vertically across the dune [55]. Water saturation values have a wider spread across the samples compared to porosity values, as indicated by the higher standard deviation (0.02578) and coefficient of variation (50.27%). The distribution of water saturation is right-skewed (positive), while porosity is left-skewed (negative). Furthermore, water saturation and water content have a higher kurtosis (leptokurtic) than porosity, with a low value (0.49916), indicating larger tails and potentially more outliers in water saturation values than in porosity values. Figure 14 shows the distribution, variability, and outlier in measured water saturation and water content values via a boxplot.

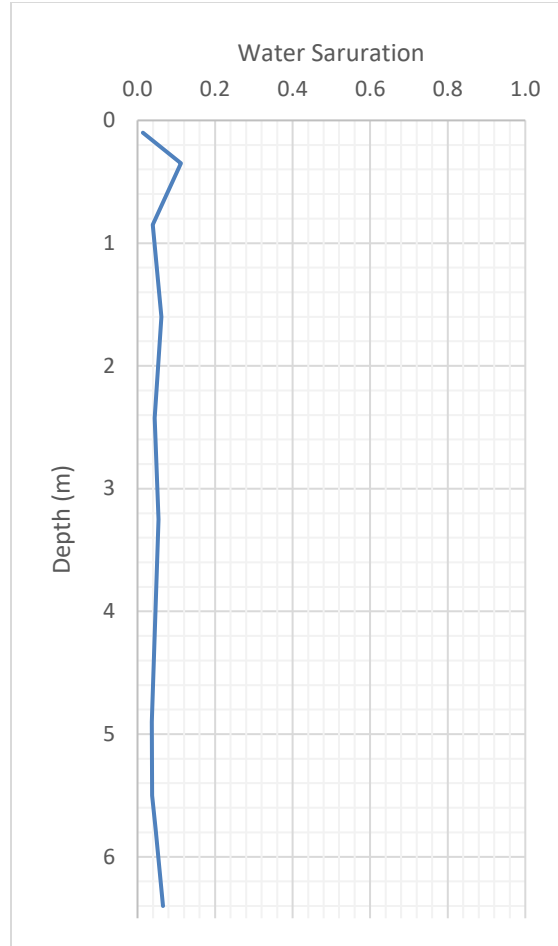


Figure 13 Measured  $S_w$  values with depth.

### 4.3 Matrix and Pore-Fluid Assumptions

Few assumptions were made to make the proposed method more practical:

- The dune has a 100% quartz matrix because it is the most predominant mineral.
- The dune has a constant average critical porosity of 35% because it is the average porosity of the acquired 10 sand samples.
- A value of 3.1 for the sphericity factor ( $f$ ) was assumed, as it was determined in the studied dune by [1].

Later in the study, I conducted a sensitivity analysis to study the effect of these assumptions on the estimated water saturation.

**Table 3: Matrix mineralogy measured in the laboratory for the 10 sand samples acquired at various depths.**

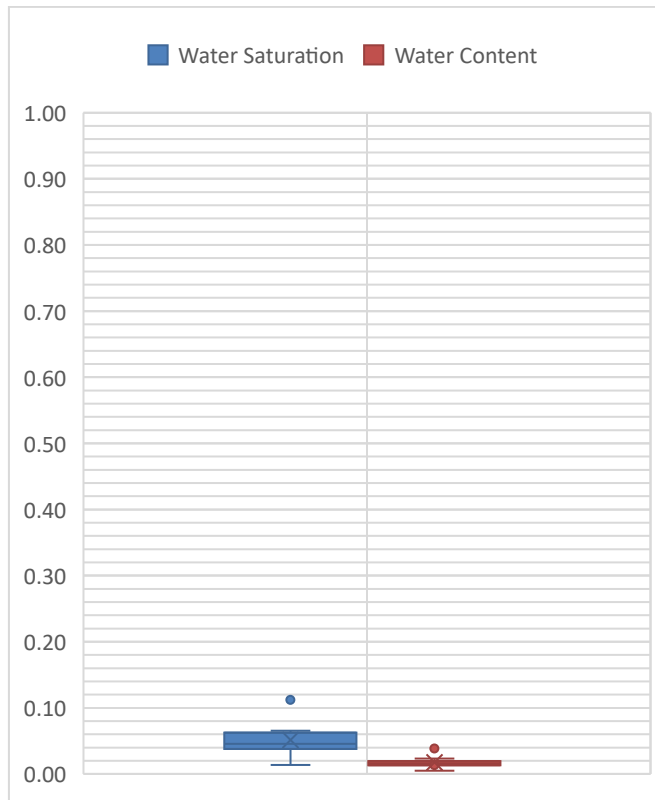
| Sample Number | <i>Mineral Composition</i> |                |               |                   |                  |                   |               |
|---------------|----------------------------|----------------|---------------|-------------------|------------------|-------------------|---------------|
|               | <i>Quartz</i>              | <i>Calcite</i> | <i>Albite</i> | <i>Microcline</i> | <i>Anorthite</i> | <i>Oligoclase</i> | <i>Gypsum</i> |
| 1             | 0.834                      | 0.036          | 0.079         | 0.039             | 0.000            | 0.000             | 0.012         |
| 2             | 0.787                      | 0.037          | 0.095         | 0.069             | 0.000            | 0.000             | 0.012         |
| 3             | 0.854                      | 0.027          | 0.000         | 0.044             | 0.000            | 0.065             | 0.010         |
| 4             | 0.835                      | 0.030          | 0.000         | 0.030             | 0.094            | 0.000             | 0.011         |
| 5             | 0.806                      | 0.024          | 0.000         | 0.043             | 0.118            | 0.000             | 0.009         |
| 6             | 0.824                      | 0.031          | 0.000         | 0.051             | 0.000            | 0.082             | 0.012         |
| 7             | 0.838                      | 0.020          | 0.000         | 0.032             | 0.105            | 0.000             | 0.005         |
| 8             | 0.812                      | 0.021          | 0.092         | 0.067             | 0.000            | 0.000             | 0.008         |
| 9             | 0.805                      | 0.021          | 0.116         | 0.051             | 0.000            | 0.000             | 0.007         |
| 10            | 0.876                      | 0.020          | 0.046         | 0.046             | 0.000            | 0.000             | 0.012         |

**Table 4: Porosity, water content, and saturation for the 10 sand samples acquired at varying depths with their corresponding offset in the sand dune.**

| Sample Number | Depth (m) | Offset (m) | Porosity | Water saturation | Water Content |
|---------------|-----------|------------|----------|------------------|---------------|
| 1             | 0.1       | 0.59       | 0.3600   | 0.0139           | 0.0050        |
| 2             | 0.35      | 2.06       | 0.3438   | 0.1120           | 0.0385        |
| 3             | 0.85      | 5.01       | 0.3429   | 0.0394           | 0.0135        |
| 4             | 1.6       | 9.42       | 0.3000   | 0.0617           | 0.0185        |
| 5             | 2.425     | 14.28      | 0.3030   | 0.0446           | 0.0135        |
| 6             | 3.25      | 19.14      | 0.3438   | 0.0538           | 0.0185        |
| 7             | 4.9       | 28.86      | 0.3636   | 0.0371           | 0.0135        |
| 8             | 5.5       | 32.40      | 0.3548   | 0.0380           | 0.0135        |
| 9             | 5.775     | 34.02      | 0.3947   | 0.0469           | 0.0185        |
| 10            | 6.4       | 37.70      | 0.3590   | 0.0655           | 0.0235        |

**Table 5: Various descriptive statistics for Barchan dune properties.**

| Descriptive Statistics   | Water Saturation | Water Content | Porosity |
|--------------------------|------------------|---------------|----------|
| Mean                     | 0.0513           | 0.0177        | 0.3466   |
| Median                   | 0.0457           | 0.0160        | 0.3493   |
| Mode                     | #N/A             | 0.0135        | 0.3438   |
| Minimum                  | 0.0139           | 0.0050        | 0.3000   |
| Maximum                  | 0.1120           | 0.0385        | 0.3947   |
| Range                    | 0.0981           | 0.0335        | 0.0947   |
| Variance                 | 0.00066          | 0.00008       | 0.00079  |
| Standard Deviation       | 0.02578          | 0.00882       | 0.02810  |
| Coefficient of Variation | 50.27%           | 49.97%        | 8.11%    |
| Skewness                 | 1.36392          | 1.40835       | -0.38982 |
| Kurtosis                 | 3.41177          | 3.48743       | 0.49916  |
| Count                    | 10               | 10            | 10       |
| Standard Error           | 0.00815          | 0.00279       | 0.00889  |



**Figure 14 Boxplots of measured water saturation and water content values.**

## CHAPTER 5

### RESULTS AND DISCUSSION

#### 5.1 Implementation of the Water Saturation Estimation Methodology

The following steps are used to invert water saturation from the measured offset data:

1. The sample depths were used to calculate the corresponding offsets by equation 38.
2. The closest measured offsets ( $X_0$ ) from Table 2 of [1] were selected.
3. A dune with pure quartz matrix and properties given in Table 2 is assumed to establish  $V_P(z, S_w)$  in equation 35.
4.  $V_P(z, S_w)$  is used in  $S_w$  inversion by equation 39.

#### 5.2 Field Data Application

[18] acquired a total of 68 different offsets (receivers) from both seismic experiments, 37 from the conventional seismic experiment at 2 m spacing and the remainder are from the high-resolution seismic experiment at varying intervals, as previously explained. This study only used 10 out of the 68 offsets that corresponded closely to the depths at which sand samples were extracted, and their properties were measured in the laboratory, analyzed, and presented by [55]. I apply the method described in Section 5.1 to the measured offsets, assuming a dune with a pure quartz matrix and the properties listed in Table 2. Table 6 shows the input and output values of the proposed  $S_w$  inversion method

when applied to the real dataset. The measured water saturation values are within a range of (0.0139 - 0.1120) with a mean of 0.0513, while the inverted water saturation values fall within the range of (0.0882 - 0.1514) and has a mean of 0.1035. On the other hand, the inverted water content values fall within the range of (0.0309 - 0.0530) and have a mean of 0.0362. It is calculated by multiplying the inverted water saturation by the assumed porosity (0.35). Table 7 presents various descriptive statistics for the inverted water saturation and water content. The distribution, variability, and outlier in the inverted water saturation and water content values is illustrated via a boxplot (Figure 15). Although there is a clear considerable difference between the individual values of the inverted and measured water contents, both generally indicate a dune with very low water saturation (Figure 16). Figure 17 shows the plot of water saturation against depth.

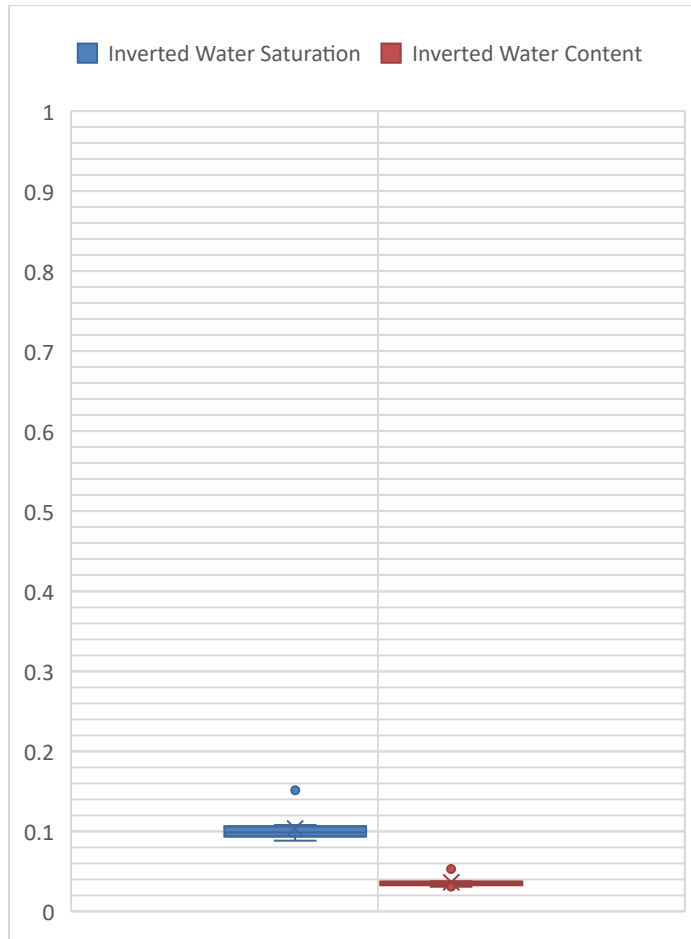
Comparing the measured and inverted water contents values in the studied dune with those measured in other dunes across the world (Figure 18), we can see that both inverted and measured water content values are within the range of world water content values. In conluc

**Table 6 The measured sample depth and its corresponding depth using equation 38. The measured water contents and corresponding water saturation are also shown, as is the inverted water saturation value from my procedure.**

| Sample Number | Depth (m) | Offset (m) | Porosity | Measured Water Saturation | Measure Water Content | Inverted Water Saturation | Inverted Water Content |
|---------------|-----------|------------|----------|---------------------------|-----------------------|---------------------------|------------------------|
| 1             | 0.1       | 0.59       | 0.36     | 0.0139                    | 0.0050                | 0.0951                    | 0.0333                 |
| 2             | 0.35      | 2.06       | 0.3438   | 0.112                     | 0.0385                | 0.1059                    | 0.0371                 |
| 3             | 0.85      | 5.01       | 0.3429   | 0.0394                    | 0.0135                | 0.1079                    | 0.0378                 |
| 4             | 1.6       | 9.42       | 0.3      | 0.0617                    | 0.0185                | 0.1514                    | 0.0530                 |
| 5             | 2.425     | 14.28      | 0.303    | 0.0446                    | 0.0135                | 0.0958                    | 0.0335                 |
| 6             | 3.25      | 19.14      | 0.3438   | 0.0538                    | 0.0185                | 0.1045                    | 0.0366                 |
| 7             | 4.9       | 28.86      | 0.3636   | 0.0371                    | 0.0135                | 0.0891                    | 0.0312                 |
| 8             | 5.5       | 32.4       | 0.3548   | 0.038                     | 0.0135                | 0.0978                    | 0.0342                 |
| 9             | 5.775     | 34.02      | 0.3947   | 0.0469                    | 0.0185                | 0.0882                    | 0.0309                 |
| 10            | 6.4       | 37.7       | 0.359    | 0.0655                    | 0.0235                | 0.0995                    | 0.0348                 |

**Table 7 Descriptive statistics for inverted water saturation and water content values.**

| Descriptive Statistics | Inverted Water Saturation | Inverted Water Content |
|------------------------|---------------------------|------------------------|
| Mean                   | 0.10352                   | 0.036232               |
| Median                 | 0.09865                   | 0.0345275              |
| Mode                   | #N/A                      | #N/A                   |
| Minimum                | 0.0882                    | 0.03087                |
| Maximum                | 0.1514                    | 0.05299                |
| Range                  | 0.0632                    | 0.02212                |
| Sample Variance        | 0.000326702               | 4.0021E-05             |
| Standard Deviation     | 0.018074894               | 0.006326213            |
| Skewness               | 2.398111597               | 2.398111597            |
| Kurtosis               | 6.629567513               | 6.629567513            |
| Count                  | 10                        | 10                     |
| Standard Error         | 0.005715783               | 0.002000524            |



**Figure 15** Boxplot of Inverted  $S_w$  and water content values.

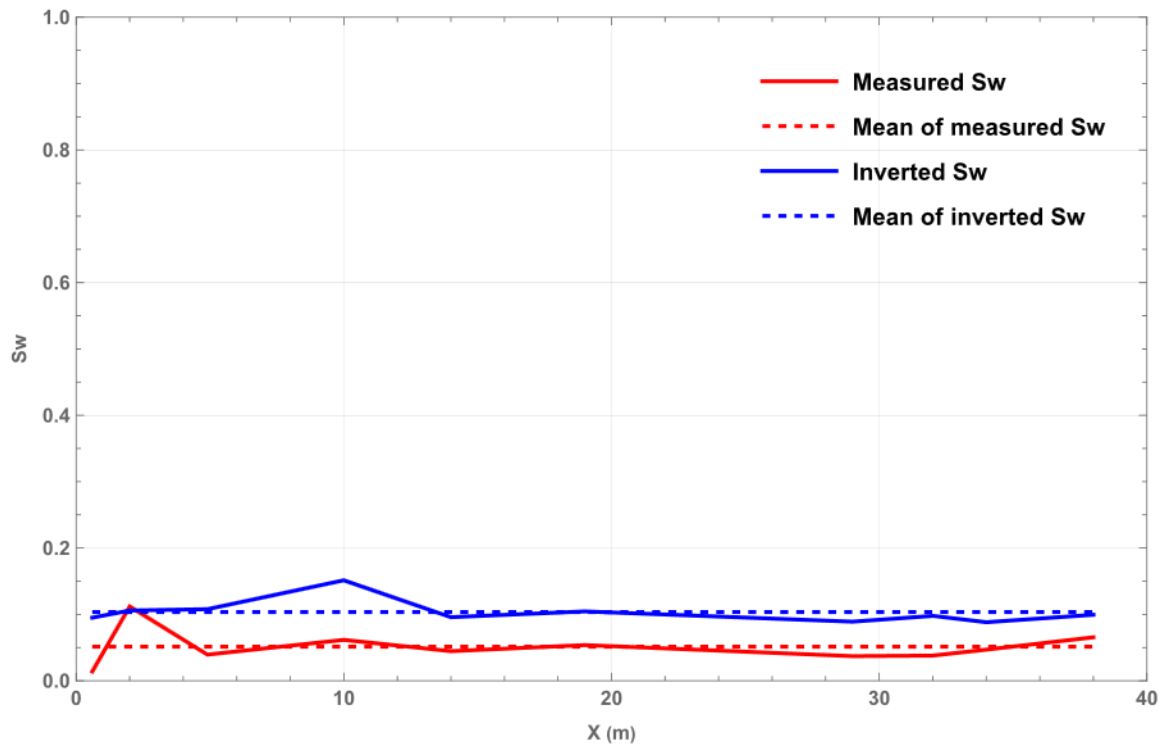


Figure 16 Measured and inverted water saturation values for the real data at the measured offsets.

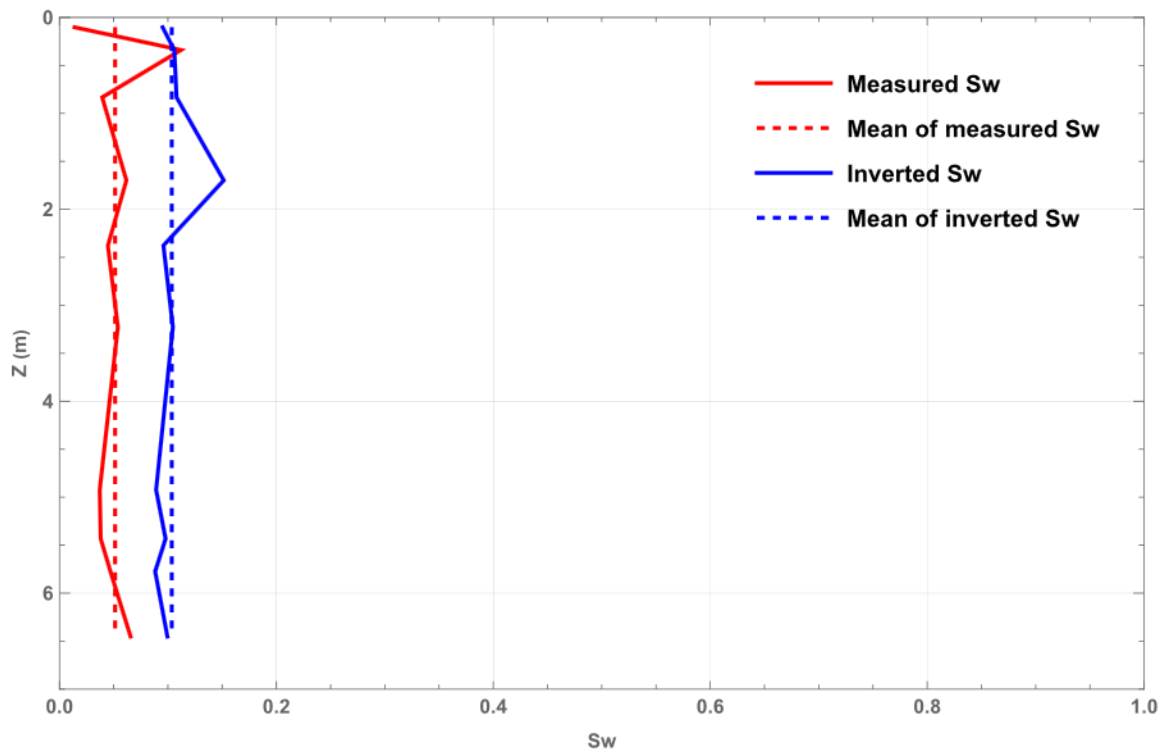
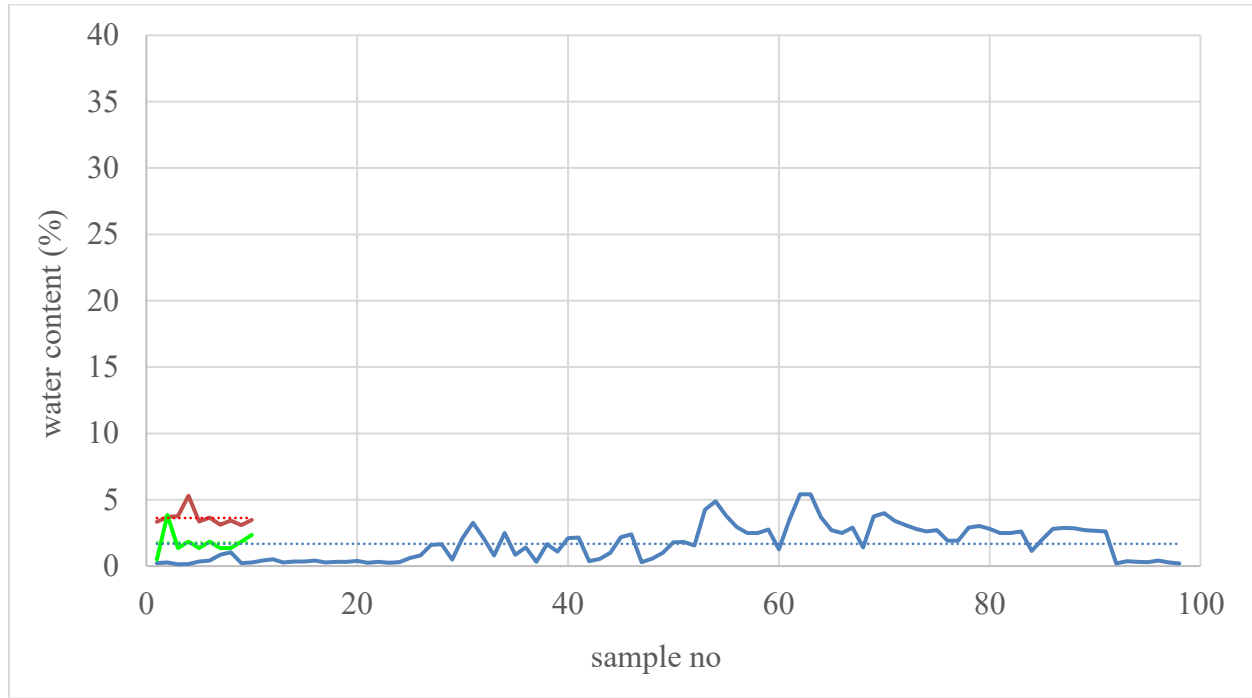


Figure 17 Saturation versus depth. The saturation values correspond to the minimum NSE.

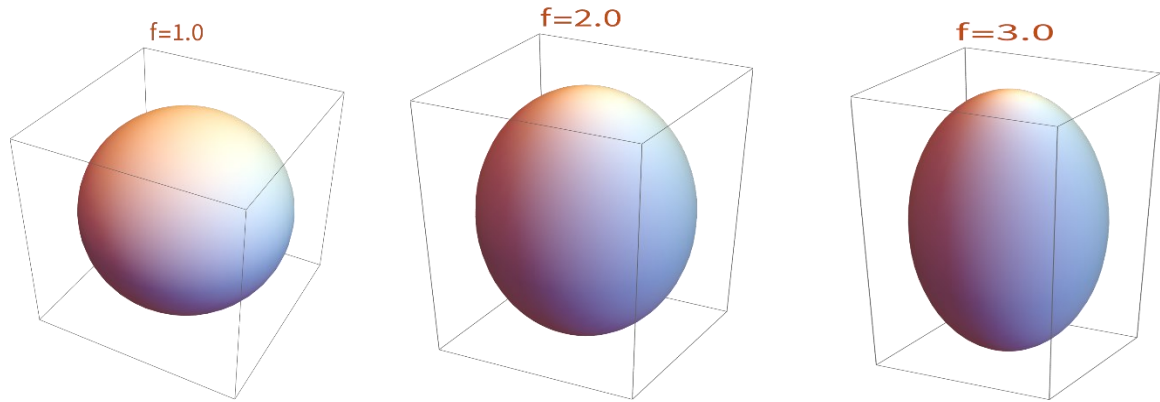


**Figure 28 Comparison of inverted (orange) and measured (green) water content values in the studied dune with those measured in world dunes (blue). Dashed lines show the average of each data set.**

### 5.3 Sensitivity Analyses

In this section, I investigate the effect of using incorrect values of some assumed rock physical parameters including mineralogy, porosity, and sphericity factors on the inversion of water saturation. Microscopic investigation of the sand grains in the studied dune indicates that they are rounded to sub-rounded. However, [55] concluded that the grains in the upper 2.5m show variable sorting (mixture of grain sizes), are poorly sorted, and are relatively more coarse while being well sorted below this depth. This suggests that the sphericity factor and hence the porosity probably vary widely within this side of the dune, as smaller grains may fit into the crevices between larger grains, resulting in different levels of contact. As depicted in Figure 19, the diagram illustrates various grain shapes ranging

from an idealized highly spherical case when  $f$  is 1 to irregular forms when  $f$  is greater than 1. For these reasons, I investigated the effect of these parameters, together with different ranges of quartz percentage mineral composition on water saturation estimates.



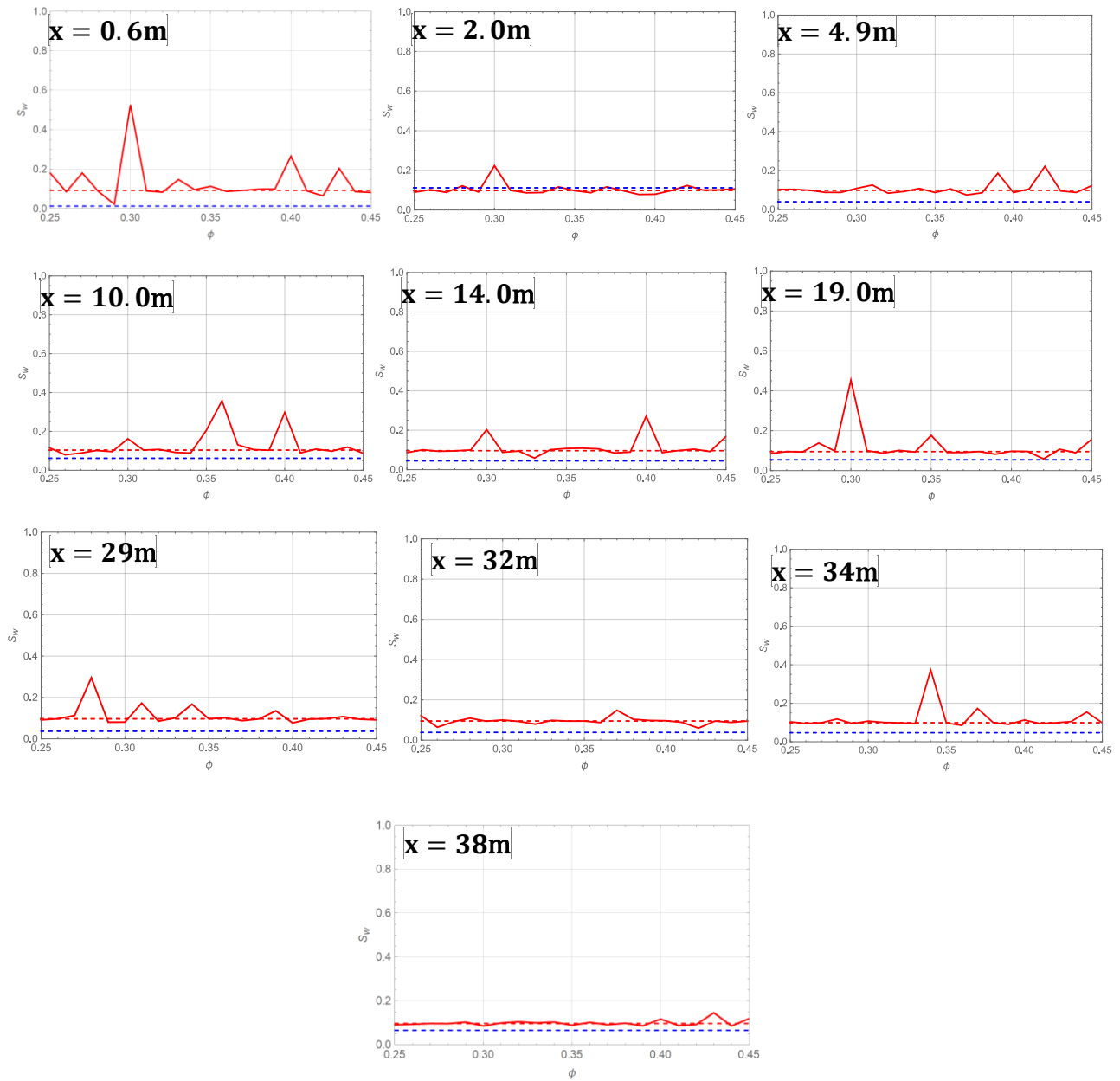
**Figure 19: 3D visualization of a spherical grain model within a cubic volume, representing the arrangement of grains and their influence on porosity.**

### 5.3.1 Effect of Porosity Changes

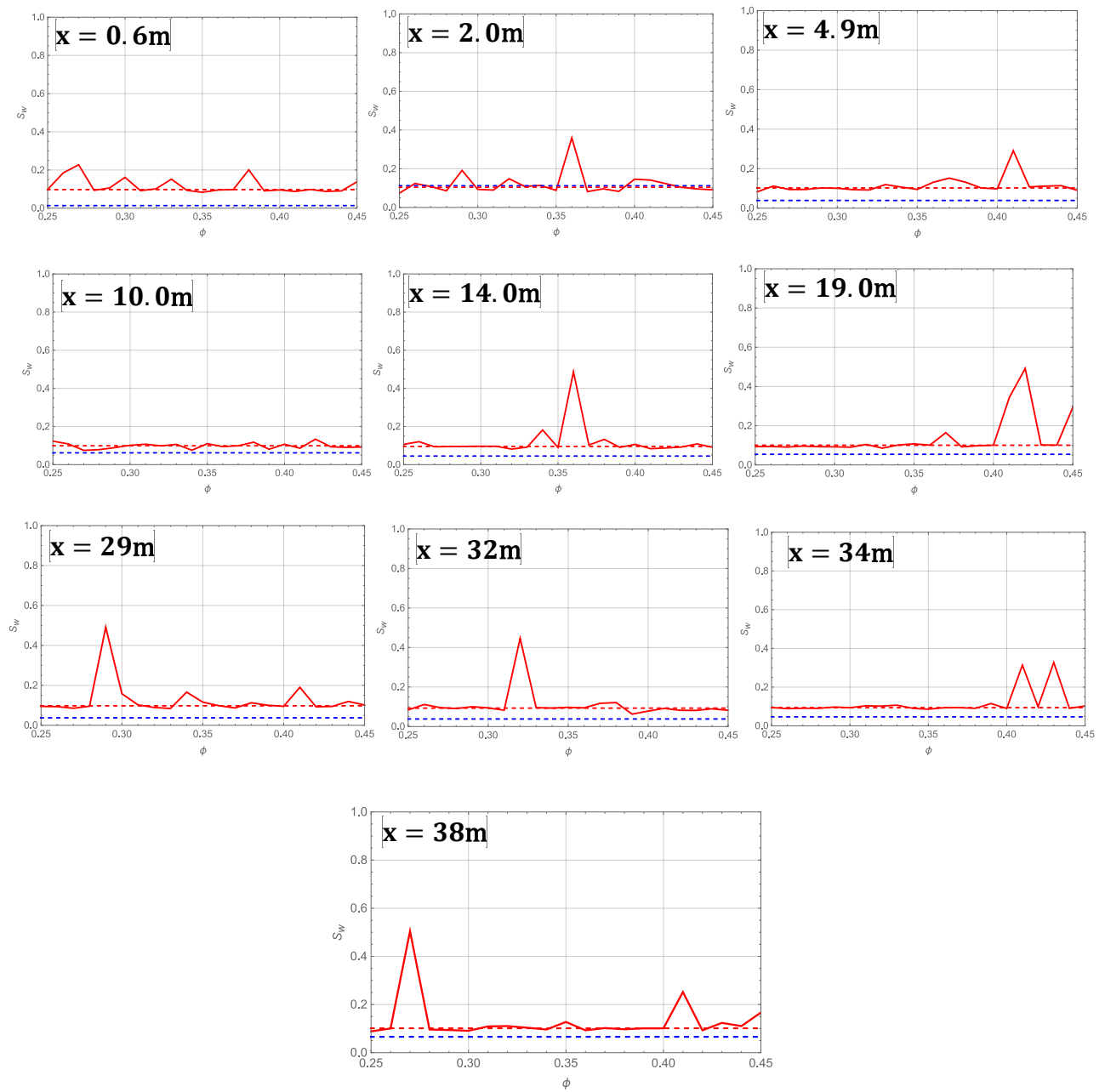
Pore fluid and matrix properties are input parameters for the proposed inversion algorithms, and the accuracy of the inversion result depends on these poorly known or sometimes unknown properties. While some properties, such as pore fluids, typically have a narrow range of values, matrix properties can vary significantly. For this reason, I assume the pore fluid's properties are the same as those given in Table 2, and I assume two cases for the matrix properties. I assume an extreme case if the dune is made up of pure quartz mineralogy (100%) and a reasonable case of 70% quartz and 30% other minerals, namely, Calcite, Albite, Microcline, Anorthite, Oligoclase, and Gypsum. This composition is based on the laboratory measurement of the mineral matrix (Table 3). Quartz, being the

predominant mineral, contributes significantly to the overall petrophysical properties of the sand dunes, such as porosity. The presence of other minerals, albeit in smaller proportions, introduces additional complexities to the petrophysical behavior of the formation. By incorporating these mineral compositions into the sensitivity analysis, the study aims to assess how variations in porosity, influenced by the mineralogical composition, impact the inversion of water saturation estimates derived from seismic data using source-receiver offset measurements. The tested porosity values range from 25% to a critical porosity value of 45% at 1% interval. This range is selected to encompass the full spectrum of critical porosities of all sedimentary rocks as reported by [60].

Figures 20 and 21 below show plots of the inverted water saturation values generated over this range of porosity value for the 10 depths assuming 100% and 70% quartz mineral composition, respectively. While the individual value of water saturation jumps around resulting from porosity changes which are expected, it does not change the overall degree of low water saturation of the dune. This is evident in the almost constant value of the median (in red dashed line) of the inverted water saturation value for all 10 depths, which is approximately the same as the median reported in the section above using my methodology at 35% porosity.



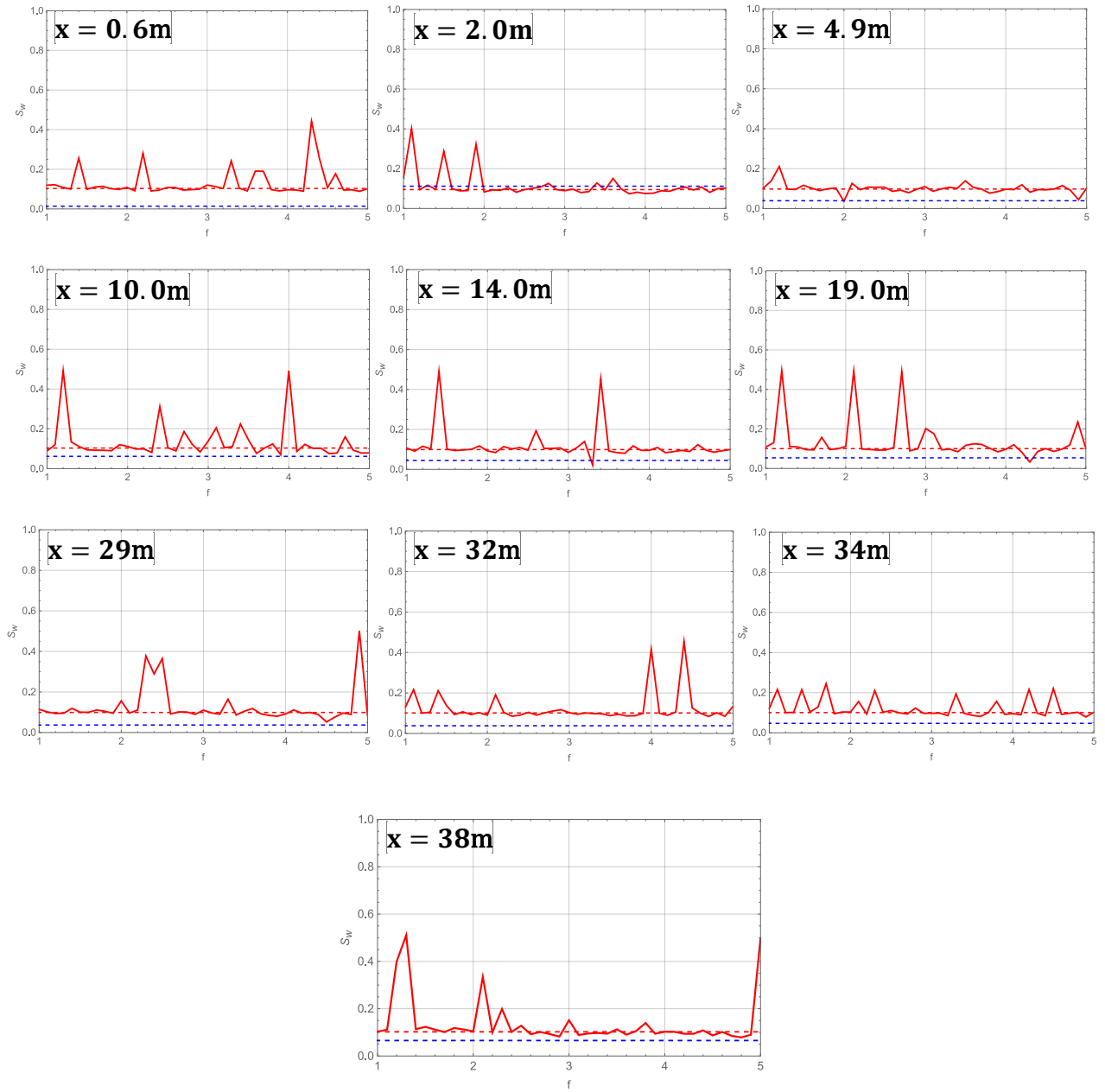
**Figure 20** Plots of the inverted water saturation generated over a range of porosity values from 25% to 45% at 1% intervals while assuming 100% quartz mineralogy. The red dashed line is the median of the inverted saturation for that depth, and the blue dashed line is the measured water saturation for that depth. “x” value indicates the offset corresponding to the sample depth.



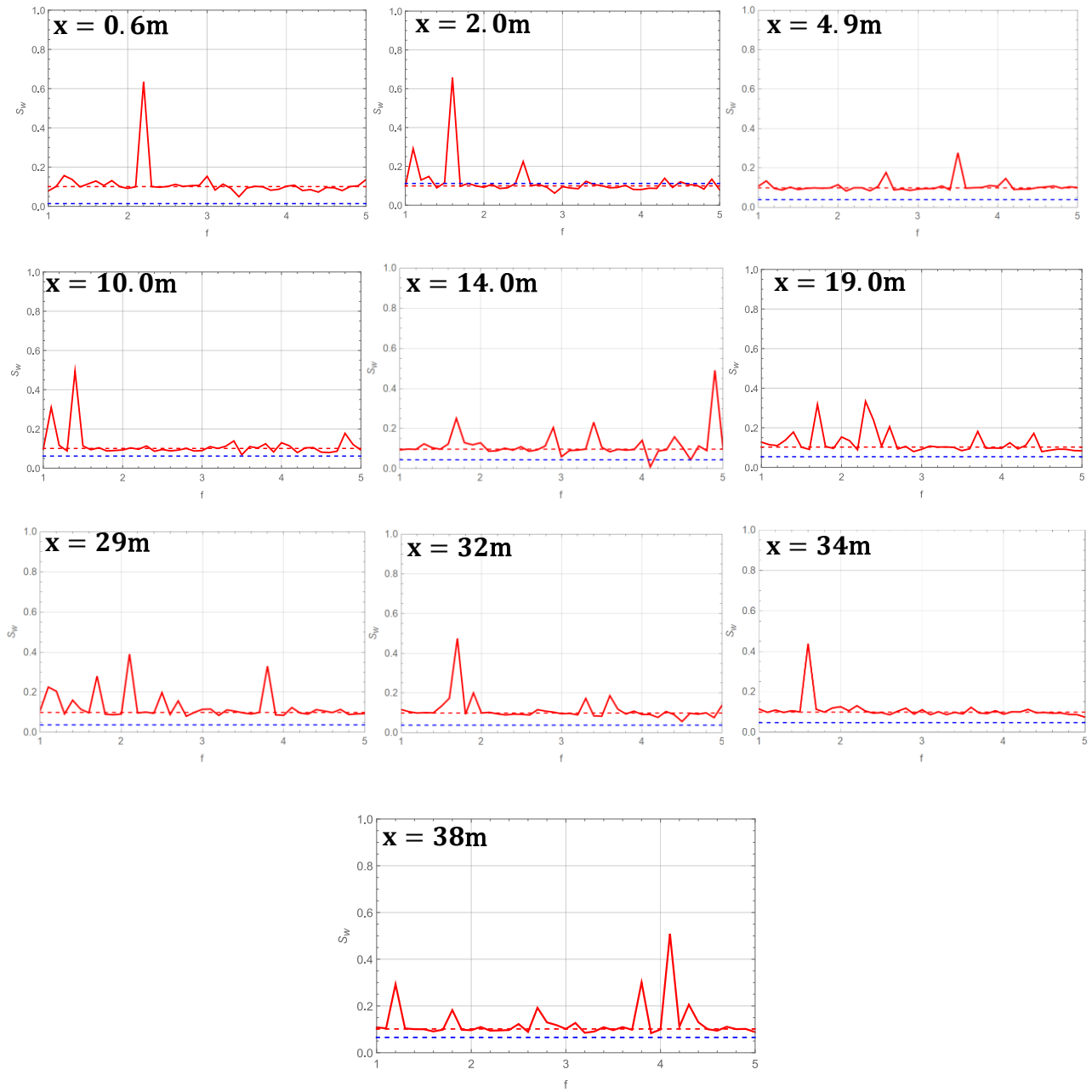
**Figure 21** Plots of the inverted water saturation generated over a range of porosity values from 25% to 45% at 1% intervals while assuming 70% quartz mineralogy. The red dashed line is the median of the inverted saturation for that depth, and the blue dashed line is the measured water saturation for that depth. “x” value indicates the offset corresponding to the sample depth.

### **5.3.2 Effect of Sphericity Factor Changes**

Figures 22 and 23 show plots of the inverted water saturation values generated over a range of sphericity factors from 1 to 5 at 0.1 interval for the 10 depths assuming 100% and 70% quartz mineral composition, respectively. Like the case of porosity, the inverted saturation jumps around and there are in fact more outliers compared to that of porosity. However, it does not change the overall degree of low water saturation of the dune.



**Figure 22** Plots of the inverted water saturation generated over a range of sphericity factors from 1 to 5 at 0.1 intervals while assuming 100% quartz mineralogy. The red dashed line is the median of the inverted saturation for that depth, and the blue dashed line is the measured water saturation for that depth. “x” value indicates the offset corresponding to the sample depth.



**Figure 23** Plots of the inverted water saturation generated over a range of sphericity factors from 1 to 5 at 0.1 intervals while assuming 70% quartz mineralogy. The red dashed line is the median of the inverted saturation for that depth, and the blue dashed line is the measured water saturation for that depth. “ $x$ ” value indicates the offset corresponding to the sample depth.

## **CHAPTER 6**

### **CONCLUSION AND RECOMMENDATION**

#### **6.1 Conclusion**

In this study, I explored the use of source-receiver offset obtained during seismic experiments in a sand dune environment to estimate the water saturation in the vadose zone of a barchan dune. The goal was to develop an inversion procedure for determining the degree of saturation in the barchan dune. By integrating existing rock physics models, granular contact and fluid replacement models, and adapting them to the unique characteristics of the sand dune environment, I have successfully formulated a water saturation estimation function. This function establishes a relationship between the P-wave velocity, water saturation, and maximum depth of the direct diving wave. It is then utilized to create an objective function based on the measured source-receiver offset and the offset calculated from the numerical integration of the offset-depth integration and minimize it for water saturation.

The inversion procedure was tested on data collected over a barchan dune in the eastern province of Saudi Arabia, where the water saturation was measured in the lab in sand samples obtained at various depths. Despite the disparity between the individual inverted saturation values and the laboratory-measured values, both sets of values have mean saturations within 10%, which suggest a low-saturated sand dune. By employing my inversion procedure, I was able to quantify the degree of water saturation with improved

precision, despite the general assumptions I made, such as pure quartz mineralogy and constant values of porosity and sphericity factor at 0.35 and 3.1, respectively, across the whole dune depth.

Furthermore, the effect of using a range of values for the porosity and sphericity factor was also investigated under two different percentages of quartz mineralogy (100% and 70%). Despite the fluctuations in individual inverted water saturation values resulting from porosity changes and sphericity factor, the conclusion that the barchan dune has low saturation remains unchanged.

## **6.2 Practical Implications of the study**

This study has several important practical implications, from hydrogeological characterization to supporting reforestation and land restoration efforts, as well as enhancing climate resilience and adaptation in line with Saudi Green Initiative (SGI). Some of the practical impacts include:

- **Hydrogeological Characterization and Groundwater Management:** Mapping the water content in the shallow subsurface environment in arid and semi-arid region can provide critical information for groundwater exploration.
- **Reforestation and Land Restoration:** The Kingdom of Saudi Arabia has plans to plant 10 billion trees over the coming decades and to restore land degraded by desertification. This study could contribute to providing an understanding of water availability that may be relied upon to identify areas of adequate groundwater resources for large-scale reforestation and land restoration projects.

### 6.3 Recommendation

As an extension of this study, I suggest the following recommendations:

1. Test other rock physics models to establish the  $V_p(z, S_w)$  formula.
2. Include other field measurements such as the arrival times of the DDW in the objective function.
3. Include anisotropic effects of dipping stratifications within dunes (K. Makki, personal communication).
4. Include viscoelastic effects within dunes [61].
5. Test the method on other parts of the same dune (e.g., windward, slip face), other dune types (e.g., sheets, star, parabolic), and other conditions (e.g., vegetated, higher saturation).

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