

University of Bahrain

College of Engineering



**Department of
Civil Engineering**

**3-D Subsurface Feature Mapping:
Integrated Geospatial Approach**

**A Thesis Submitted in Partial Fulfillment of the Requirements for
The Ph.D. Degree in Civil Engineering**

Prepared by

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Associated Professor

October 2021

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بسم الله الرحمن الرحيم

يَرْفَعُ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ
دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ

صدق الله العظيم

سورة المجادلة آية (11)

In the name of Allah most Gracious, the most Merciful

"Allah will exalt in degree those who believe, and those who have been granted knowledge, And Allah is well-acquainted with what you do."

Surratt AlMujadillah (11)

Thesis Discussion Committee Decision

University of Bahrain
Deanship of Graduate Studies
And scientific Research



جامعة البحرين
عمادة الدراسات العليا والبحث العلمي

Thesis Discussion Committee Decision

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The Discussion Committee met on 06-Oct-21 In MS-teams online. Upon discussing the student whose details are stated above in public, the discussion committee recommends the following:

The student is awarded a grade A- in the thesis subject.

- ☐ Without making any changes to the thesis.
- ☒ After making the modifications attached with this decision.

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6 Approved at the University Council 6th meeting, 2013
In accordance with Decision No. 736/2013 dated 14/3/2013
Modified by University Council Decision No. 2043/2013 dated 20/11/2013.

Abstract

Besides geophysical inspections, the most common methods employed in near subsurface mapping are destructive and non-destructive excavation. This research focuses on studying the last method. Intensive literature and industrial search reveal firstly: There is no universal procedure or system that standardizes the best subsurface mapping approach. Secondly, the geophysical inspection's output is not directly compatible with other thematic layers. Lastly, there are no databases or official records for the interaction of subsurface features with the different sensors and host materials and their conditions. Therefore, this research aimed to design an experimental prototype that leads to finding and storing these interactions to be used in feature detection. This information was called the Feature Characteristics (FC). In addition, it aimed to design a prototype for a new feature detection system called the Integrated Subsurface Mapping System (ISMS). This system proposes a new procedure that guides the user to determine the detectability of targeted features and the best combination to do it. The ISMS depends on the obtained FC. The outputs of the ISMS are a regular geophysical profile, 3D maps and diagrams, and a compatible Geographic Information Systems (GIS) thematic map. To achieve the mentioned goals, it was required to design and implement several experiments to study the subsurface FC. Then, these characteristics were used to design the proposed system. Next, the system was designed using a high-level Unified Modelling Language (UML) chart. Lastly, a MATLAB programmed code was used to produce a 3D spatial map using the experimental results. The designed experiments focused on three features: Municipal Solid Waste (MSW), voids, and plastic features, due to their high potential impact on the civil, structural design, and the environment. Besides, they are rarely addressed in the literature. Three detection methods were selected for the near subsurface mapping experiments, because of their applicability: Ground Penetrating Radar (GPR), Ultrasound Waves, and thermography. In addition, sand, gravel, and loamy soils were selected because they are among the most common soils. The research findings were significant because: It is the first research to investigate and develop the FC for MSW, voids, and plastic. Secondly, ISMS became the foundation for a novel decision support system (DSS) that facilitates detection procedures. Furthermore, ISMS produces a 3D thematic layer that could be integrated with other thematic maps. Lastly, the obtained map accuracy was assessed by comparing the mapped features with their actual location. The accuracy of the resulted maps was within acceptable civil engineering limits. This research recommended extending the work to study more variables, features, sensors, host soils, and conditions. So, the FC database could be comprehensive, and the feature detection yields more accuracy. Finally, it is recommended to program the ISMS and write the operational manual to facilitate the feature detection process.

Publications and Participations

Near Subsurface Mapping Using Ground Penetrating Radar Time Vs Frequency Domains: Literature Review (2010 Till 2019)

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A Prototype to Produce an Integrated GIS-SUE Map

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Experiment to Assess the Feasibility of Using a Thermal Camera to Locate Municipal Solid Waste Deeper Than Half-Foot

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Dedication

To my parents, family, and friends

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Abbreviations

ADC	Analog to Digital Converter
AFO	Acoustic Fiber Optics
B	Bandwidth
CW	Continuous Wave
DF	Daul Frequency
DIP	Digital Images Processing
DR	Direct Resolution
DSS	Decision Support System
EC	Electrical Conduitivity
ECG	ElectroCardioGram device
EM	Electromagnetic
EML	Electromagnetic Locator
ERT	Electrical Resistivity Tomography
FC	Feature Characterisitics
FIR	Far InfraRed
FMCW	Frequency Modulated Continuous Waves
FT	Fourier Transformation
FFT	Forward Fourier Transformation
GIS	Geographical Information System
GPIR	Ground Penetrating and Imaging Radar
GPR	Ground Penetrating Radar
GPS	Global Positioning System
GSSI	Geophysical Survey Systems Inc.
GSSI	Geophysical Surveying System Incorporation
HPF	High Pass Filter
HRR	High Resolution Radar
IDFT	Inverse Discrete Fourier's Transformation
IRT	Infrared Thermography
ISMS	Integrated Subsurface Mapping System
LIDAR	Light Detection and Ranging
LIR	Long Infra-Red band = TIR
LPF	Low Pass filter
MASW	Multichannel Analysis of Surface Waves

MIR	Middle InfraRed
MSW	Municipal Solid Waste
MTU	Mapping The Underworld
NDT	Non-Destructive Testing
NDVI	Normalized Difference Vegetation Index
NIR	Near InfraRed
PRF	Pulse Repetitive Frequency
PVC	Polyvinyl chloride
RRI	Ramp Repetition Interval
RR	Range Resolution
RS	Remote Sensing
SAR	Synthetic Aperture Radar
SFCW	Stepped Frequency Continuous Waves
ISMS	Integrated Subsurface Mapping System
SLAR	Side Looking Airborne Radar
SNR	Signal to Noise Ratio
SSET	Sewer Scanner Evaluation Technology
SUE	Subsurface Utility Engineering
TDEM	Time Domain Electromagnetic
TIR	Thermal Infra-Red = LIR
TM	Thermatic Mapper
UAW	Ultrasound Acoustic Wave
UAW	Ultrasound Acoustic Wave
UML	Unified Modelling Language
UPV	Ultrasonic Pulse Velocity
USW	Ultra-Sound Waves
WB	Wide Bandwidth

Chapter 1: Introduction

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Chapter 1 Introduction

1.1 General

Urban development, rapid population growth, and the technological development revolution required transforming and developing the services network in the cities, especially when the countries aim to adopt the smart cities concept. Therefore, became vital to embrace new and innovative technology solutions to map subsurface material. However, the conventional method to locate the underground materials was merely dependent on boreholes, trenching, and trial pits. These destructive are time-consuming and include a potential risk to damage subsurface utilities and structures. Thus, several geophysical technologies have been utilized to produce effective subsurface mapping. The most common techniques are:

- 1- Ground Penetrating Radar (GPR)
- 2- Ultrasound Acoustic Wave (UAW)
- 3- Thermal Mapping
- 4- Seismic Tomography
- 5- Magnetic exploration
- 6- Resistivity Tomography
- 7- Other Geophysical technologies

This research will discuss the first three types only due to the applicability of these technologies. The GPR represents the most recommended non-destructive tool or technology (NDT) for locating some near subsurface features, notably “utility pipes.” The GPR uses the electromagnetic wavelength in the microwave region, which is transmitted into the ground to detect and identify the buried object information. These

objects scatter signals back to the surface, where the controller detects the received signal's inhomogeneity. Therefore, it is classified as an active close-range remote sensing technique (Jaw, Hashim, & Goh, 2015). The GPR detection depends on the variation of electrical properties between the targeted object and the host material. GPR's spatial output is determined by integrating with the Global Positioning System (GPS) for object locations. The depth is determined from the reflected signal. The result might be used to produce a 3D digital map. Also, it could be integrated with satellite imagery or orthophoto as done by (Al-rizouq & Abueladas, 2013).

Thermal mapping was used in similar research (Okamoto & Liu, 1998; Okamoto, Liu, Agu, & Inagaki, 1997) to detect shallow objects such as buried ancient tombs and slabs. Also, it has been used in agricultural applications such as irrigation scheduling, soil properties mapping, plant disease detection, crop yield estimation, and evaluating the crop's maturity (Aryalekshmi, Biradar, & Mohammed Ahamed, 2019). This technique is either utilized on a small scale with shallow depths less than 15cm (concrete inspection) or on a large scale to inspect deeper depths.

The ultrasonic non-destructive testing measures the thickness of testing objects or delineating subsurface features' internal structure. This method uses a high-frequency sound wave range from 500 KHz to 20 MHz, which is higher than the human hearing range limit. (Sölken, 2020). The frequencies lower than 500 KHz have limitations due to scattering in concrete testing (Bungey, Millard, & Grantham, 2006). The ultrasound concept depends on the variation in the mechanical properties between the targeted object and host.

Intensive literature and industrial research ensured that despite the success of the previous technologies in subsurface mapping, several issues are still not resolved yet. Each technique required specific conditions to provide accurate results. Although combining these techniques provides better results, there is no rule of thumb or accurate procedure to determine the best combination to map specific features. The choosing of these techniques depends on the experience of the operator (which is usually has a geophysical background) in the area of study, targeted object, and the available devices.

On the other hand, remote sensing (RS) technologies can detect and define the surface object features by knowing their spectral signature. However, there are no similar data for subsurface features.

1.2 Research Problem

The most common methods to investigate and detect underground materials are destructive, non-destructive excavating (such as boreholes and trial pits), and geophysical inspection. The first two methods are tedious, time-consuming, costly, and in some conditions inviable. Although geophysical inspections succeeded in some feature detection and location, they cannot delineate the feature type. For example, GPR can locate the pipe's location, but it can not determine its material. As a result of several critical factors such as signal wavelength, soil type, moisture contents, object size, and dielectric properties, the geophysical experts recommend integrating several technologies to enhance the subsurface feature detection. In addition, there are no available procedures to determine the required techniques and the method of scanning to detect a specific feature. Besides, the common output of geophysical scanning is a 2D image that cannot be

easily integrated with other spatial information. The detecting technique also requires highly trained professionals to operate and analyze the obtained data. The targeted subsurface features are Municipal Solid Waste (MSW), voids, and plastic. These features are rarely addressed in the subsurface mapping literature, especially in near subsurface and small-scale projects, besides their potential effects on the civil and structural design.

1.3 Research Questions

- How to understand the interaction of the targeted subsurface features (MSW, voids, and plastic) with RS sensors and host materials and develop a subsurface feature detection procedure similar to spectral signature in RS?
- How to enhance the subsurface feature mapping and produce a Geographical Information System (GIS) compatible thematic map?

1.4 Research Objectives

- To integrate various non-destructive remote sensing techniques and assess the interaction of targeted objects with them, then save these results in a central database called feature characteristics.
- To design an Integrated Subsurface Mapping System (ISMS) that produces a 3D GIS compatible map that incorporates spatial and nonspatial information to interpret subsurface features efficiently.

1.5 Research Significance

This research is vital since it investigates the following genuine issues:

1. The first research provides a prototype for finding the feature characteristics for specific features with RS sensors, similar to the spectral signature in traditional RS technologies.
2. The integration between time and frequency domains GPR, thermal camera, and ultrasonic sensors represent a new contribution to the knowledge since it has not been previously utilized.
3. All previous literature that dealt with similar techniques focused on the geophysical point of view (because all available researches were done by or with geophysicists). In this research, the investigation was done from a Geomatics and remote sensing point of view.
4. Developing the ISMS for mapping subsurface features is considered a contribution to the knowledge.
5. ISMS might contain a database for all targeted features
6. The proposed system gives the user the ability to know his requirement.
7. Pave the way for future exploration of detecting more features.

1.6 Research Scope

Although the mapping of subsurface features was enhanced exponentially in the last years. Still, the final products are vector or raster data, where the attributes, metadata, and other information (such as the accuracy of collected and analyzed data) might be done later by data entry or by the user manually. Besides, the traditional geophysical methods concentrate on the techniques and depend heavily on the operator and analysts' experience.

Therefore, the scope of this research is to develop an optimum approach for mapping the subsurface feature from Geomatics and RS perspectives, to help the user know more about the available data and their reliability. Besides, to guide the user from the planning stage to decide the optimum integration and procedure of scanning and detection for his targeted features.

1.7 Definition of Terms

Electrical Conductivity (EC): is the ability of a material to transmit the electrical current. It is usually measured by milli-siemens (mS/m) or deci-siemens (dS/m) (deci = 100 milli). EC in the soil delineates the amount of salts in soil (salinity of soil).

Dielectric constant (K): also called **Relative Permittivity**. The ratio of the permittivity of the specific substance to permittivity of free space (vacuum).

Emissivity: is the ratio to measure an object's ability to emit (radiate) infrared energy to a black body. Which can have a value from 0 (shiny mirror) to 1.0 (blackbody). (“What-is-emissivity,” 2021)

Feature Characteristics: the interaction between targeted subsurface features, sensors, and host material.

Fourier Transformation: is an important image processing tool used to decompose an image into its sine and cosine components. (the principle of Fourier Transform that any function could be represented in a series of sine and cosine functions). (Fisher, Perkins, Walker, & Wolfart, 2021)

Forward Fourier Transform: is a mathematical technique to transform the time function $x(t)$ to Frequency Function $x(\omega)$. (Wolfe, 2016)

GPR: a close-range remote sensing tool based on using an electromagnetic signal to detect underground materials.

Gravity Surveying Method: It is a relatively inexpensive, non-invasive, and non-destructive remote sensing method that measures differences in the earth's gravitational field at specific locations. It provides information about rocks' densities underground, voids, and water table levels. (Mickus, 1980)

Inverse Fourier Transformation: “A mathematical operation that transforms a function for a discrete or continuous spectrum into a function for the amplitude with the given spectrum; an inverse transform of the Fourier transform.” (Www.definitions.net, n.d.)

Magnetic Surveying is a geophysical subsurface mapping method to find the subsurface anomalies by measuring the earth's magnetic field intensity and recording its changes.

Multi-Channel Analysis of Surface Waves (MASW): A seismic exploration technique first introduced in Geophysics (Park, Miller, & Xia, 1999). It was developed for imaging and characterizing the shallow subsurface features up to 30m depth. MASW is based on utilizing the properties of Rayleigh-type surface waves.

Remote Sensing: “is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation.” (Lillesand, Kiefer, & Chipman, 2004)

Seismic Reflection Method: A geophysical exploration method provides information about the subsurface feature by sending artificially generated acoustic waves. These reflected waves by subsurface features are recorded by geophones. Then, the data are processed to produce a visual representation of the subsurface features.

Spatial Analysis: An analytical toolset considers an object's spatial frame and uses it to produce a valuable product. (Longley, Michael, Maguire, & Rhind, 2005)

Spatial Modeling: is one of the spatial analysis tools to find the relation between several objects. (Longley et al., 2005)

Subsurface Utility Engineering: “is a discipline of civil engineering that involves the investigation of buried utilities and identifies the conflicts they may pose to a project design to mitigate associated risks.”(Gil Horrocks, 2020).

1.8 Research Outline

The thesis comprises seven chapters. Chapter 1 outlines the introduction to the study. Chapter 2 discusses the theoretical framework and provides a literature review of subsurface mapping techniques. Chapter 3 explains the methods and procedure, including the design and implementation of the experiment. Chapter 4 describes the data analysis for subsurface data and the finding of the feature characteristics. The proposed prototype for Integrated Subsurface Mapping System (ISMS) is illustrated in Chapter 5. Chapter 6 discusses the research results. Lastly, chapter 7 provides conclusions and recommendations.

Chapter 2: Theoretical Framework and Literature Review

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Chapter 2 Theoretical Framework and Literature Review

This chapter illustrates remote sensing's fundamentals and then presents the theoretical framework of the available subsurface mapping techniques. Next, the latest literature review related to the research scope will be listed and discussed before summarizing the chapter and stating the knowledge gaps to be investigated in the research.

2.1 Remote Sensing

Remote sensing (RS) is “the science (and to some extent, art) of acquiring information about the earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information.”(Rees, 2012), (Kindaya, 2017).

Remote sensing depends on measuring electromagnetic, acoustic, or potential energy. The incident energy in active and passive sensors is reflected, refracted, transmitted, or absorbed by observed objects. On the other hand, the emitted energy such as heat is recorded in special sensors. The most common sensors use specific parts of the electromagnetic energy spectrum. Each part of the spectrum has its own characteristics. Therefore, RS scientists studied the interaction characteristics between the object under study and the EM energy (Feature Spectral Signature) and obtained the reflectance diagrams shown in Figure 2-1. These diagrams represent the core of choosing the satellite imagery bands design and analysis. For example, Green and Infrared bands signals would work better to detect the

vegetation. This is because the vegetation has high reflectance in these bands, whereas the water has higher reflectance in blue.

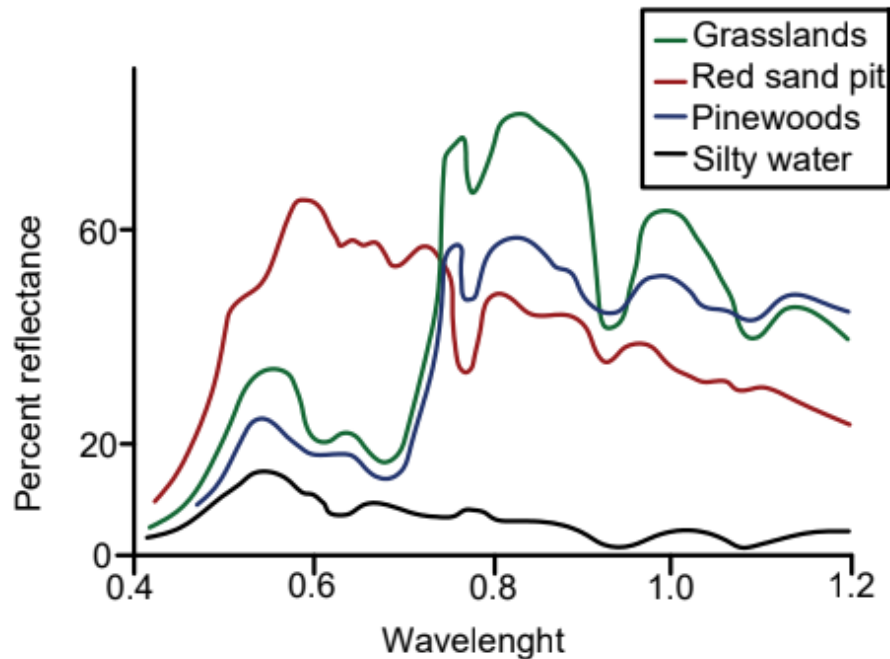


Figure 2-1 Energy reflectance of different earth surface objects (Harris, 2018)

The previous information leads to enhancing, utilizing, and developing different RS sensors. RS sensors are also classified into two main categories: passive and active sensors based on energy sources utilized, as shown in Figure 2-2. The passive sensors are designed to detect indirect energy (reflected and emitted) from the sun. On the other hand, active sensors are designed to detect the energy generated by the sensor itself or by an integrated device as in radar sensors. Although, the active sensors are usually used in studying the subsurface's features. They have several applications in studying the elements on the earth's surface and in other applications such as medical subjects.

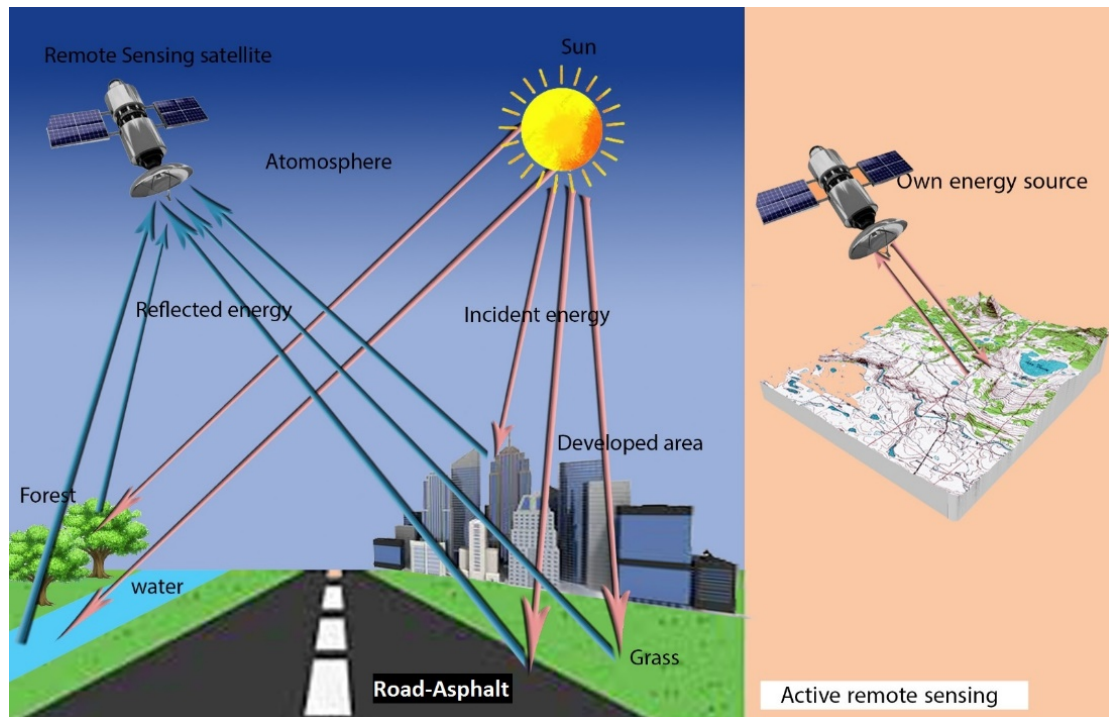


Figure 2-2 Basic of RS passive and active sensors (Harris, 2018)

The most common active sensors to study the subsurface feature are Synthetic Aperture Radar (SAR), GPR, Acoustic and Seismic Mapping, Electrical Resistivity, Magnetic, Gravity, and other techniques. This research will discuss GPR, UAW, and Thermal Mapping due to the applicability and availability of these technologies. Also, they could be used in small-scale civil and construction projects. The following sections will discuss the physical concept and benefits of these techniques.

2.1.1 GPR

GPR is considered one of the most common technologies for near subsurface mapping. It uses the electromagnetic wavelength in the microwave region that is transmitted into the ground to detect the buried object information, which will scatter the signals back to the surface. In addition, the controller will detect the inhomogeneity of the

received signal. Therefore, it is classified as active close-range remote sensing techniques (Jaw et al., 2015). The GPR concept measures the time delay for receiving the transmitted signal by the receiver base in Equation 2-1.

$$\text{time delay, } \Delta t = (2 \cdot d) / c \quad 2-1$$

Where, Δt is the measured time delay, d is the distance between the object and device, and c is the speed of light.

The GPR electromagnetic fields propagate as essentially nondispersive waves. The emitted signal travels through the material is absorbed, scattered, or reflected by impedance changes. This impedance happens by the boundaries of the dielectric properties of different objects. The signal recognition is straightforward because the return signal looks like the emitted signal (Utsi, 2017). The GPR antenna receiver records these signals (if not absorbed by the object) as a two-way travel time versus amplitude, as shown in Figure 2-3.

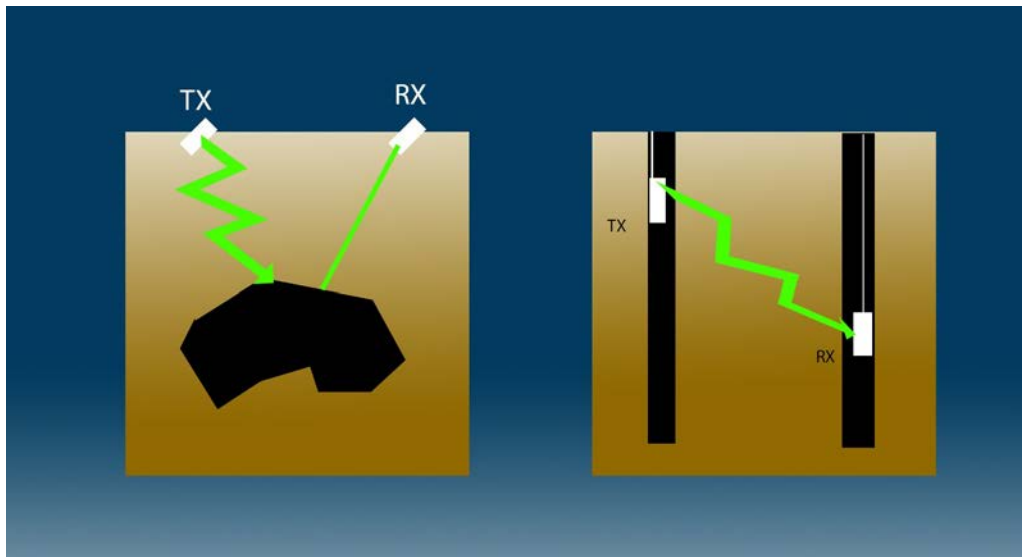


Figure 2-3 Reflection and transmission of radar signal (Annan, 2003)

The simulation of the previous attenuation of GPR signal might be achieved by measuring the signal velocity changes while probing different materials. The velocity of microwaves for material as a function of its dielectric and conductivity is given by (Cassidy (2009) as cited by (Goodman & Piro, 2013)) using Equation 2-2.

$$v(f) = \frac{c}{\sqrt{\epsilon'(f)\mu_r \frac{1+\sqrt{1+\tan^2\delta}}{2}}} \quad 2-2$$

Where f is the frequency, μ_r is the magnetic permeability, ϵ' is the real dielectric, and the δ is the loss tangent. The effect of these parameters is usually considered neglected, so the equation is reduced to Equation 2-3 (Goodman & Piro, 2013). Then, the target's depth could be obtained using Equation 2-4 (David J.Daniels et al., 2004).

$$v(f) = \frac{c}{\sqrt{\epsilon'}} \quad 2-3$$

$$d = v \frac{t}{2} \quad 2-4$$

Nevertheless, the acquired data will not be interpreted directly due to system noise and other electromagnetic interference (Benedetto & Pajewski, 2015). The next subsections illustrate the most popular object detection shape (Parabolic shape) and other important aspects of the GPR concept. After that, a subsection discusses the two main GPR technologies: frequency domain and the time-domain GPR.

2.1.1.1 Parabolic Shape in GPR:

The parabolic shape in GPR data represents one of the most important aspects of GPR data collection, especially when tracking

or investigating linearly laid objects. Figure 2-4 illustrates the case for determining the buried pipe's location, where the backscatter of signals by the underground object will be shown as a parabola in the GPR controller, and the location will be determined using equation 2-5 (JAW, HASHIM, & GOH, 2015).

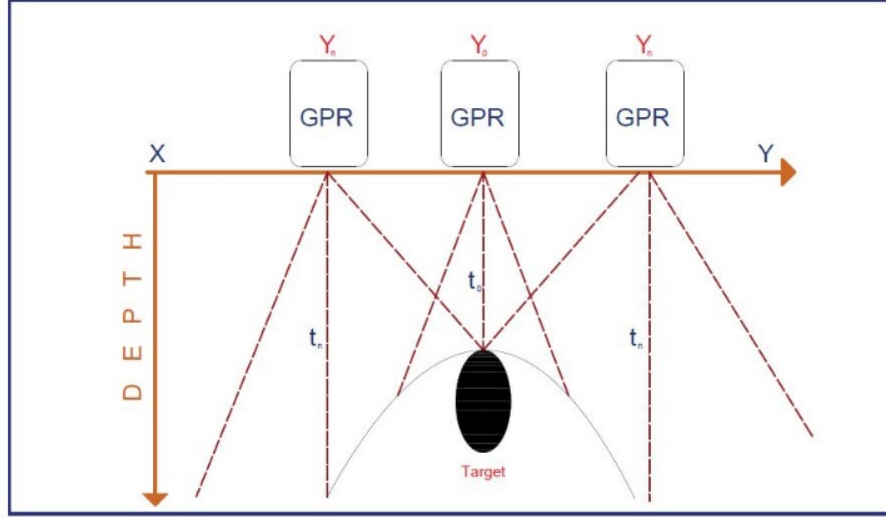


Figure 2-4 Hyperbola formation in the GPR controller (JAW, et al., 2015)

$$\frac{t_n^2}{t_0^2} - \frac{4(y_n - y_0)^2}{(vt_0)^2} = 1 \quad 2-5$$

Where, v = velocity of the EM wave; t_n = echo delay in position y_n ; and t_0 = echo delay.

On the other hand, detecting a single feature (such as pipes or steel bars) usually appears as a parabola, especially when it has been scanned perpendicularly to its original orientation. From experiences and references such as (Bigman, 2019) and (David J. Daniels et al., 2004), the sizes of these parabolas depend on four factors:

- 1- The depth of the scanned object as the depth increased, the parabolic size increased.

- 2- The size of the object, as the size increased, the parabolic shape size increased
- 3- The scanning angles (direction); if the scanning angle is less or more than the right angle, the parabolic shape size increases.
- 4- The material properties (velocity of the signals). The parabolic shape size increased as the velocity increased, such as in sandy soil. Also, where the velocity decreased as in clay soil, the parabolic size decreased.

The ratio between the buried objects' sizes to their depth plays a role in the detection process. The rule of thumb by the technical experts in GPR surveying projects is “the detectability ratio of the buried pipes to their sizes is 1-inch diameter per 1-foot depth (or 10cm per 1-meter)” (Rana & Swarup, 2018). The deeper object will be undetectable. The velocity could be calculated from equation 2-6.

$$v_r = \frac{c}{\sqrt{\epsilon_r}} \quad 2-6$$

Where ϵ_r is the relative permittivity of the medium, c is the speed of light, then the depth d could be derived by measuring the travel time to the object (t) using equation 2-7.

$$d = v_r \frac{t}{2} \text{ in meter} \quad 2-7$$

The relative permittivity is usually unknown. Therefore, it could be measured in the lab using soil sampling by trial holes or multiple measurements of known objects (called site calibration).

Table (2-1) shows the important properties of some common materials that could be used to plan the scanning steps.

Table (2-1) Dielectric properties for common objects

(Annan, 2003)

Material	Relative Permittivity K (ϵ_r)	Conductivity σ (mS/m)	Velocity v (m/ns)	Attenuation α (dB/m)
Air	1	0	0.3	0
Distilled Water	80	0.01	0.033	2×10^{-3}
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	3000	0.01	103
Dry Sand	3-5	0.01	0.15	0.01
Saturated Sand	20-30	0.1-1	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shale	5-15	1-100	0.09	1-100
Silt	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry Salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

The total signal loss can be modeled as (David J.Daniels et al., 2004) in equation 2-8.

$$L_T = L_e + L_m + L_{t1} + L_{t2} + L_s + L_a + L_{sc} \quad \mathbf{2-8}$$

Where,

L_m = antenna mismatch loss in dB

L_{t1} = transmission loss from air to material in dB

L_T = antenna efficiency loss in dB

L_{t2} = transmission loss from material to air in dB

L_s = antenna spreading loss in dB

L_a = antenna loss of material in dB

L_{sc} = target scattering loss in dB

The total loss L_T is about -38 dB, where the frequency is 100 MHz for a depth of 1m. The clutters recorded with GPR signals are different from those in regular radar signals. The clutters here are

caused by signals unrelated to the target scattering. Nevertheless, it has the same characteristics as the target wavelength.

2.1.1.2 Other information about GPR:

Based on the available literature, several functions affected the GPR surveying process, some of them were used to enhance the detection process, and some have still been considered limitations. The following brief discussion of the most common ones (Bigman, 2019; Costello, Chapman, Rogers, & Metje, 2007; David J. Daniels et al., 2004; Hashim, Jaw, & Marghany, 2010; Utsi, 2017; Wei et al., 2011):

- a. The material properties: (such as dielectric permittivity, conductivity, and permeability) the changes in these properties affect the received signal's power, so it could be used to distinguish between several buried objects. The ability of GPR to detect objects depends on the differences in electrical and magnetic properties between the objects and the surrounded materials.
- b. The moisture content is still considered a limitation that has not been solved yet. Because the increase of water contents in the subsurface affects the penetrative power of GPR. On the other hand, moisture content plays a significant role in distinguishing the pipes, cavities, and material with low dielectric constant. Because the moisture content will raise the soil's dielectric properties surrounding the object under investigation, it could be more obvious to interpret.
- c. The soil type plays a significant role in the received signal's power. The clay soil scatters the electromagnetic waves more

than sandy soil. The compaction of the soil also plays a vital role in detecting the buried object. “GPR performs better in unsaturated coarse-texture or moderately coarse-textured soils.” (Hubbard, Grote, & Rubin, 2002).

- d. The direction of scanning: could affect the ability to detect buried objects. Scanning perpendicular to the linear feature (pipes and rebars) gives the highest reflected wave amplitude. (Sahamitmongkol, 2010)
- e. The surveyor and the analysts’ experience are still the main factors to delineate the surveying accuracy using GPR.
- f. The GPR frequency depends on the investigated object's size and the required depth. Therefore, the user must use the proper frequency that is not too high, so it does not reach the required object’s depth (using a 2GHz frequency to detect pipes more than 70cm depth). Also, must not use a lower frequency with a wavelength more than the object size and depth (such as using a 200MHz frequency antenna to detect small pipes 2.5 cm on shallow depth less than 20 cm, which might be undetectable in such frequency). As mentioned previously, the rule of thumb for this issue is that the object size to maximum depth for detectability is more than 1 to 12. In other words, the object's size and depth might be more than half of the used wavelength to be detected.
- g. The object contrast depends on the difference in characteristics between the targeted object and the medium (host).

Several studies such as (Rangaswamy, Monte, & Wicks, 2016) (Algeo, Van Dam, Slater, & Rutgers, 2016) (Costello, Chapman,

Rogers, & Metje, 2007), and others discuss the utilizing of **GPR** technology to identify the location of services beneath the surface. Alternatively, the integration of GPR with other procedures and tools to enhance the certainty and results such as (Zhang, Hancock, Lau, Roberts, & Xu, 2016), (Bian, et al., 2009), and (Uslu, Yeun, & Sinha, 2016).

lastly, the most critical information mentioned by (Utsi, 2017) and might be considered is “the radar is always right, and our interpretation may or may not be correct.”

2.1.1.3 Time domain vs frequency domain:

The Time domain is how the signals change over time, whereas the frequency domain means how many signals lie in the frequency range. Thus, frequency is nothing but the number of times each event occurred during the total observation period.

The time domain radars are usually known as impulse radars. The transmitted pulse (with a delay between several pulses) of the radar’s wave is received as a function of time, where the amplitude of energy for the scattered waves by subsurface objects has been recorded versus time. The resulting range versus amplitude represents an A-Scope or A-scan data shown in the right part of Figure 2-5. The A-scan is a time-domain data accumulated along the scan line to construct the profile shown on the left side of Figure 2-5. This profile is called B-scan and represents the data in the space-time domain. The low cost of parts and simplicity of generating an impulse wave represent the main advantages of time-domain radar.

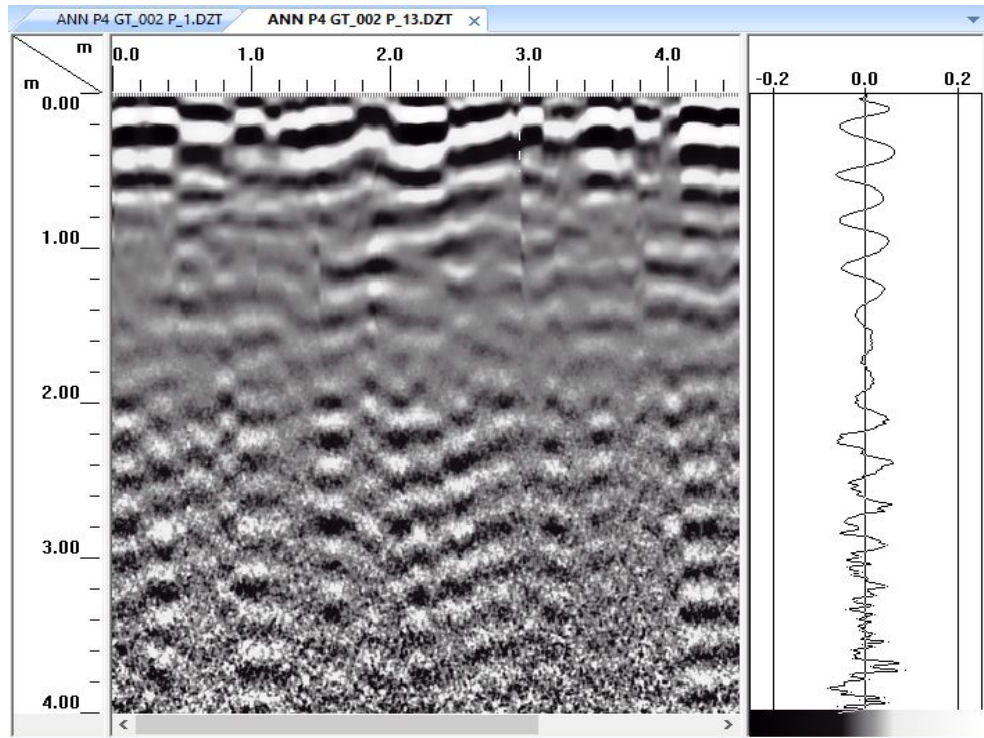


Figure 2-5 GPR data sample A-scan (right) and B-Scan profile (left)

On the other hand, these systems have several disadvantages, such as requiring high power for transmitting signals, the resolution being limited by pulse width, and undesirable ringing. Some of these disadvantages could be resolved by post-processing (filters) or using more than one antenna. (Jol, 2009).

The Frequency Modulated- Continuous Wave (FMCW) is the simplest frequency domain radars, where the frequency of waves sweeps continuously over fixed bandwidth from the starting frequency to the stop frequency. The amplitude of the reflected waves from subsurface objects is received as a function of frequency. First, the received signals are filtered, digitized, or sampled. Then, the digitized signals are transformed using an Inverse Discrete Fourier's Transformation (IDFT) illustrated in the following subsection. The resulting signals are called synthesized

pulses. The disadvantages of this type are the slowness of digitizing and sampling because part of the transmitted signals is received with the reflected signal (Jol, 2009).

The Stepped Frequency Continuous Waves (SFCW) is similar to the FMCW (sweep frequency) except that the transmitted frequencies stepped in linear increment over fixed bandwidth. The received discrete signal is digitized and sampled for each frequency step, then transformed by IDFT to produce a synthesized pulse. The main advantages of this type are the efficient use of power, the ability to step signals faster, and the production of high-quality data. However, it required faster processing and transformation programming and significant memories for the massive amount of data, which is available with modern big data technologies and fast communication tools—besides, its higher cost than FMCW and impulsed GPR.

By referring to Figure 2-6 that shows the relation between pulse time and frequency for a simple radar pulse, the following several terms and relations will be defined to understand the concept of frequency and time domain radar systems and the differences between them (Jol, 2009; Noon, 1996):

- The range resolution ΔR is “the ability to distinguish between two solely objects from the measurements of their ranges” (Noon, 1996). The range resolution in equation 2-9. is related to the bandwidth and the velocity

$$\Delta R = \frac{v}{2B} = \frac{v\tau}{2} \quad 2-9$$

Where **B**: is the band width, τ is the delay time for the received signal

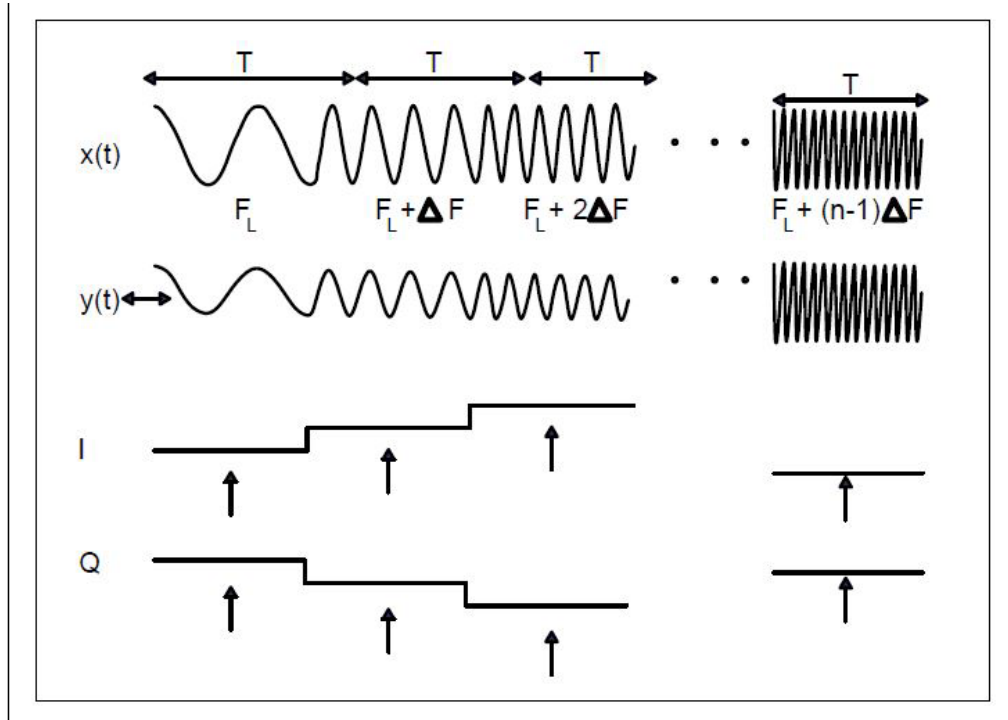


Figure 2-6 Stepped frequency waveform techniques

$x(t)$ is the transmitted wave, $y(t)$ is the received wave with a delay τ , where **I** and **Q** are the complex baseband components of the received waveform (Noon, 1996)

- The lateral resolution is the ability to distinguish between two objects in the perpendicular direction of range resolution, as shown in Figure 2-7. The lateral resolution could be obtained using equation 2-10.

$$\Delta l = \sqrt{\frac{vR}{B}} = \sqrt{vR\tau} \quad 2-10$$

- The radar's dynamic range was defined by (Hamran, Gjessing, Hjelmstad, & Aarholt, 1995) as “the maximum loss the transmitted radar signal can sustain and still be detectable at the receiver. This

factor can be used for comparing different systems and when computing the potential penetration range of a system”.

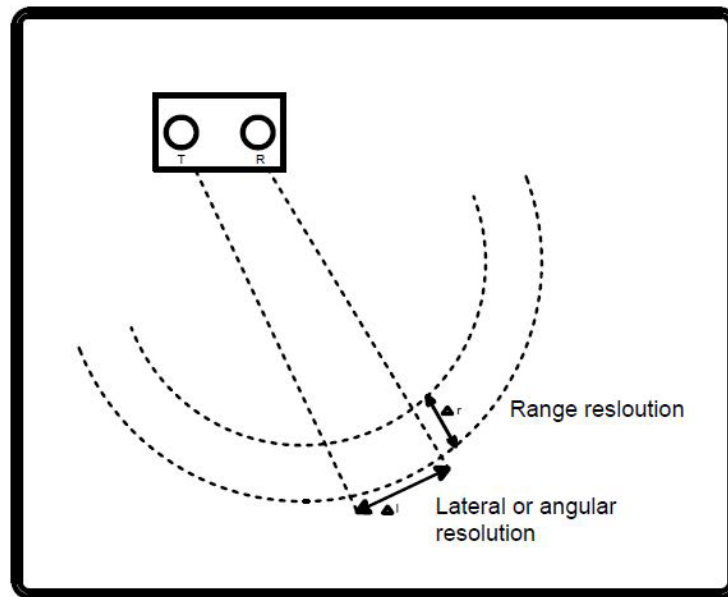


Figure 2-7 Range Resolution Vs Lateral Resolution

From the previous terms and equations, it could be noticed that the power and bandwidth represent a limitation for the pulse radar resolution in the time domain. Therefore, the High Resolution Radar (**HRR**) represents an alternative to pulse radar, where it allows high mean power through longer transmitted pulses (a continuous wave **CW**) and retaining wide bandwidth (several narrow bandwidth pulses) for high resolution. Hence, it is also known as Wide Bandwidth (**WB**), which is used in SAR and GPR. (Catapano, Gennarelli, Ludeno, Soldovieri, & Persico, 2019; Jol, 2009; Noon, 1996).

The simple form that is allowing WB is the FMCW. it transmits a CW with bandwidth (B) in Hertz within dwell time (t_d) (known as Ramp Repetition Interval (**RRI**) see Figure 2-8). The different or beat frequency f_b generated in these system could be

calculated using equation 2-11. However, it is sensitive to frequency sweep nonlinearities that cause resolved power degradation. Therefore, SFCW represents a better alternative to FMCW (Catapano et al., 2019) and (Tronca, Tsalicoglou, Lehner, & Catanzariti, 2018).

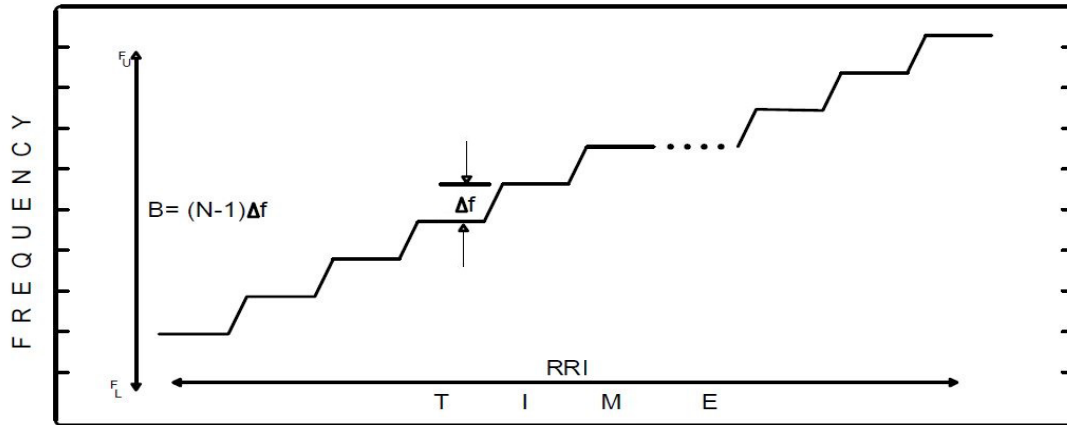


Figure 2-8 Frequency step in time

(the n narrow band frequency transmitted from f_L to f_U in Hertz across the bandwidth B) (Noon, 1996)

$$f_b = \frac{B t_t}{t_d} \quad 2-11$$

Where t_t is the travel time for the different signals.

Frequency domain analysis is more straightforward. One can figure out the critical points in the total interval rather than focusing on every variation in time domain analysis. Table (2-2) shows some models to compare the three mentioned systems.

Table (2-2) GPR Processing values summaries

Item	Pulse Radar	SFCW	FMCW
Attenuation α : the received GPR signal has less	$\alpha = k_0 \sqrt{\frac{\epsilon_r}{2} \left(\sqrt{1 + \left(\frac{\sigma}{2\pi f \epsilon_0 \epsilon_r} \right)^2} - 1 \right)}$		

energy than the transmitted one, due to the attenuation by the conductivity, and dielectric permittivity of the medium (in dB) (Catapano et al., 2019)	σ : electric conductivity (measures the materials' capability to be crossed by electric charges) f : frequency ϵ_0 : dilectric permittivity of space = 8.85×10^{-12} F m ⁻¹ , ϵ_r : relative dilectricity (dimensionless quantity varies from 1-81) $\epsilon_r = \frac{\epsilon}{\epsilon_0}$ ϵ : dielectric permittivity (represents the materials' capability to store electric charge) k_0 : propagation constant = $\frac{2\pi f}{c_0}$ c_0 : speed of light in space 3×10^8 m/s		
Frequency (in Hz)	Central frequency = B/R B: Bandwidth R: Range resolution	Step frequency $\Delta f = \frac{c_0}{4R\sqrt{\epsilon_r}}$	Instantaneous frequency of baseband (beat frequency): $f_{xb} = \frac{2\gamma\sqrt{\epsilon_r}R}{c_0}$
Bandwidth (B)	$B = \frac{1}{\tau}$	$B = f_{max} - f_{min}$	
Unambiguous Range R_{un}	$R_{un} = \frac{Tc_0}{2\sqrt{\epsilon_r}}$ T: the Pulse repetition Period (PRI)	$R_{un} = \frac{c_0}{4\Delta f\sqrt{\epsilon_r}}$	$R = \frac{c_0 f_{xb}}{2\gamma\sqrt{\epsilon_r}}$ γ : the slope of the frequency-time curve
Range Resolution: the distance to distinguish between two objects according to their range		$\Delta R = \frac{vt}{2} = \frac{v}{2B}$	
Dynamic range (DR): the ratio between the higher receivable signal and the smallest detectable signal (Koppenjan, 2009)		$DR = 20\log\left(\frac{V_{max}}{V_{min}}\right)$	

2.1.1.4 Discrete Fourier Transformation (DFT) and filters

It is vital to illustrate the Fourier Transformation (FT) and its utilization in Digital Image Processing (DIP). The Fourier transformation is a mathematical model representing any function in a series of sine and cosine. The forward Fourier transformation (FFT) is a continuous function that is hard to program and manipulate in computers. Thus, it is discretized into a programmable

form of DFT. FT is a helpful tool in DIP, where it is used to analyze the spectrum of the image, apply filters, and find a correlation of patterns in an image. The most common use is to apply the filters to images, according to the simple flowchart shown in Figure 2-9.

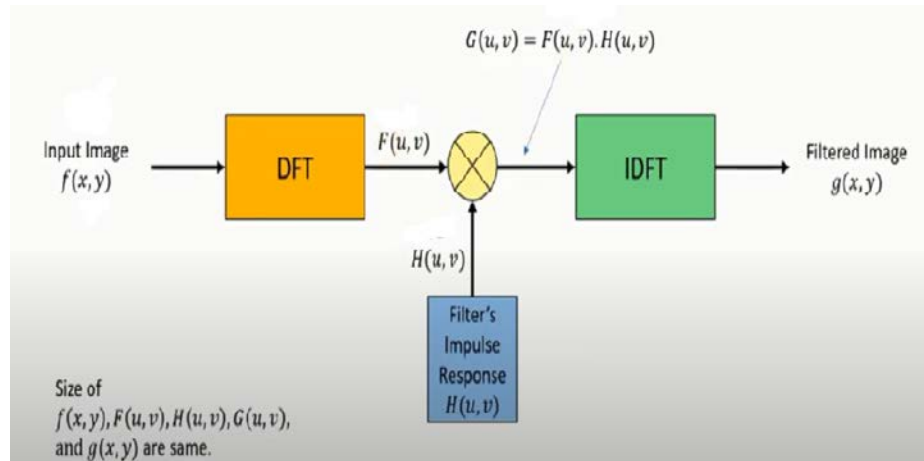


Figure 2-9 Apply filter to image using DFT & IDFT

When applying FT, the critical issue is to keep both parts of products in DFT the magnitude and phase to retrieve the image by applying the inverse Discrete Fourier transformation (IDFT). Figure 2-10 shows the effect of applying the DFT on black images containing different white squares sizes. It can be noticed that the sharp spatial domain image will have the coarse frequency domain DFT effect.

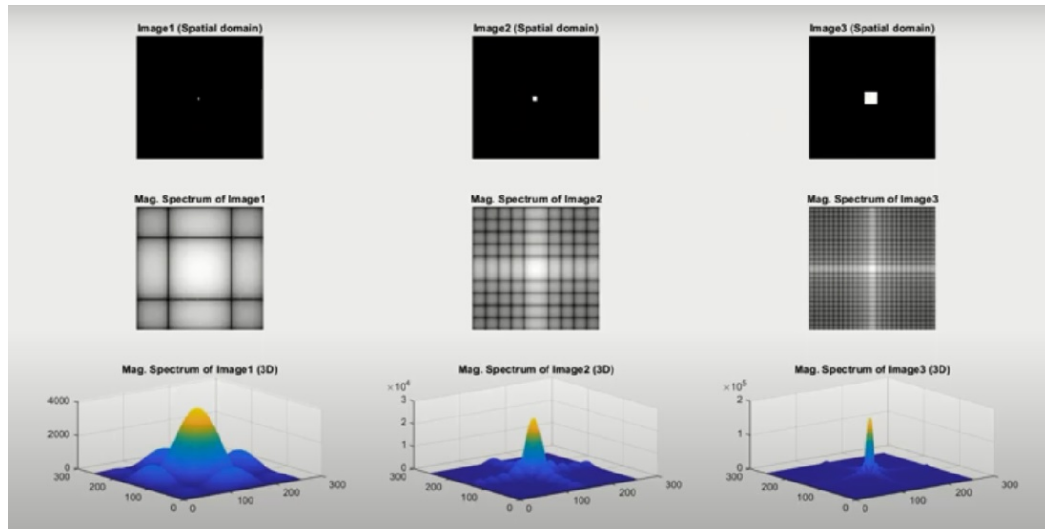


**Figure 2-10 DFT effect on images of different square sizes
(Belaid, 2009)**

To see the effect of applying filter using DFT, Figure 2-11 and Figure 2-12 show the concept and effect of applying the low pass filter (**LPF**), high pass filter (**HPF**) on image processing. The LPF is a filter used to remove the sharp edges in the image. Where the filter prevents high frequencies, this filter produces a blurred image. The HPF is a filter used for edge detection, where it allows high frequencies. The resulting image has high contrast and sharp edges. Another helpful filter is the notch filter used to remove specific parts of frequencies, such as removing perpendicular or horizontal lines from the image, as shown in Figure 2-13 (Verma, 2020). There is another crucial filter in GPR post-processing called the deconvolution filter.

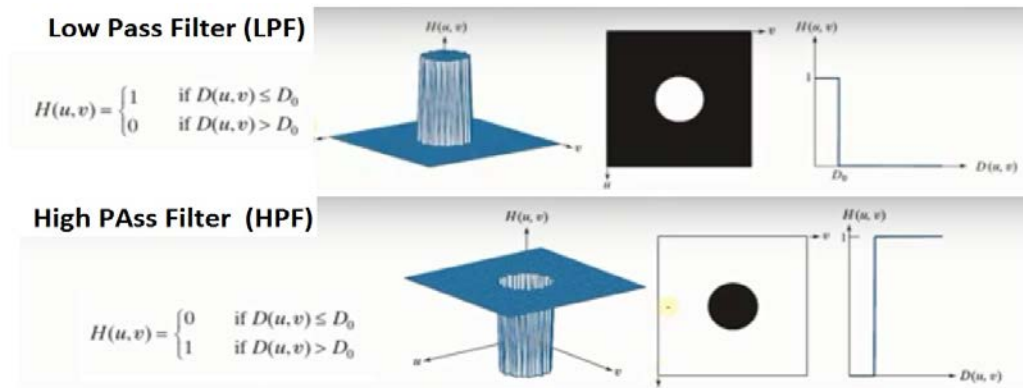


Figure 2-11 Concept of LPF and HPF
(Belaid, 2009)

The deconvolution filter is used to remove the ranging in GPR images. It removes the repeated horizontal anomalies (successive peaks in the A-scan vertically). Figure 2-14 shows the effect of applying this filter to the GPR B-scan profile in Figure 2-5. It could be noticed that some ranging was disappeared from the image. However, the crucial issue is that this filter might lead to losing some essential data in the profile. Thus, it must be used with care.

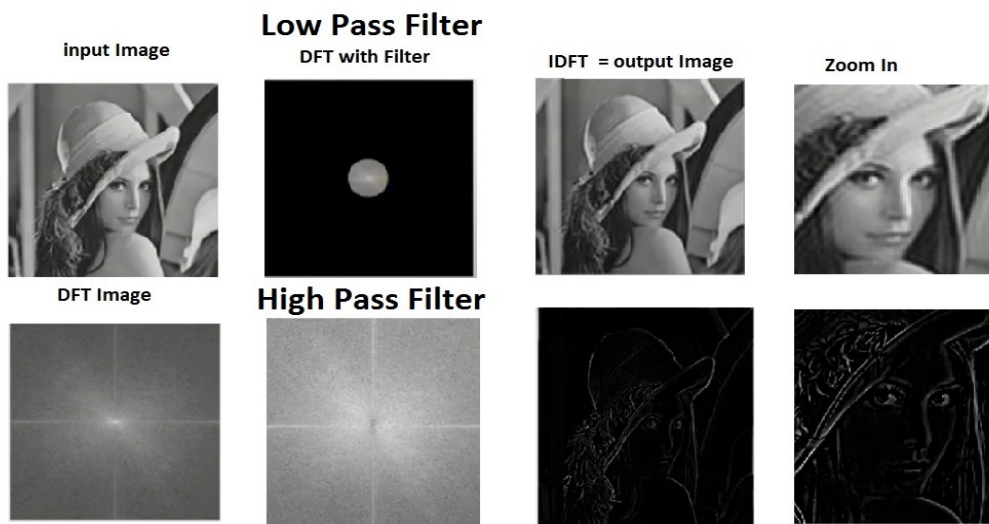


Figure 2-12 Example of applying LPF and HPF on image
(Belaid, 2009)

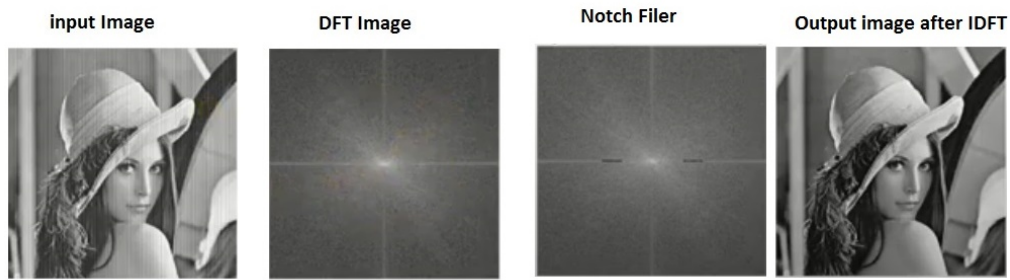


Figure 2-13 Notch filter in DIP
(Belaid, 2009)

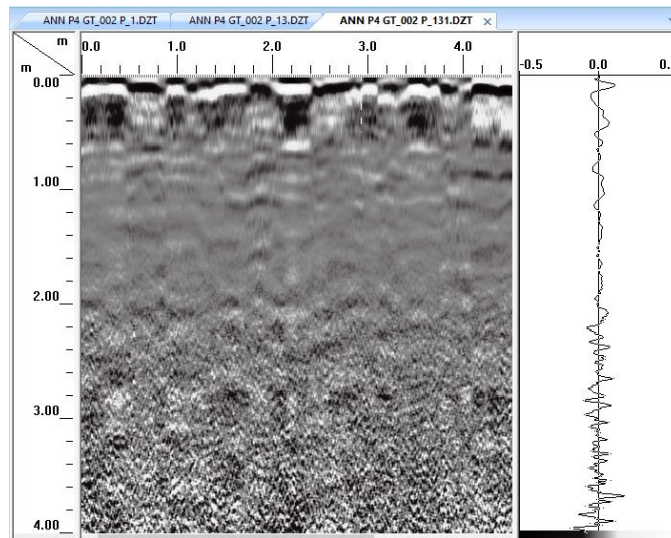


Figure 2-14 Deconvolution filter applied on GPR data

2.1.2 Ultrasound Acoustic Wave (UAW)

The sound waves cannot propagate through a vacuum contrariwise the electromagnetic waves. The sound wave required a medium of matter such as gas, fluid, or solid. UAW's physical principle is like the human voice, where the sound is generated, propagated with air, and then reflected from objects or detected by ears. The propagation of UAW occurs when the waves hit the medium particles that vibrated and transfer the vibration to the neighbor particle until facing any change in the physical characteristics of the medium, then the wave is either reflected,

refracted, distorted, or absorbed. Therefore, the UAW depends on the medium and objects' mechanical properties compared to GPR, which depends on the medium and object's electromagnetic properties. (Xu & Wei, 2019). UAW required a medium to transfer, where GPR could move in space. Therefore, UAW was expected to perform better in wet and saturated mediums, where GPR penetration is reduced with the high conductive medium. Thus, it is expected that the integration of UAW and GPR might represent a potential enhancement in near subsurface mapping. The following paragraphs illustrate the physical concept of UAW.

The UAW starts with a frequency that human ears cannot hear. However, since the human ears can detect the range from 1 to 20 KHz, the UAW range is 20 KHz to 50MHz. Therefore, the UAW can be classified into three main categories: low frequency 20-80 KHz, Medium Frequency 80-150 KHz, and High frequency 150- 2000 KHz. (Effendi, Wulandari, & Setiadi, 2019).

Despite the significant benefits of UAW in medical imaging and inspection, this technology was developed for concrete inspection in civil engineering. Moreover, as shown in Figure 2-15 this technology is booming in environmental aspects such as air cleaning, water and sewerage treatment, and soil remediation (Mason, 2007). In soil remediation, a high-frequency UAW was utilized to segregate oil and metal from the soil. Because UAW affects the adsorption process of hydrocarbons in soil and increases the chemical reaction too. (Effendi et al., 2019), (Sillanpaa, Pham, & Shrestha, 2011). The maximum depth of detecting rigid nonmetallic big objects using UAW in

farmland soil (clay soil) as mentioned in (Z. Zhao, Ma, & Luo, 2019) was 40 cm only.

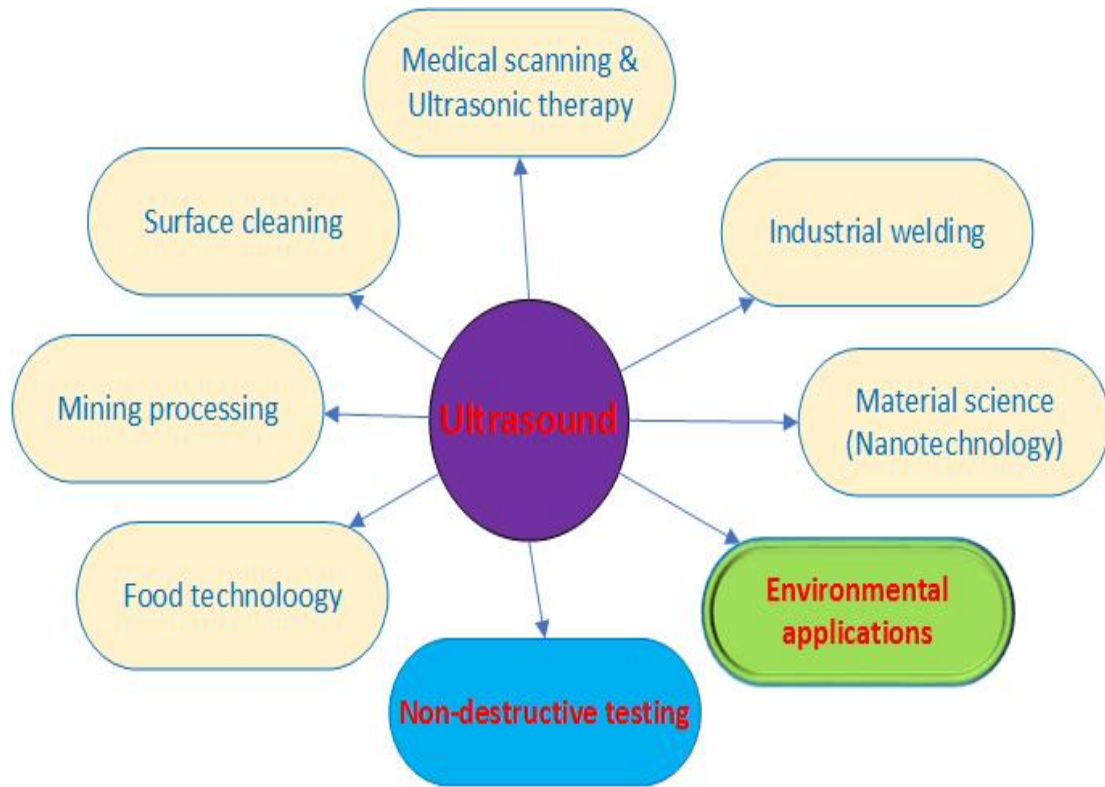


Figure 2-15 Different applications for Ultrasound waves in civilian industries

The sound speed can be derived from Wavelength and Frequency, but it does not depend on them. For example, changing the frequency will affect the wavelength, where the speed depends heavily on the medium's mechanical properties. (Henderson, 2020). The density (ρ) of the solids also represents main factor that affects the speed of sound waves (V) as shown in equation 2-12.

$$V = \sqrt{\frac{C_{ij}}{\rho}} \quad 2-12$$

Where C is the elastic constant. The elastic constant for longitudinal (compress wave) is different from that for shear wave (“Elastic Properties of Solids,” 2020) . Table (2-3) shows the definition of typical elastic constants and when they are often used.

Table (2-3) The Elastic Modulus types and use in Ultrasound waves
(“Elastic Properties of Solids,” 2020)

Constant	Definition	Used to calculate
Young Modulus (E)	A proportionality constant between uniaxial stress and strain	Longitudinal wave
Poisson’s Ratio (σ)	The ratio of radial strain to axial strain	Longitudinal wave
Bulk modulus (K)	A measure of the incompressibility of a body subjected to hydraulic pressure	Longitudinal Wave
Shear Modulus (G)	A measure of a substance’s resistance to shear is called Rigidity too. Its independent of moisture contents since the water has no shear modulus.	Shear Wave
Lame’s Constant (I and m)	A material constant that are derived from Young’s modulus and Poisson’s Ratio	Shear Wave

The Poisson ratio (μ) for concrete is usually used as 0.15, where it varies in soil depending on its properties, water contents, compaction, and other factors. On the other hand, the Young modulus or the elasticity modulus in concrete varies from 30 – 50 GPa, wherein soil is less than that. However, it varies depending on soil type from 2MPa to 5GPa (Bowles, 1996). Table (2-4) shows different values for Young Modulus and Poisson’s ratio for different soil types. For example, the range for (dry to wet loose) sand properties varies from 0.1 to 0.5 in Poisson’s ratio (Bowles, 1996) and from 0.2 MPa to 2.8 GPa in Elastic Modulus (Sarro & Ferreira, 2019). The significant ranges are due to stress history, water contents, and density.

Where the velocity of longitudinal wave (V_l) can be calculated using 2-13.

$$V_l = \sqrt{\frac{E(1-\sigma)}{2\rho(1+\sigma)(1-2\sigma)}} \quad 2-13$$

**Table (2-4) The values of Elastic Modulus of different types of soil
(Bowles, 1996)**

Type of soil	Young Modulus (MPa)	Poisson's Ratio
Clay very soft	2-15	0.1-0.3 Unsaturated 0.4-0.5 Saturated
Clay -medium	15-50	
Clay- hard	50-100	
Clay-sandy	25-250	0.2-0.3
Sand and gravel (loose)	50-150	-0.1-1.00
Sand and gravel (dense)	100-200	
Sand silty	5-20	(0.3-0.4) most common
Sand loose	10-25	
Sand Dense	50-81	
Silt	2-20	0.3-0.35
Shale	150-5000	

The elastic modulus values in the soil vary based on different literature in Table (2-5), representing updated values than Table (2-4). The Elastic Modulus value was obtained using ultrasound techniques denoted by EUS, and the value obtained using destructive testing was denoted by EST.

Table (2-5) Table of Elastic Modulus obtained by different Authors
(Sarro & Ferreira, 2019)

Author	Material	Elastic Modulus GPa
(Sarro & Ferreira, 2019) - E _{ST}	Sandy	1.25-2.5
Ferreira et al. - E _{US}	Sandy	1.66
Hoffmann & Goncalves (2010) - E _{US}	Sandy	1.14
Christ & Park (2009) - E _{US}	Silty	2.5
Milani (2008) - E _{US}	Sandy (soil-cement)	5.7
Wang et al. (2006) - E _{US}	Clayey	2.75
Champire et al. (2016) - E _{ST}	Sandy	1.2-2.8
Lombillo et al. (2014) - E _{ST}	Sandy	0.36
Bui et al. (2006) - E _{ST}	Sand-silt 2%-11% moist.	0.58-0.18
	Sand-clay 3%-8% moist.	0.95-0.39
Miccoli et al. (2014) - E _{ST}	Sandy	2.2

Due to the velocity differences in objects, then the longitudinal wave will be refracted with an angle similar to the incident angle. Simultaneously, some object particles will move in the transverse direction with a slower speed, which leads to converting part of these waves to shear waves. Some waves will also penetrate the new medium with new angles of longitudinal waves and shear waves, as shown in Figure 2-16 based on Snell's law equation 2-14. ("Ultrasonic Flaw Detection Tutorial," 2020), (Dubberke, 2012), and (Henderson, 2020).

$$\frac{\sin \theta_1}{v_{L1}} = \frac{\sin \theta_2}{v_{L2}} = \frac{\sin \theta_3}{v_{S1}} = \frac{\sin \theta_4}{v_{S2}} \quad \mathbf{2-14}$$

Figure 2-17 shows the relation between the incident angle and the type of sound wave. It could be noticed that the shear waves started from 30 to 60 degrees. If any defect (such as voids, cracks, or other objects) in the medium, the density, elastic modulus, and Poisson's ratio will differ from the intact medium. This defect makes

the wave refract, reflect, and diffract so that the wave will be attenuated. (Xu & Wei, 2019).

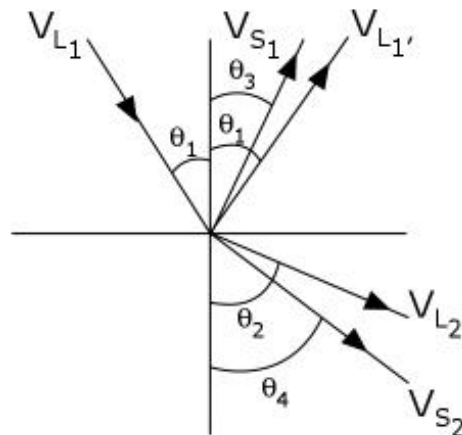


Figure 2-16 A diagram shows how the incident sound wave could be refracted or transmitted and converted to shear wave

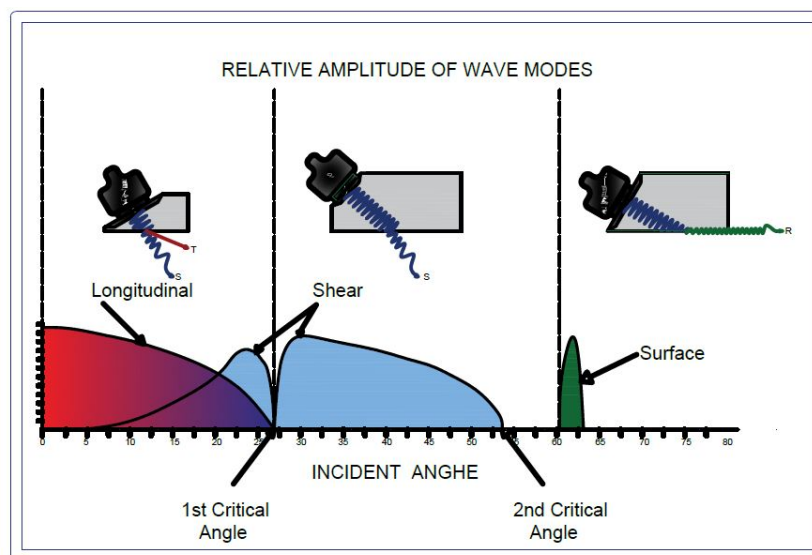


Figure 2-17 How the incident angle affect the type of velocity of sound wave

As the incident angle increased, the conversion from longitudinal to shear increased, and finally to a surface (Rayleigh wave) (“Ultrasonic Flaw Detection Tutorial,” 2020)

Using the velocity equations (2-12 and 2-13), the shear wave’s velocity ranges from 65 m/s to 225 m/s, where the longitudinal wave

ranges from 70 m/s to 1100 m/s in uncompacted sand. The literature mentioned that the velocity +

of shear waves ranges from 150 m/s to 800 m/s (Sarro & Ferreira, 2019).

Finally, the reflection coefficient of waves between two objects depends on the difference in the acoustic impedances (Z) between them, similar to the dielectric constant in GPR. This impedance is defined as material density multiplied by sound's velocity ($\text{Kg}/(\text{m}^2.\text{s})$). The amount of reflection amplitude could be obtained using equation 2-15. ("Ultrasonic Flaw Detection Tutorial," 2020), where the transmission coefficient could be obtained using equations 2-16 (Butler, 2005).

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2} \quad 2-15$$

$$T = \frac{2\sqrt{Z_1 * Z_2}}{Z_1 + Z_2} \quad 2-16$$

The previous relations are very important to understand the feature detection processes using UAW technologies.

2.1.3 Thermal Mapping

Thermal mapping is usually applied to surface mapping investigations, but some researchers tried to utilize this technology in subsurface inspections such as (AL-Qurishee, Wu, Atolagbe, El-Said, & Ghasemi, 2019; Bian et al., 2009; Okamotoa et al., 1997). This technology is generally known as InfraRed Thermography (IRT).

IRT helps detect industrial problems that are hard to detect by traditional inspection or other sounds or vibration techniques.

Especially in some electrical faults and moisture hazards (“Why use a thermal imager?,” 2019). As mentioned by (Hiasa, Birgul, & Catbas, 2016), the IRT: “has been developed to detect existing subsurface deteriorations, including delamination’s and voids in concrete.”

This technique represents an essential tool in civil engineering to detect subsurface features. However, this tool depends on several factors that should be considered while using thermal sensors. These factors, as mentioned by (Weil & Graf, 1991) are:

- 1- Solar Radiation: the data acquisition using this technique might be made during the highest and lowest solar radiation (daytime and night) to measure the heating and cooling of the ground surface by solar radiation.
- 2- Cloud Cover: the reflected infrared radiation by clouds reflects the heat transfer process to the sky. Therefore, the scanning using thermal sensors (from sky or space) should be performed when little or no cloud cover.
- 3- Ambient Temperatures: this factor affects the time window to assess the rapid heating and cooling for the ground surface. Therefore, the scanning should be done for a wide time window to detect the temperature variation due to subsurface features.
- 4- Wind Speed: the wind has a significant effect on cooling the ground surface. Therefore, the scanning should be done when the wind speed is less than 15 km/h.
- 5- Moisture on the ground: the moisture diffuses the surface heat and reduces the temperature differences due to subsurface anomalies. Thus, the scanning should not be performed when water or snow is accumulated on the surface.

To study the effect of changing the capturing angle of thermal images in civil engineering assessment (Hiasa et al., 2016), three different cameras with three different angles to detect delamination in concrete. They found that the perpendicular angle is less sensitive than other certain angles, and they found that the camera's sensitivity and accuracy affect the damage detection. (Heitger, 2006) in his research stated that more experiments were required to consider several factors affecting the detection of subsurface emitted heat such as wind speed, shape and size of subsurface object, an optimum time for inspection, the rate of heating and cooling of the surface and environs, and soil (host) condition. The results mentioned that they succeeded in monitoring the temperature for a few centimeters depth and expected to reach more than 1 meter if the previous factors were considered. In addition, a very sensitive camera was utilized.

One recent study (Janků, Cikrle, Grošek, Anton, & Stryk, 2019) used thermal cameras to enhance detecting and structure faults and assess the concrete structures. First, they used it as a guide to reduce the suspected error of testing. Although the thermal images will not provide any information about the depth, they will show the variation in concrete temperature caused by faults. Then they used a combination of GPR and Ultrasonic devices to inspect the structure and delineate the deterioration.

Despite the type of cameras and methodologies, most of the literature used thermal imagery in civil engineering mentioned that it would only be valid to detect lower than 10 cm. The maximum depth in thermal imagery was mentioned by (Okamoto & Liu, 1998) during

their study of 15-20 cm of radiation heat by the sun of the buried object (metal plates).

2.2 Literature Review

The subject of near subsurface mapping began taking attention in the seventeenth of the last century. The utilities locating problem represents the hottest topic for research to develop, enhance, and update the techniques for accurately finding the underground features in civil engineering. Several other issues and projects in subsurface mapping meet scientists, developers, and researchers' attention, such as geological investigations, bathymetric surveying, oil and gas, and several subjects.

The following paragraphs present some of the essential available publications related to this research topic. Starting with subsurface mapping sensors integration in civil engineering applications, then the NDT researched in soil characteristics and type of soil in Bahrain. In addition, the inspection of MSW using NDT, then subsurface mapping using Geographical Information Systems (GIS), and the Subsurface Utility Engineering (SUE). These topics are outlined due to their impact on the core of this research.

The first step to summarize the available technologies is to list some available techniques in one table literature. Table (2-6) summarizes these technologies, their advantages, drawbacks, and where mentioned in the literature. The following paragraphs outline several pieces of literature that utilized this project's techniques with other available technologies, starting with the GPR.

Table (2-6) Available methods for near subsurface mapping

Technique	Advantages	Disadvantages	References
Visual			
Visual inspection	• Most accurate for areas which can be seen	• Most of the utilities do not allow human access; • Slow; Subjective and good training required; • Only to be carried out in big and accessible pipe/sewer/tunnel; • Cannot see inside defects	(Hao, et al., 2012)
Electromagnetic (EM)			
Ground Penetrating Radar (GPR)	• Real-time assessment. • Can determine ground condition. • Trenchless inspection,	• A skilled operator is required. • The signal may be fully attenuated in a particular type of soil. • Modulation schemes can improve efficiency.	(Agrawal, George, & Prashant, 2015; Annan & Diamanti, 2016; Bianchini Ciampoli, Benedetto, Pajewski, Alani, & Tosti, 2016; Francese & Morelli, 2006; Hugenschmidt, 1998; Idi & Md. N. Kamarudin, 2011; Lester & Bernold, 2007; Moore & Grinstead, 2006; Thitimakorn, Kampananon, Jongjaiwanichkit, & Kupongsak, 2016)
Radio Frequency (FR)			
Vibro-acoustics	• Suitable for all types of pipes and cables.	• Geophones need to be half-buried; thus may not work for hard ground surfaces. • Bends in the pipework can pose problems for signal propagation. • Significant attenuation in certain types of soil.	(Muggleton & Rushtighi, 2013)
Infrared thermography (IRT)			
Infrared thermography technique	• Trenchless method	• Ground cover and wind speed can influence results. • It cannot measure depth.	(K. Al-Joburi, 2017; Choi, Kang, Park, Kim, & Kim, 2008; Hiasa et al., 2016; Péronnet et al., 2012)
Combined sensors			
Acoustic Fiber Optics (AFO), GPR	• Suitable for long term monitoring;	• Expensive; • Fibers are easy to break and difficult to repair	(Chen & Jeng, 2015; Dutta, Cohn, & Muggleton, 2013)
GPR with resistivity measurements device	• Real-time system	• Access to pipe required; hydrophone on the umbilical cable inside pipe needs to be traced on the surface of the ground in order to pinpoint leaks	(Arvidson & Torp, 2015)
GPR, Acoustic, Magnetic, and LFEF		• These sensors cannot combine together in one platform	(Royal et al., 2011)

The GPR technology was started more than 70 years ago, and the enhancement for collecting data using this technology represents a continuous work that did not stop. Most of the available publications for utilizing the GPR in civil engineering are in utility inspection. The research (Birken & Miller, 2002) provides an efficient large-scale mapping system for big areas using a multichannel GPR. The new system is called Ground Penetrating and Imaging Radar (GPIR). The system was tracked by laser theodolite to determine its location while scanning. Nowadays, the GPS could play this role after the revolution in data transfer and increasing the number of available satellites in space. Besides, the availability of highly accurate real-time GPS network systems. On the other hand, the designed system used multichannel ranging from 50 to 400 MHz, providing a penetration depth of up to 6m in average soil. The project's targeted depth was up to 3m in high organic soil. The system required a cart pulled by a vehicle. Therefore, this system could be selected for the national mapping system (roads scanner), but it will not be feasible for daily or small-scale projects.

The research of (Costello et al., 2007) assessed several available technologies for utility mapping. They stated that no single Non-Destructive Testing technique could locate subsurface features without errors (with 100% accuracy) or assess the conditions of the subsurface utilities. They mentioned that the trenchless techniques became vital to protect the subsurface assets. This report's main finding is a table listing the available technologies to find water and wastewater pipes (see Table (2-7)). Then, the table summarizes the technologies' capabilities and limitations. Finally, their report discussed and recommended some combinations between these devices. The report of (Young & Kennedy,

2015) for the second strategic highway program that published as a book also discusses the combination of GPR with other Time Domain Electromagnetic (TDEM) technologies, or with Electromagnetic Locator (EML) that work on the induction principle rather than reflection as in GPR and TDEM. The report mentioned that this combination would increase the accuracy of 3D mapping for subsurface utilities. In addition, the report recommends developing a decision support tool to select the appropriate combination of several technologies depending on the application and detecting objectives. This outcome represents an important step to be considered in this project.

**Table (2-7) Different locating technologies
(Applications and limitations) (Costello et al., 2007)**

	Technology	Applications and limitations
1	Magnetometers	It can only be used for targets containing iron
2	Electromagnetic line locators	- Can only detect metallic objects - This can be overcome using an in-pipe transmitter sonde or tracing wire. - Access to the pipe can be overcome for new installations if new non-metallic pipes have trace wire incorporated - Possible interference by other nearby metallic pipes - Unaffected by surrounding soil and table water
3	GPR	- Independent of pipeline material - Greater signal attenuation with conductive soil such as clay and saturated soils, reducing the depth of penetration - Cannot distinguish between the type of pipe (such as gas, water, or electricity.) - Requires highly skilled operators to interpret GPR outputs
4	Infrared thermography	- Affected by properties of the surrounding ground - Wind speed and ground cover influence results - Unable to measure the depth
5	Acoustic techniques	- It can be influenced by background noise such as traffic - No depth measurement is possible. - Needs access to the pipeline in active mode

The same problem was covered in more detail by (Uslu, Jung, & Sinha, 2016). The main target in this research was the water and wastewater subsurface utilities. The study determines the limitation of the available technologies and the recommendations to enhance the

investigation results to inspect and assess the mentioned targets (water and wastewater pipes). This research started from the direct inspection by exposing the natural ground to other NDT techniques such as those mentioned in the previous research and tables. The mentioned studies list the limitations and advantages of integrating several technologies to locate map subsurface features. That will be summarized at the end of this chapter.

After discussing the literature about sensors and their integration, herein briefing for some studies that discussed utilizing NDT sensors in investigating the major soil characteristics. For example, several studies listed the essential characteristics of soils and other host materials measured using GPR. Most of these results are obtained from (Davis & Annan, 1989). In addition, the researchers (Manonmani, Prabakaran, Vidhya, & Ramalingam, 2012) and (Wu & Huang, 2006) also list the electrical specification and constants for several soils. These results are accumulated in Table (2-8). However, there were no available studies for utilizing ultrasound waves in soil mapping.

The article (Thomas, Metje, Rogers, & Chapman, 2006) represents an important reference in stating the relation between frequency, soil properties, and penetrating depth in utility mapping. The article listed the important rule of thumb that **“the objects to be detected might be bigger than a quarter of the GPR signal’s wavelength.”** The research documents the difficulties facing the GPR interpretation, prediction of penetrating depth, and GPR resolution with the absence of laboratory inspection to determine the soil characteristics. The article recommends that the GPR interpreter fully understand soil types, especially when dealing with important utility mapping projects. Because the scattering

and attenuation in the two-way travel time depend on the soil characteristics and the used frequency. Thus, he must also fully understand the frequency range, multiplicity of pipes, road layers, and moisture content range if he needs complete certainty of interpretation. These outcomes will be utilized in planning and designing the experiment of this research.

Table (2-8) Typical Dielectric constant, conductivity, velocity, and attenuation
(For several materials observed at 100 MHz EM wave)
(Davis & Annan, 1989; Everett, 2013; Manonmani et al., 2012; Wu & Huang, 2006)

Material	Dielectric constant	Conductivity mS/m	Wave velocity m/ns	Attenuation dB/m
Air	1	0	0.3	0
Fresh Water	81	0.5	0.033	0.1
Distilled Water	80	0.01	0.033	0.002
Seawater	81	30.00	0.1	1000
Ice	3-4	0.01	0.16	0.01
Granite	4-6	0.01-1	0.13	0.01
Dry Salt	5-6	0.01-1	0.13	0.01-1
Baselt	8	10	0.11	
Limestone dry	4-8	0.5-2	0.12	0.04
Limestone wet	8	25	0.11	
Shale	5-15	1-100	0.09	1-100
Sandstone	6	40	0.12	
Sand dry	3-5	0.01	0.15	0.01
Sand wet	20-30	0.1-1	0.06	0.03
Loam dry	2.5	0.11	0.19	
Loam wet	19	21	0.07	
Silt	5-30	1-100	0.07	1-100
Clay	5-40	2-1000	0.06	1-300
Concrete	6-11		0.1	
Pitch	3-6		0.12	

On the other hand, the case study of this thesis is located in the Kingdom of Bahrain. Thus, it is essential to know about the available soil to be investigated and utilized in the experiment. Only two researches have been found (K. Al-Joburi, 2017; Bridges & Burnham, 1980). The oldest article (Bridges & Burnham, 1980) represents an important

reference for the type of soil in Bahrain and its effect on agriculture. The article mentioned that there are four main groups of soil in Bahrain:

- 1- Solonchaks: defined as the soil that have high salinity. This type includes loamy, sandy, and clay soil.
- 2- Regosols: defined as the sand that deposited by aeolian action (dunes sand)
- 3- Yermosols: Soils that occur under an aridic moisture regime. This type includes stone and gravel soil.
- 4- Fluvisols: contains the marine and Alluvial soils

The article of (K. Al-Joburi, 2017) represents the latest digital map for the soil of Bahrain. The produced map shows the historical Bahrain soil and the newly reclaimed areas. The resources of (K. Al-Joburi, 2017) were the historical hardcopies maps that have been digitized and georeferenced, the location of the borehole as points, and satellite imagery that was classified and used. The analysis of these previous data concluded several dumping solid waste locations in the sea and lowland areas.

This research on studying the MSW because it is vital to civil engineering and other disciplines. Most of the literature in this field usually utilizes geophysical techniques to detect illegal dumping sites or locate buried hazardous waste on a large scale. The utilized techniques are the Thermal Imagery, ERT, or magnetometric surveys as primary techniques, then use the GPR for delineating the subsurface feature objects. The research (Atekwana, Sauck, & Werkema, 2000) was conducted to investigate the efficiency of using a combination of 2D-resistivity mapping (from soil boreholes), GPR, EM tomography technique, besides geoelectrical surface measurements. The objective of this research was to investigate the effect an old water leakage in

subsurface layers. Their main finding related to this project was the efficiency of using the in-situ resistivity measurements combined with surface geoelectrical measurements, which can characterize conductive zones' distribution. This finding could help know the high conductive areas of higher GPR attenuation due to organic materials, minerals, and other highly conductive materials in the MSW. (Marchetti, Cafarella, Di Mauro, & Zirizzotti, 2002) studied the locating of steel waste drums using the magnetometric surveying methods and GPR. The research (Wu & Huang, 2006) utilized thermal cameras and GPR for finding buried hazardous waste. (Alile, Ighodalo, & Aigbogun, 2017) studied the effect of the illegal landfill sites on soil contamination using ERT and GPR. However, most of these studies were designed to locate the metal parts and objects, not the MSW components.

This research aims to enhance the mapping of subsurface features using the integrated NDT sensors. Therefore, the article (Al-ruzouq & Abueladas, 2013) represents an important study that combines the subsurface mapping techniques (GPR), Geological maps, and geomatics techniques (GIS and orthophoto). They produce a 3D subsurface map for documenting the archeological features in Al-Salt Castle. In addition, the updated GIS database shows a map for the castle, with potential caves and archeological subsurface features extracted from GPR profiles. On the other hand, the article (Li, Cai, & Kamat, 2015) combines mapping and uncertainty assessment. This article started by listing the most common sensors in utility mapping, but they selected the GPR for Geospatial Mapping. Then, the article presents an integration for GPS, GIS, and GPR to produce a 3D mapping for utility assets. The mapped model contains

not only the location of the assets. However, it enhanced to show the uncertainty of locating the asset too.

The book section (Kvamme, Ernenwein, & Menzer, 2019) discusses GIS's role in integrating different geophysical subsurface techniques. This reference shows that most of the previous methods in utilizing the GIS in mapping the geophysical data were dealt with listing raster data. Also, it listed several techniques used to digitize and locate the anomalies in the digital map. Starting from using the digital image processing techniques to find continuous anomalies in GPR data slices to integrate 2D satellite imagery or aerial photos with 2D geophysical maps. Finally, integrate 2D data and include the object's depth to form a 3D data set.

Finally, the SUE is the only available international procedures to assess the mapping certainty. SUE is an international standardization process adopted by geophysicists, civil and utility engineers to define the subsurface utilities collected information's potential risk and reliability. The SUE's first official start was in 1980 by the Virginia Department of Transportation (VDOT), then in 1989, it was adopted by the Federal Highway Administration (FHWA) (Jeong, Abraham, & Lew, 2004). Nowadays, SUE is considered and adopted in several countries and regions to manage utility assessment and mapping. An example of SUE standardization is the American Society of Engineering (ASCE) standards ASCE-38-02 that describe the four levels of quality and their meanings. A similar framework was adopted in Canada and Malaysia. The British Standards proposed PSA 128 standard to establish a framework for quality levels and data achievement. (Tabarro, Laval, & City, 2018)

SUE is to classify the acquired utility features according to the data acquisition method. By defining the level of accuracy, the site engineer

will know the degree of confidence in the drawings he deals with before he starts construction. The SUE categorizes the collected and mapped data according to their accuracy. SUE has four levels of accuracy. Level D represents the historical data, and as-built drawings usually have up to 25% accuracy. Level C category contains the topographical surveying for the surface utility markers and structures that will increase the accuracy up to 50%. The geophysical surveying and investigation techniques increase the detected feature's accuracy up to 80% and are categorized as Level B. Finally, the ground-truthing using borehole (either by destructive or NDT tools) and opening utility chambers will give the feature location up to 100% accuracy. Thus it is categorized as Level A. (A. Nashwan & Al-Joburi, 2021a).

The SUE levels were designed as an inverse proportion between the risk and cost, as shown in Figure 2-18. It was noticed that as the SUE level moved from D to A, the SUE cost increased the risk decreased. Therefore, the investment in SUE is a worthy and feasible investment that will be reflected in other shapes of saving in time and cost. The benefit of using SUE on highway projects was evaluated several times. It was noticed that the benefit to cost ratio for utilizing SUE increased with time, as shown in the report of FHWA that for each \$1 spent on SUE, the benefit will be \$4.62 (Leuderalbert, 1999). The analysis done by (Jung, 2012) shows that the benefit is \$11.39 for each \$1 spent on SUE.

SUE represents the only available standards for defining subsurface utility mapping accuracy of an existing map. The SUE advance workshop held in Hyderabad, India, in October 2018 represents an essential reference for this research (Rana & Swarup, 2018).

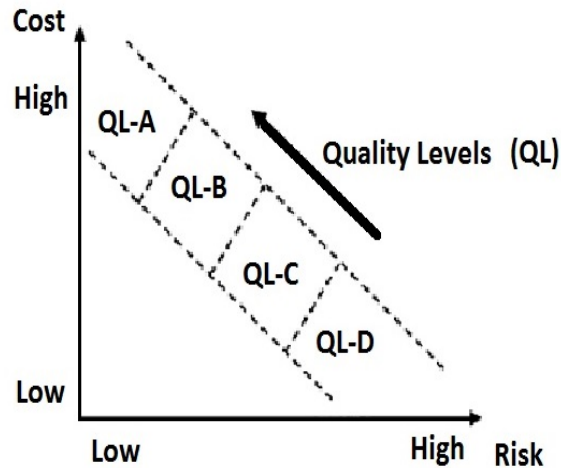


Figure 2-18 SUE Classes (quality levels)

2.3 Summary

The most significant conclusion from previous literature is that no standalone remote sensing technology can locate, delineate, and identify subsurface features within acceptable certainty. Besides, most subsurface technologies continue to face severe limitations in terms of accuracy, precision, and feature range that can be identified. However, integrating various techniques and technologies tends to be the future trend.

The majority of the available literature focuses on locating near subsurface utilities, and the available integrations and procedures are specifically for utility mapping. On the other hand, limited literature discusses the MSW mapping using any of the above-mentioned technologies. Moreover, the available studies dealt with industrial hazardous waste metal waste drums, not the regular MSW that contains a high percentage of organic materials.

In civil engineering, the research on voids detection depends mainly on integrating time-domain GPR with ERT or other geophysical methods.

However, the limitation of such methods is that they are designed for large scale and tend to have a low spatial resolution. Therefore, this research suggests integrating the high-frequency GPR to enhance the resolution of the inspection process.

The literature shows that the GPR (time and frequency domain) and ultrasound technologies were not used to map and identify the MSW. Voids mapping was only investigated for large areas, primarily for minerals exploration and concrete inspection. The ultrasound shear wave was not addressed in the literature of soil subsurface feature mapping. In addition that no previous literature was focused on studying the feature characteristics with the subsurface sensors.

Literature shows that soil and target properties (the conductivity, moisture contents, and dielectric permittivity) play a vital role in detecting the objects, penetration depth, and the frequency of used technologies. The following are the most extracted relation between these factors(Young & Kennedy, 2015):

- As the frequency increased, the resolution increased, and the penetration depth decreased.
- The detectable size of objects depends on the wavelength of the used technology. The wavelength changed as the host material's dielectric properties changed
- The frequency is fixed, so as the speed changes, the wavelength changes.

Several Aspects also was excluded from the literature were used as benchmarks in designing and revising the experiment:

- 1- The GPR waves cannot penetrate perfect conductors such as metal sheets or have shallow penetration in conducted hosts (seawater, clays).
- 2- The GPR antenna cannot identify objects near each other if the distance is closer than a third of wavelength (Ibrahim, Singh, & Khan, 2002).
- 3- The integration methods mentioned in (Kvamme, Ernenwein, & Menzer, 2019) represent the starting point of this research's mapping part.
- 4- No single or integrated technique is available to map subsurface voids for civil engineering purposes accurately.
- 5- Researchers, engineers, and environmentalists have not addressed mapping MSW on a small to medium scale. Large-scale landfill sites were located using traditional remote sensing techniques.
- 6- Although GPR technology matures, it does not provide satisfactory solutions for all utility mapping, especially in complex environments.
- 7- None of the aforementioned technologies and techniques are capable of identifying subsurface features. For example, GPR can locate utility pipes or subsurface linear features. However, it cannot identify whether they are steel, plastic, pottery, or concrete. In fact, this topic has not been addressed in any literature. However, identifying asbestos is very critical for environmental and health purposes.
- 8- Quantifying locating accuracy of subsurface features (MSW and voids) is still vague and not fully scientifically analyzed. Furthermore, error propagation was never addressed either.

9- It is essential and significant to mention that mapping subsurface utilities using SUE is relatively mature. However, there is no system (as yet) for mapping other subsurface features. This led to the development of such a system.

Finally, in addition to Table (2-6) that list some techniques from literature, Table (2-9) summarizes all found subsurface mapping technologies, concepts, applications, advantages, and limitations. This table might be used as a reference in selecting the sensors. This table was collected from several industrial sites, webinars, and workshops attended.

Therefore, the previous literature was used to produce a new prototype for integrating the available techniques to study the feature characteristics and facilitate feature detection procedures. This prototype required to design of an experiment to investigate the research hypothesis. The next chapter will discuss the research experiment's design to fill this knowledge gap.

Table (2-9) Summary of Geophysical methods
(Technology principle, application, advantages, and limitations)

Geophysical Method	Measured Parameter & Physical Property Model	General Application	Major Limitations	Major Advantages
Ground Penetrating Radar (GPR)	• Travel time & amplitude of EM waves • Record the reflected waves when the dielectric properties change. • Can detect both metallic & nonmetallic targets.	• Several investigations (geological and hydro-geological) such as mapping bedrock topography, water levels, solution features, soils and aggregates, and glacial structures. • Engineering investigations to evaluate dams, sea walls, tunnels, pavements, roadbeds, railway embankments, piles, bridge decks, river scour, buildings, and monuments. • Locating and evaluating buried structures, including utilities, foundations, reinforcing bars, cavities, tombs, archaeological artifacts, animal burrows, and underground storage tanks. • Subsurface mapping for cables, pipes, and other buried structures before trench-less operations.	• Penetration is limited by soil type & saturation conditions. • Performing the survey is necessary before the preparation of the site's cost. • Most GPR units are towed across the ground surface. • A topography and surrounding electromagnetic fields can quickly degrade the quality of the data.	• The data could be interpreted instantly in the field. • Can provide high-resolution data under favorable site conditions. • Very effective in sandy soils. • Allows subsurface site conditions quick evaluation. • Provide an excellent cross-sectional representation of the subsurface for several Applications.
Magnetic	• Measure the spatial variations in the strength of the earth's magnetic field. • Measures magnetic field strength units are gammass (1 gamma = 1 nanotesla = 0.00001 gauss).	• Profiling & mapping geological structures and detecting buried metal objects. • Can be used to detect voids, hazardous waste, and groundwater pollution.	• Only applicable in specific rock environs. • Very sensitive to cultural noise of metal features that degrade the data quality. • Unable to differentiate between various steel objects. • Cannot determine the content of buried features.	• Low costs. • Effective and time-saving in conducting the survey. • Requires minor site preparation. • Surveying requirements are not as strict compared with other methods.

Gravity	• The gravity method involves measuring the changes in the acceleration due to the earth's gravitational field. • These measurements are generally made on the earth's surface. • The variations in gravity depend upon lateral changes in the subsurface density in the measuring point's neighborhood.	• Location of buried ferromagnetic objects. • Archaeology • Mineral exploration • Geological mapping	• Each station must be precisely surveyed for elevation and latitude control. • Consumes cost and time to survey a large area. • The gravity data interpretation requires many computations.	• The gravity measurements are not sensitive to cultural noise. • Gravity readings can be taken virtually at any location, even indoors.
Electrical Resistivity (ER)	• ER methods measure the bulk resistivity of the subsurface. • ER measured in ohmmeters. • ER is a function of porosity, permeability, water saturation, and the concentration of dissolved solids in pore fluids within the subsurface. • The current in ER method is injected into the ground through surface electrodes. • ER is effectively used to get detailed information of deeper layers in sensitive areas.	• Soundings or profiling and mapping. • Can determine depth & thickness of geological layers. • Determine the underground water resources. • Bedrock quality and depth measurements • Mineral prospecting • Dam structure analysis • Landfill • Contamination source detection.	• The data quality degradation depends on site characteristics. • Requires a reasonably large area and far from cultural noise to investigate groundwater pollution sites. • Need more staff than some other geophysical techniques.	• Computer Software or Published Master Curves could be utilized to do quantitative modeling. • These models provide accurate depth estimation, thickness, and electrical subsurface layers resistivity.
Induced Potential (IP)	• IP measures the slow decay of voltage in the subsurface following the cessation of an excitation current pulse. • The IP is like electrical resistivity tomography (ERT), and it is used in mineral exploration. • In addition to resistivity, capacitive properties of subsurface materials are determined. • The IP method measures the bulk	• Determine electrically conductive targets such as clay content or metallic. • Polarization diff.& induced current Elect. Capacity model.	• More sensitive to cultural interference sources, • Requires more power, cost, and complexity in the data interpretation, • Requires two to three field crew (Labor-intensive). • Requires a large area, free from power lines and grounded metallic structures such as metal fences,	• It can be collected during an electrical resistivity survey, which improves the resolution of the Resistivity Data analysis. • It can be used to distinguish and investigate the geologic layers that respond weakly in ER surveys.

	electrical characteristics of the geologic unit, such as; Mineralogy, Geochemistry.		pipelines, and railway tracks	
Electromagnetic (EM)	• Measure bulk conductivity (the inverse of resistivity) Published modeling or computer modeling.	• Profiling, mapping, & sounding, • Very rapid measurement. • Detection of buried metallic objects. • Contaminant mapping • Mineral's exploration (ground and airborne) • Groundwater exploration	• Affected by cultural features. • Maximum depth is 150 FtdEM (Time domain) does not provide measurement shallower than 150 feet, • Conductive anomalies or lineation caused by lateral variability in the geology features can easily be misinterpreted as a contaminant plume.	• Usually, EM Equipment used in groundwater investigations are portable, rapid, and lightweight • Required low staff. • Capability to electronically store data, more accurate & • faster than Analog Instruments.
Very-Low Frequency (VLF) Electromagnetic (EM)	• Using the ratio of Horizontal-to Vertical Magnetic Field Curve matching or Simple numerical forward modeling In-phase and quadrature components.	• Profiling & mapping	• Affected by all electrical conductors (such as power lines, wires, fences, and pipes), unscheduled VLF transmitting stations shut down or maintenance, halting data collection.	• Effective to locate high conductive areas. • Can be used to locate, monitor, and treat wells. • Fast data collection • requires only one or two field staff.
Seismic Refraction	• The arrival of seismic waves with respect to time (voltage output versus time) Graphical or Computer models Precise determination of soil thickness • Precise determination of seismic velocities • Precise determination of water table in the overburden. • Localization and identification of geological units • Detailed analysis of soil. • Excellent accessibility to rough	• Profiling & mapping Bedrock profile, rock quality, and depth. • Thickness of overburden • Fractures and weak zones • Topography of groundwater • Rip-ability assessment in mines • Slope stability studies • Pipeline route studies	• Data collection can be labor-intensive. Sensitive to ground vibrations, considerable line lengths are needed. • Its success depends on the following conditions: • The increase of seismic velocities with depth increases the contrast between geological layers. • The geophones' geometry affects the refraction of waves and helps to study geologic layers. • Hidden layer & Blind Zone	• Study the subsurface features in the areas between boreholes or wells, which saves the drilling cost. • Map the thickness and depth to bedrock in buried areas • A differentiation between specific units with divergent seismic velocities (such as Shale and Granites). • Rapid ground coverage • The only option is rough remote terrains. • Provides a continuous profile

	terrain and remote regions.		anomalies.	of subsurface, critical for engineering projects.
Refraction Micro-tremor (ReMi)	• ReMi is based on evaluating Rayleigh waves that are generated by the active or passive source. • ReMi is a new seismic method with low cost and time in studying shear wave velocity. • The same geophones for refraction studies are used in testing the surface using the same vertical P-wave.	• ReMi can be used to obtain Vs. profiles for: • Earthquake site response • Liquefaction analysis • Mapping the subsurface material's strength. • Finding buried cultural features (e.g., dumps and pipes). • Offshore surveys to determine the depth to bedrock for harbor and pier extensions	• ReMi tests a larger volume of the subsurface compared to borehole measurements.	• ReMi can determine shear wave velocities between 40m and 100m depth.
Seismic Tomography	• is used to derive an image of seismic velocity between two or more boreholes by measuring travel time between source and receivers along various ray paths.	• The technique allows the determination of material property for each cell. • identification of features like fault zones and voids • Mapping of loose zones, sinkholes, anomalous zones in structures like dams • study of old foundations	•	•
Passive Seismic Tomography	• is a new revolutionary geophysical exploration technique that uses the natural seismicity (microearthquakes) as seismic sources and a portable seismological network as receivers to perform a detailed 3-D seismic velocity and Poisson ratio model of the upper few Km of the crust	• useful in complex geological and mountainous areas as it can provide information on hidden structures. • Both reconnaissance and detailed 3-D surveys can be provided. • Interpretations of velocity structure characteristics relative to oil/gas prospects are based on survey results integrated with other existing geologic and geophysical data. • The assessment of the 3-D variations of Poisson's ratio can indicate the	•	•

		presence of gas and fluids in sedimentary formations.		
Geophysical borehole methods	• Several borehole tools and technologies could be used for logging wells. • The same principles of surface geophysical methods are used in borehole methods. • The two most used borehole methods in the water well industry are Natural Gamma Ray and Resistivity Log	• It supplies an abundance of subsurface information like stratigraphy, hydrogeology, and contamination of groundwater. • It can sometimes be used to monitor the remediation of a site.	• Borehole Logging is expensive. • If subsurface conditions vary between wells, discrepancies must be qualitatively evaluated, and Logging tools must be used in uncased or un-grouted wells. • Specific logging tools require different borehole conditions, which must be considered when planning the investigation.	• Provide detailed information on stratigraphy and the engineering properties of subsurface soils and rock
Downhole Seismic	• Used in measuring the velocity of the seismic waves in the vertical distribution. • required only one borehole	• provide detailed information on stratigraphy and subsurface soils and rock engineering properties, such as Bulk Modulus, Young, Modulus, and Poisson Ratio.	• Downhole is a lower-resolution approach than Cross-hole.	• Provide information that cannot be achieved by surface seismic do. • Data analysis is relatively straightforward compared to a Cross-hole survey
Cross-hole Surveys	• Similar to Downhole, but required two boreholes • The velocity results could be used to evaluate lateral and vertical material properties. Such as continuity, deformation studies, and soil mechanical properties	• Provides accurate and essential information on soil and rock characteristics, such as the Poisson ratio and Young Modulus.	• Required drilling and excavating. • Expensive. Thus, it is used as phased two after surface geophysical survey.	• Very important to locate and evaluate manmade activities.
MASW (Multi-Channel Analysis of Surface Waves)	• MASW method makes use of the dispersion property of surface waves. • The data are collected through an array of geophones on the surface without the need for boreholes. • The technique uses geophones of 4.5 Hz frequency.	• Mainly used within geotechnical applications. All infrastructure projects require engineering properties of the material in the top 30m strata. • Soil bedrock mapping delineating interface of soil and bedrock. • Variation of speeds within soil/ rock.	• Maximum mapping depth 30 m	• No need for boreholes • Better in flat ground

	• 10kg hammer used as an active source. • Tests were carried out with a 2D profile. • The maximum depth of investigation (Z-max) is usually 10-30 m.	• Locating loose soil areas and soft clay areas. • Mapping voids • Used for evaluating elastic conditions of ground		
Induction Locator	• Active Methods: a signal that an external source has artificially generated. • Passive Method: Passive radio detection methods will provide an indication only that services are present underground. • The radio-detection method, coupled with GPR, provides excellent data on underground utility networks.	• Detection of Live Power Cables & Telecom cables	• Necessary experience to get accurate information. • Required to integrate with other techniques to get accurate and faster data acquisition.	• Easy • Cheap • Fast • Integrated with GPR and provide better results
Ultrasound Waves	• An active RS technology to detect the reflected wave vibration.	• Medical investigation. • Concrete and metal inspection • Voids	• Porosity is considered significant in this technique. • Low penetration depths.	• Accurate and fast. • High-resolution data.

Chapter 3: Methods and Procedures

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Chapter 3 Methods and Procedures

Based on the summary of previous chapters, this research suggests a new system for subsurface mapping and feature detection. The new system is called Integrated Subsurface Mapping System (ISMS). The main idea of this system is to guide the user to decide the best integration to detect targeted features. Besides, assist in producing 3D GIS compatible maps. The first step in designing this system is determining the subsurface feature interactions with sensors, host material, and other conditions. These interactions are called **Feature Characteristics**. The methodology to build this system is described in Figure 3-1. That includes five stages:

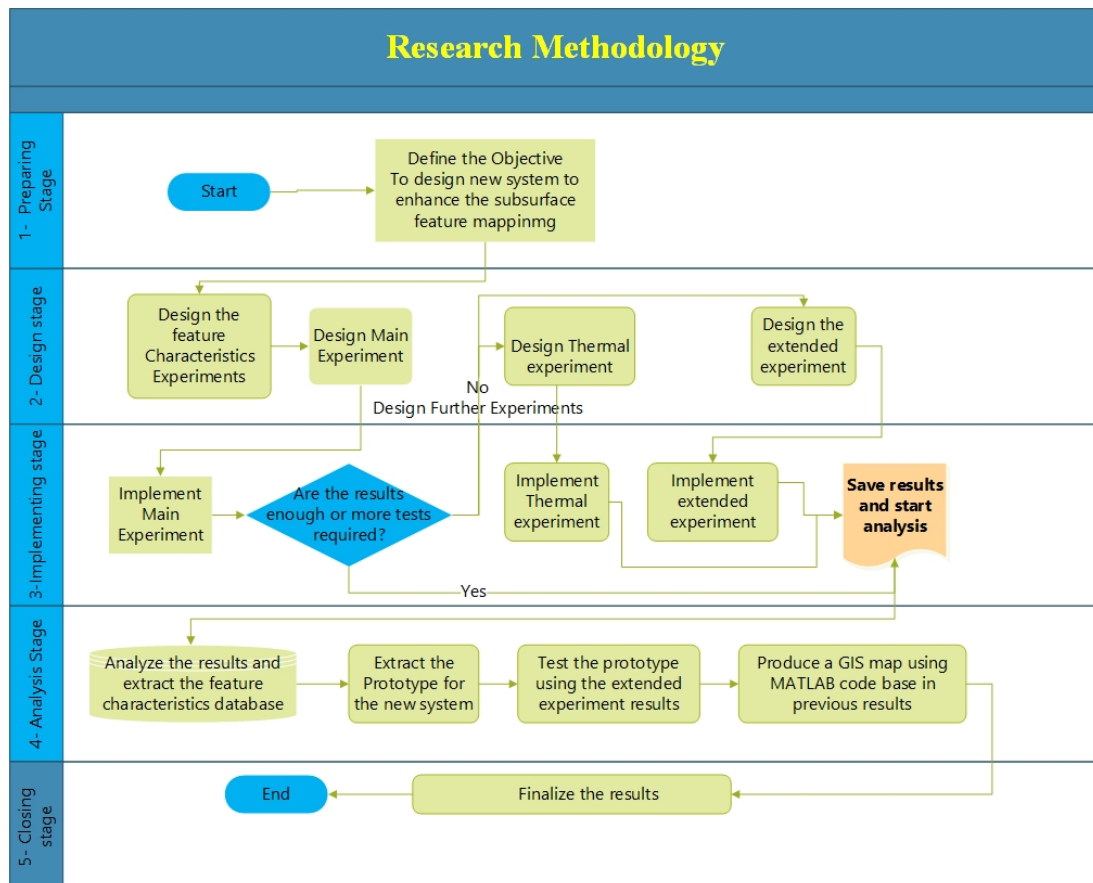


Figure 3-1 Research methodology

1. The preparing stage:- this stage includes collecting the available literature related to the research topics to ensure this research's contribution to knowledge. In addition, it includes defining the project objective that already stated as: to design and set a new system for subsurface mapping.
2. Design stage:- this stage contains the design of required experiments in this research. Starting from designing the main experiment that will be discussed in the next section. In addition, the advanced thermal experiment and the extended experiment. This stage includes the seven-step design plan to define the experiment parameters and boundary conditions.
3. Implementation stage:- this stage includes the implementation of the required experiments. It contains the following:
 - a. Select and prepare the host material to be used in the study area. The material used to fill the boxes (the host material) was dredged sand, loamy soil, and gravel soil (limestone).
 - b. Select and prepare the targeted features to be investigated. The targeted features for investigation were municipal waste materials, voids, and plastic materials.
 - c. Select and prepare the instruments for scanning the experiment area. The available devices were a Thermal Camera (digital camera with 0.01°C accuracy), GPR (frequency and time domain), and an Ultrasonic Acoustic Waves sensor. The justification for choosing these devices will be discussed later.
 - d. Start scanning, save the measurements files, and do the initial check for collected data. This stage is illustrated in section 3.3
4. Data Analysis Stage:- This stage includes:
 - a. Check the preliminary results if they are accepted or if the scanning needs to be repeated. The criteria for assessing the results are the

quality of data (noise level) and the success of grid scanning (each box might have 7 or 14 lines in each direction, as will be shown later). High noise or blur profiles and missing lines must be repeated.

- b. Delineate the analysis software and mapping package. GSSI RADAN7 software was used to analyze the GPR data collected by GSSI devices. Proceq GPR and ultrasound IPAD applications were used to collect and analyze the data collected by Proceq devices. MATLAB was used for image processing and extracting spatial data. Finally, the ArcMap –10.8.1 software was used for the mapping process.
 - c. Compare the results with the designed data.
 - d. Based on the results, the researcher will state the integration process algorithm. In addition to collecting and combining the found results to standardize the subsurface detection procedures.
5. Closing stage:- This is the final stage of the research and encompasses the design of a prototype for a new mapping system for subsurface features. Chapter six discusses the results, and the thesis conclusions and recommendations are stated in chapter seven.

3.1 Experiment Design

The experiment's design was accomplished according to the general seven steps design flow chart shown in Figure 3-2. These steps are illustrated as follows (Smith, 2021):

- 1- Question: What are the features characteristics during mapping with specific RS sensors?
- 2- Variables: Change, measure, and control.

The change (Independent) variable is the host material and its condition. The measurements (dependent) are the detection of MSW, Voids, and plastic. The controls are the RS sensors. The next subsections explain these variables and the justifications for selecting them.

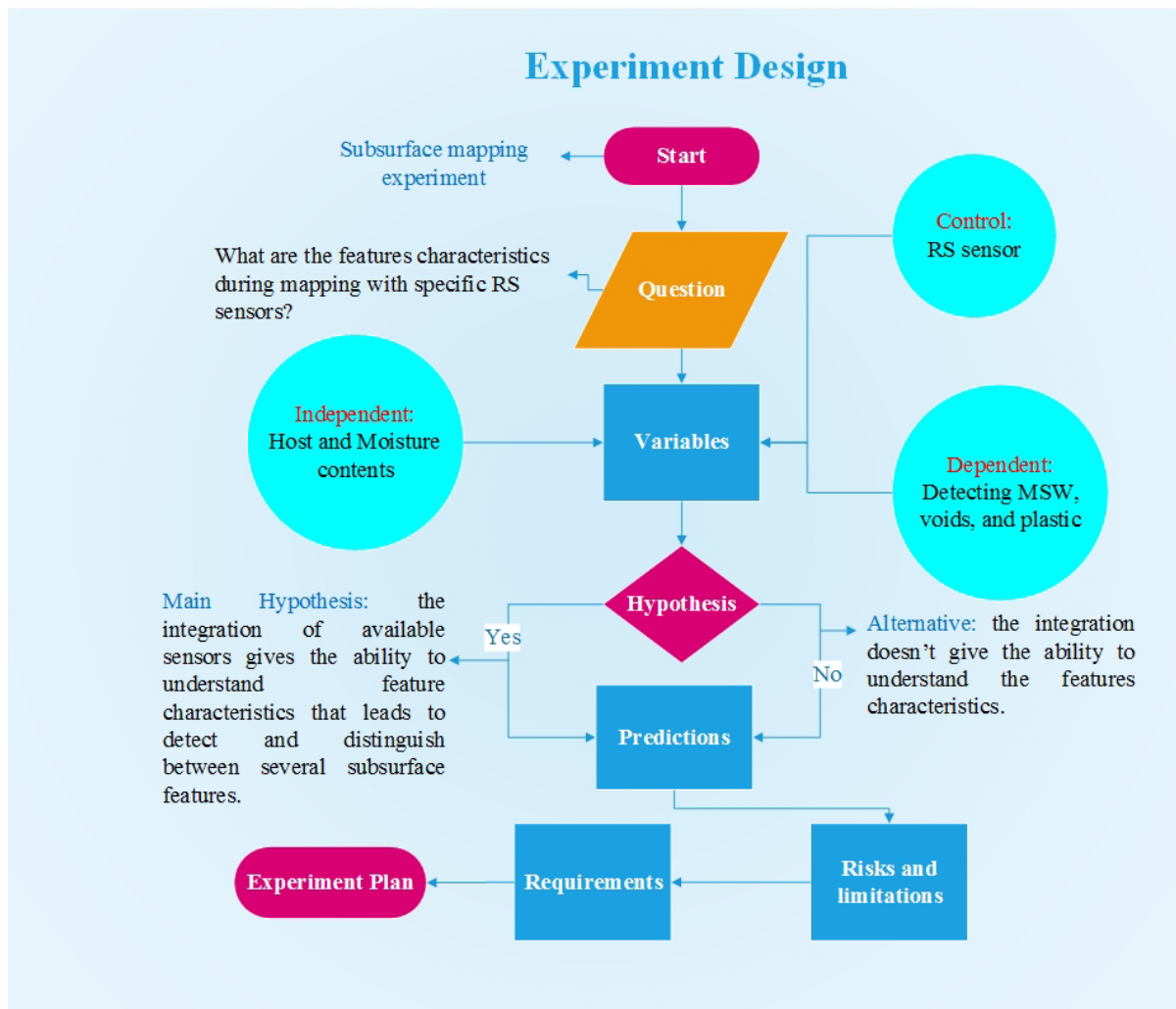


Figure 3-2 General layout for experiment design

- 3- Hypothesis: “the integration of available sensors gives the ability to understand feature characteristics that leads to detect and distinguish between several subsurface features.”

Alternative hypothesis: “the integration does not give the ability to understand the feature's characteristics.”

4- Predictions: the following are the main predictions (derived from previous literature and intensive training) expected and need to be considered in the design stage:

- The change in moisture contents in host material increases the ability to detect MSW in some sensors and decrease it in others and vice-versa.
- The change of host material type increases the detection of voids while not affecting plastic detection.
- The thermal part will be feasible only with MSW inspection. The IR thermography might not give any direct result for the subsurface objects, mostly those more than 15cm, but the combination of different conditions might provide some indicators.
- The GPR is the primary sensor expected to give results interpreted on-site or at the office.
- The combinations of all previous data will enhance the productivity of the GPR data.

5- Risks: In this experiment, there are several limitations, challenges, and risks. That might affect and interrupt the results, such as the noise on gathered data. Therefore, it is essential to know each RS sensor's noise factors and avoid these sources or plan to reduce or eliminate its effect.

6- Requirements: Several requirements and materials need to be prepared and collected to perform the experiment. This will be discussed in detail in the experiment plan.

7- Experiment Plan: This experiment plans to prepare 12 boxes 4 for each type of host material. The experimental boxes were numbered as per contents (host material and targeted object). The numbering and coding were as follows:

Box 01 SC: Sand control with steel angle box

Box 02 SW: Sand with MSW material box.

Box 03 SP: Sand with Plastic material box

Box 04 SV Sand with Voids box

Box 05 LC: Loamy soil control with steel angle box

Box 06 LW: Loamy soil with MSW material box

Box 07 LP: Loamy soil with Plastic material box

Box 08 LV: Loamy soil with Voids box

Box 09 GC: Gravel soil control with steel angle box

Box 10 GW: Gravel soil with MSW material box

Box 11 GP: Gravel soil with Plastic material box

Box 12 GV: Gravel soil with Voids box

The location of the control items and buried features were sketched using AutoCAD. The sketches show the box's top view, where the object's depths were typed on it. The layout of the 12 Boxes with their numbering depends on features and host materials, as shown in Figure 3-3. **Appendix C** contains the experiment's dimension details of all boxes in the three phases.

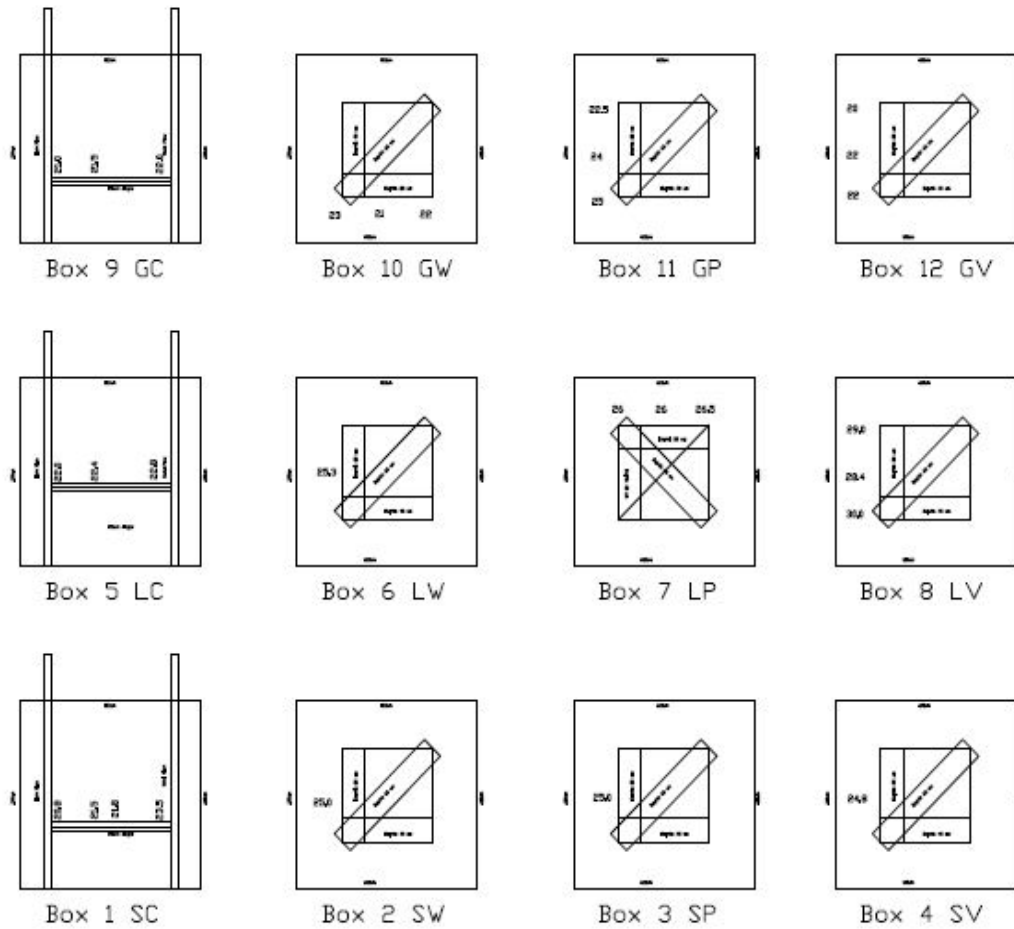


Figure 3-3 Phase one - layout of all boxes

The experiment is planned to be performed in three phases depending on moisture contents: Dry host (moisture contents 0-1), Saturated host: when the moisture content is 10, and wet host when the moisture content is less than 6. Each sensor will measure each phase twice (day and night). After completing the primary three phases, the data validity will be checked and analyzed to decide if any parts need to be repeated. After checking and analyzing all data, from the main three phases or any parts or phases being enhanced or repeated, the results will be listed, and the experiment's hypothesis will be examined and evaluated.

3.1.1 Dependent Variables

This experiment's main objective is to study mainly three subsurface features (dependent variables to be investigated): voids, plastic, and municipal waste. The justifications behind the selection of these variables are as follows:

- 1- Voids: This feature is a critical factor affecting the structure and infrastructure construction and could cause settlement, cracks, and deterioration in the constructed elements. Finding the void's locations before construction and maintenance results in future cost savings. These voids usually result from natural geological evolution or leakage in the surrounding material of water and sanitary services pipes.
- 2- Plastic material: plastic is a human-made material such as utility pipes or other plastic items. The risk of such existing materials will weaken the structure of the topsoil layer. When these plastic materials have been broken or compacted, a settlement on the top layer will start. On the other hand, the construction engineer should know the subsurface utility features' location before starting construction to prevent expected damage to these services. Plastic drinking water pipes mixed with asbestos also represent significant health, safety, and environmental hazard.
- 3- Municipal solid waste (MSW): the buried MSW is a critical factor that affects the construction process. Of particular relevance, the illegal MSW fills in the absence of viable and feasible MSW treatment processes (either filling, burning, or recycling). This absence leads the people to practice the illegal fill of their waste. These subsurface materials represent a hazard and dangerous factor to any structure over them in addition to environmental factors. These materials' softness and

chemical reactions will cause a deterioration of the structure on the top layer of MSW. More than 9,000 deteriorated houses in Bahrain are reported in the literature; MSW is founded in more than 50% of them. (K. I. Al-Joburi, 2018)

The accurate location of the previous features will reduce the impact risk through the construction process. However, the traditional methods to locate the subsurface features are classified either as destructive (such as trial holes) or nondestructive inspection (such as using the remote sensing technologies described in the previous chapter). Although the third object (MSW) is an essential factor, it was not considered in non-destructive testing researches. Therefore, it has been selected in this research.

3.1.2 Control Variables

The control variables are the sensors to be used. The GPR is selected as the primary tool in this research, as a result of being one of the most common non-destructive technology, especially in civil engineering and utility inspection. The initial finding was to delineate some factors that affect the GPR expected results, which are listed as follows:

- 1- The minimum position to start detecting objects: the object might be located at a 45-degree vertical angle from the scan's start.
- 2- The depth and size: both depend on the used frequency and wavelength.
- 3- Moisture contents: this factor is usually considered a limitation since it will decrease GPR signal penetration and increase the soil's dielectric properties. On the other hand, it might play a vital role in distinguishing between several objects, especially when the measurements were repeated on several moisture content conditions.

- 4- The dielectric constant of subsurface material is the most critical factor in detecting the type of objects and their correct locations. Therefore, the targeted features might be investigated on several hosted soils.
- 5- External noise from mobile devices: sometimes, mobile effects could be noticed, especially with the low-frequency GPR.
- 6- The existence of vertical surfaces such as wooden box edges has been found to add some extra unwanted noise to the measurements.

The previously listed factors might be considered a limitation, and some instances represent an essential factor in distinguishing between different objects. Nevertheless, the previous initial information represents the primary foundations for the experimental design procedures. Therefore, three different devices have been obtained, where each one represented a specific technology described as follows:

- 1- The utility GSSI: dual-frequency impulse GPR (300 & 800 MHz).
- 2- The concrete GSSI: impulse GPR (2700 MHz).
- 3- The concrete Proceq: live array stepped frequency GPR (200 – 4000 MHz). The calculated step is 50 MHz.

In addition to GPR, this experiment chose ultrasonic (acoustic wave) and thermal cameras as control variables. The justifications for using these sensors are their ability to be utilized in small-scale civil engineering projects and their availability.

3.1.3 Independent Variables

In this experiment, three types of soil (independent variables to be changed) were selected as a host medium. These soils were dredged sea sand (the most common soil for filling the utilities), loamy soil (the natural soil in the agricultural areas), and gravel soil (limestone filling material) used to fill in roads and building construction (as sub-base). (K. Al-Joburi,

2017). Figure 3-4 and Figure 3-5 show the washed dredged sand. These photos are for the host materials before filling in boxes.



Figure 3-4 Loamy soil to the right and gravel soil on the left



Figure 3-5 Washed dredged sand – Dry soil

3.1.4 Experimental Environment

After delineating the host material, the experiment's environment might be selected (where to lay the material in-ground or in-boxes).

Firstly, it has been noticed in some available literature that the GPR experiments were conducted in the laboratories using wooden boxes, such as (Eyuboglu, Mahdi, & Al-shukri, 2003; Rangaswamy, Lo Monte, & Wicks, 2016) and (Benedetto & Pajewski, 2015). Therefore, the wooden boxes were utilized in this experiment instead of burying them directly in the ground. Secondly, another material such as metal is rejected due to

their high attenuation for sensors signals. In addition, the third available option is to use glass boxes, the glass can transfeere heat from host to out side and vice versa. As a result, controlling external factors such as the shallow water table, temperature, humidity, depth, and target location will be easier in wooden boxes.

On the other hand, the concrete GPR devices were programmed to work on small areas (grid of 60X60 cm), where the maximum penetration depth is less than 80 cm in concrete (less in soil). Therefore, the wooden boxes were chosen because they are the most available resource. The boxes' size was then selected to be 120x120x80 cm (length, width, and depth, respectively) since the wooden sheets' width is 120cm, and the required grid 60X60 cm could be placed in the middle of the box. The 80cm depth is the maximum depth the available devices could inspect. A sample of these boxes is shown in Figure 3-6. The thickness of the wooden boxes was chosen based on the available waterproof wood (12mm thickness), which can survive in saturated sand and have enough strength to collect the host material. The scanning of each box was designed to be done twice (in the morning and at night, as mentioned previously) because the experiment will be implemented in the hot summer. Thus, besides getting redundancy in the measurements, the effect of temperature on data acquisition could be checked.



Figure 3-6 Sample of the used boxes

The experiment was divided into three phases to study the moisture content's effect on the observations. The first phase was to investigate the case of dry soils. The second phase was to examine moisture (saturated) soil 90-100%. Where the third phase represents the case of moderate moisture contents less than 50%. This moisture content will be measured using a moisture content meter (digital and analog) with a scale of 0-10.

The subsurface features (plastic, MSW, and voids) were fixed on three different depths 20 cm, 40 cm, and 60 cm. Each object was laid on linear shape with thickness 10-20 cm, oriented on the perpendicular, parallel, and oblique (45 degrees) direction according to the X-axis, for the mentioned depths 20, 40, and 60 cm, respectively. The scanning is designed to be in the two directions of the grid. The grid contains 14 lines 7 in each direction with a spacing of 10 cm between lines. The line numbering is accumulated in nature. Starting from lines 1 to 7 in the Y-direction, then from lines 8 to 14 in the X-direction as shown in Figure 3-7. GSSI Structure-Scan device works with a grid containing 26 lines, 13 lines in each direction with a spacing of 5cm. Starting from lines 1 to 13 in the X-direction, then from lines 14 to 26 in the Y-direction. Scanning in two directions is related to the finding that the “parallel to the pipes scanning gives the best accuracy and the strongest penetration power.” (Hashim, Wei, & Marghany, 2010). Besides, producing a grid that could be used to get a 3D data model.

The experiment was designed to be conducted in an open area, not in a lab, to simulate the measured variable's actual condition. In addition, because most of the soils are in an open space, it will also get more reliable and trusted results during the ground-truthing at the end.

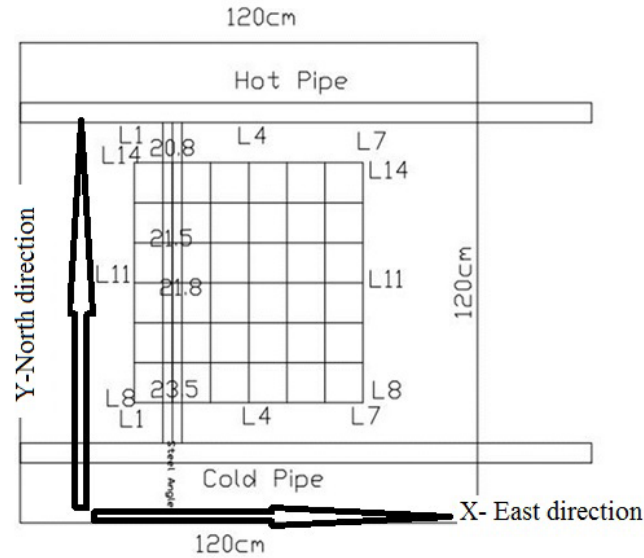


Figure 3-7 Two direction scanning

For the thermal camera to ensure the same coverage of each picture, a special frame was manufactured to provide a fixed snapshot height and resolution for area dimensions of 17cm *17cm and height of 25cm, as shown in Figure 3-8. The specifications of the thermal camera and the calibration of sensors will be listed in the implementation stage.

Figure 3-8 Using the thermal camera and a special frame

3.2 Perform the Experiment

The plan procedures shown in Figure 3-9 were followed to perform the experiment. The experiment was performed in three phases depending on the moisture condition.

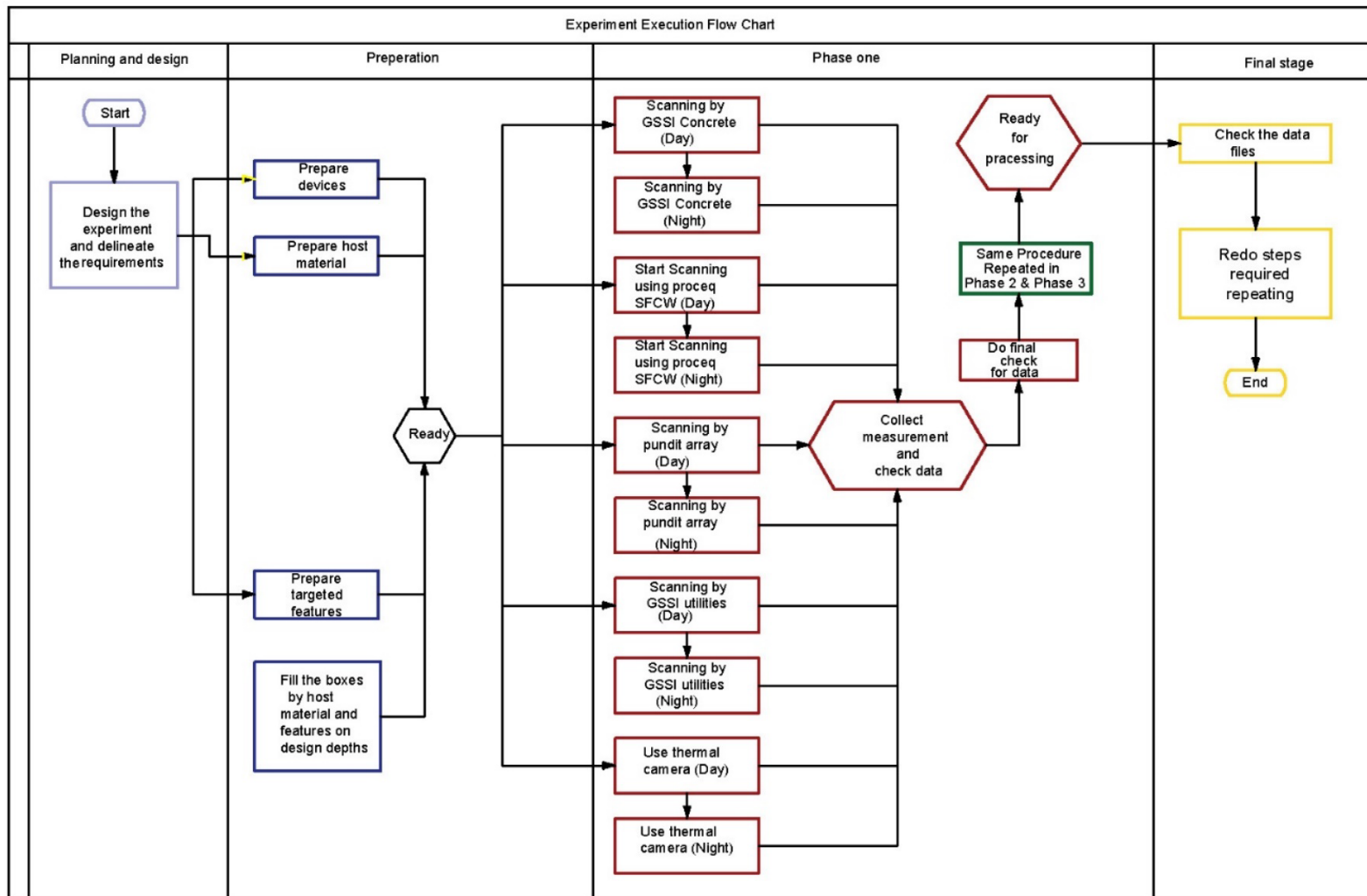


Figure 3-9 Flowchart for experiment's performing procedure

The first phase represents dry soil condition, the second phase is saturated soil, and the wet soil is the third phase. The performing starts by applying the mentioned items in the experiment plan mentioned in the previous section.

Each phase was started by scanning control boxes to calibrate the devices with each type of host material, and the scanning procedures in the three phases are the same. The initial scanning in each phase is performed on the control boxes to calibrate the used sensors. The calibration of used devices are:

1- IR Thermography camera:

The user must know the target's emissivity (0.01-1.0) to calibrate the device. This value was founded by manually measuring the target's temperature using a direct method; then, the emissivity value was changed until the thermal camera achieved the correct temperature. The calibration results for the material host were found as follows:

i- Dry material:

- a. Sand emissivity is: 0.95
- b. Loamy soil emissivity is: 0.96
- c. Gravel soil emissivity is: 0.97

ii- Wet Material emissivity: 0.93

iii- The saturated soil emissivity is 0.90

The previous values were compared with the given values on the camera manual, and they are close to it.

Finally, two pipes were added: hot water and cold water in each type of host soil (in the control boxes) at different depths to check how the thermal camera could detect the temperature change.

2- GPR – Multi-antenna (Proceq stepped frequency and GSSI time-domain sensors):

To calibrate all GPR devices, a steel angle (5cm width) was fixed in the control boxes at a specific depth to find the correct dielectric properties for each GPR type since the dielectric constant is changed with different frequencies. In addition to using the two plastic Polyvinyl chloride (PVC) pipes for extra calibration and verifications. Expert in the industry used this procedure to calibrate GPR and Ultrasound. (Bigman, 2019; Rana, 2020)

3- Pundit Array – Ultrasonic – Proceq

The calibration tools were the same as the mentioned tools and procedure in the GPR devices, except the calibration is to find the wave velocity instead of soil properties.

An essential issue for calibration and measuring was noticed during the training and preparation of the experimental tools. This issue was that some devices inspection were unable or unfit to measure and inspect the soil directly because they were designed for concrete. In addition, There was a potential risk that these devices might be broken or destroyed by small sand particles such as the sand stuck in Proceq and GSSI concrete GPR wheels. Therefore, an external thin frame or plate must be used during the measurements. Therefore, after listing and trying several mediums, a PVC plate was chosen for this task. The suggested mediums were the paper and wood rejected due to high noise results with ultrasonic waves device. Steel plates were rejected due to high reflectivity with GPR. The PVC sheet is a plastic material that provides penetration by all devices. Using PVC with all devices avoided bias in testing and doing all measurements in a typical environment.

The scanning for the three phases was performed in the same order, and the following subsection discusses the scanning and calibrating results for each sensor, as mentioned in **Figure 3-9**.

3.2.1 Scanning with GSSI Structure-Scan

The device specifications and general information are shown in Table (3-1). The first scanning session with this device started on the 6th of August 2019 at night time and was repeated on the 7th August 2019 morning time. All boxes were scanned with a 60*60 cm grid area with 5 cm spacing. Additional lines scanned along lines 16, 20, 26 (2,4,7 on other devices), and line 7 (11) and the two pipes (hot and cold). The additional lines were used to determine the dielectric constant for the host materials and verify the calibration. The results of this calibration are shown in Table (3-2).

Table (3-1) Specification of GSSI Concrete GPR

Device model	Structurscan Mini XT
Serial Number	0235
Controller Type	Internal touch screen
Operating Software	Internal Software
Technology	Pulsed Radar – Time-Domain
Central Frequency	2700 MHz
Maximum Depth	60 cm
Designed Application	Concrete inspection
Supplier	GSSI Distributer – Behbehani Brothers
Supplying Type	Borrowed for academic purposes (several times)
Grid spacing	5 cm
Grid Dimension	60*60 cm
Availability in Bahrain	Hiring and purchasing
Outputs	RADAN files - DZT & BZX

Table (3-2) Dielectric constant founded by calibration GSSI Structural

	Phase 1	Phase 2	Phase 3
Sand	4.0	25*	4.5
Loamy	4.0	26*	20*
Gravel	3.75	27*	5.0

The star (*) means that the values were extracted from the literature review because the calibration cannot be performed.

As mentioned earlier, the numbering and spacing of the grid are different from other devices. There were 26 lines in this grid (13 lines in each direction) with a spacing of 5 cm between lines, as shown in Figure 3-10. The device was operated by internal software, where the post-processing was done with RADAN 7 software. The device photo is shown in Figure 3-11.

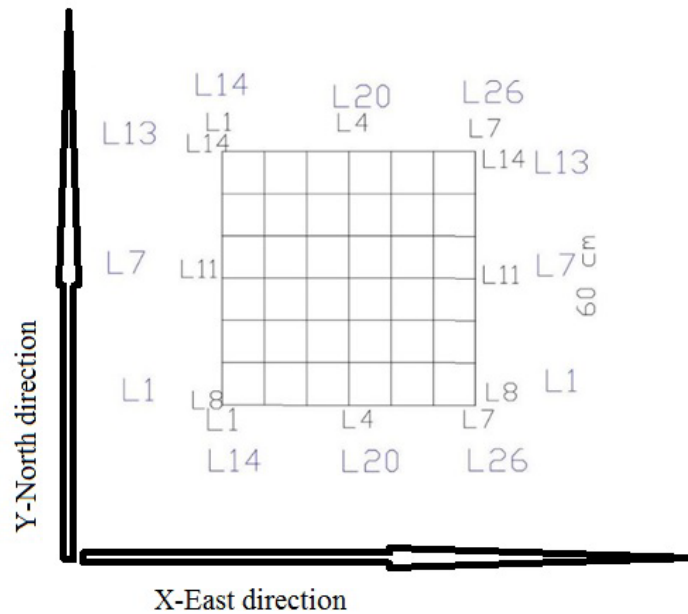


Figure 3-10 The distribution of scanning grid lines

The 14 lines grid (7 in each direction) and the 26 lines grid (13 in each direction)



Figure 3-11 GSSI Structscan mini GPR (time domain pulse radar)

Figure 3-12 shows a sample of the data collected by this device. It represents the same scan in Figure 3-14 (Proceq). The Dielectric in this image is 4.0. the parabolic shape is there but not clear as in the Proceq device. Also, it could be noticed that the area below 40 cm contains noise (weak responses).

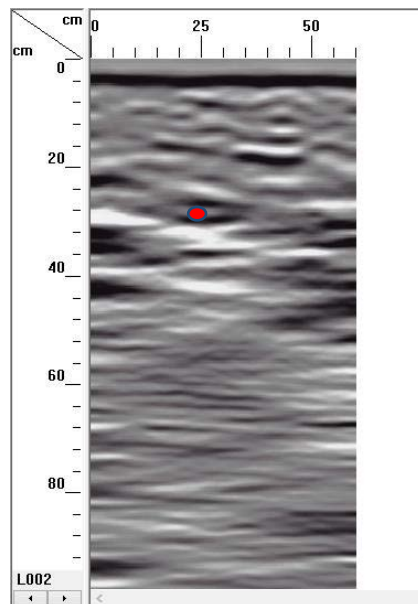


Figure 3-12 Sample of GSSI structural scan collected on Box 1, Phase 1, Line 2, and K=4

3.2.2 Scanning with Stepped Frequency GPR (SFCW)

The device specifications and general information are as shown in Table (3-3).

Table (3-3) Specification of Proceq Concrete GPR

Device model	Proceq GP8000
Serial Number	PM08-001-0085
Controller Type	iPad Air 2 – 10 inches
Operating Software	GP – Proceq GPR live
Technology	Stepped Frequency Continuous Wave
Frequency Range	200 MHz – 4000 MHz
Step size (bandwidth)	50 MHz
Designed Application	Concrete inspection
Supplier	Proceq Middle East Office
Supplying Type	Rental for academic purposes (one time only)
Date Collected	28 th July 2019
Date Returned	05 th October 2019
Availability in Bahrain	Not available
Outputs	URL, segy files, HTML, and images (snapshots)

All boxes were scanned with a 60*60 cm grid area with a spacing of 10 cm. Additional lines scanned along lines 2, 4, 7, and 11 and the two pipes (hot and cold) in the control boxes as shown in Figure 3-13. The extra lines were used to determine the dielectric constant for the host materials and verify the calibration. The results of this calibration are shown in Table (3-4).

Table (3-4) Dielectric constant founded by calibration of Proceq GPR

	Phase 1	Phase 2	Phase 3
Sand	2.8	>20	4.0
Loamy	4.0	>20	>20
Gravel	3.8	>20	4.8

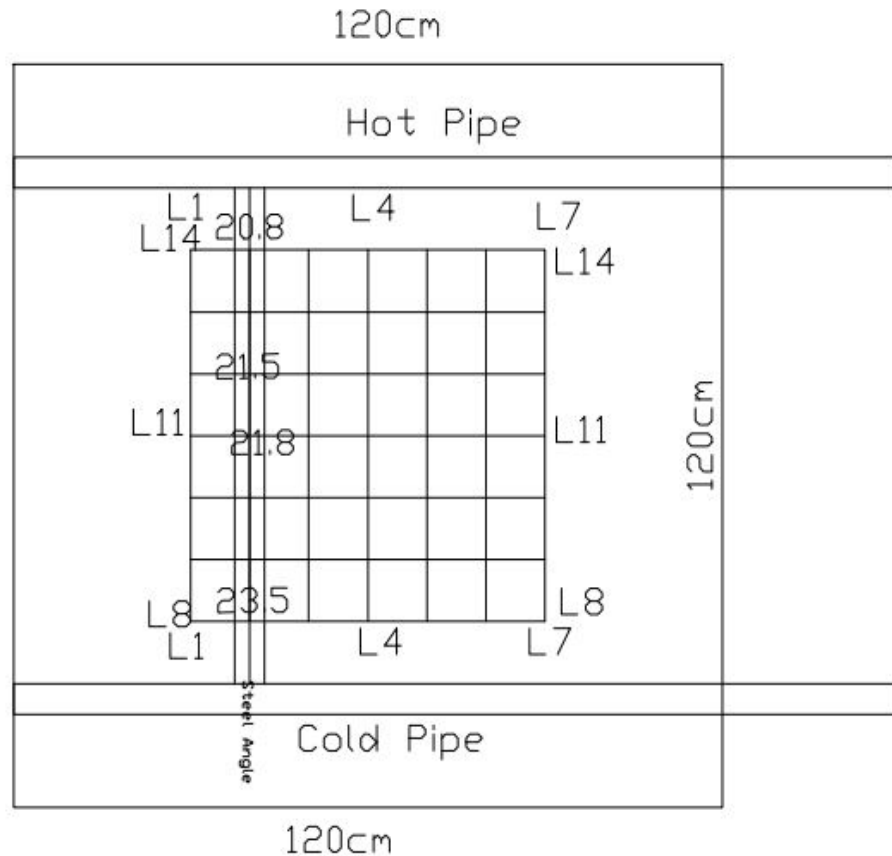


Figure 3-13 Lines and metal feature in box1 at phase 1

This device was operated and controlled by an Apple -IPAD Air 2- via Wi-Fi communication technique. Unfortunately, this device does not deal with materials with a dielectric constant of more than 20. The controller allows calibration for dielectric properties using the fitting parabola process to find the correct depth and fitting of a parabolic shape in the B-scan profile image or enter it manually. Figure 3-14

represents a sample of the data collected by this device and shows the calibration result for Box1 that contains a metal angle. The metal angles appeared as a three-parabolic shape in black-white-black tones. The new dielectric constant was set using the fitting parabola by changing the dielectric value or the parabola edges in yellow.

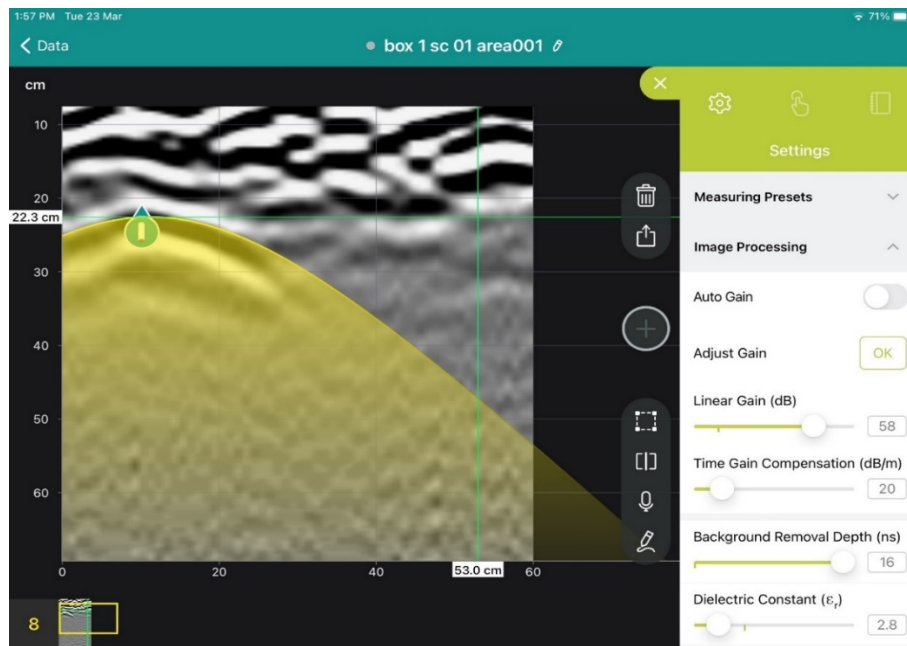


Figure 3-14 Sample of calibrating Proceq GPR data using fitting parabola.

3.2.3 Scanning with Proceq Pundit Array (USW)

This device is working on ultrasound shear waves technology. The speed of sound waves is too slow in the soil. It was designed for concrete inspection. The device is susceptible and requires a rigid surface to push the sensors inside and work properly. Therefore, using the PVC sheets with this device was the right choice. The device specifications and general information are shown in Table (3-5). The device dimension scanning was 10*27 cm. Thus, all boxes were scanned with a 60*60 cm grid area with 10 cm spacing. Additional lines scanned along lines 2, 4, 7, line 11, and the two pipes(hot and

cold). The additional lines were used to determine the wave's velocity in the host materials. The calibration results of these are shown in

Table (3-6). The device and the PVC sheet are shown in Figure 3-15. Like the calibration in GPR devices, the calibration was done using the control boxes manually. Started by determining the location of a known feature in the profile, then set the value of its correct depth, the device recalculates and sets the waves' speed, as shown in Figure 3-16. Figure 3-17 shows a sample of the data collected by this device.

Table (3-5) Specification of Proceq Ultrasound waves concrete scanner (Pundit Array)

Device model	Proceq Pundit Array
Serial Number	PE05-002-0004
Controller Type	iPad Air 2 – 10 inches
Operating Software	PT – Proceq Pundit array
Technology	Ultrasound – Waves
Minimum Speed	500 m/s
Maximum Depth	80 cm
Designed Application	Concrete inspection
Supplier	Proceq – Middleast Office UAE
Supplying Type	Hired for academic purposes (several times)
Availablity in Bahrain	Not Available
Outputs	URL, CSV files, HTML, and images (snapshots)

Table (3-6) Ultrasound shear waves speed (m/s) founded by calibration of Proceq Pundit Array

	Phase 1	Phase 2	Phase 3
Sand	650	560	600
Loamy	700	600	625
Gravel	700	620	650



Figure 3-15 Proceq ultrasound (Pundit Array) during data acquisition



Figure 3-16 Setting the depth of a feature to calibrate Pundit Array data

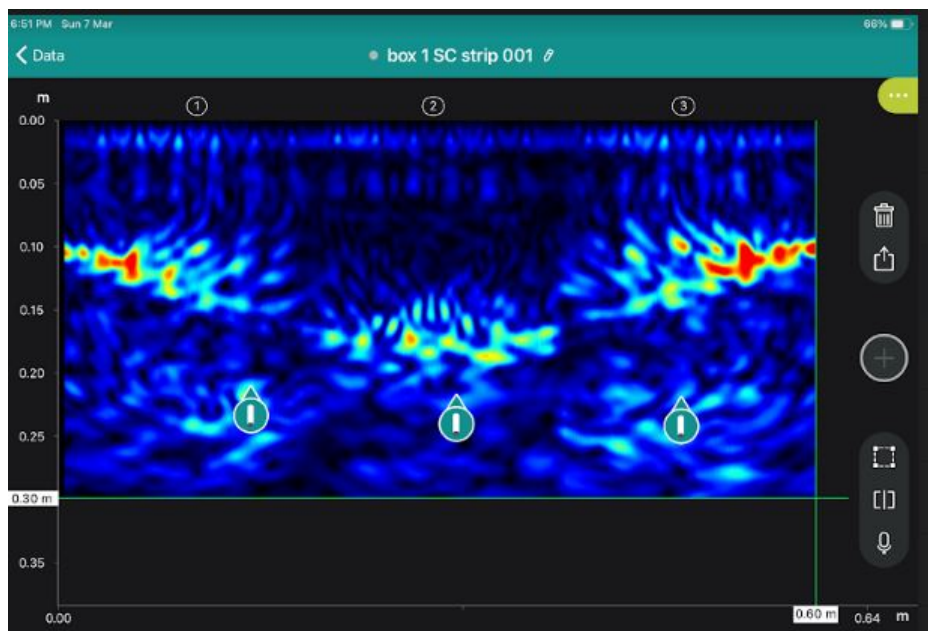


**Figure 3-17 Sample data of Proceq ultrasound (Pundit Array)
(For Phase 1, Box1, Line 2)**

3.2.4 Scanning with GSSI Dual-Frequency

The device specifications and general information were as shown in Table (3-7). All boxes were scanned with a 60*60 cm grid area with 10 cm spacing. Additional lines scanned along lines 2, 4, 7, line 11, and the two pipes (hot and cold). The additional lines were used to determine the dielectric constant for the host materials and verify the calibration. The results of this calibration are shown in Table (3-8). The numbering and spacing of grading were the same as the Proceq devices. There were seven lines in each direction. The device was operated by GSSI software using Panasonic tablets working on the windows operating system. The device is shown in Figure 3-18.

Table (3-7) Specification of GSSI Utility Scan Dual Frequency GPR

Device model	GSSI Utility Scan DF
Serial Number	FZ-G1 0432
Controller Type	Panasonic Professional Controller tablet (10")
Operating Software	GSSI Utility scan
Technology	Pulsed Radar – Time-Domain – Dual frequency
Central Frequency	300 MHz & 800 MHz
Minimum Depth	20 cm
Designed Application	Utility inspection
Supplier	GSSI Distributer – Behbehani Brothers
Supplying Type	Borrowed for academic purposes (several times)
Grid design	Post processing
Availability in Bahrain	Hiring and purchasing
Outputs	RADAN files - DZT & BZX

Table (3-8) Dielectric constant founded by calibration of Proceq GPR

	Phase 1	Phase 2	Phase 3
Sand	5	25*	6
Loamy	6.5	26*	22*
Gravel	6	27*	7

The star (*) means that the values were extracted from the literature review because the calibration cannot be performed.



Figure 3-18 GSSI Utility scan – time pulsed dual-frequency GPR

Figure 3-19 and Figure 3-20 show samples of the data collected by this device. The data was extracted after two post-processing steps stretching and background removal. The background removal is a filter applied to remove the horizontal line representing the device's default noise. The stretching was applied because the default horizontal scale in the Dual Frequency (DF) profile is greater than the vertical. So the original image was narrow. The stretching was applied to compare these data and other devices. It could be noticed in Figure 3-19 and Figure 3-20 that the maximum depth of medium frequency (800 MHz) is similar or a little more than depth in higher frequency (2700 MHz). The difference is because the dielectric constant K for this frequency is greater than the high frequency. In contrast, the maximum depth in the

profile for low frequency is more than medium because both used the same K value. In addition, it could be noticed that the images are a blur (due to rescaling), and both images have a coarse resolution.

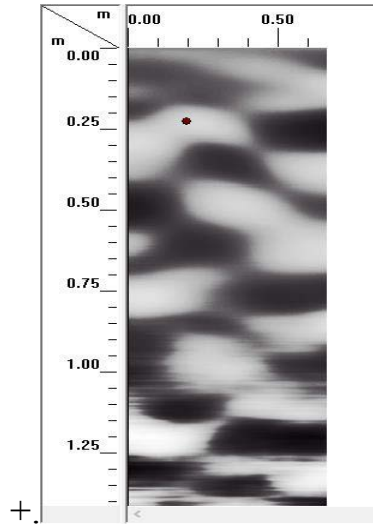


**Figure 3-19 Sample data of GSSI Utility DF – Band $f= 300$ MHz
(For Phase 1, Box1, Line 8, $K= 5$)**

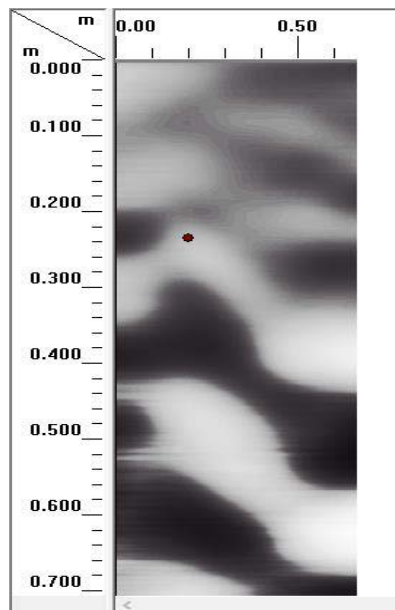


**Figure 3-20 Sample data of GSSI Utility DF – Band $f= 800$ MHz
(For Phase 1, Box1, Line 8, and $K=5$)**

3.2.5 Using Thermal Camera

The device specifications and general information are listed in Table (3-9). The emissivity of the targeted object must be set in the camera to get accurate measurements. An object's emissivity depends on several factors, such as moisture content, roughness, dielectric properties, and other factors (Calla & Deka, 2000). For example, soil emissivity ranges from 0.90 to 0.99 (Engineering ToolBox, 2003), but it differs according to the soil condition (wet or dry). Also, the emissivity varies with surface and weather temperature.

Table (3-9) Specifications of Thermal Imaging Camera

Thermal Camera Model	Hti – HT-04
Serial Number	X001T7C9X5
Resolution (pixel)	220*160
Total Pixels	35200
Sensitivity	0.07 °C
Wavelength range	8-14 Mm
Measuring Accuracy	±2.5 °C
Emissivity	0.1-1.0
Outputs	JPEG

The easiest way to calibrate and find the emissivity was by measuring the soil temperature using an accurate manual or digital temperature meter. Then, the emissivity value was changed in the camera until the correct temperature was achieved. The start values for checking were extracted from the device manual. These values were 0.90 for sand (0.92-0.96) for water, and the default camera value was 0.95. The result of this calibration is summarized in Table (3-10).

The data was collected on a 60 * 60 cm grid, containing four images in the X direction and four in the Y direction (total 16 images). The size of each image is approximately 17cm*17cm. There was an

overlap between images to ensure full coverage for the entire area. In addition, a strip of photos was collected over each pipe (hot and cold) in the control boxes. The objective of this scanning was to find and assess the relationship between temperature and depth changes.

Table (3-10) Emissivity values for different types of soil

Type of material	Emissivity
Dry sand	0.95
Dry gravel soil	0.97
Dry loamy soil	0.96
Saturated soil	0.90
Wet soil	0.93

The filename of the digital thermal photo represents the image's date and time. Manual procedure using windows explorer is required to adjust the name of these files if required. Thus, the pictures and other instruments files were exported and registered daily. As with any other field and experimental work, the field's notes had recorded in a separate field book. As mentioned in chapter two, the thermal images cannot provide direct or detailed information about small-scale near subsurface materials. However, it might still indicate changing surface temperature related to specific subsurface material, such as steel, MSW, and water, if the area was scanned several times (day and night). (AL-Qurishee et al., 2019; Gade & Moeslund, 2014)

Figure 3-21 shows a sample of the photos captured by this camera for the exact location. It could be noticed that there is a difference of 10 degrees between the two photos. In addition, the highest and lowest temperature points are not the same, which means that this is not reflected in the subsurface temperature. The weather temperature is

shown on the left corner of the image. The soil surface was measured using a soil thermometer with an accuracy of up to 1 degree. It gives almost the same temperature.

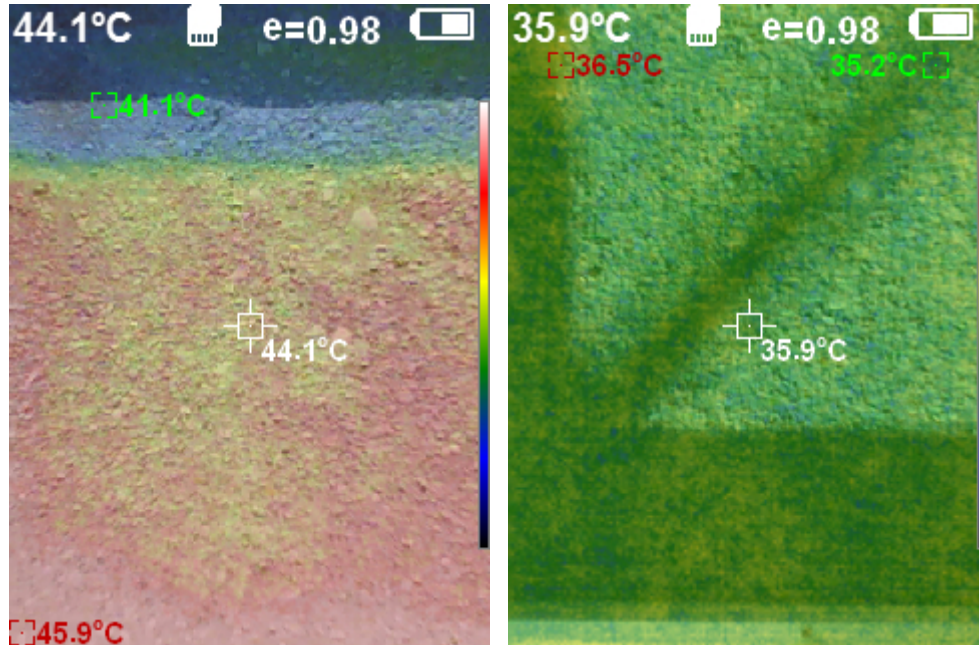


Figure 3-21 Sample of the photos captured by the thermal camera for the same location

(Left photo captured during day time, right photo captured during night)

3.3 Summary

The experiment summary was performed based on seven steps experimental design to achieve the following goals:

- To develop an integrated approach for mapping subsurface features.
- To explore the potential of using GPR for mapping the subsurface voids, plastic, and MSW materials.
- To explore the potential of using InfraRed Thermography (IRT) for mapping the subsurface voids, plastic, and MSW materials.

- To explore the potential of using Ultrasonic technology (Bundit device) for mapping the subsurface voids, plastic, and MSW materials.

This chapter discussed the experimental design and implementation. The next chapter will discuss the initial results, repeating the advanced thermal experiment, performing the extended experiment (ground-truthing), data analysis, and evaluating the hypothesis of the designed experiment.

Chapter 4: Data Analysis and Feature Characteristics

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Chapter 4 Data Analysis and Feature Characteristics

After finishing the experiment's design and implementation as described in Chapter Three, the experiment's initial results and data were assessed. As a result, it was found sufficient, and some scan lines were repeated. Therefore, the following sections will discuss data evaluation and analysis. Besides, illustrating the thermal experiment. Then, the enhanced experiment (ground-truthing) will be discussed in section 4.3. After that, section 4.4 summarized the results and listed the proposed feature characteristics.

4.1 Data Evaluation & Analysis

Upon completing the three phases of the experiment, an evaluation process was conducted to assess the gathered data, detected objects, and the need for repeating. The analysis stage started after completing phase three and finished data checking and storing. The data analysis was done using different software, as shown in Table (4-1).

GPR Slice is the only recommended software to analyze SEG Y files and GSSI files efficiently. Unfortunately, This software was unavailable at The University of Bahrain and did not have any representatives in the region. Since the available RADAN7 version does not support 3D mapping, then all data has been analyzed in the 2D profile mode (B-Scan mode). The files were revised manually one by one, and the designed location of the targeted object was marked manually on these files. Finally, all files were exported as JPEG or PNG images by the software or the tablet's snapshot option. The locating and mapping of these locations will be illustrated in detail in the next section.

Table (4-1) Used Software for data analysis

Technology	Software	Data format	capabilities	Limitations
The Stepped frequency GPR	Proceq GPR Application	URL , HTML, SEGYP* file	1D, 2D, and 3D data visualization. Parabolic fitting.	Limited exporting features And Import only Proceq data
Acoustic Ultrasound - Pundit Array	Proceq Pundit Application	URL or raw data (CSV file)	1D, 2D, and 3D data visualization.	Limited exporting features
Concrete Pulse GPR	GSSI – RADAN 7 – Road scanner version	Export data as image, .dxf, .shp, .kml, or .csv files.	Can open segy files	The options are limited to the available model. Road scanner does not support 3D analysis
Utilities Pulse GPR				
Thermal Images	Digital image viewer	.jpg file		

*SEGYP file or SGYP: a seismic data format file designed by the Society of Exploration Geophysicists. Initially, it was set for seismic data, but it was feasible to represent the GPR data.

The initial designed concept of data analysis was to find the effect of combining and integrating several technologies. The main goal was finding the best combination of technologies to increase each targeted object's inspection accuracy. In other words, to find the feature characteristics for each item with each technology. Although, this goal was not ultimately achieved in this experiment. The following challenges and their solution should enhance the outcome for feature characteristics determination that will be discussed later:

- 1- The initial results showed that the collected thermal images were unhelpful. The hot weather was an obvious obstacle with this technology, where the changes in temperature between night and daytime were more than 10 degrees. This difference means that the thermal camera will not provide any evidence or indicator that the

temperature changes are related to subsurface materials. Therefore, this part was repeated in a controlled environment to find the relation between subsurface objects' depth and surface temperature. The repeated process will be illustrated later in subsection 4.1.1.

- 2- The primary experiment was designed on a limited area, making the low and medium GPR frequencies unfeasible. As a result, the extending experiment was repeated to utilize these bands. In addition, to do the ground-truthing too.
- 3- There is no available software that can open and manipulate all collected data. The diversity of software and output represents a challenge for data integration. Thus, the manual integration using programmed code is the solution. MATLAB code to open the different raster outputs and convert them to vector 3D spatial database is the solution to this challenge. The code and the outputs will be discussed in chapter five.

The second issue in evaluating the measurement that could be considered the first step in data analysis is delineating the dielectric properties and ultrasound waves' speed in each soil type. These two factors were essential to achieving the objects' accurate depth in each testing box. The control boxes were used to find the most precise value for the mentioned factors since they contain pipes and a steel bar (controlled features). The steel bar has very high dielectric properties and moderate reflectiveness with sound waves. The bar's location was used to calibrate the instruments, delineate the value of dielectric properties and the acoustic wave's speed. The penetration depth (the signal floor) for each device was also estimated. The calibration results from Table (3-2), Table

(3-4), and Table (3-8), and the penetration depths were listed in Table (4-2).

Table (4-2) The measuring devices' calibration results
Including the signal floor in each type of soil in the three phases (Dry, saturated, and wet)

Type of soil and phase	Dielectric in GSSI concrete	Dielectric in Proceq	Dielectric in GSSI Utilities	Signal Floor in GSSI concrete (cm)	Signal floor in Proceq (cm)	Signal floor in GSSI utilities (cm)
Phase 1 -Sand	4.0	2.8	5	48	35	70/>80
Phase 1 -Loamy	4.0	4.0	6.5	35	25	65/>80
Phase 1 -Gravel	3.75	3.8	6	38	40	70/>80
Phase 2 -Sand	25*	20*	25*	20	12	25/50**
Phase 2 -Loamy	26*	20*	26*	18	10	25/50**
Phase 2 -Gravel	27*	20*	27*	19	15	25/50**
Phase 3 -Sand	4.5	4.0	6	40	35	>80
Phase 3 -Loamy	20*	20*	22*	35	15	>80
Phase 3 -Gravel	5.0	4.8	7	60	35	>80

*: Assumed value

** : The first values are for channel 1 (800 MHz)/Channel 2 (300 MHz) respectively

Table (4-2) data's first conclusion is that the loamy soil has the lowest penetration depth among the three host materials in all phases. Because this host contains silt, organic material and has the highest dielectric constant. The second notice was that the signal floor in the saturated phase is less than 20 cm in all host material (using the high-frequency device), which means no object could be detected in this phase. Because all targeted objects were laid below 20 cm. Also, there was a high noise using the time domain device.

Besides the penetration depth, An essential aspect of GPR pulsed devices was the minimum depth to detect an object (the blind zone). This depth must be greater than half the central frequency wavelength. Also, the smallest object's size can be detected (quarter the wavelength of central frequency). (Utsi, 2017; Y. Zhao, Wu, Wang, & Wan, 2001). The initial

insensitivity area or (the blind zone) depends on the antenna frequency and host material dielectric properties. Therefore, equation 4-1 was applied for each dielectric constant with the concerned frequency to calculate this thickness of the blind zone. Lastly, all the previous values were calculated and listed Table (4-3).

$$\text{Blind zone} = \frac{\lambda}{2} = \frac{c}{2 * f * \sqrt{\epsilon}} \quad \text{Equation 4-1}$$

Table (4-3) Calculated wavelengths, blind zones, and the smallest object to be detected for each frequency with the host dielectric constant.

Frequency (GHz)	Dielectric constant (ε)	Velocity = c /sqrt (ε) (nm/s)	Wavelength = v/f (m)	Blind zone (m)	Smallest object size (m)
0.3	5	0.134	0.447	0.224	0.112
0.3	6	0.122	0.408	0.204	0.102
0.3	6.5	0.118	0.392	0.196	0.098
0.3	7	0.113	0.378	0.189	0.094
0.3	22	0.064	0.213	0.107	0.053
0.3	25	0.060	0.200	0.100	0.050
0.3	26	0.059	0.196	0.098	0.049
0.3	27	0.058	0.192	0.096	0.048
0.8	5	0.134	0.168	0.084	0.042
0.8	6	0.122	0.153	0.077	0.038
0.8	6.5	0.118	0.147	0.074	0.037
0.8	7	0.113	0.142	0.071	0.035
0.8	22	0.064	0.080	0.040	0.020
0.8	25	0.060	0.075	0.038	0.019
0.8	26	0.059	0.074	0.037	0.018
0.8	27	0.058	0.072	0.036	0.018
0.8	25	0.060	0.075	0.038	0.019
2.7	3.1	0.170	0.063	0.032	0.016
2.7	4	0.150	0.056	0.028	0.014
2.7	4.5	0.141	0.052	0.026	0.013
2.7	25	0.060	0.022	0.011	0.006
2.7	27	0.058	0.021	0.011	0.005
2.7	4.5	0.141	0.052	0.026	0.013
2.7	20	0.067	0.025	0.012	0.006
2.7	5	0.134	0.050	0.025	0.012

The most significant value of the last column in Table (4-3) was 11 cm. Therefore, all targeted objects have more than 10 cm in width from the design stage. Also, they were below 20 cm in depth (to avoid the blind zone). The signal floor (the maximum penetrating depth) in Table (4-2) shows that all phases cannot detect the targeted objects in a loamy soil. Also cannot be detected in any soil of phase two because the signal floor was shallower than the targeted objects. Table (4-4) summarizes all findings from collected data and previous tables.

Table (4-4) Summary results for the inspection of the targeted features in several soils using both GSSI concrete & utility and Proceq GPR

	P 1 GSSI concrete	P 2 GSSI concrete	P 3 GSSI concrete	P 1 GSSI utility	P 2 GSSI utility	P 3 GSSI utility	P 1 Proceq	P 2 Proceq	P 3 Proceq
MSW in sand	ND	NA	ND	ND	NA	ND	ND	NA	WD - Detected
MSW in loamy	ND	NA	ND	ND	NA	NA	ND	NA	NA
MSW in gravel	Detected	NA	Detected	ND	NA	ND	Detected	NA	Detected
Plastic in sand	WD	NA	WD	ND	NA	ND	ND	NA	Detected
Plastic in loamy	WD	NA	ND	ND	NA	ND	ND	NA	NA
Plastic in gravel	WD	NA	WD	WD	NA	NA	Detected	NA	WD - Detected
Void in sand	ND	NA	WD	ND	NA	ND	ND	NA	WD
Void in loamy	ND	NA	ND	ND	NA	NA	ND	NA	NA
Void in gravel	Detected	NA	WD	WD	NA	ND	Detected	NA	Detected

* NA= Not Applicable, ND = Not detected, WD =Weak detection, P 1, 2 or 3 = Phase one, two, or three

In phase one, the gravel soil was the only soil that showed some signals at the targeted features' depth. The gravel soil could then be considered the best host to detect MSW and voids using the time-domain impulsed GPR (High frequency). On the other hand, the frequency domain device was better to detect all features in the gravel host material. Phase

two represented a blind host using all GPR devices with low penetration depth due to high dielectric constants. As a result, the signal floor was shallow than the targeted object. The only thing that was noticed was noise. Phase three (moderate moisture contents) showed better detection for some objects than phase one in gravel and sand.

The first object is MSW, which could not be detected in the three phases of sandy soil. There is no distinctive difference in dielectric constant between the MSW and the dredged sand using impulse and stepped frequency GPR. Also, the MSW was undetected in the loamy soil due to the presence of organic material in this soil, which was a common characteristic with the main contents of MSW. The plastic is weakly detected in phase one because the dielectric properties of soil are close to dry soils, which leads to a lower distinguish likelihood. Besides, the high noise from vertical objects (box sides) using the high-frequency impulse GPR (GSSI). Also, the SFCW GPR (Proceq) has better achievement in detecting the plastic in the sand and weak detection in gravel in phase three. The last targeted object was the voids that have been detected in gravel using both GSSI structural scan and Proceq GPR devices in phases 1 and 3. Nevertheless, it was not detected in sand using impulse GPR (high frequency). However, the SFCW GPR (Proceq) shows some signals in the depth of the voids in the sand.

On the other hand, finding the proper ultrasound pulse wave speed for each soil medium is necessary. This issue will be similar to the finding of dielectric properties in GPR data analysis. Unfortunately, the software supported with this device (the mobile application to collect, store, process, and manipulate the Pundit Array data) cannot show the results with a speed of less than 500 m/s. The ultrasound shear wave speed in soil

usually ranges from 150 to 800 m/s, as mentioned by (Sarro & Ferreira, 2019), and it is less than 300m/s in the sand, loamy, and gravel soils shown by (Oelze, Brien, & Darmody, 2000). Therefore, it was considered useless in soil investigation. Also, the device was unable to take any measurements on soft surfaces. Thus, a PVC sheet was used to increase the average velocity in the medium and provide a hard surface to push the pins inside the device and take measurements. This procedure successfully gave an average speed of more than 500m/s in all available soils. The attained speed results in the three phases are listed in Table (3-6). Based on the speed of shear waves in Table (3-6), the subsurface objects were examined, and the results of these visual and manual image inspections were summarized in Table (4-5). It could be noticed that the ultrasound technology using the PUNDIT Array device performs better than GPR with saturated soil, which will represent a genuine contribution to the NDT of soil from civil engineering perspectives. On the other hand, the maximum depth using this technology was less than 40 cm because the available device was designed to measure concrete.

Table (4-5) Subsurface object inspection results using Proceq Pundit Array

Type of feature and soil	Phase 1	Phase 2	Phase 3
Plastic in Sand	Detected	Undetected	Not sure (*WD)
Plastic in Loamy	Detected	Not Sure (WD)	Not sure (WD)
Plastic in Gravel	Not sure (*MD)	Not sure (MD)	Detected
Voids in Sand	Not sure (*WD)	Undetected	Not sure (WD)
Voids in Loamy	Undetected	Undetected	Undetected
Voids Gravel	Not Sure (WD)	Not Sure (WD)	Not sure (MD)
MSW in Sand	Detected	Undetected	Not sure (WD)
MSW in Loamy	Detected	Detected	Detected
MSW in Gravel	Detected	Detected	Detected

*WD: weak detection, **MD: Medium Detection

4.1.1 Controlled Thermal Experiment's

As mentioned previously, the part of the thermal reaction was repeated in a controlled environment. It was clear that the only variable measured with the thermal camera is the MSW. Because the plastic does not emit heat, react, or decompose with soil in a short time (Adhikari, Dahal, & Nath Khanal, 2014). In addition, The void contains air, which primarily has a stable temperature (no comical reaction could generate heat from the air alone, which is a scientific fact). Thus, this experiment focused only on the MSW. The experiment was designed to investigate the subsurface and surface temperature changes in a small-scale area using the seven-step design flowchart shown in Figure 4-1 (A. N. Nashwan, Al-Joburi, & Bin Shams, 2021). The experiment preparations were as follows:

- 1- The waste was collected from Urbaser company (responsible for collecting and disposing of the waste in Bahrain's southern and northern governorates). They provided a random actual waste bin sample that contains about 100 kg of municipal waste. The waste was distributed randomly in separate bags (plastic and paper bags). These bags have different weights (not volume) because the standard waste measurement units are Tons and Kilograms.
- 2- Only one soil type was used: the loamy soil because it is the most common soil in practice to fill the waste. See Figure 4-2.

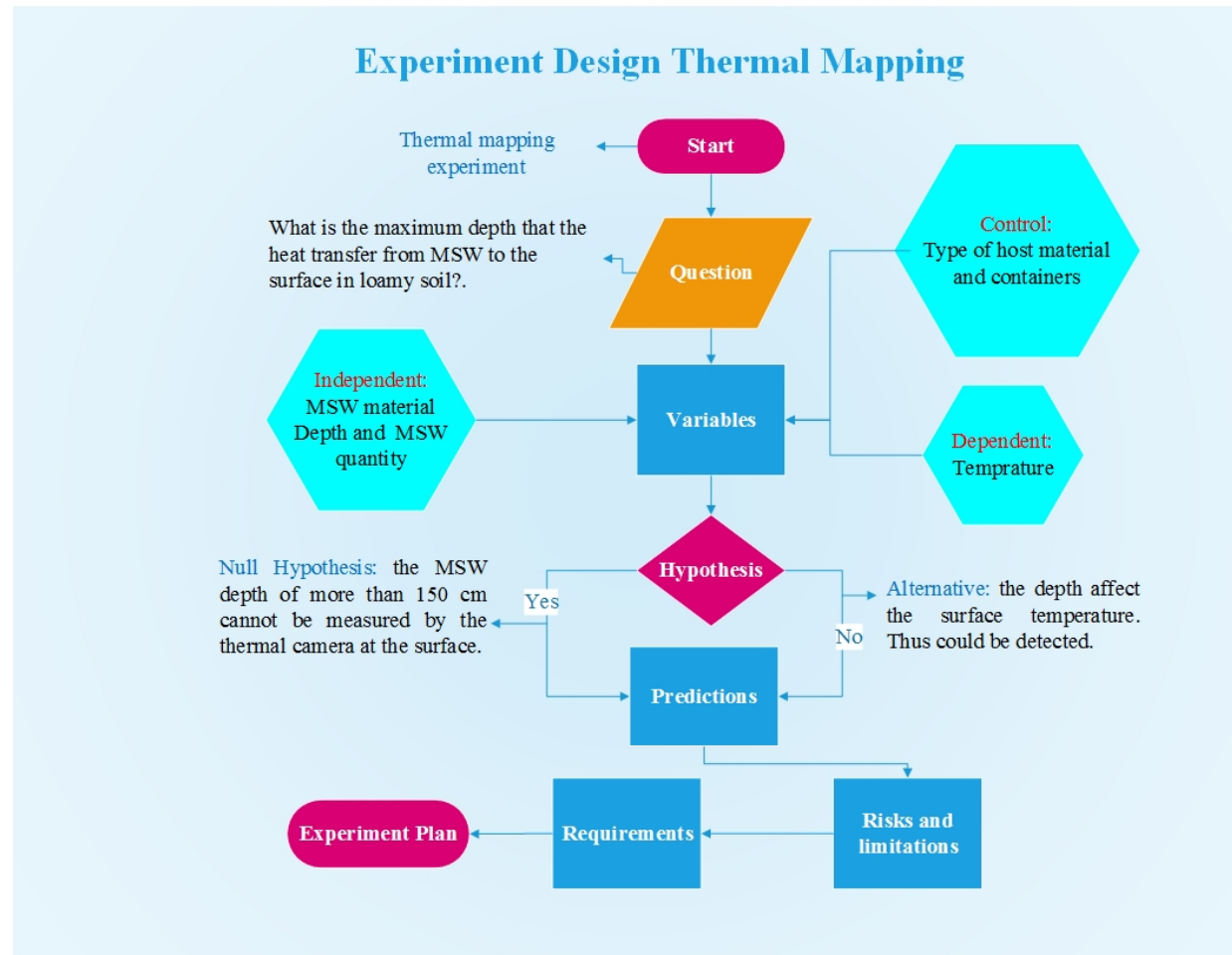


Figure 4-1 Design flowchart for the enhanced thermal experiment

Figure 4-2 Loamy soil has been used for repeated phase

- 3- The containers were selected to be 4mm thickness PVC pipes with a diameter of 6 inches to ensure maximum isolation from the outside temperature. See Figure 4-3.
- 4- A soil temperature meter (a commercial one) was used to measure the internal temperature. In addition, homemade temperature sensors were programmed by Urdino technology.
- 5- The moisture content also was measured and registered using a soil moisture content meter.



Figure 4-3 All sample pipes before visual inspection

(Captured on 06/01/2020)

- 6- All pipes were initially closed from the bottom to isolate the underground effect, then filled by a sand layer with 150 mm thickness, then the wastes were added with different thicknesses.
- 7- The soil over the waste was also added with different thicknesses, as shown in Table (4-6).
- 8- The first six samples were designed to study the depth effect on the decomposition's emitted energy (heat). Thus, the MSW amount was fixed as 1.5 Kg per sample, and the depth was varied from 15-90 cm.
- 9- The measurements were designed to be taken daily or weekly for two months. This period was selected because it is the time required for meat and organic material to decompose.
- 10- The samples were stored in a store at natural room temperature.
- 11- The minimum depth of waste material was 15cm, and the maximum was 90 cm.
- 12- The instruments that have been used in this experiment are:
 - a. Digital thermometer (1-degree Fahrenheit accuracy),
 - b. Moisture Content sensors (digital and manual)

Table (4-6) Second thermal experiment for waste samples

Number	Length	Amount	Sand Depth (cm)	Contents (Kg)	Remarks	Date DD/MM/YY	Notes after eight weeks
1	50	1.5	15	MSW in a plastic bag	1kg=range from 20*20*20 to 30*30*30 cm, D=0.0370 to 0.125g/cm ³	09/11/2019	Low decomposition
2	60	1.5	30	MSW in a plastic bag		09/11/2019	Low decomposition
3	75	1.5	45	MSW in a plastic bag		09/11/2019	Low decomposition
4	90	1.5	60	MSW in a plastic bag		09/11/2019	Low decomposition
5	105	1.5	70	MSW in a plastic bag	Pipe too short	09/11/2019	Low decomposition
6	120	1.5	90	MSW in a plastic bag		09/11/2019	Low decomposition
7	120	2	30	MSW in a Paper bag		09/11/2019	Low decomposition
8	120	6	15	MSW in a plastic bag		09/11/2019	Low decomposition
9	105	6	30	MSW in a plastic bag		09/11/2019	Low decomposition
10	63	2	15	MSW in a plastic bag		09/11/2019	Low decomposition
11	93	4	30	MSW in a plastic bag		09/11/2019	Low decomposition
12	72	4	15	MSW in a plastic bag		09/11/2019	High Decomposition with stinky smell and high moisture content
13	50	No waste	50	Sand only	Control-Sand only	09/11/2019	Control Sample
14	50	1.5	15	MSW only vegetation without bag		16/11/2019	Decomposed with stinky smell and high moisture content

- c. Urdino system contains sensors, a programmable control panel, and a power supply. See Figure 4-4.
- d. Thermal Camera (mentioned previously).
- e. Manual meter and Laser EDM to measure the accurate depth of material. See Figure 4-5. Figure 4-6 Shows a cross-section of the pipe, host material below and over MSW, and the primary sensors to take the measurements.



**Figure 4-4 Removing the digital sensor from the sample in pipe # 3
(Captured on 06/01/2020)**



Figure 4-5 Bosch laser EDM that used to measure depth inside pipes



Figure 4-6 Cross-section for MSW container with all sensors used

The experiment was performed based on the flowchart procedures shown in Figure 4-7. The following are some extra notes on the performing procedures:

- 1- The experiment started by measuring the soil's surface using a thermal camera and measuring the soil temperature up to 10 cm depth using a digital thermometer (Fahrenheit – converted to Celsius).
- 2- After inserting the sensors to the MSW level and measuring it correctly, measuring the soil temperature was stopped (no added value expected).
- 3- On the 16th of November, add a new sample for 1.5 kg of waste without a bag.

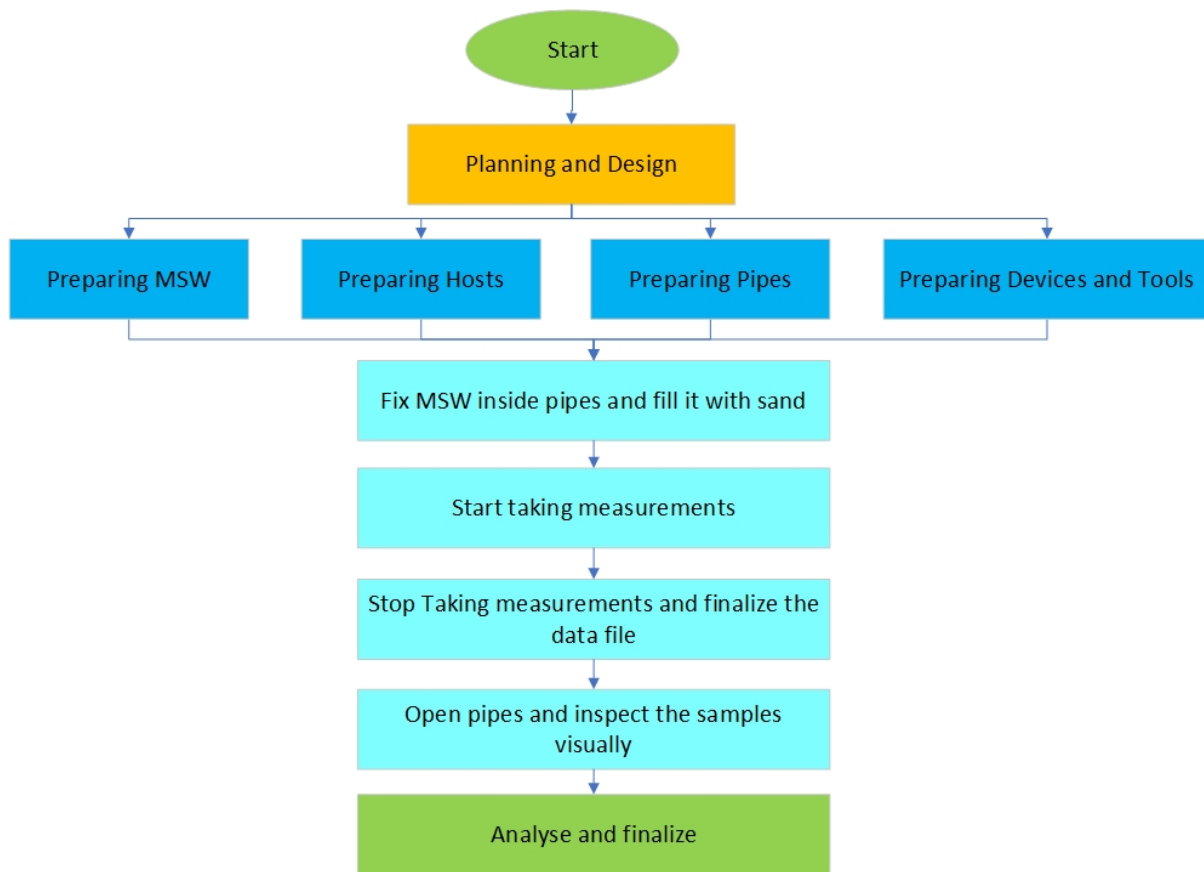


Figure 4-7 Flowchart for performing the thermal experiment

- 4- The experiment started on 08/11/2019, ended on 06/01/2020. The readings were started on 09/11/2019, and the last measurements were collected on 03/01/2020.
- 5- The starting of decomposition was noticed when flies were seen in the closed store after one week.

The initial noticed results could be summarized as there is no obvious evidence that a thermal camera can detect the change in temperature that 15 cm or more, which is agreed with the finding of (Okamoto & Liu, 1998). Therefore, more data analysis is required to check subsurface temperature changes.

4.1.2 Analysis of Controlled Thermal Experiment

The MSW decomposition waste is classified into five phases by (Adhikari, Dahal, & Nath Khanal, 2014) based on the rate of decomposition and biogas production. These phases are:

- 1- The initial adjustment phase: the aerobic decomposition changes the organic materials to CO_2 , H_2O , and considerable temperature rise.
- 2- The transition phase: the moisture contents increased, the aerobic decomposition ended, and the anaerobic decomposition started.
- 3- The Acid formation phase: the volatile organic acids (VOA), ammonia, and CO_2 production increased. The acidogenic microorganism increases the degradation of nutrients and substrate.
- 4- The Methane fermentation Phase: the microorganism converts the acids to methane and CO_2 . This phase started after 4 to 10 years and continues for several years.
- 5- The maturation phase: the low biological activity leads to stabilized organic compounds and reduces gas production.

This research concentrated on studying the MSW during the period of phase one and part of phase two. Therefore, the data might be analyzed based on the characteristics of these phases.

The data analysis started with focusing on the first six samples to check the effect of depth on the emitted energy. After that, the other samples provide indicators on the impact of the MSW amount per sample on the radiated heat. In addition, other factors were found to affect the emitted heat, such as the type of bag and the amount of organic materials in the sample.

Several extra analyses could be performed on the results of this experiment. However, the essential results related to this research were

those that discuss the effect of MSW on surface temperature. The results extracted are as shown in the following paragraphs.

Firstly, Figure 4-8 shows emitted energy (difference between surface and MSW temperatures) against the burial depth. The figure shows that the amount of emitted energy decreases as depth increases. However, the change rate in the bagged sample is higher than in a bagless sample. In addition, it was noticed that most MSW samples showed an increase in the emitted energy in the first 17 days, then decreased. Due to the fast and high decomposition, the 15cm sample of MSW bagless (Yellow color) shows a different trend than the 15cm plastic bag (Blue color) sample. Although the energy continued to emit in the blue color sample due to a low decomposition rate, the moisture contents from decomposition reduced the emitted energy significantly. The maximum point in the trend lines of samples means that phase one was ended and decomposition phase two has started.

Figure 4-9 shows the relation of emitted heat at 15cm depth with different quantities. A bagless sample of 1.5kg was added to compare the effect of the bag on emitted energy and decomposition. It could be noticed that as the quantity of MSW increased, the maximum emitted energy point (point of inflection) shifted left. Significantly, it could be interpreted as the higher quantity, the faster decomposition occurs.

Figure 4-10 shows similar results to Figure 4-9 but the MSW at 30cm depth. The same previous comments and trends were found in this figure. On the other hand, the reduction in emitted energy with an increment of a quantity means that the decomposition rate is slow. At the same time, the moisture from the decomposition reduces the emitted energy by decomposition.

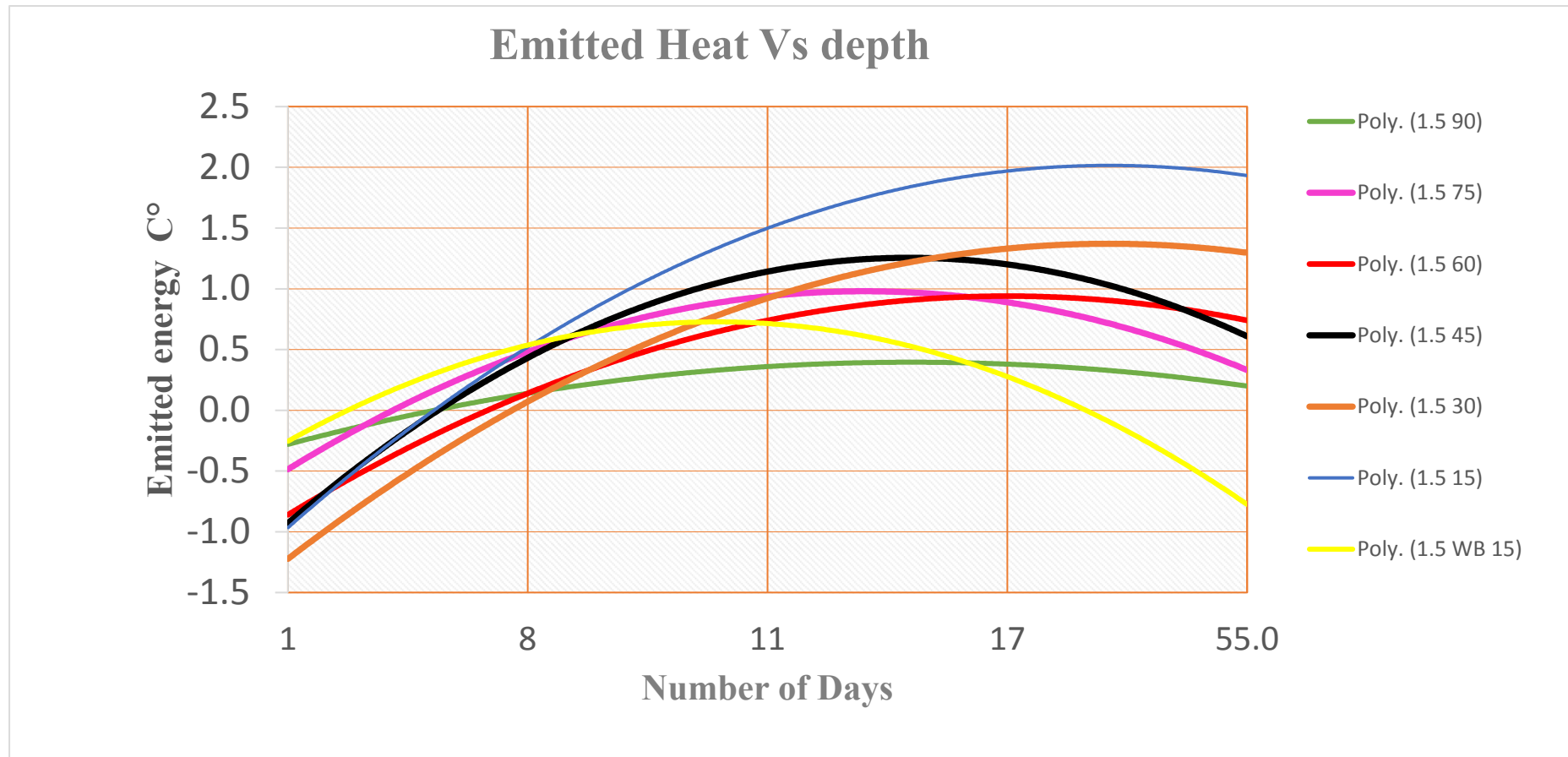


Figure 4-8 Emitted Heat differences with Depth

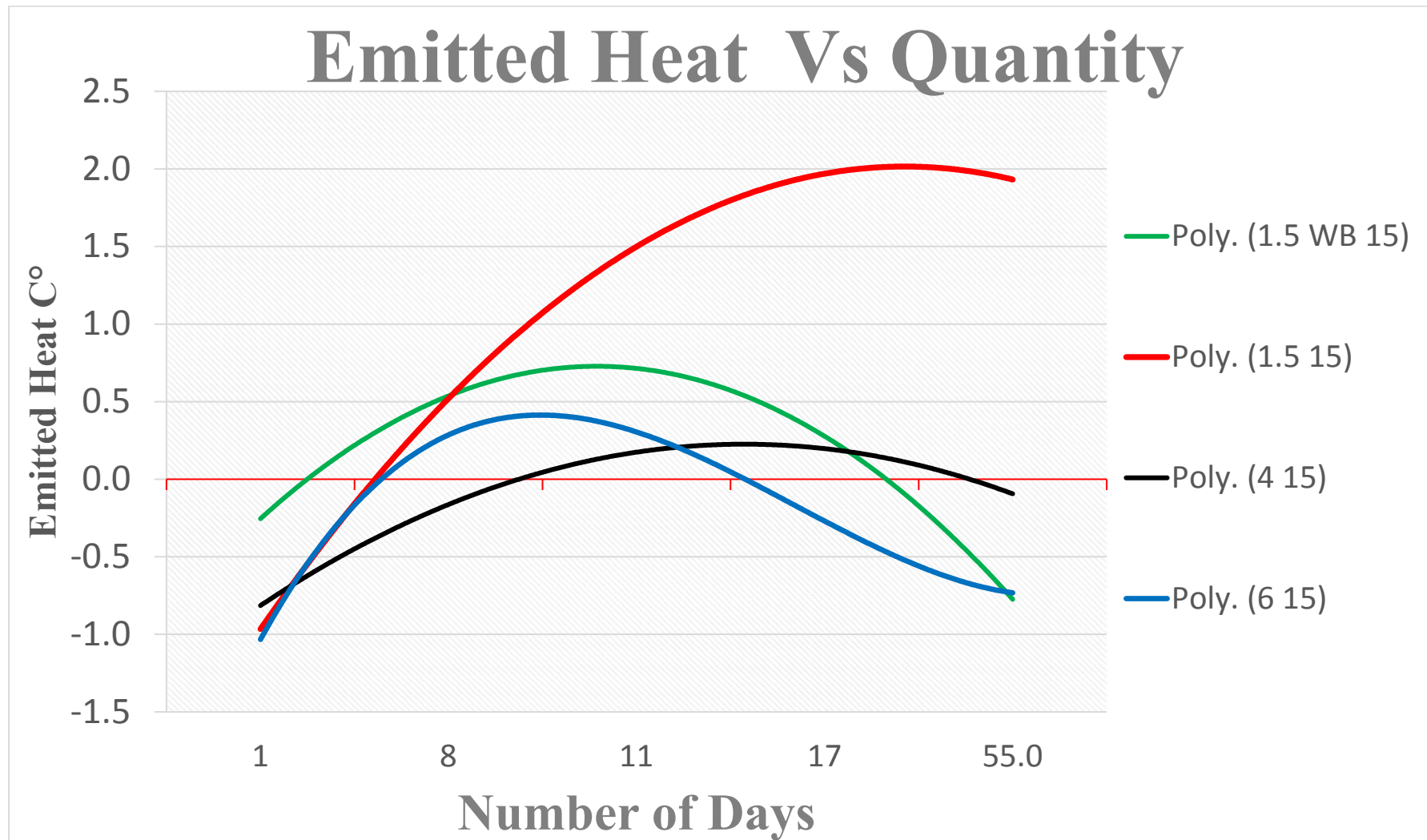


Figure 4-9 The emitted energy against quantity at 15cm depth

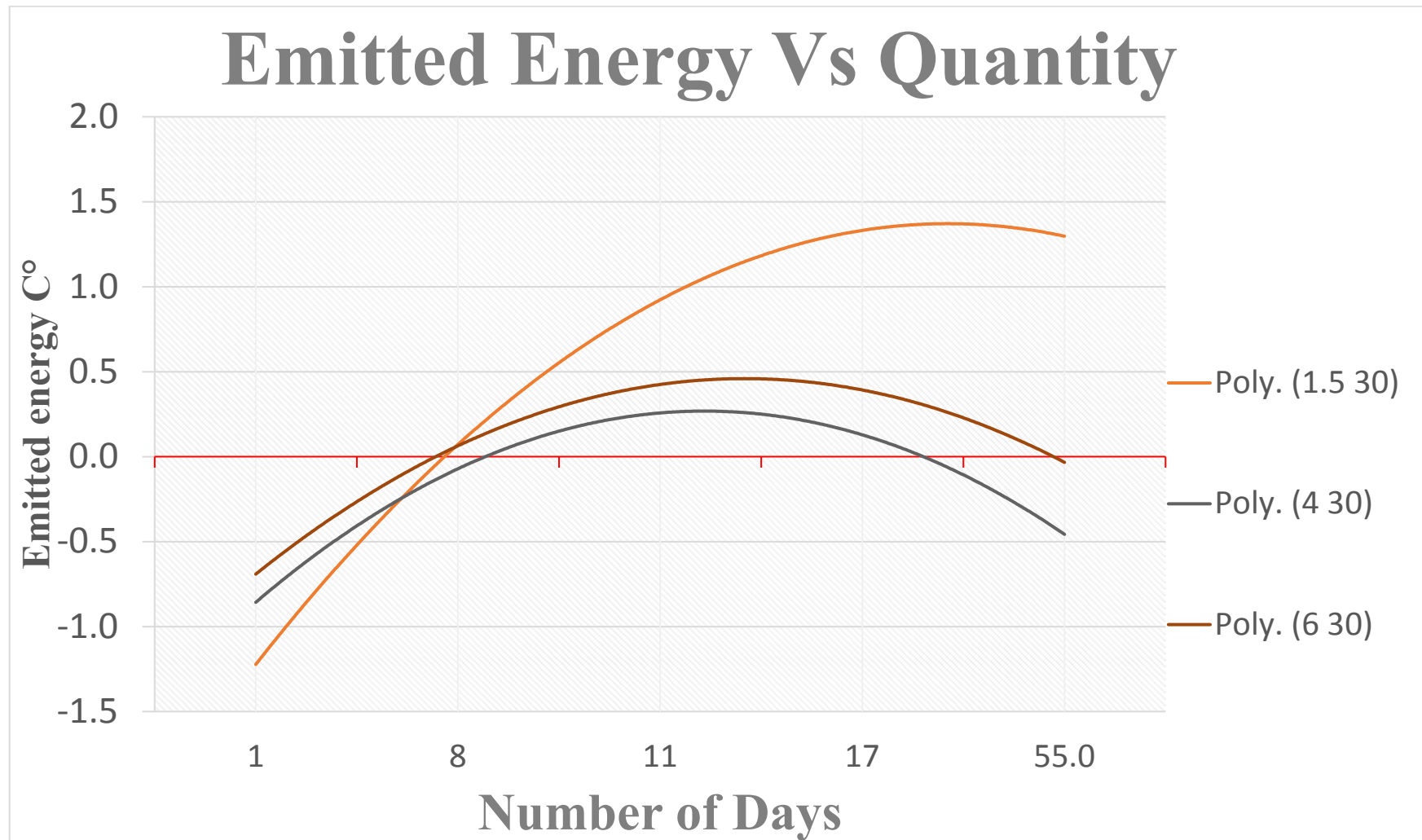


Figure 4-10 The emitted energy against quantity at 30cm depth

Figure 4-11 shows how the surface temperature was affected by MSW temperature with depth. It is vital to mention that the surface temperature was controlled since the samples were kept in a closed and dry room. There are no significant temperature changes from external factors. The trends indicate that most samples have increased surface temperature after six weeks, which means the decomposition process is still active. The samples with high organic materials and high decomposition (bagless sample) reflect decreasing temperature (due to moisture contents). In addition, as the depth increased, the effect on surface temperature decreased.

Figure 4-12 shows how the surface temperature changes by MSW quantity. It was clearly obvious that the surface temperature decreased when the MSW quantity increased. The interpretation for this decrease in the sample of 6 kg is related to the decomposition in the top bag of MSW, where the lower plastic bag prevents the moisture from penetrating down, which causes cooling on the surface temperature. The high moisture content on sample 14 that these samples were at the end of phase one or the onset of phase two. Therefore, the temperature of MSW decreased at the end of the experiment.

Accordingly, we could conclude that a thermal digital camera can detect temperature variation lower than 15 cm depth. However, it becomes less evident for deeper depths. The obtained results exceed the finding of (Okamoto & Liu, 1998), who succeeded earlier in detecting objects up to 15 cm in depth. However, the detection for depths more than 60 cm seems to be infeasible using a thermal camera unless more factors (wind, medium condition, and shape of object) and devices have been considered in the measurements and analysis. Therefore, measuring the temperature using subsurface meters or sensors is recommended. We conclude that inserting temperature sensors is good to detect subsurface temperature changes.

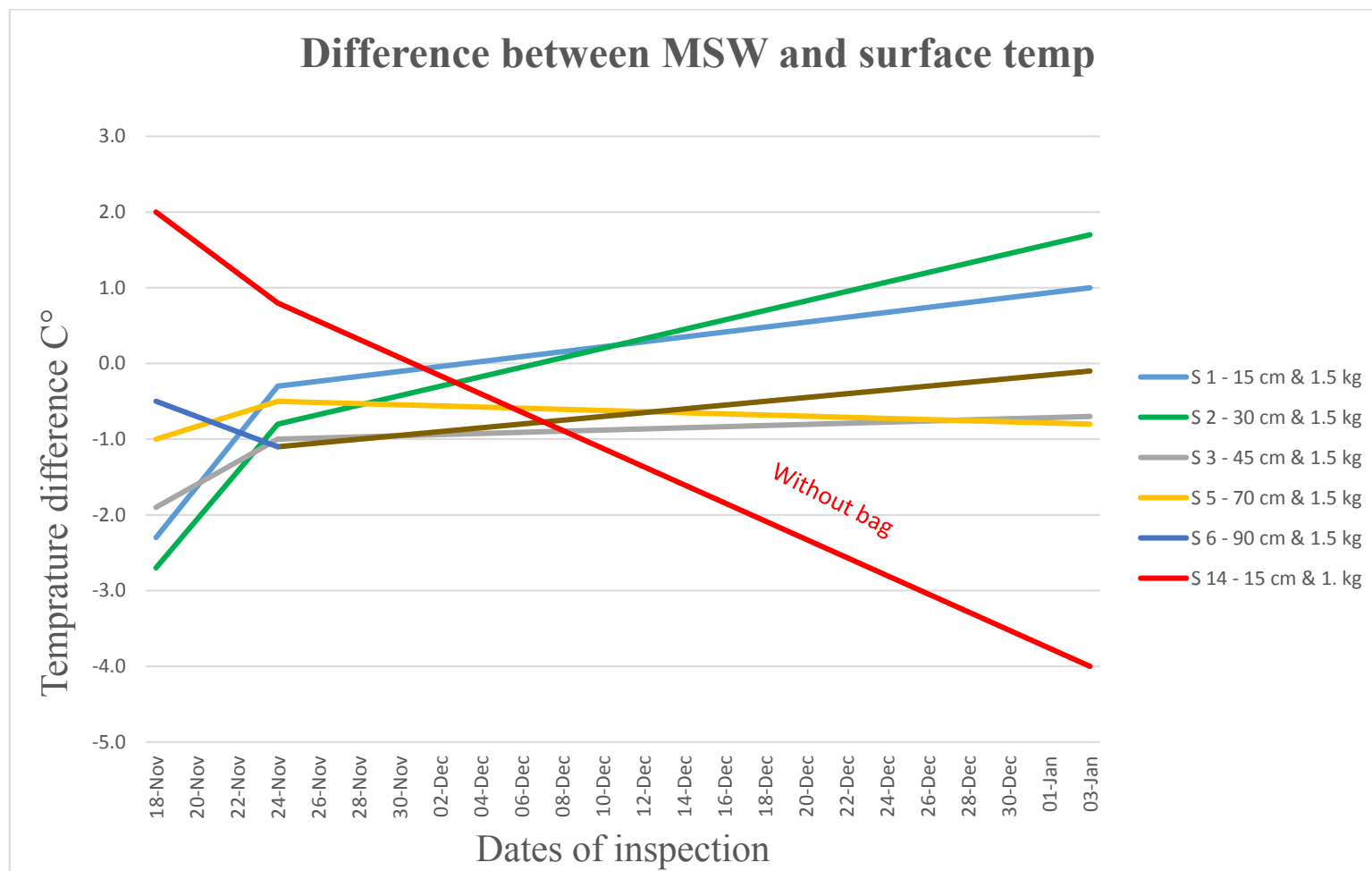


Figure 4-11 Changes of Surface Temperature from MSW Level for 1.5 kg samples

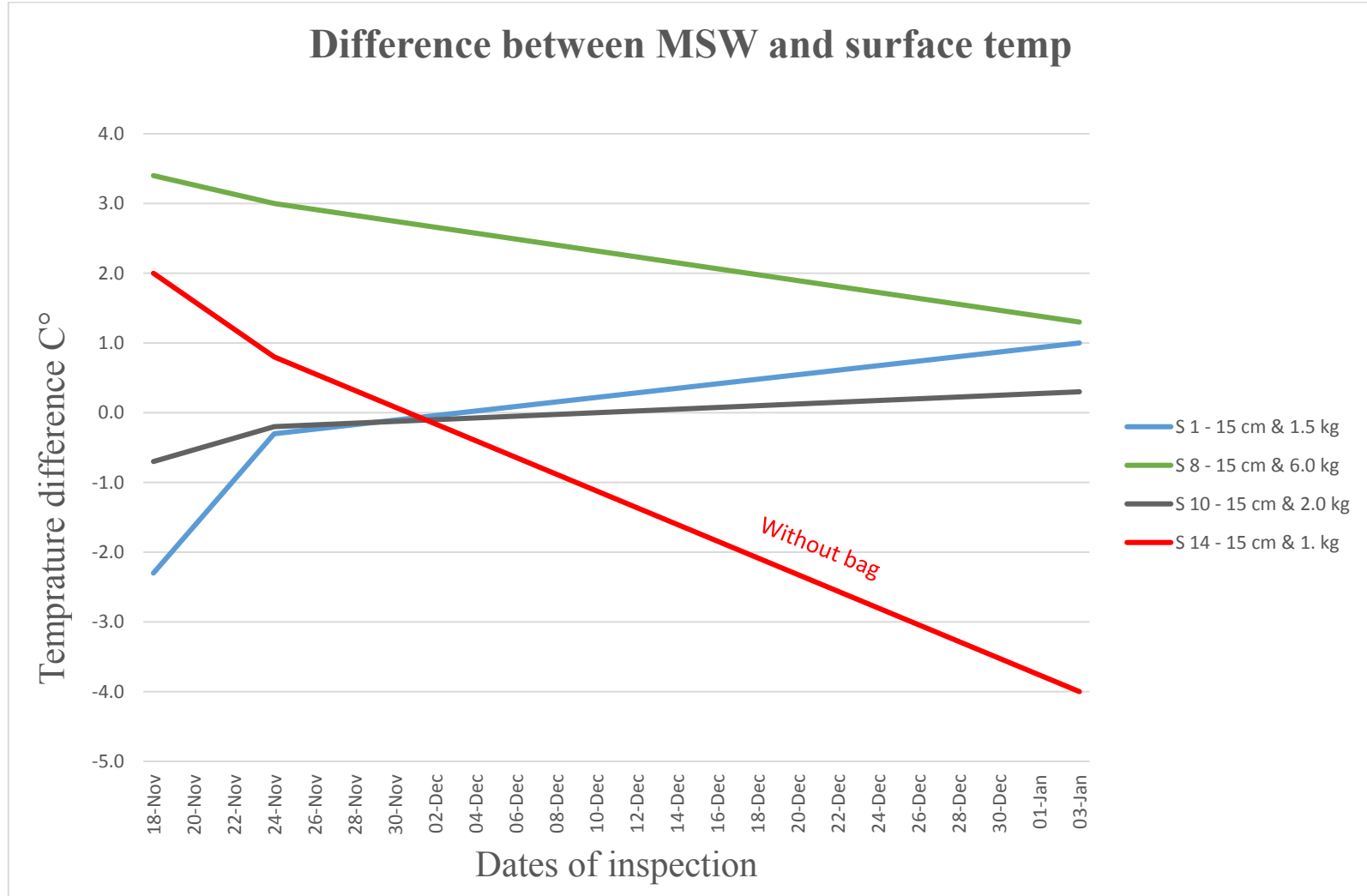


Figure 4-12 Changes of Surface Temperature from MSW Level for 15 cm samples

These results show that the MSW's emitted heat could be detected using a thermal camera for more than 15 cm depths. This finding leads to rejecting the null hypothesis mentioned in the design flowchart Figure 4-1. In addition, the experiment recommends that the monitoring with a precise thermal camera be continued for more than six weeks. Also, to include a controlled area free of MSW in the study area to use as a control sample.

4.2 Enhanced Experiment (Ground Truthing)

The initial experimental demonstrates that there are limitations due to using a small box size. Therefore, an enhanced experiment was designed to minimize these limitations. In addition, there is a need to do ground verification for the results obtained in the main experiment. Besides, the new experiment might investigate to what extend the uncharacterized features can be detected. The experiment question, hypothesis, and variable are the same as the preliminary experiment. Because this is just an extension to the original experiment.

4.2.1 Design of Enhanced Experiment

The following essential issues were taken into consideration during the design of this experiment:

- 1- The availability and feasibility of the devices to be utilized. Since the Proceq devices (GP and Pundit Array) were unavailable in this part of the experiment due to the COVID 19 pandemic in the whole world. On the other hand, the thermal part will not be conducted in the verification experiment since the targeted depth exceeds the maximum limit this technology could achieve. However, the experiment's instruments were the GSSI dual-

frequency pulse GPR (Time-domain low and medium frequency) and the high-frequency GSSI structural scan GPR.

- 2- The experiment's location was in the Sukhair Area near the Tree Of Life (see Figure 4-13). This area was selected because it is away from the urban areas and assimilated real-life situations as close as possible. As a result, approval for excavating and burring the investigated features was attained. The dimensions of the selected area were 6m*6m*2m. The site dimension was ten times the original experiment to compare the original and the enhanced experiments.



Figure 4-13 Tree of Life Site location

- 3- The investigated features' depth was chosen to be from 50 cm to 2m. This range was selected due to instrument limitations, governmental guidelines (the experimental site owner), and to avoid water depth.
- 4- Additional investigated features were added to this part besides MSW, voids, and plastic. The new features were: The construction waste (Debris) was added because it is one of the most common hazardous wastes been filled illegally. The water was selected to check the cases were voids filled with water or part of it. The voids in this experiment were voids below concrete, wood sheets, and voids made of potteries. MSW contains vegetables and random trash bags. The Plastic was composed of plastic bottles, plastic sheets, and other plastic materials. The total number of the targeted features was 15 features. The dimensions and depths of these objects are listed in Table (4-7).
- 5- This experiment aimed to verify the initial thesis experiment's finding and complete the missing part due to depth limitations. In addition, it is aimed to verify some of the results in the main experiments in an actual ground environment.
- 6- Due to time limitations and the landowner restriction, only the dry condition will be applied in this experiment.

The design shown in Figure 4-14 contains 26 lines. The first 13 lines represented the Y- North direction scanning, and the next 13 lines were in the X- East direction.

Table (4-7) Enhanced Experiments targets descriptions, specifications, and dimensions

Feature No	Description	Top-level	Thickness	width
1	Steel beams covered by steel drum (Metal Object) represented by one dot.	9.5	<0.6	<0.5
2	Void pottery is represented by one dot. (Void Object).	9.5	<0.6	<0.5
3	Plastic drum filled with water (Water Object), represented by one dot.	9.0	<0.4	0.5
4	Slope plastic line, represented by one dot in the cross scanning, and several dots in the along scanning, each point opposite to similar in the cross direction.	9.3-8.44	<0.3	0.5
5	Slope void line, represented by one dot in the cross scanning, and several dots in the along scanning, each point opposite to similar in the cross direction.	9.44-8.50	<0.25	<0.5
6	Slope MSW line, represented by one dot in the cross scanning, and several dots in the along scanning, each point opposite to similar in the cross direction.	9.36-8.28	<0.3	0.5
7	Steel beams covered by aluminum plate (Metal Object), represented by one dot.	9.0	<0.6	<0.35
8	Vertical 30 cm PVC pipe (Void Object), represented by one dot.	9.0	1.0	0.3
9	Two bags filled with random MSW (MSW Object majority organic), represented by one dot.	9.5	0.5	<0.5
10	Two bags filled with random MSW (MSW Object majority organic), represented by one dot.	8.5	0.5	<0.5
11	Plastic drum half-filled with water (Void +Water), represented by one dot.	9.5	0.6	0.4
12	Square metal plate (aluminum) (Metal Object), represented by one dot.	9.5	0.05	0.5
13	Debris stock, represented by one dot. (Construction waste materials)	9.17	0.5	0.5
14	Two bags filled with random MSW (MSW Object majority organic), represented by one dot.	8.25	0.5	<0.5
15	Debris material, represented by one dot (Construction waste materials).	8.4	0.5	0.5

The objects were laid as points. The layout represented these points as a circle with a 50 cm diameter. In addition, some linear features representing the MSW, void, and plastic were laid in slope direction with a width of 50 cm, as shown in Figure 4-15 and Figure 4-16. The profiles for these were prepared to show each object's depth. The horizontal distance between two successive targets on the same line was spaced by at least 2 m to avoid signal overlap or reduce it.

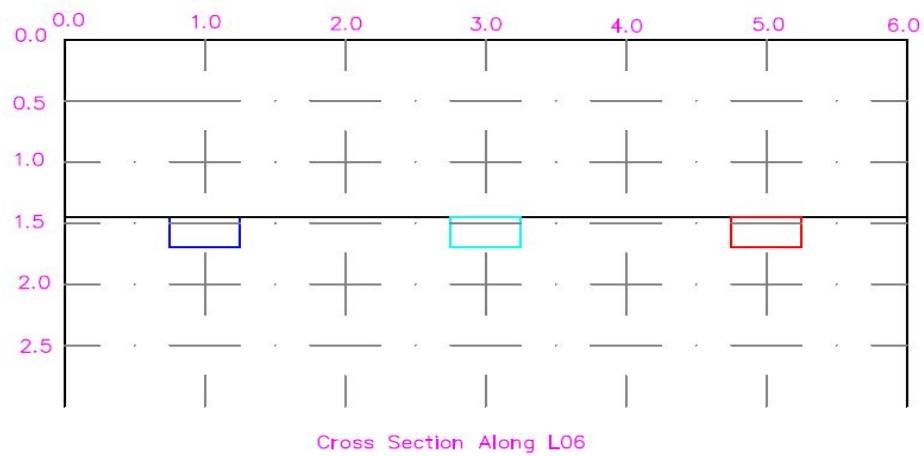


**Figure 4-15 Enhanced experiment cross section for the sloped materials
(Blue: Plastic, Cyan: Void, and Red: MSW)**

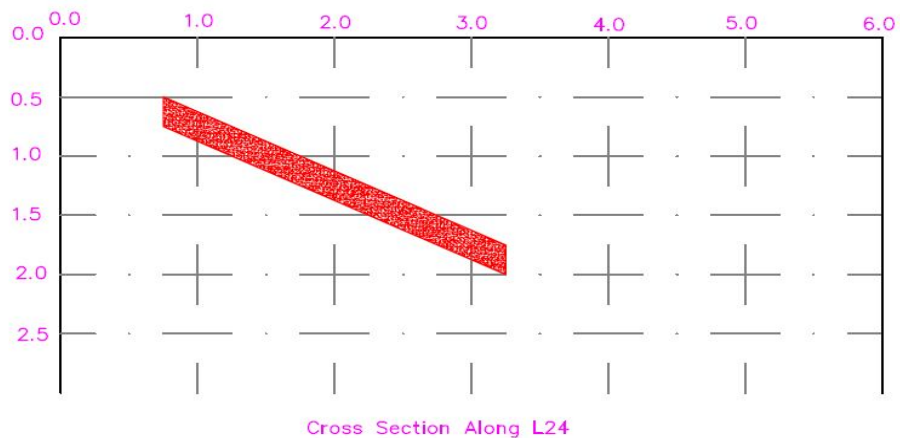


Figure 4-16 Enhanced experiment profile section along with the sloped MSW on line 24

The scanning was done in both directions in the same manner that was accomplished in the original experiment. The steel plates and beams were laid for calibration.

4.2.2 Execution of the Enhanced Experiment

Initially, after getting all approvals and liaison with the services department, the experiment was performed based on the procedures shown in Figure 4-17.

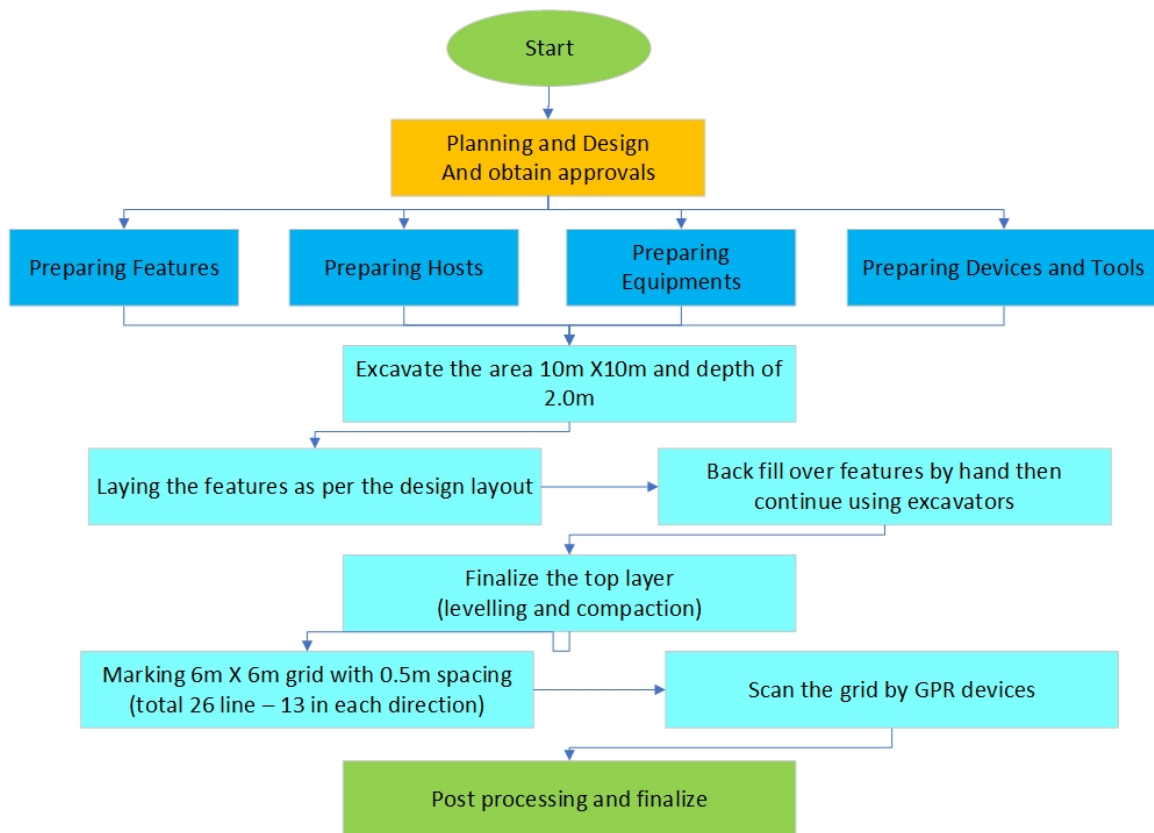


Figure 4-17 Flowchart for performing the enhanced experiment.

These procedures started by preparing the equipment (excavators, plate roller, and hand tools), host material, materials to be studied

(MSW, Plastic, Voids, Water, Metal, and Debris), and scanning devices. Next, the experimental area was excavated using a large chain excavator. The excavated area was 10X10 m. Then, dredged sand and gravel soil host material were imported to the site to simulate the typical substandard filling process. Firstly, the investigated materials were carefully laid according to their designed location using GPS. Secondly, the host materials were manually laid over the features, and then a small excavator was used to continue the filling process without compaction.

Thirdly, the top 10 cm layer was compacted using a plate roller compactor to provide a smooth surface for the GPR devices. Finally, a 50 cm grid was marked on the top of the filled area. Total of 13 lines in each direction as shown in Figure 4-14. These lines act as the scanning guidelines.

The used instruments were only the time-domain (pulsed) GPR devices (low, medium, and high frequency). Each line was scanned twice in opposite directions (east-west then west-east and north-south then south-north), making 26 scans in each direction. Initial visual analysis shows that the collected data is acceptable and there is no fault, and no line needs to be repeated.

There was a noted horizontal signal ranging for several reasons: the device body, stones in the filling materials, and the thin compacted layer at the surface. To remove this horizontal ranging, a deconvolution post-processing filter could be applied. This filter helps recognize objects at deeper depths after removing the ranging noise. However, it

cannot be used at every step because it will remove a significant part of the horizontal signal for the flat objects or the geological layers.

This filter was not used in the previous main experiment because most of the noise refers to the reflected signals of the box wall, a vertical object, not a horizontal one. Thus, using it adds extra noise or removes parts of the original signal for the targeted object.

In post analysis, RADAN 7 software was used. The software is primarily capable of producing a profile view along any particular scan line. Also, the software is capable of removing noise. However, the software cannot identify the location of any particular feature. This detection depends primarily on prescanned data plus the operator's skills. Even though the advanced version of this software can produce 2D slice view (C-Scan) and 3D solid surface, this is again nothing more than profile views. Features' locations are identified based on the information available to the operator (designed by the researcher) and the pattern in the profile view. The targeted features' locations were marked as colored dots in the B-scan, as shown in Figure 4-18. For example, the MSW was marked in red, the void in green, the plastic in yellow, the metal in dark brown, and the water in blue. The dot locations were marked as per the designed depth. Then the evaluation was done to check if the points were in their current location or not based on the interpreter experience on GPR data. Then the assessment for the success of feature detection was determined. The most detection is expected to be achieved by the medium frequency band (800 MHz) because it covers the maximum required depth and has a lower

wavelength than the low-frequency band (300 MHz). Therefore, the experiment's results were listed in three columns for each targeted feature (based on each device's central frequency). The feature detection results are As shown in Table (4-8).

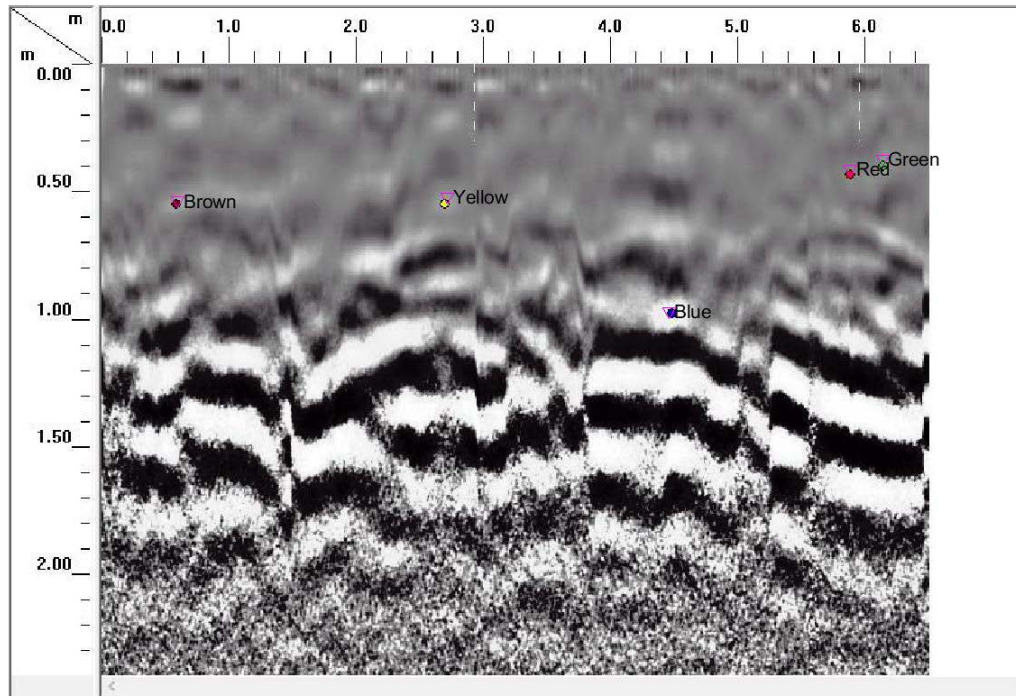


Figure 4-18 Sample of a scan-line in GSSI Utilities F=800 MHz

Careful examination of Table (4-8) shows:

- The features at a depth lower than 1.25 meters were detected better by the medium frequency GPR. On the other hand, the deeper features can be detected on medium and low-frequency bands. Furthermore, the surface compaction effect can be noticed on the medium and high-frequency scanning in the first 10 cm from the surface.

Table (4-8) Results of the enhanced experiment using GSSI utility and structure scan GPR

No	Description	Depth	300 MHz	800 MHz	2700 MHz
1	Metal	0.5	Weak detection	Detected	Weak detection
2	Void	0.5	Weak detection	Detected + Deconvolution Post Analysis (DPA)	Weak detection due to noise level
3	Water	1.0	Weak detection	Detected + (DPA)	ND lower than maximum depth
4	Slope plastic line	0.7-1.56	Weak detection	Weak Detection	ND lower than maximum depth
5	Slope void line	0.56-1.5	Detected + (DPA)	<i>Medium detection</i>	<i>ND lower than maximum depth</i>
6	Slope MSW line	0.64-1.72	Medium detection	Weak detection	ND lower than maximum depth
7	Metal	1.0	Detected + (DPA)	Detected + (DPA)	ND lower than maximum depth
8	Void	1.0	Weak detection	Medium detection + (DPA)	ND lower than maximum depth
9	MSW	0.5	Med-detection (DPA)	Medium detection	Medium detection
10	MSW	1.5	Detected (1 direction)	Medium detection	ND lower than maximum depth
11	Void + Water	0.5	Weak Detection	Detected + (DPA)	Medium detection
12	Metal	0.5	Detected	Detected	Medium detection
13	Debris	0.83	Med-Detection (DPA)	Medium detection	ND lower than maximum depth
14	MSW	1.75	Weak detection (DPA)	Not detect	ND lower than maximum depth
15	Debris	1.6	Detected + (DPA)	Weak Detection	ND lower than maximum depth

- The high-frequency GPR provides medium detection for some objects because their location was near the noise level. However, simultaneously, it could not detect the object with a depth of more than 80 cm, representing the maximum depth for this technology.
- The plastic in dry soil had weak detection, which is an expected outcome because the dielectric properties of plastic and sand are close or similar. Therefore, the reflection will be more miniature than been detected. The plastic pieces' air gaps are also smaller than the minimum detected object in the medium and low-frequency bands.

4.3 Feature Characteristics

Based on the analysis of previous experiments Table (4-9), Table (4-10), and Table (4-11) respectively show the summary of technologies, their utilization in Civil engineering, their capability to detect Plastic, voids, and MSW, and the contribution found in this research. On the other hand, these experiments aim to understand the feature characteristics and to be able to decide which sensors to be used for mapping. Therefore, the results from Table (4-4) and Table (4-5) are updated and listed in Table (4-12). Then, Table (4-8) and Table (4-12) are converted into UML charts that define the relationship between the available host, sensor, and targeted feature. The UML charts represent an easier way to program and save the feature characteristics in a database. Although the tables in previous experiments could be sufficient to understand the relations and feature characteristics, An advanced experiment with more sensors and variables will produce results with dozens of columns and rows that will be hard to read and analyze. Besides, UML charts represent the core of the proposed ISMS.

Table (4-9) Characteristics and information about used software in data analysis

Software	Outputs	capabilities	Limitations	Postprocessing software
Proceq (GP) Application For GPR (SFCW)	URL and SEG Y	Can change the dielectric properties and to locate the type of the detected features manually, Can produce 3D slice image (C-scan) and 3D model Can remove the background noise	GPS data cannot be added, and no desktop software for postprocessing, and can export only to SEG Y format	RADAN 7, RGPR, or MATLAB
Proceq PD (for ultrasound data)	URL and CSV	Can change the speed of signal and to locate and identify the location of objects manually, also can produce a 3D image (C-scan)	No GPS data, the limited functionality of post-processing	Not Applicable
GSSI Concrete and utilities	Images, shapefile (3D data), DZT files	Can change the dielectric properties and several exporting functions, besides professional post-processing functions.		RADAN 7
Thermal camera images	JPG file	Save the name of images with time and date on different color pallets	No post processing possibilities	Image processing software

Table (4-10) Characteristics and specifications of used instruments

Instrument	Specifications	Intended Application	Limitations
Thermal Imager HTi-HT-04	Sensitivity 0.07 C Resolution 220*160 total pixels 35200 Wavelength 8-14 Micrometer Emissivity Adjustable 0.1-1.0 output -JPG	Construction inspection such as leakage and voids	Cannot determine depth, maximum depth 15 cm
GSSI Structure Scan GPR concrete	Central frequency 2700 MHz – Pulse Time GPR	Concrete inspections	Cannot determine object time automatically
Proceq GPR Concrete	Stepped Frequency continuous wave (SFCW) Domain with a range of 200 MHz to 4000 MHz	Concrete Inspections	The technology designed for concrete application only
Proceq Ultrasound Pundit Array	Acoustic sound waves with 27 antennas divided into 3 rows each row have 9 antennas	Concrete and structure inspection such as voids, ducts, rebars, cracks,	The technology designed for concrete application only
GSSI GPR Utilities	Dual Frequency 300 MHz and 800 MHz	Utilities, sand, plastic pipes, and Archeological and Geological inspection	Depends heavily on the operator and analyzer's experience.
Small accessories and devices to measure moisture contents and Temperature	Digital and analog models	Agricultural soil testing	Accuracy, and need to register the reading manually

Table (4-11) General information and characteristics of used technologies

Technology	Application in civil Engineering	Capabilities with investigating Plastic	Capabilities to detect voids in soil	Capability to detect MSW	Contribution
Proceq GPR SFCW	Concrete voids and rebars	Good depends on size and depth	Detected on dry gravel soil	Detected on Gravel soil only	Use this technology with MSW
GPR Structure Pulse Radar	Concrete: voids and rebars	Good depends on depth and size	Detected on dry gravel soil	Detected on dry gravel soil only	Use this technology with MSW
GPR Dual Frequency Pulse Radar	Utilities: sand and asphalt	It cannot be determined due to depth limitation	It cannot be determined due to depth limitation	It cannot be determined due to depth limitation	The integration with other technologies
Ultrasound	Concrete voids and Rebars	Detected on Dry soil	Not detected	Detected on gravel and loamy soil	Using this technology in sand
Thermal Camera	Concrete - Void and Leakage	NA	NA	Possible but not found in literature due to limitation	The integration with other technologies

Table (4-12) Summary results for the inspection of targeted features in several soils
(Using both GSSI concrete & utility and Proceq GPR)

	P 1 GSSI concrete	P 2 GSSI concrete	P 3 GSSI concrete	P 1 GSSI utility	P 2 GSSI utility	P 3 GSSI utility	P 1 Proceq	P 2 Proceq	P 3 Proceq	P1 Pundit	P2 Pundit	P3 Pundit
MSW in sand	ND	NA	ND	ND	NA	ND	ND	NA	MD	Detected	ND	WD
MSW in loamy	ND	NA	ND	ND	NA	NA	ND	NA	NA	Detected	Detected	Detected
MSW in gravel	Detected	NA	Detected	ND	NA	ND	Detected	NA	Detected	Detected	Detected	Detected
Plastic in sand	WD	NA	WD	ND	NA	ND	ND	NA	WD	Detected	ND	WD
Plastic in loamy	WD	NA	ND	ND	NA	ND	ND	NA	NA	Detected	WD	WD
Plastic in gravel	WD	NA	WD	WD	NA	NA	Detected	NA	MD	WD	WD	Detected
Void in sand	ND	NA	WD	ND	NA	ND	ND	NA	WD	MD	ND	WD
Void in loamy	ND	NA	ND	ND	NA	NA	ND	NA	NA	ND	ND	ND
Void in gravel	Detected	NA	WD	WD	NA	ND	Detected	NA	Detected	WD	WD	MD

* NA= Not Applicable, ND = Not detected, WD =Weak detection, MD= Medium Detection, P 1, 2 or 3 = Phase one, two, or three

The detection charts from the existing experiment to represent the detection characteristics for targeted features (MSW, Plastic, and void) in the gravel, loamy, and sandy hosts are shown in Figure 4-19, Figure 4-20, and Figure 4-21, respectively. These are general characteristics for each host. The yellow line in each figure represents the detection in dry soil, the red line represents wet, and the green line represents the saturated soil condition. The continuous line represents clear detection with acceptable certainty, the dashed line represents low or medium detection, and the stopped line means no detection. The blue diamond represents the sensor type. These charts show that the maximum likelihood detection is in gravel soil due to more lines inside it. Also, the green line is continuous only in gravel soil, passing the USW sensor to MSW, which means that only MSW can be detected using USW in saturated soil.

In addition, there are extra simplified charts for the feature characteristics in each condition of each host. The chart actions and numbers are listed in Table (4-13). The corresponding charts for this table are shown in **Appendix B**. Depending on the results and the charts that are shown in Table (4-13), the following example will explain the characteristics of MSW in gravel soil:

- The user will know that MSW is more likely to be detected in gravel soil with all sensors in both wet and dry conditions and detected by USW in a saturated condition. If the user finds an anomaly in all sensors in dry gravel, there is a high potential for an MSW than Plastic or void. If the feature were detected in USW in saturated gravel, it would be an MSW, not plastic nor void.

These likelihoods cases were collected and converted to UML diagrams to design the ISMS.

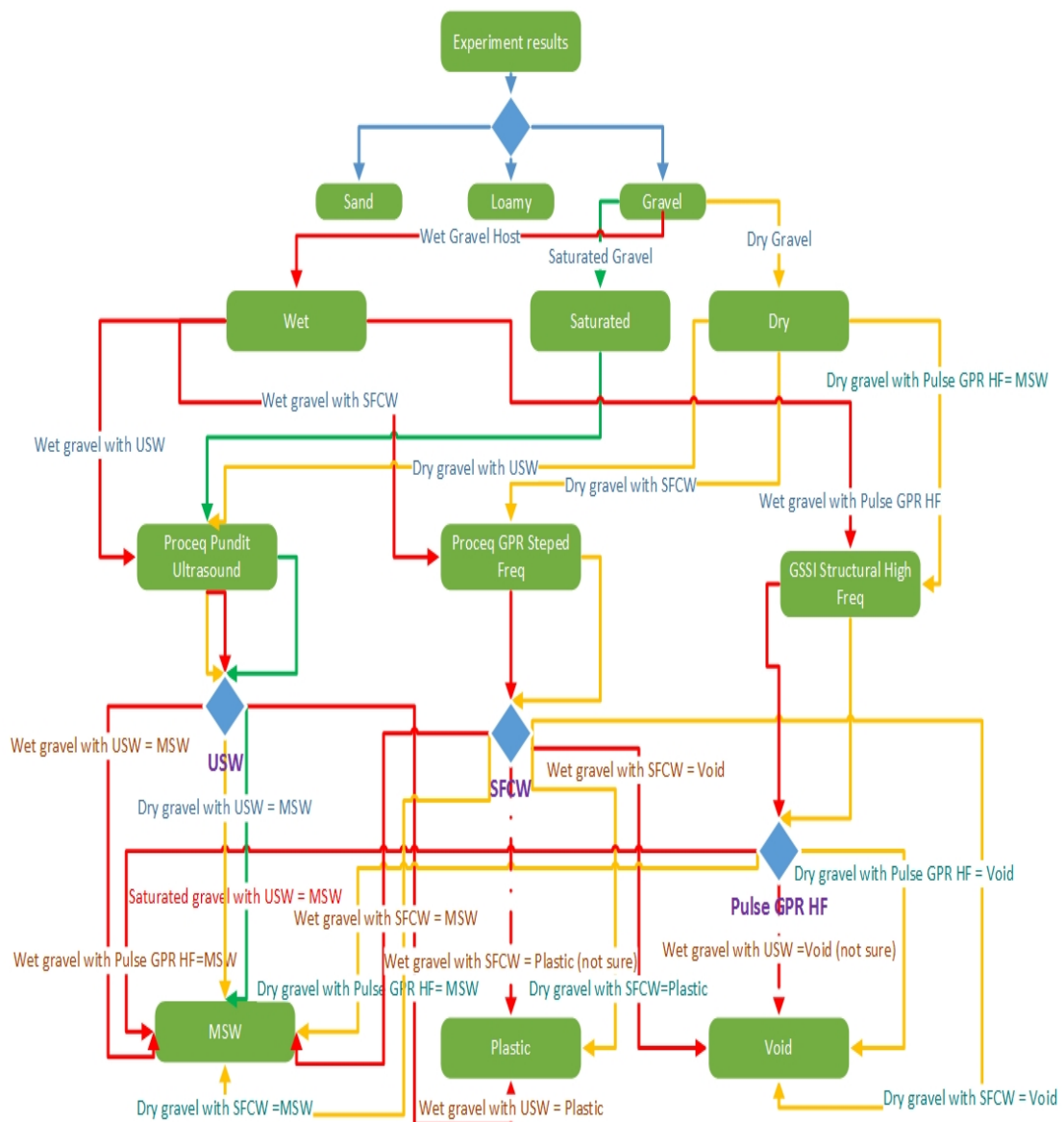


Figure 4-19 UML chart for the feature characteristics in a gravel host

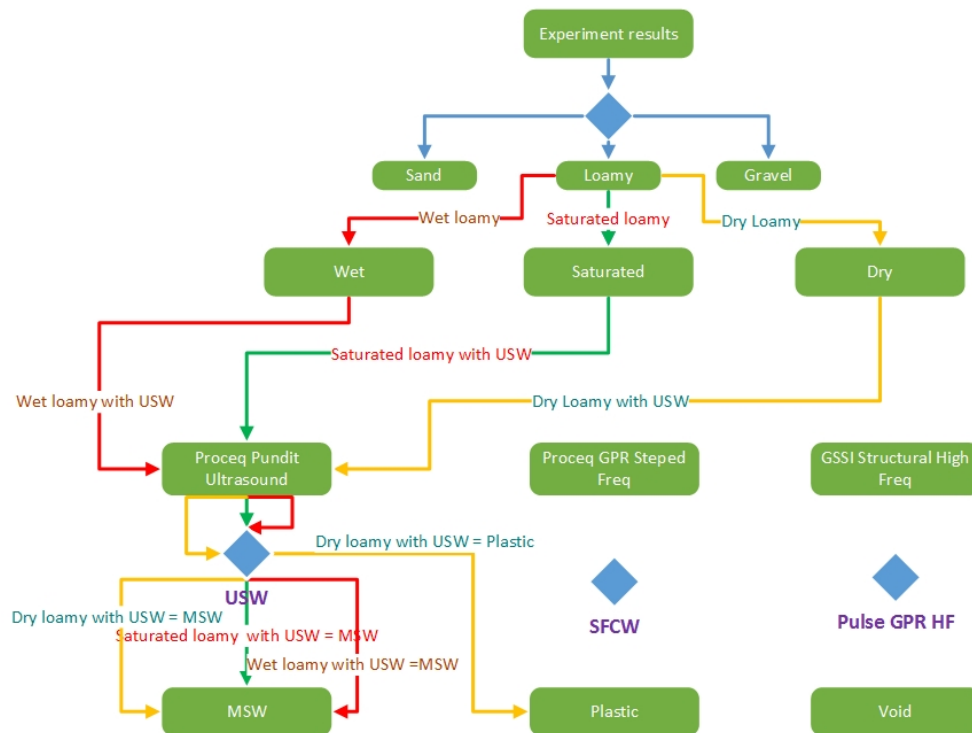


Figure 4-20 UML chart for the feature characteristics in the loamy host

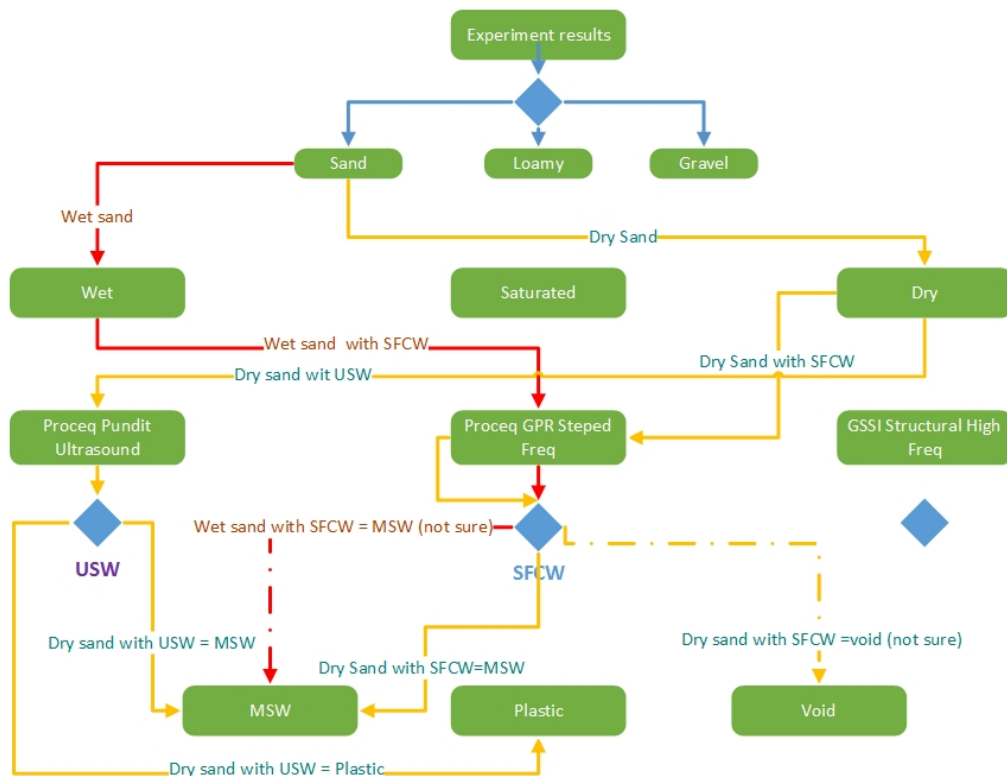


Figure 4-21 UML chart for the feature characteristics in the sandy host

Table (4-13) Extra feature characteristics charts with action and chart number

Host	Condition	Chart No	Results	Action
Sandy	Dry	Figure B. 1	Only USW will be available to detect plastic and MSW, and low chances of detecting voids	The user should use the thermal sensors as an indicator of shallow MSW or use another sensor to detect the object type.
	Saturated	Figure B. 2	No detection available	Another sensor might be used
	Wet	Figure B. 3	Low chance to detect MSW using the SFCW	The user will use SFCW to find MSW, but he needs another sensor to find voids and plastic in this wet sandy host
Loamy	Dry	Figure B. 4	The USW was able to detect MSW and plastic	The USW technology will find plastic and MSW, so the thermal sensor might be used as an indicator of shallow MSW or to use another sensor
	Saturated	Figure B. 5	Only MSW could be detected using USW	MSW can be detected in this host using USW
	Wet	Figure B. 6	Only MSW could be detected using USW	MSW can be detected in this host using USW
Gravel	Dry	Figure B. 7	- MSW could be detected with all sensors, - Voids could be detected using SFCW and impulse GPR - Plastic could be detected using only SFCW	- The user should use all sensors; if he detected the object with all sensors, then it will be MSW, - Where if detected in SFCW only it will be plastic - If detected impulse GPR and SFCW, then it is a void.
	Saturated	Figure B. 8	Only MSW could be detected using USW	MSW can be detected in this host using USW
	Wet	Figure B. 9	- MSW could be detected using impulse GPR, SFCW, and Pundit. - Voids could be detected using SFCW, and low chances using USW. - Plastic could be detected using USW and low chance with SFCW	- In wet gravel, the user will find the MSW in all sensors - The user will get voids using SFCW, and with low certainty in USW, - If the object appears in USW, it will be plastic.

4.4 Summary

This chapter discussed the data evaluation that led to the design and execution of the thermal experiment and assisted in designing the ground-truthing experiment (enhanced experiment). After that, the experiments' results were summarized and listed in tables. Lastly, these tables were converted to a UML chart. The charts represent the core for the ISMS that will be discussed in chapter five.

The most important findings in the experiments' results are:

- 1- The GPR devices could not detect anything in all types of saturated soil, where the ultrasound pundit Array works well and can detect in this condition.
- 2- The loamy soil performs better with Ultrasound Acoustic waves than with GPR electromagnetic waves. This is due to the presence of organic material and moisture within loamy soil that reduces the GPR capability.
- 3- Using the PVC sheet with The Ultrasound (Proceq Pundit device) device represents a new utilization of this device in soil. This device initially is designed and programmed to work in the concrete inspection only.
- 4- The maximum depth to penetrate and detect objects was less than 40 cm in all devices in the initial experiment due to technology limitations or high noise from box sides. Therefore, this point was considered during the design of the enhanced experiment.
- 5- In the enhanced experiment, the MSW has medium to low detection with lower and medium frequency impulse GPR due to low moisture contents in this material. On the other hand, voids, metal, and water features were detected.

6- There is a need to design new devices to use the pundit USW and the SFCW GPR in deeper depths. This point will be discussed later in the results and discussion.

7- The integration of the technologies will enhance the ability to detect and define the subsurface feature's type.

Finally, The experiment's hypothesis for the main experiment was: *“the integration of available sensors gives the ability to understand features' Characteristics, leading to detecting and distinguishing between several subsurface features.”*

Since the characteristics of the targeted feature with the available sensor were defined, listed, and converted to charts, **then the Hypothesis is accepted.**

Chapter 5: Proposed Design of ISMS

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Chapter 5 Proposed Design of ISMS

In order to design the Integrated Subsurface Mapping System (ISMS), an in-depth understanding of subsurface feature characteristics is needed. This chapter discusses how to utilize the feature characteristics shown in chapter four and produce a feature detection prototype. This prototype represents the backbone of the ISMS system. Then presents a UML chart for ISMS and the programming code. Lastly, the results of the ground verification experiment were discussed.

5.1 Integrated Subsurface Mapping System (ISMS)

This system is a prototype for detecting any subsurface feature if the feature characteristics (with the host type and available sensor) were defined. The system is designed based on the prototype experiment illustrated in Chapters 3 and 4 and literature research. However, as mentioned earlier, this system does not exist in literature nor industry. The system works in two phases; the first phase is a decision support system that recommends the most appropriate subsurface mapping methods and technologies based on specific inputs from the user. Phase two -based on the results of phase one- the actual mapping will occur within specific procedures. The final outputs of this phase are:

- 1- Scan lines in a time-space domain (profile view) using the sensors suggested in phase 1 for the area of interest, delineated and requested by the user. These scan lines will be used as input data to produce the other outputs. Samples of these outputs using GPR and USW devices are shown in Figure 5-1, Figure 5-2, Figure 5-3, Figure 5-4, and Figure 5-5.

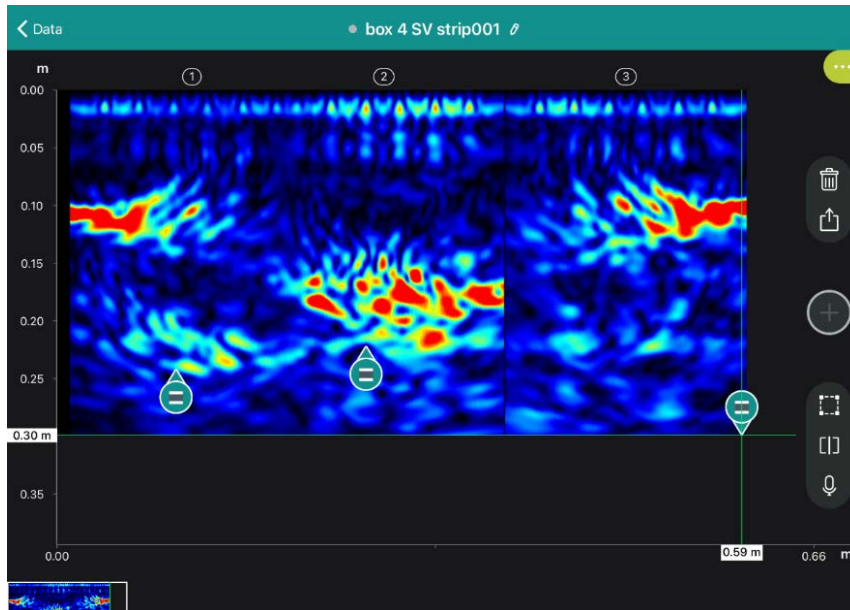


**Figure 5-1 Sample for Proceq Pundit Array Ultrasound wave
(Medium detection of voids at proposed location in Phase 1, Box 4, Line 2).**

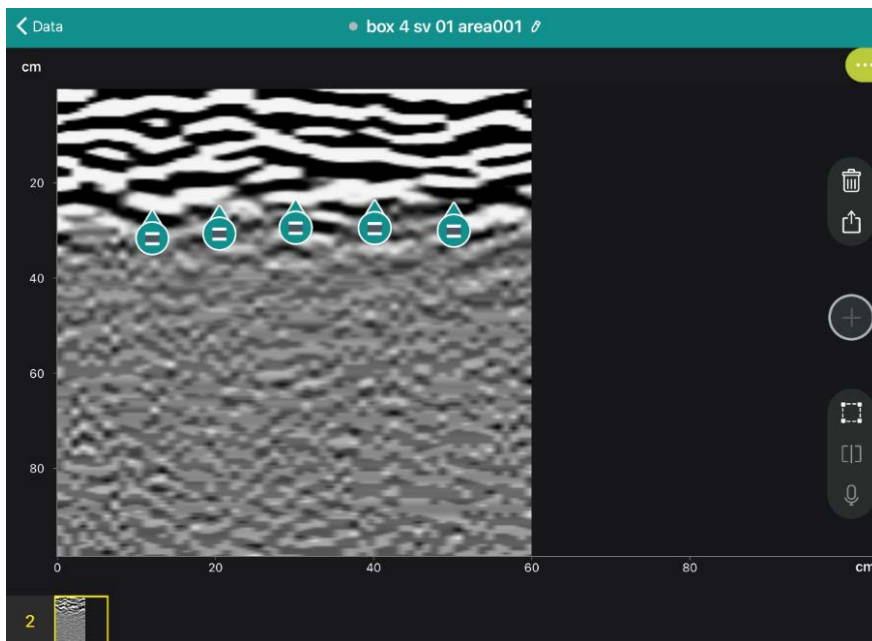


**Figure 5-2 Sample for Proceq Step Frequency GPR
(Void cannot be detected due to high noise in Phase 1, Box 4, line 2)**

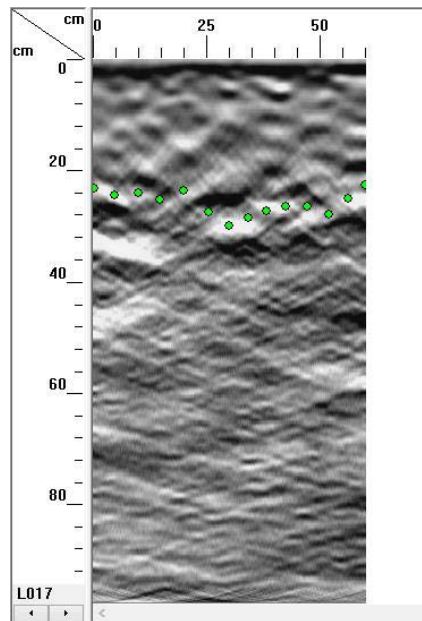


Figure 5-3 Sample for GSSI structural scan F= 2700 MHz
(Exported by RADAN 7: void's partial detection can be noticed.in Phase 1, Box 4, line 17)

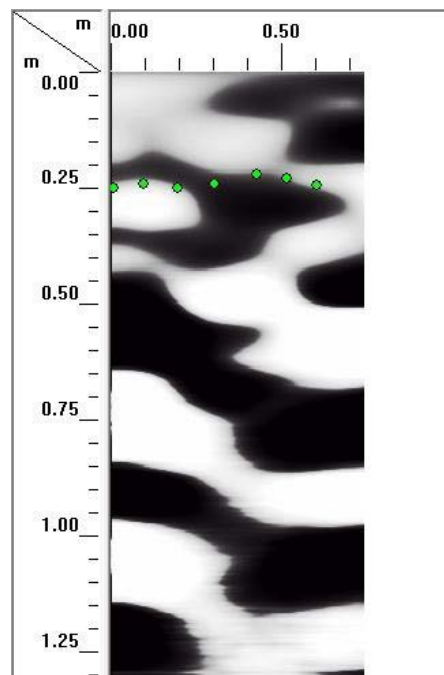


Figure 5-4 Sample for GSSI utilities F= 300 MHz
(Exported by RADAN 7: noise very high, detection is not possible in Phase 1, Box 4, line 2)

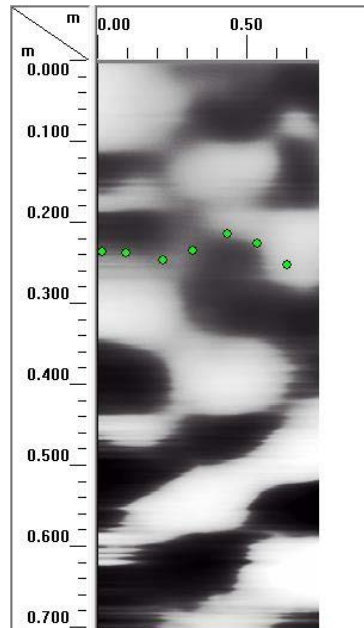


Figure 5-5 Sample for GSSI utilities F= 800 MHz

(Exported by RADAN 7: noise is very high; then detection is not correct in Phase 1, Box 4, line 2)

- 2- A 3D image for the area of interest is extracted from the profile. Similar to the image in Figure 5-6. This image is generated using advanced software or functions if the scan lines represent a grid.

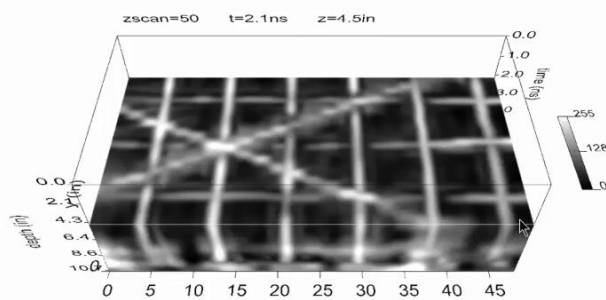


Figure 5-6 A 3D image extracted by GPR RADAN 7 software

(Rana, 2020)

- 3- A compatible GIS map for the located features contains their coordinates, the source of data, the scan line file name, and the

certainty of detecting this data as estimated by the technology used and the operator experience. This GIS map is generated by a combination of MATLAB code and ArcGIS. Figure 5-7 shows the attribute data extracted by MATLAB in excel format. Figure 5-8 shows these attributes for the shapefile in ArcGIS software, and Figure 5-9 shows the GIS map for the same attributes. The procedure to produce these maps will be discussed in section 5.3.

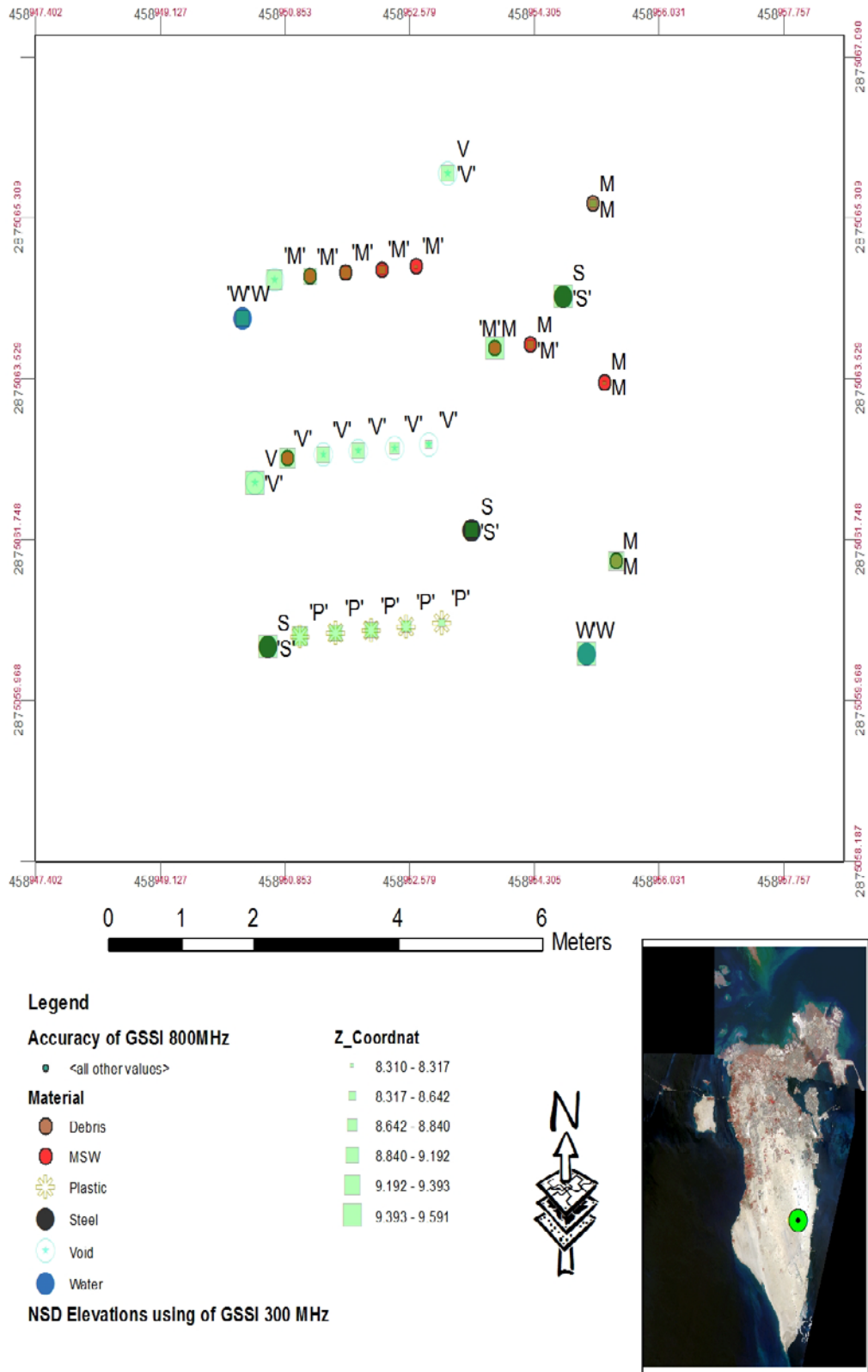
X	Y	Z	code	File Name	Tot Point in file	Feature	SUE
458952.6104	2875060.266	9.541666667	'S'	'P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG'	3	Steel	A
458952.6104	2875062.306	9.483333333	'V'	'P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG'	3	Void	B
458952.6104	2875064.246	9.008333333	'W'	'P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG'	3	Water	B
458952.3804	2875060.805	9.283333333	'P'	'P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG'	3	Plastic	B
458952.3804	2875062.716	9.391666667	'V'	'P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG'	3	Void	B
458952.3804	2875064.825	9.3	'M'	'P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG'	3	MSW	B
458952.1503	2875060.837	9.058333333	'P'	'P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG'	5	Plastic	B
458952.1503	2875060.867	9.041666667	'P'	'P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG'	5	Plastic	B
458952.1503	2875062.747	9.154166667	'V'	'P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG'	5	Void	B

Figure 5-7 Attributes output samples from MATLAB Code (Excel format)

Table																
Accuracy of GSSI 800MHz																
ID	Shape *	Fileindex	Filename	Totalpoint	Color	X. Coordinat	Y. Coordinat	Z. Coordinat	Phase	Time	Box	Line	Gain	K	Freq	Material
1	Point	1	P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG	3	S	458952.621	2875060.56	9.541667	4 Day	13	2	6	5	800	Steel	1
2	Point	2	P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG	3	V	458952.444	2875062.379	9.483333	4 Day	13	2	6	5	800	Void	1
3	Point	3	P4-DAY-B13-L02-G=06-K=5.0-F=800.JPG	3	W	458952.288	2875064.180	9.008333	4 Day	13	2	6	5	800	Water	1
4	Point	4	P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG	3	P	458951.987833	2875060.673611	9.283333	4 Day	13	3	6	5	800	Plastic	1
5	Point	5	P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG	3	V	458950.892167	2875062.645167	9.391667	4 Day	13	3	6	5	800	MSW	1
6	Point	6	P4-DAY-B13-L03-G=06-K=5.0-F=800.JPG	3	M	458950.7165	2875064.616722	9.3	4 Day	13	3	6	5	800	Void	1
7	Point	7	P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG	5	P	458951.550503	2875060.711417	9.058333	4 Day	13	4	6	5	800	Plastic	1
8	Point	8	P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG	5	V	458951.38475	2875062.68375	9.154167	4 Day	13	4	6	5	800	Void	1
9	Point	9	P4-DAY-B13-L04-G=06-K=5.0-F=800.JPG	5	M	458951.210917	2875064.656003	9.079167	4 Day	13	4	6	5	800	MSW	1
10	Point	10	P4-DAY-B13-L05-G=06-K=5.0-F=800.JPG	3	P	458952.0475	2875060.740222	8.897756	4 Day	13	5	6	5	800	Plastic	1
11	Point	11	P4-DAY-B13-L05-G=06-K=5.0-F=800.JPG	3	V	458951.871833	2875062.723333	8.952618	4 Day	13	5	6	5	800	Void	1
12	Point	12	P4-DAY-B13-L05-G=06-K=5.0-F=800.JPG	3	M	458951.696167	2875064.895444	8.857856	4 Day	13	5	6	5	800	MSW	1
13	Point	13	P4-DAY-B13-L06-G=06-K=5.0-F=800.JPG	4	P	458952.43003	2875060.787028	8.732618	4 Day	13	6	6	5	800	Plastic	1
14	Point	14	P4-DAY-B13-L06-G=06-K=5.0-F=800.JPG	4	V	458952.369917	2875062.760917	8.733167	4 Day	13	6	6	5	800	Void	1
15	Point	15	P4-DAY-B13-L06-G=06-K=5.0-F=800.JPG	4	M	458952.19975	2875064.734806	8.583541	4 Day	13	6	6	5	800	MSW	1
16	Point	16	P4-DAY-B13-L07-G=06-K=5.0-F=800.JPG	4	P	458953.027167	2875060.824833	8.534447	4 Day	13	7	6	5	800	Plastic	0
17	Point	17	P4-DAY-B13-L07-G=06-K=5.0-F=800.JPG	4	V	458952.8515	2875062.7985	8.634656	4 Day	13	7	6	5	800	Void	1
18	Point	18	P4-DAY-B13-L07-G=06-K=5.0-F=800.JPG	4	M	458952.675833	2875064.774187	8.2881	4 Day	13	7	6	5	800	MSW	0
19	Point	19	P4-DAY-B13-L08-G=06-K=5.0-F=800.JPG	2	S	458953.435333	2875061.850261	9.014614	4 Day	13	8	0	5	800	Steel	1
20	Point	20	P4-DAY-B13-L08-G=06-K=5.0-F=800.JPG	2	V	458953.195333	2875065.80125	9.022865	4 Day	13	8	0	5	800	Void	1
21	Point	21	P4-DAY-B13-L09-G=06-K=5.0-F=800.JPG	1	M	458953.765333	2875063.964770	9.540771	4 Day	13	9	0	5	800	MSW	0
22	Point	22	P4-DAY-B13-L10-G=06-K=5.0-F=800.JPG	1	M	458954.02003	2875063.90375	8.530622	4 Day	13	10	0	5	800	MSW	0
23	Point	23	P4-DAY-B13-L11-G=06-K=5.0-F=800.JPG	3	W	458955.024003	2875060.481011	9.524000	4 Day	13	11	0	5	800	Water	1
24	Point	24	P4-DAY-B13-L11-G=06-K=5.0-F=800.JPG	3	S	458954.712003	2875064.437167	9.562403	4 Day	13	11	0	5	800	Steel	0
25	Point	25	P4-DAY-B13-L12-G=06-K=5.0-F=800.JPG	3	M	458955.444752	2875061.5005	9.160399	4 Day	13	12	12	5	800	Debris	1
26	Point	26	P4-DAY-B13-L12-G=06-K=5.0-F=800.JPG	3	M	458955.285625	2875063.487056	8.278586	4 Day	13	12	12	5	800	MSW	0
27	Point	27	P4-DAY-B13-L12-G=06-K=5.0-F=800.JPG	3	M	458955.126456	2875065.465611	8.473605	4 Day	13	12	12	5	800	Debris	1
28	Point	28	P4-DAY-B13-L13-G=06-K=5.0-F=800.JPG	2	S	458955.821	2875060.56	9.58024	4 Day	13	15	12	5	800	Steel	1
29	Point	29	P4-DAY-B13-L15-G=06-K=5.0-F=800.JPG	2	W	458955.024003	2875060.481011	9.53	4 Day	13	15	12	5	800	Water	1
30	Point	30	P4-DAY-B13-L17-G=06-K=5.0-F=800.JPG	1	M	458955.444752	2875061.5005	9.177453	4 Day	13	17	6	5	800	Debris	1
31	Point	31	P4-DAY-B13-L18-G=06-K=5.0-F=800.JPG	1	S	458953.438333	2875061.850361	9.047817	4 Day	13	18	0	5	800	Steel	1
32	Point	32	P4-DAY-B13-L18-G=06-K=5.0-F=800.JPG	2	V	458955.444	2875062.379	9.509356	4 Day	13	19	0	5	800	Void	1
33	Point	33	P4-DAY-B13-L21-G=06-K=5.0-F=800.JPG	1	M	458954.288833	2875063.90375	8.619751	4 Day	13	19	0	5	800	MSW	1
34	Point	34	P4-DAY-B13-L21-G=06-K=5.0-F=800.JPG	1	M	458955.285625	2875063.487056	8.286033	4 Day	13	21	0	5	800	MSW	1
35	Point	35	P4-DAY-B13-L22-G=06-K=5.0-F=800.JPG	1	M	458953.765333	2875063.964770	9.518033	4 Day	13	22	6	5	800	MSW	0
36	Point	36	P4-DAY-B13-L23-G=06-K=5.0-F=800.JPG	2	W	458955.026	2875064.180	9.016667	4 Day	13	23	6	5	800	Water	0

Figure 5-8 GIS attribute for the layer of data collected of GPR 800MHz

Ground Verification Results



5.1.1 ISMS Procedures

The first step to illustrate the procedures of ISMS is to define its goals. Then, to mention the ISMS components. These information will be inserted in a Unified Modelling Language (UML) diagram. This diagram can be programmed and built by any programmer.

5.1.1.1 ISMS's goals:

This ISMS is intended to do the following:

- 1- Determine the best combination of devices to integrate to find and locate the MSW, voids, and plastic features.
- 2- Determine the proper procedures and steps to achieve the first goal.
- 3- Produce the following outputs:
 - a. Time space-domain profile view for every scan line (if needed). As shown in Figure 5-1, Figure 5-2, Figure 5-3, Figure 5-4, and Figure 5-5.
 - b. 3D time-space view as shown in figure Figure 5-6.
 - c. GIS-compatible maps can easily be integrated with other theme maps for spatial and non-spatial analysis, as shown in Figure 5-9.

5.1.1.2 ISMS UML Components:

The main components of this system are:

- 1- Targeted features (Objects to be mapped).
- 2- Host material where the features are located (type, moisture contents, dielectric properties, and other conditions)

- 3- Methods, techniques, and types of equipment that would be used for mapping (Proceq SFCW GPR, GSSI GPR, or Proceq Pundit Array Ultrasound)
- 4- Mapping procedures or the steps to be followed.
- 5- Required certainty (A, B, C, and D as adopted in SUE standards).
- 6- The final product (GIS map, 3D images, and time-space domain profile)

The first three components will be considered classes in the UML diagram, where the rest will be activities. The UML classes diagram is shown in Figure 5-10. These components are essential, and minor changes could be applied to them after completion.

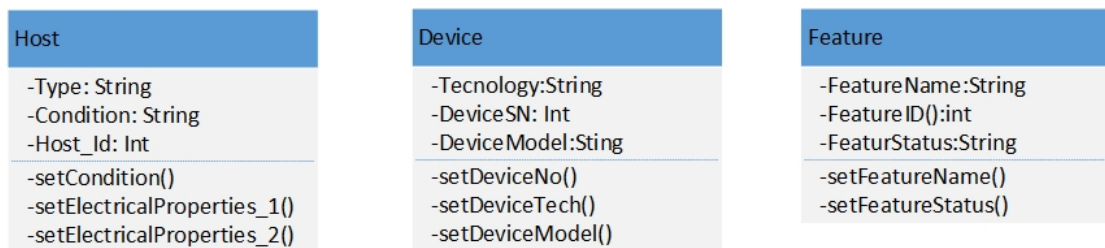


Figure 5-10 ISMS classes in UML

5.1.1.3 The ISMS Algorithm

The ISMS's algorithm starts from one of the two following scenarios shown in the general flowchart for detection procedures as in Figure 5-11:

- 1- The feature characteristics are not defined: then the prototype experiment mentioned in chapter three must be applied in similar procedures to detect the feature characteristics. In this step, either a new feature could be used or new sensors.

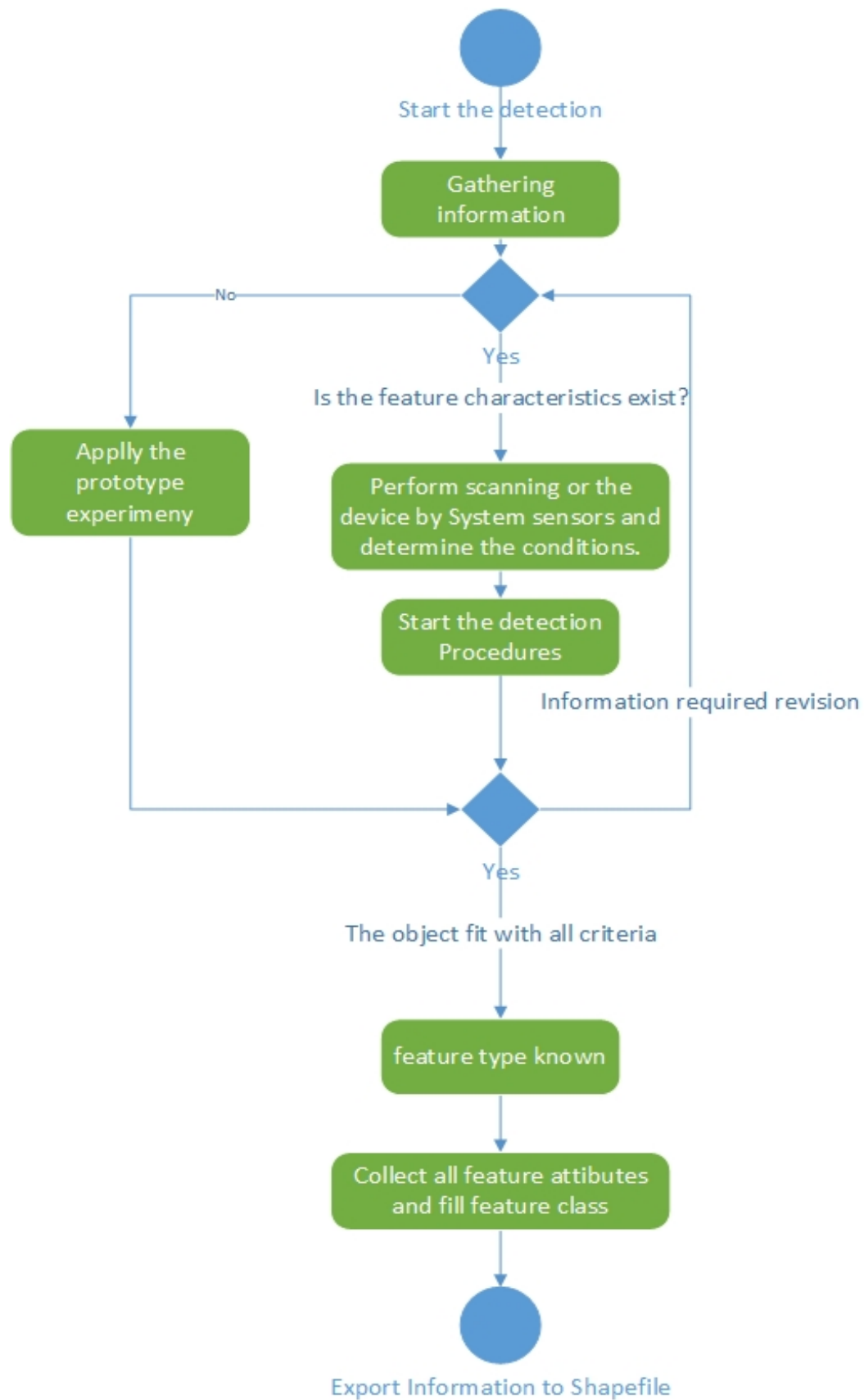


Figure 5-11 Flowchart for general detection procedure

- 2- The feature characteristics are defined, then the steps depending on the existing feature characteristics and available devices are to be followed.

For the first scenario, the features characteristics are not defined, such as the electronic, toxic, and construction waste, black water and gasoline dissolved in soil, or any other feature that has not been mapped before. Then, the experimental prototype shown in Figure 5-12 will be applied.

This prototype starts by answering several questions. These questions are important to determine the number of boxes for each feature in the experiment. Also, the user should not know the answer to all questions. These questions are as follows:

- 1- What is the feature to be investigated?
- 2- What are the sensors to be used? Means: what are the available sensors?
- 3- Is the host a homogenous medium (one type of soil) or combined materials? Are they common (known) materials? Is it compacted or not?
- 4- What is the moisture content in these hosts? Is it a dry, wet, or saturated host?
- 5- What is the expected depth range to find the features?
- 6- Are the features located in lines, areas, or points?
- 7- What are the expected features' dimensions?

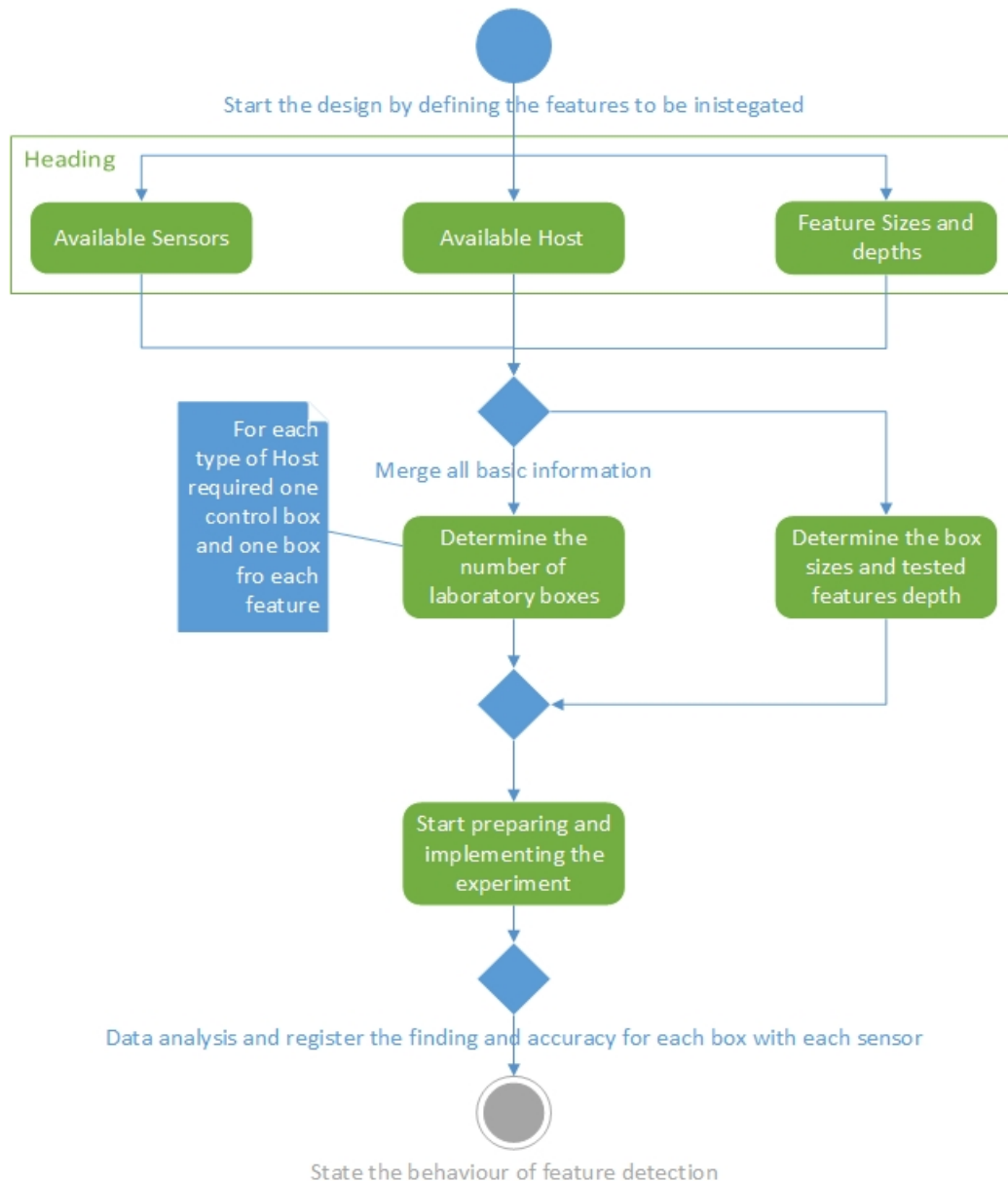


Figure 5-12 General experiment prototype to be followed.

Based on the previous questions, the lab or the experimental conditions to study the feature characteristics can be designed, prepared, and implemented. The first two questions are general questions to define the variables to be detected (feature) and the dependent variable to be measured (the detection availability with each sensor). The rest of the questions are designed to define the independent variables that need to be changed during the experiment (host, moisture content, temperature, and depth).

The charts in **Appendix B** show the detecting results likelihood depending on changing two independent variables, moisture content and host type. In addition, the charts in Figure 5-13, Figure 5-14, and Figure 5-15 represent the available detection depending on host type dry, saturated, wet, respectively. Thus, these charts show the likelihood of detecting features in each host.

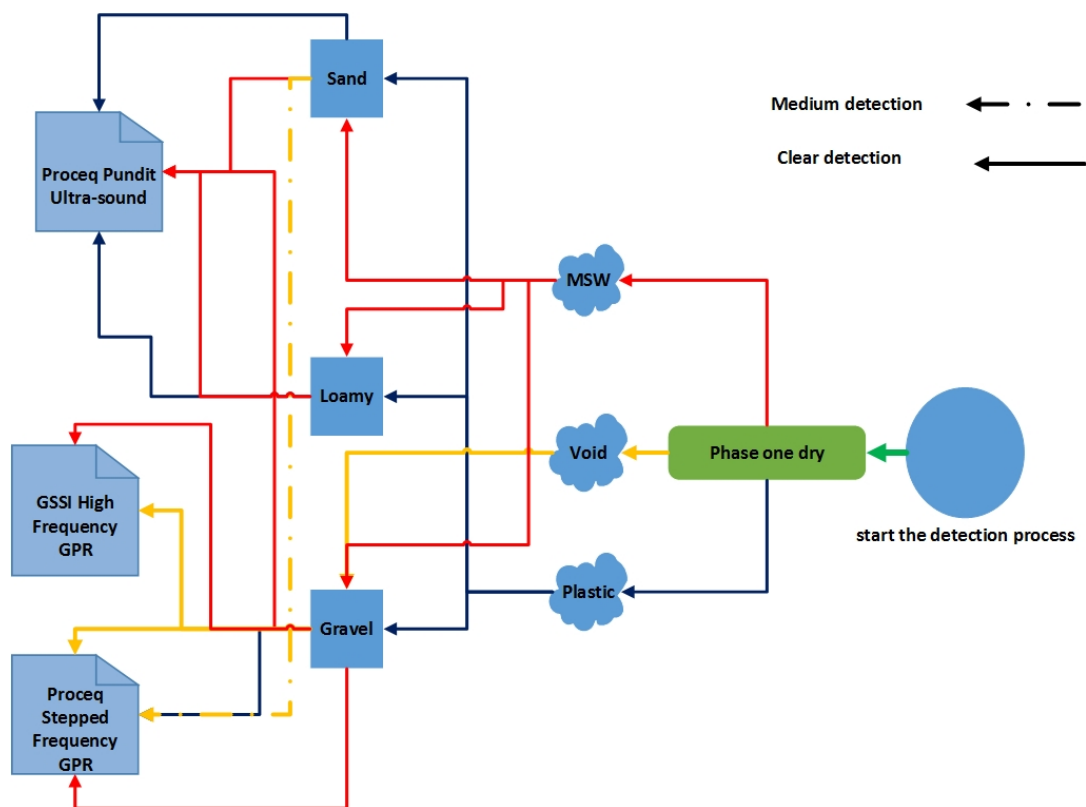


Figure 5-13 Dry host detection chart

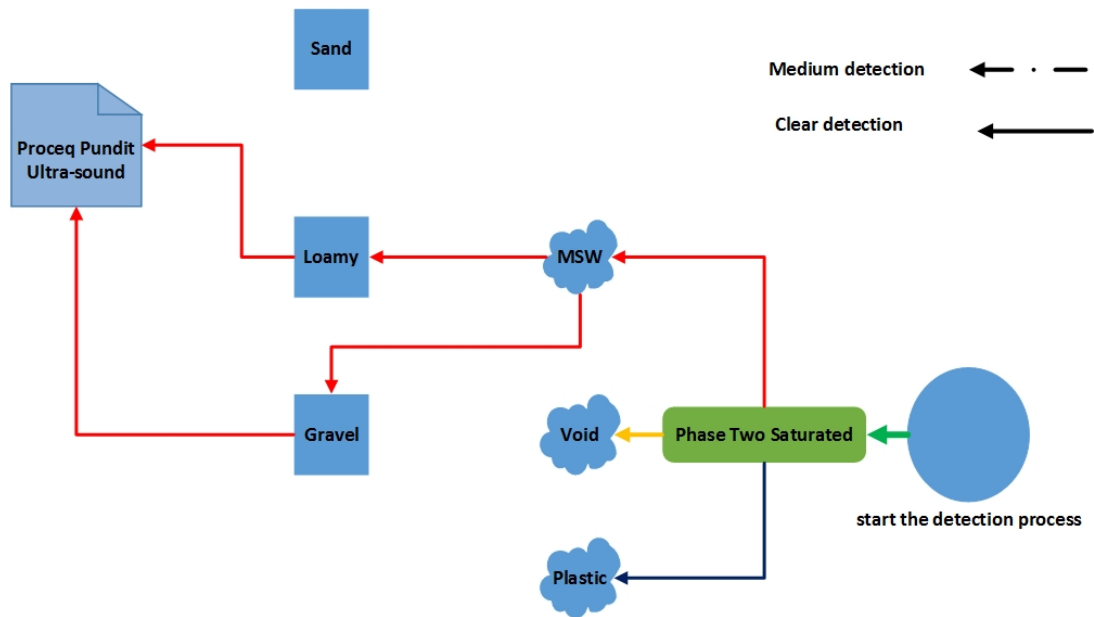


Figure 5-14 Saturated host detection chart

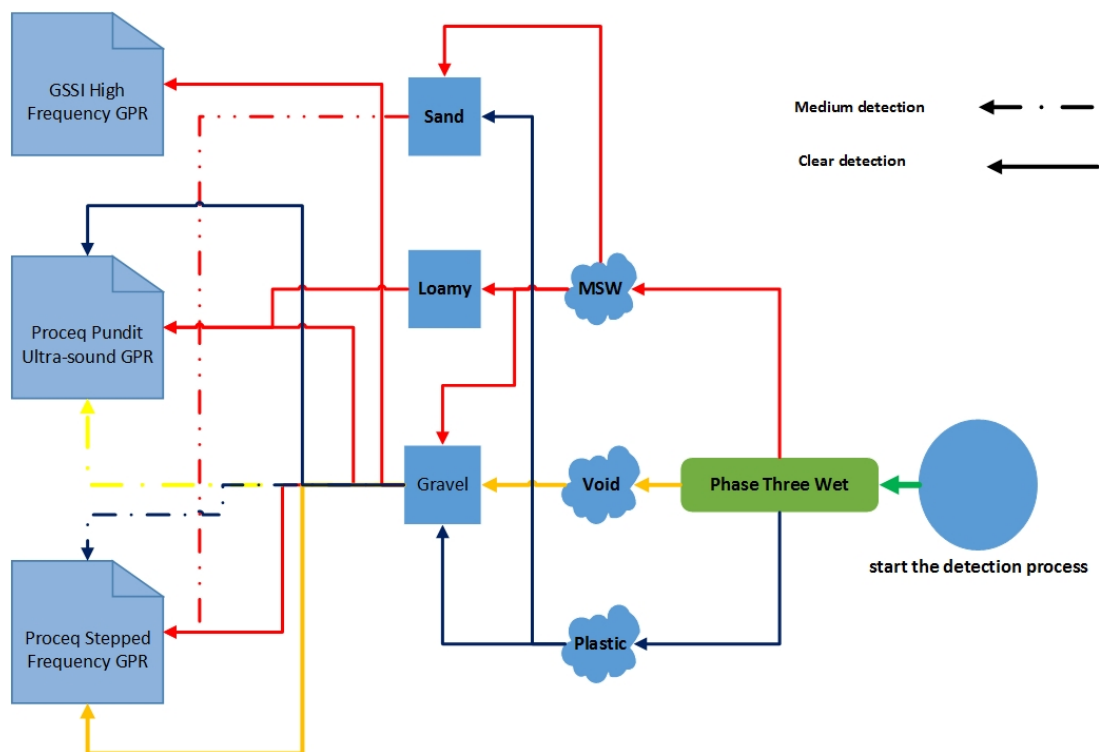


Figure 5-15 Wet host detection chart

After defining the feature characteristics, the general ISMS flowchart in high-level UML shown in Figure 5-16 could be applied. This flow chart represents the steps the user might follow to detect the targeted features. The designed prototype will state the steps that

the user must follow to locate a specific feature or to determine if he can be detected or not. Also, it gives him the capability to know the best practice procedures of detecting. The ISMS, after compilation in a programming language such as VB.Net, Python, or C#. will be considered a decision support system for subsurface feature detection.

As shown in Figure 5-16, the procedure started by defining the user's needs. The first examination is to check if the targeted feature characteristics are defined. Then, based on existing characteristics, the examination is performed on the data entered by the user. If the characteristics are enough, the system will put the procedure to detect the targeted feature, the sensors to be used, and the scanning process. If the data is not enough, the user might add a new sensor for the detection. After scanning the investigated area, the files where the detected features are located will be converted to a spatial layer, as shown in the next section.

This system guides the user from starting his project until converting the survey results into a GIS-compatible map. This system does not require any experience from the user on geophysical engineering as the traditional case unless he will do the feature locating by himself. In addition, the system products will be feasible in cost estimating the subsurface mapping project because it gives the user the information about the requirements to detect the features.

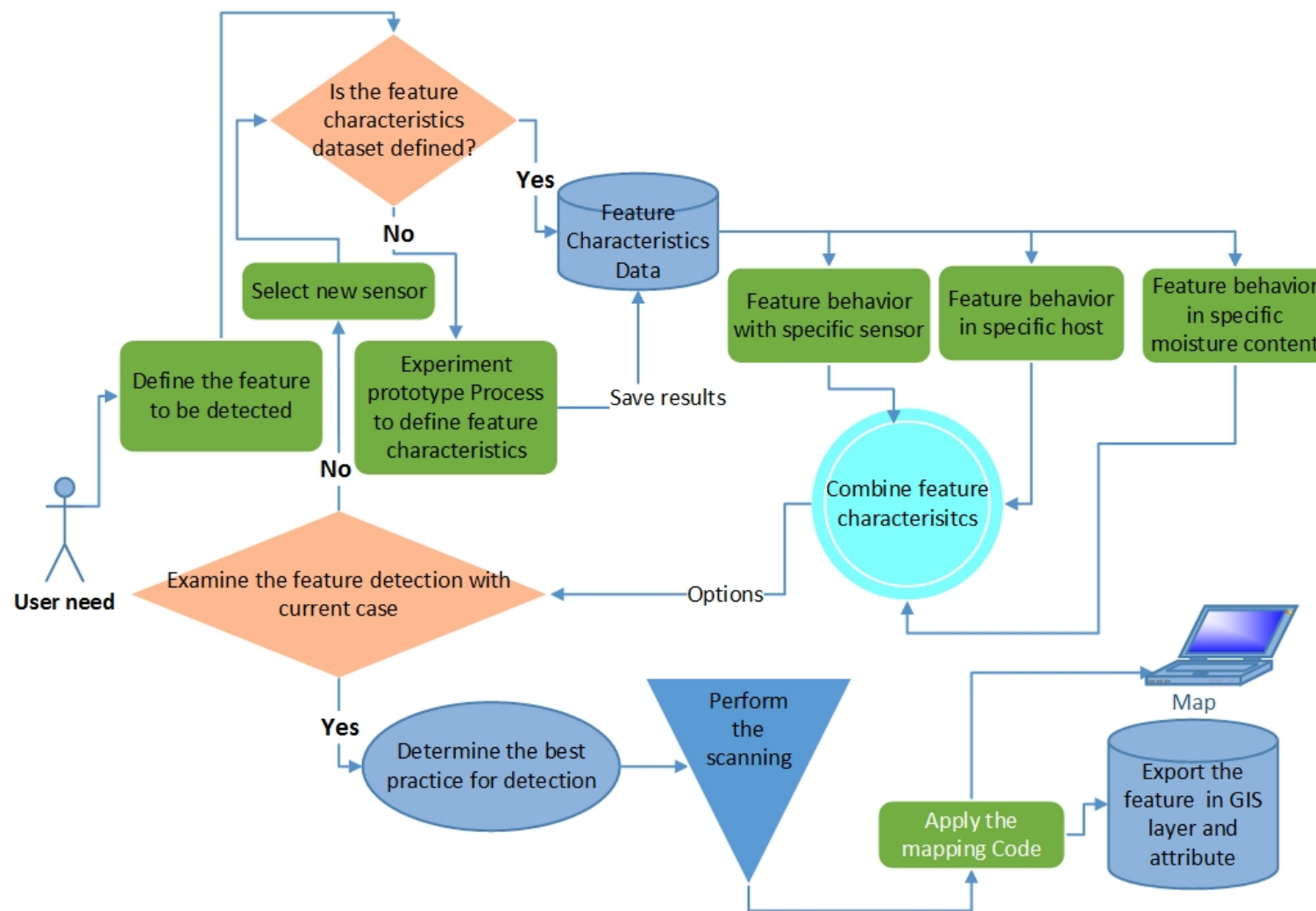


Figure 5-16 UML high-level chart for ISMS detecting procedures

5.2 ISMS Software Development

The initial inspection results are profile images in two dimensions (2D). The corresponding images of specific scanning paths show the locations (in X, Y plan) in the scanning direction and the Z coordinate in depth from the surface. These results are the input to create a GIS-compatible map using MATLAB code and ArcMap (the desktop product of ArcGIS package from ESRI company). MATLAB was selected because it is available licensed in the University of Bahrain, easy, and accessible.

The first step was to define the actual coordinates for each location and GIS data model (point, line, or polygon). These are the necessary spatial information to build a GIS-compatible map. All other information such as object type, instrument type, and any additional technical information about the object is considered nonspatial data registered in a database (mainly the excel sheet in this code).

The spatial mapping starts by converting the detected features and designed points marked by the user in the extracted images from the GPR and ultrasound devices from raster data to vector data. For example, there were five colored points in GSSI - RADAN 7 exported images. These points either represent a point object or a line object.

Figure 5-17 shows the general flowchart for how the scanned lines have been digitized and converted to a GIS-compatible map. This flow chart contains two MATLAB code procedures to digitize the inspected features and convert them to shapefiles (or Excel sheets). The flowcharts for these codes are illustrated in Figure 5-18 and Figure 5-19 for Proceq and GSSI data. These two codes are illustrated in **Appendix A**.

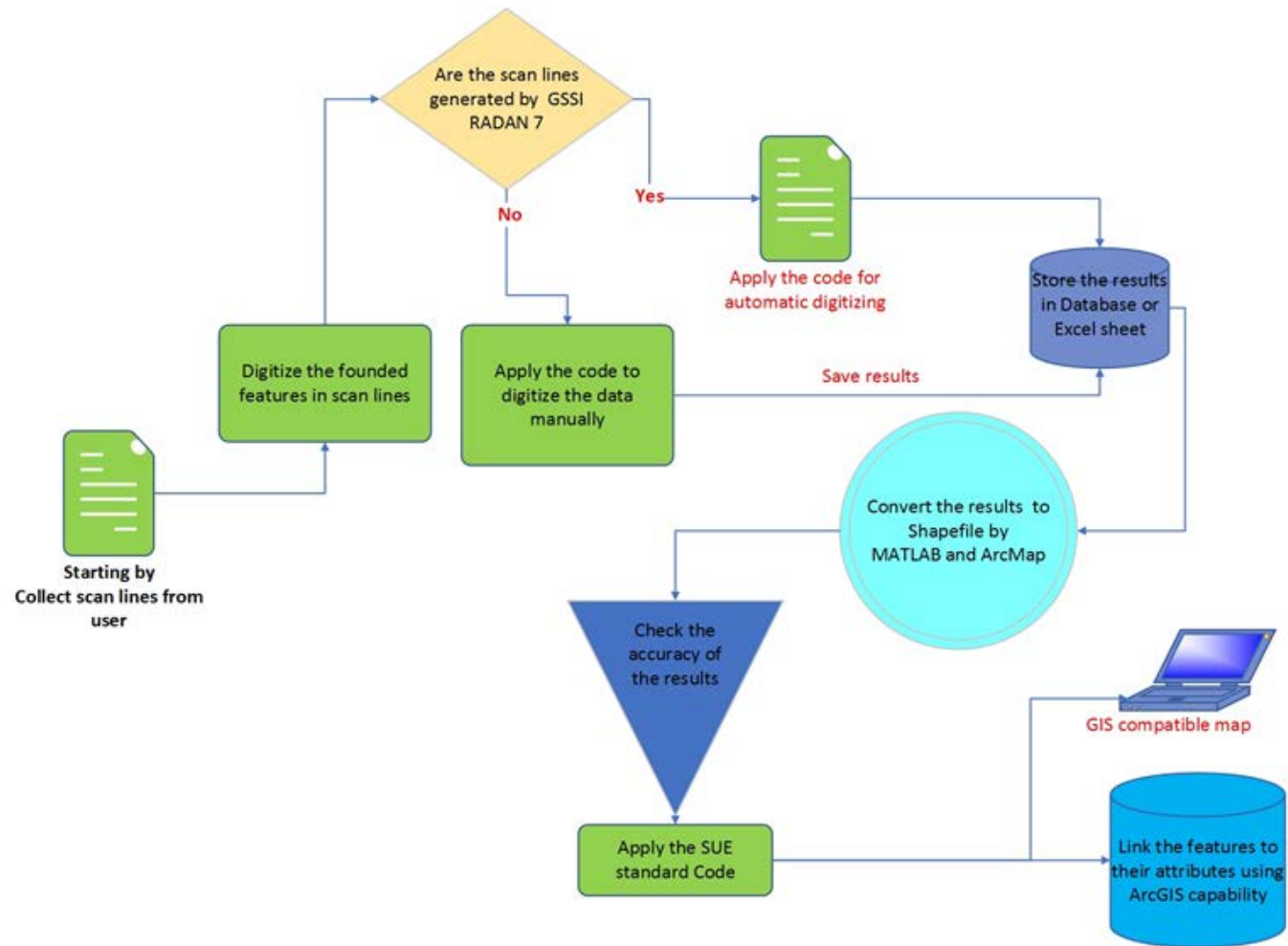


Figure 5-17 Flowchart for the steps of producing a GIS map using MATLAB and ArcGIS

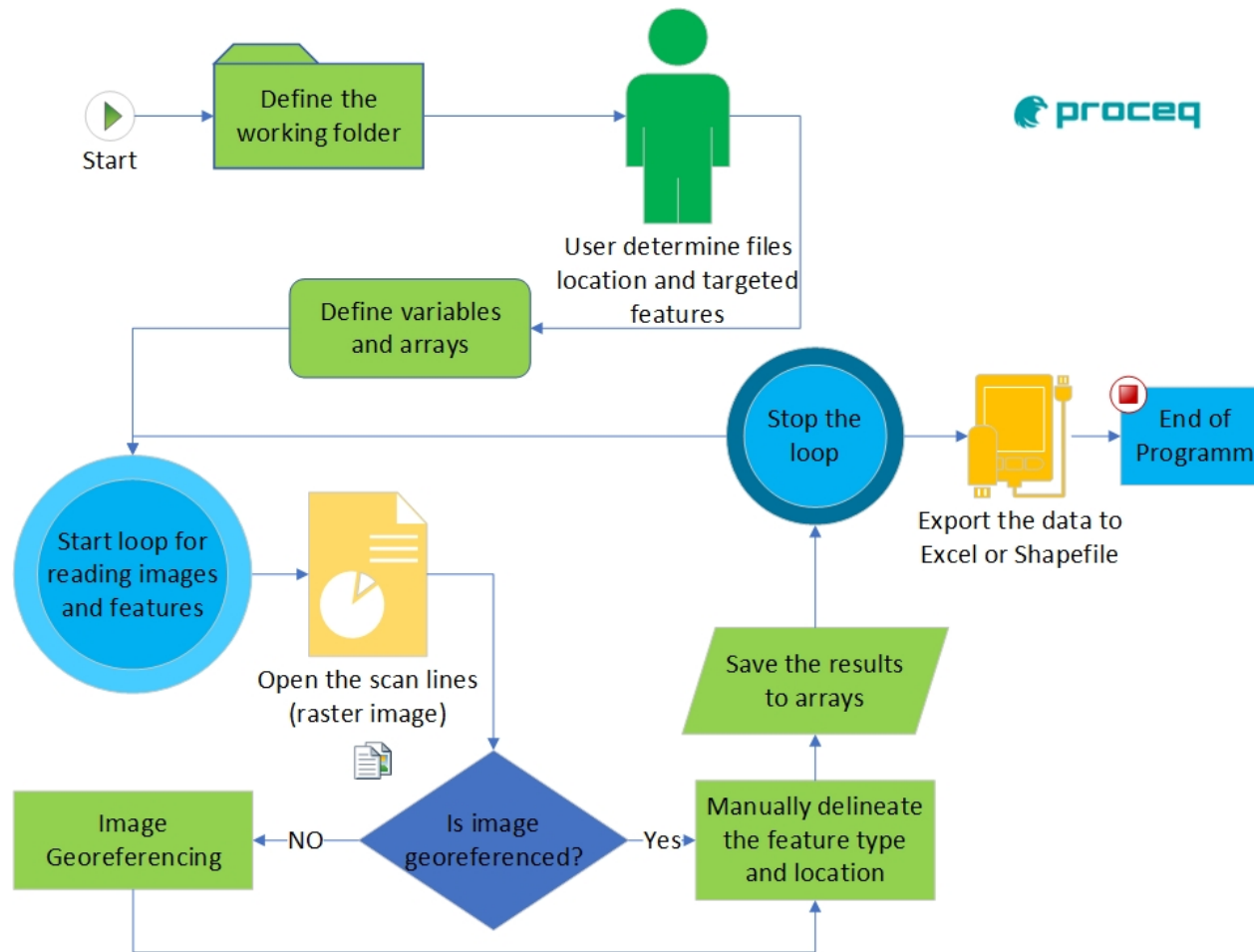


Figure 5-18 Flowchart for MATLAB code to convert Proceq data to Shapefile

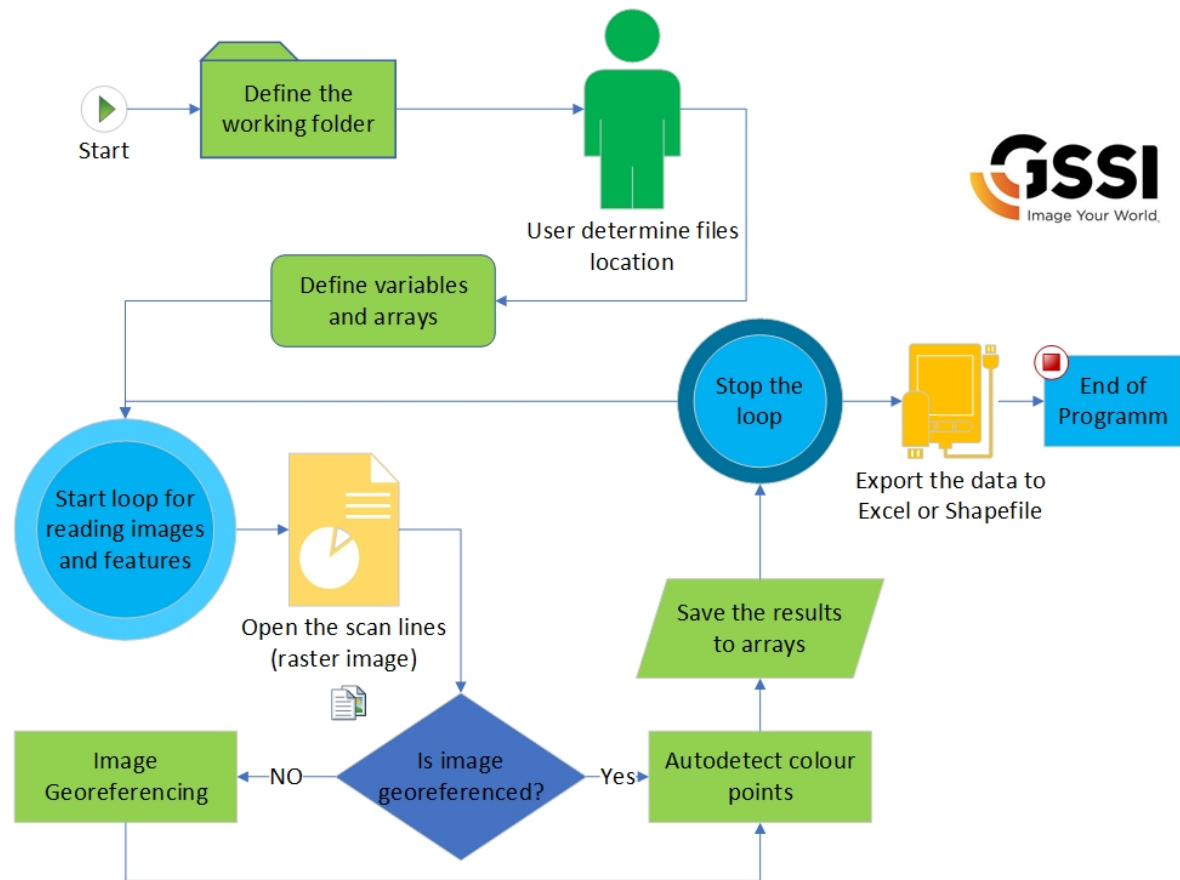


Figure 5-19 Flowchart for MATLAB code to convert GSSI data to Shapefile

The main output of this programming is the 3D geodetic spatial coordinates (East, North, and Elevation) of the targeted object with extra information (attributes) related to it; the source of the data (sensor type), file name, phase number, box number, line number, the inspection time (day or night), the gain, the frequency for GSSI GPR, dielectric properties, the type of filter used if any, the feature type, and certainty.

For the GSSI GPR data, the conversion of point locations was automatically done using the MATLAB code. However, the points from Proceq devices (where the symbols were more prominent and had specific characteristics) were digitized using another MATLAB code. The code results will be an excel file containing all spatial and nonspatial information that could be opened by any GIS environment and converted to spatial files or directly to a shapefile using a MATLAB function.

Finally, a comparison between the detected object using several technologies was performed. The accuracy of locating targeted features will be determined by comparing the location for the same feature in different scan lines (different sensors) if available.

Figure 5-7 shows a sample of the output generated by MATLAB code. The sample contains the file name, the coordinates, the code for the feature that leads to feature type, and the SUE code. The table and attribute were converted to a GIS shapefile and Thematic layer using ArcMap software, as shown in Figure 5-9. The work will continue after the research to be done automatically using programming code by WinMapGIS (an open-source software).

5.3 Ground Verification

Ground verification represents a significant part in assessing the successfulness of the proposed system. Therefore, the ground-truthing

was done partially during the enhanced experiment. Although the enhanced experiment was done to complete some part of the main experiment, it has another two goals; firstly, it acts as a benchmark in determining the proposed system capabilities to assess the accuracy of mapped features. Secondly, it assesses the system's potential to map uncharacterized features. At the same time, adding uncharacterized features in this experiment paves the roads for adding new features and sensors in the future when possible. The results of this experiment that listed in Table (4-8) was converted to a flowchart, as shown in Figure 5-20. The results of ground verification will be discussed in more detail in the next chapter.

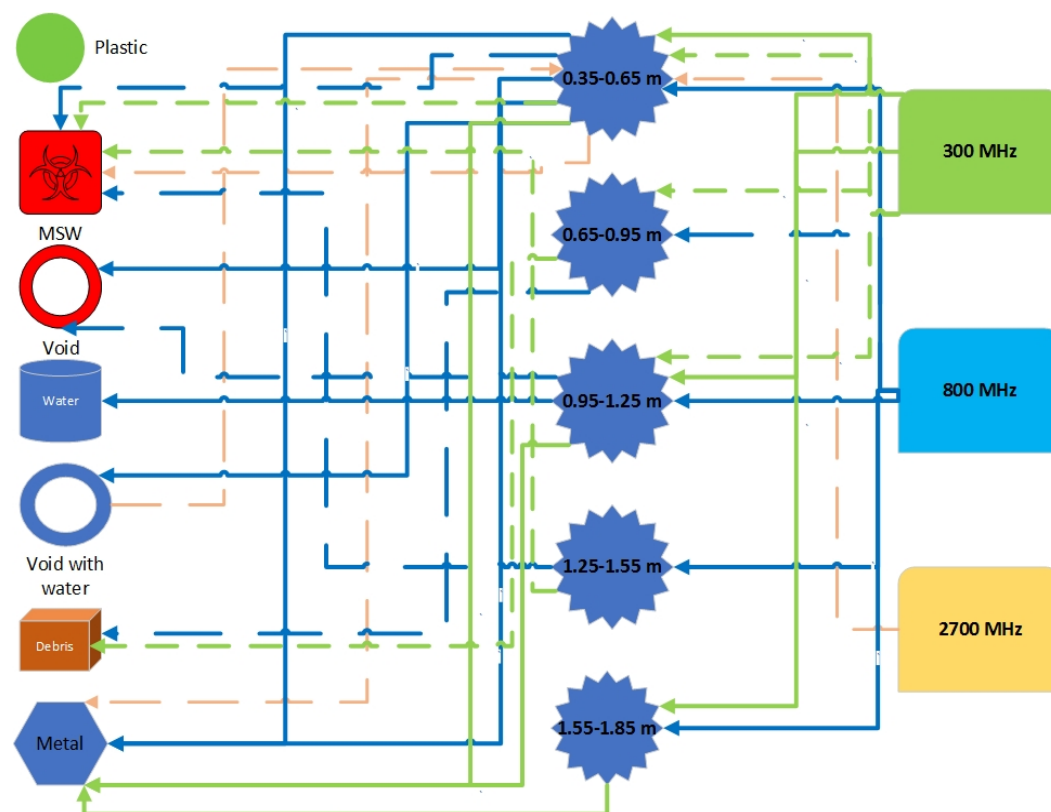


Figure 5-20 Enhanced experiment results in a flowchart

The red lines in this chart represent the detection in high-frequency GPR, the blue lines represent the medium frequency (800 MHz), and the green lines represent the low-frequency GPR (300 MHz). The continuous

line represents a clear detection, while the dashed line represents weak or medium detection. The numbers inside the blue stars show the inspection level (the subsurface feature location). Finally, the icons on the left are the inspected (targeted) features. The dashed lines to MSW mean it has weak to medium detection in the dry host used in the enhanced experiment, which complies with the results obtained in the main experiment. Unfortunately, the Proceq devices were not available in the ground-truthing to cross-check and confirm the ability to detect the MSW using the Pundit Array (USW) device.

5.4 Summary

This chapter started by discussing ISMS's goals, procedures, and algorithms. Then ISMS software development using MATLAB and ArcMap GIS was briefly illustrated. Lastly, the results of Ground verification were discussed.

Chapter 6: Results and Discussion

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Chapter 6 Results and Discussion

This chapter highlights: the main research findings, obtained results, in-depth discussions, and the limitations – obstacles and proposed possible solutions.

6.1 Findings in Literature and Industrial Search

The literature review shows that no single technology or technique can locate, map, and identify most subsurface features (Rana, 2020). Although the technologies' accuracy varies and is getting updated and improved, there are still limitations preventing reliable detection. Nevertheless, these findings comply with the industries experts' recommendations to integrate several technologies to achieve the goal and scope of surveying work. The integrations available such as those mentioned in the second part of Table (2-6), were designed to meet the inspection goals (project perspectives). In other words, there is no available methodology or procedure that guides users to determine the best technology integration that would yield the best results.

Most literature and industries projects discussed the locating and mapping subsurface utility features, such as the British project called mapping the underworld. In addition, the integration likelihood and accuracy assessment were developed to enhance utility mapping techniques. This research aimed to study these technologies and determine the possibility and feasibility of locating, identifying, and mapping other subsurface features.

The industries and technologies developments focus on concrete inspection because it is a rigid field. Therefore, the technologies reach a high level of confidence in mapping and identification. This confidence refers to the specification of the concrete environment, which is rigid and

less affected by surrounding and environmental conditions. Therefore, integrating SFCW GPR and ultrasound wave technologies is recommended to inspect and map the concrete defects and reinforcement locations. On the other hand, subsurface mapping inside the soil is more complicated than concrete. Therefore, more technologies were utilized in soil subsurface mapping. Table (2-9) mentioned some of these technologies. However, utility, subsurface structure, and archeological mapping are maturing. Nevertheless, many issues are still involved, namely-identification issue remains a challenge.

There are not enough studies or research for locating and mapping the MSW, hazardous and/or toxic waste, gasoline and other oil products, and black water in the soil. Most of the available literature and industrial projects aim to locate utilities, buried metal objects (barrels), shallow tombs in archaeological studies, or any shallow subsurface structure. GPR is the most common method used throughout the industry for near subsurface mapping in civil engineering. However, it might be integrated with other techniques to achieve better results.

Finally, the accuracy and reliability of the geophysical techniques depend heavily on the user's and the analyst's experience about the technologies and the study area. (Rana, 2020)

6.2 Results of Experiments and ISMS

Firstly, the thermal experiment was considered a separate experiment even it was done during the primary thesis experiment. The first result of this experiment is that: there is an ability to detect the released heat and temperature changes for near subsurface features using the IRT. In addition, the first months of laying, dumping, and burying MSW material are better to locate them using IRT. Also, several factors

affect the emitted energy from MSW, such as the amount of waste, the depth, and packaging (if the MSW is in bags or loose). As the depth increases, the energy decreases. As the amount increases, the energy increases. Also, if the MSW is in loose condition will release more energy. Finally, the suspected area must be monitored for 6-8 weeks to locate the heat released from subsurface materials successfully.

On the other hand, the primary experiment representing the backbone of this research finds that the characteristics of subsurface features could be obtained and saved in a proper database, similar to the spectral signature of RS objects and sensors. These characteristics could be used later to set the detection procedures. In addition, the integration of using SFCW GPR and Ultrasound waves represent a good practice to locate and identify the MSW. Besides, Ultrasound waves technology represents an excellent option to locate the subsurface features in saturated soil. These results will be discussed in the next section.

In addition, the enhanced experiment is the part that integrates incomplete issues from the primary experiment. In addition, it is considered a ground verification experiment. The first result of this experiment is that the better detection was with the impulse GPR medium frequency. This frequency has a better resolution for the targeted depth of 0.5-2.0m from the surface. This result is due to the long-wavelength of low-frequency GPR (44 cm). Referring to Table (4-3), the smallest feature detected with low frequency is >11cm, and 5cm by medium frequency. On the other hand, the high-frequency GSSI impulse GPR could not detect features below 80cm because it was designed to work in the concrete host. Finally, the MSW has not been detected on the dry soil because the MSW is recently buried (not been decomposed yet). Besides,

it has low moisture contents. On the other hand, the debris was detected due to air gaps, concrete, and other construction materials.

The new system ISMS represents the core of this research. This system aims to find procedures to facilitate and enhance the subsurface feature mapping. This goal fills the gap shown before in the literature results. The proposed prototype of ISMS focused on MSW, voids, and plastic due to their massive effect and potential hazard on civil engineering construction. This proposed system puts the foundation for a novel decision support system that facilitates the detection procedures. The UML charts in previous chapters represent the basics of developing a DSS to help the user select the technologies and the procedures to locate the features of interest.

Lastly, Using the MATLAB code developed in ISMS, the features in the enhanced experiments were mapped, as shown in Figure 6-1. This figure's results are considered ground verification by comparing the detected features with their designed and as-built locations measured by GPS. The verification leads to assessing the features' detection accuracy using the available devices. For example, it could be noticed in Figure 6-1 that only six features were detected using high-frequency GPR due to the shallow penetration depth of this device in this zone of the electromagnetic spectrum. On the other hand, the slope plastic feature is clearly identifiable with medium and low-frequency bands. Furthermore, the water features and debris were detected, and the MSW has medium to weak detection using these bands. These results will be discussed in the next section.

Ground Verification Results

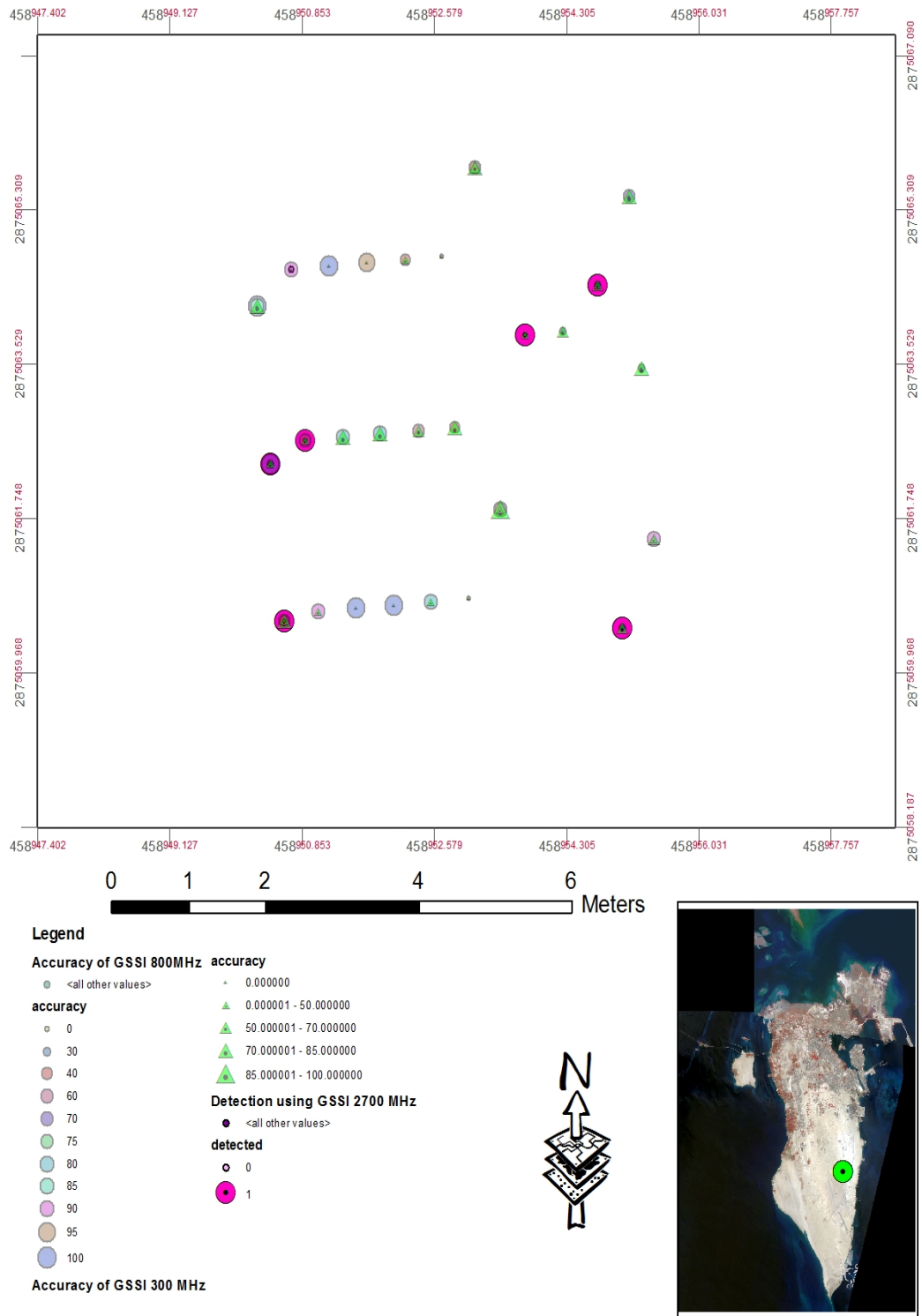


Figure 6-1 Ground verification accuracy percentage

6.3 Discussion

6.3.1 Results Induction

Before discussing the results of material characteristics and the findings, the following clarifies the relation between the factors that affect the scanning and locating subsurface material. The dielectric properties (K-value) represent the main factor affecting the GPR penetration and feature locating. The changes in K-value lead to an increase in waves reflection. The more electromagnetic wave reflection, the more electromagnetic contrast (C_e), the easier to distinguish between subsurface anomalies and better detection. Furthermore, the frequency and moisture contents affect the K-value: The K-value decreases as the frequency increases, as shown in Figure 6-2 (A graph extracted from Table (4-2)).

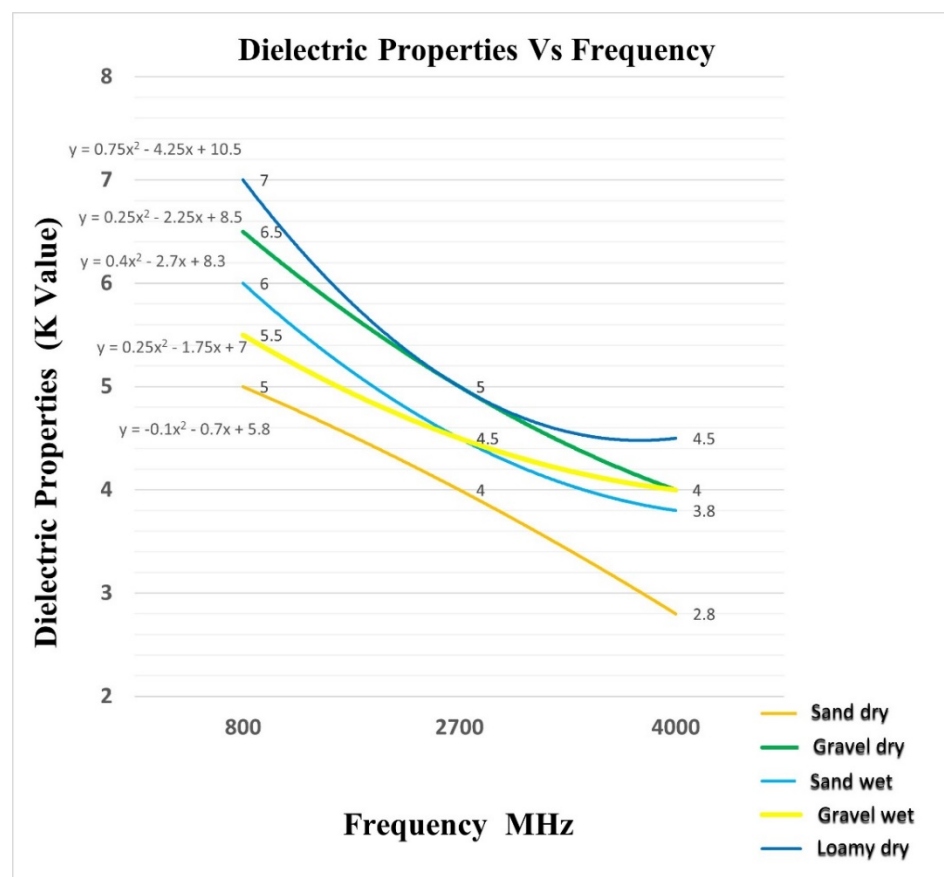


Figure 6-2 Dielectric Properties Vs. Frequency

Also, the K-value increases as the moisture content increases, as shown in Figure 6-3. In this figure, the saturated soil and wet loamy soil are not shown because the K-value for these hosts is from the literature and approximated. However, the dielectric permittivity (K-value) is independent of the material's conductivity, as mentioned by (Campbell, 1990).

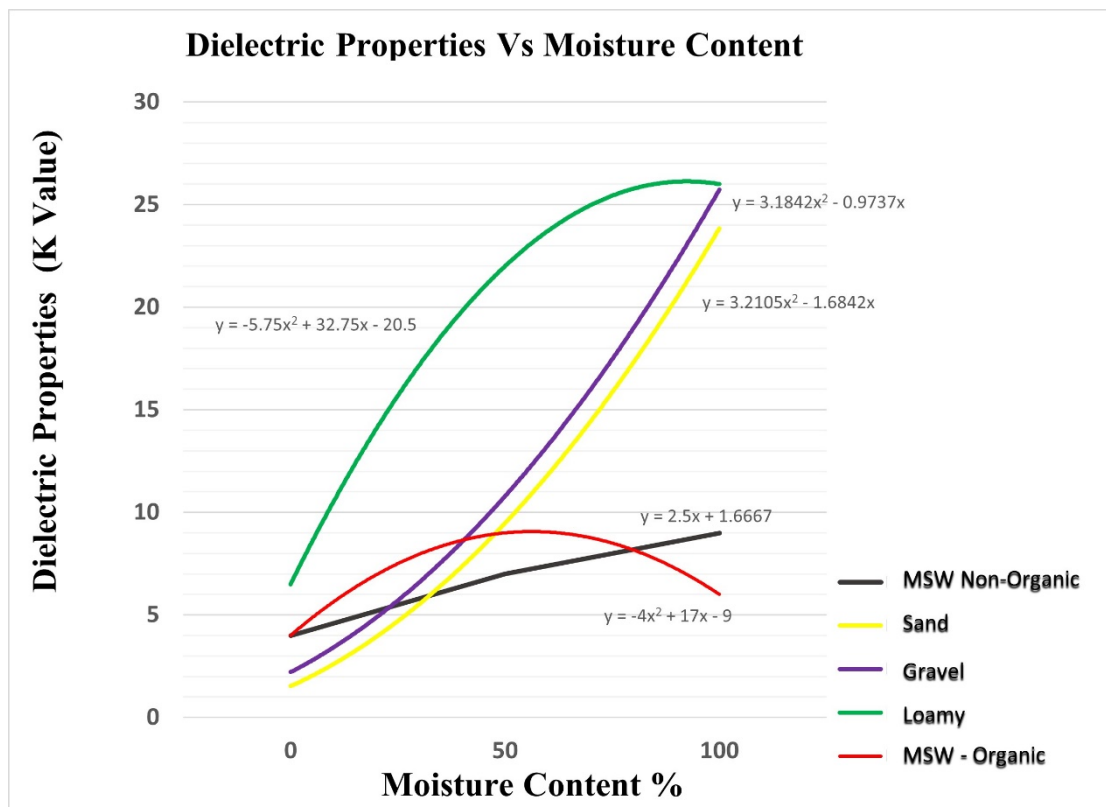


Figure 6-3 Moisture content vs. the dielectric properties of soil

The electrical conductivity (EC) also affects the penetration and wave scattering. EC in soil depends on both the moisture and the amount of salt. As salinity or water content increases, EC increases. The increase in EC causes to raise the attenuation and scattering of electromagnetic waves and prevent deeper penetration. This prevention, in turn, reduces the detection and increases noise.

The detection contrast using USW depends on the change in the sound wave and density through different materials, as shown in equation 2-15. Since the samples in this research have the same density for the same host, this factor could be neglected. Thus, sound velocity is the most critical factor to distinguish between subsurface features. The sound velocity contrast (C_v) depends on the moisture contents. As the moisture increases, sound velocity decreases, as shown in Figure 6-4. As mentioned in the literature in chapter two, the shear wave velocity is always less than longitudinal velocity.

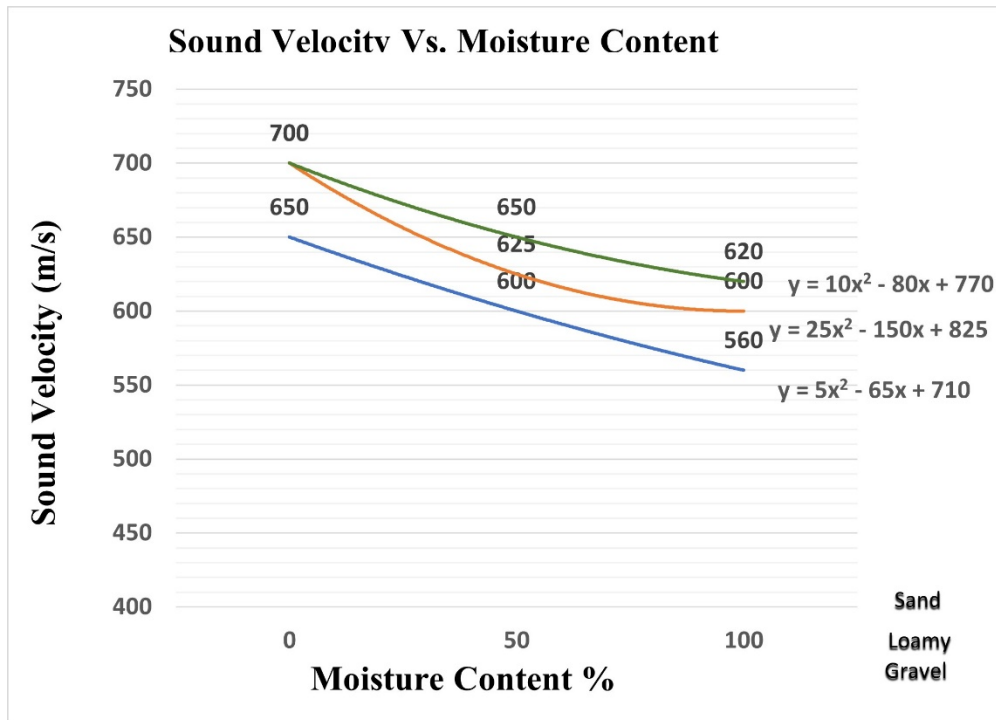


Figure 6-4 Relation between a shear sound wave and moisture content

The previous relation can be expressed on the following mathematical functions to simplify the relation between object detection (C_e and C_v) and the affecting factors (frequency (f), EC, moisture contents (MC), Sound Velocity (V_s), object density (ρ), and the dielectric properties (K)):

$$Detection_{Electromagnetic} = \begin{cases} C_e \propto K \\ C_e \propto \frac{1}{EC} \end{cases}$$

Where

$$K \propto \frac{1}{f}, \frac{1}{MC}, EC \propto S, MC, \text{ and } S = \text{Salinity}$$

$$Detection_{Ultrasound} = \{C_v \propto Z$$

where

$$Z: \text{Sound Impedence } Z \propto \rho * MC$$

Since ρ is designed to be fixed, then

$$C_v \propto \frac{1}{MC}$$

Based on the previous clarifications, the MSW can be detected in dry and wet gravel soil using all devices because of the C_e between the dielectric properties of organic material and gravel. Table (4-12) shows that the K-value for dry gravel ranges between 3.8 in high-frequency to 6 in low-frequency. Where the K-value for wet gravel ranges from 5 to 7. The MSW has a K-value that ranges from 4 to 9, depending on the decomposition level. Fully decomposed MSW has higher dielectric properties, more than 9. Thus, it can be detected.

On the other hand, MSW could be detected with low certainty using SFCW GPR in wet sand. In addition, nothing could be detected in saturated sands using the available technologies. The weak detection in wet and saturated sand soil is due to the conductivity of sea sand that increases in wet conditions. In turn, this will attenuate and scatter the GPR signal and prevent the

electromagnetic wave from penetrating deeper. Furthermore, the MSW in the extended experiment has medium to weak detection. This is due to the low percentage of moisture contents (dry MSW), and the organic material K-value is close to that of the used host.

The plastic could be detected using SFCW in dry gravel for the same reason (plastic has $K=4$). Also, it was detected using USW in wet gravel but could not be detected in saturated gravel. In addition, the plastic features can be detected using USW in dry loamy and sand. However, it cannot be seen in other conditions of these hosts. The interpretation is that the velocity of ultrasound waves becomes slower when the moisture contents increase. This velocity slowness indicates that the penetration is decreasing and the noise increasing.

The void can be detected using all types of GPR in dry gravel soil. It can be detected using the SFCW GPR in wet gravel. This detection is due to the difference in K-value mentioned earlier. The voids contain air with $K=1$. However, the voids have not been detected in loamy and sandy soil due to noise related to soil conductivity. Besides, another noise causes low certainty in dry sand using the USW. The interpretation of the previous result refers to the noise reflected from the wooden box wall affecting the reflection from air gaps inside the voids and producing a similar signal that could not be detected with the available software. On the other hand, the voids were detected using the medium and low-frequency GPR in the extended experiment.

As mentioned in the ground verification results, the plastic feature was identifiable using the low and medium frequency GPR. This unexpected detection is interpreted by the existence of some

air gaps between plastic materials. In addition, The water was detected using all GPR impulse frequencies. This result complies with the GPR theory for features detection because the K-value of water is 81, where the hosts vary from 2 to 26 in soils. Thus, a clear contrast might be there. On the other hand, the detection of debris material is interpreted by: the debris contains some airgaps, concrete, and other construction material.

6.3.2 Accuracy

The researcher could not find any literature about quantifying the accuracy of subsurface feature mapping. However, the only existing system is the SUE. Therefore, the accuracy mentioned in the contest of this research is an estimated certainty based on the operator experience. Thus, the available literature shows that no physical, mathematical, or statistical model was proposed to assess accuracy. In the ground verification results, the following procedure was followed to assess the accuracy of detecting the object: During the data analysis, the designed location for the object was marked on the profiles. Then locations were compared with the interpretation of the profile. If there is a GPR anomaly in this location, the object is marked as detected. GPR anomaly means: three different colors were shown: black-white-black or white-black-white, as in Figure 6-5.

The certainty of subsurface feature locating is assessed and converted to SUE standards ($A > 80\%$, $B=50-80$, $C = 30-50$, and $D < 30$). By comparing the ground verification results, it was generally noticed that all devices detected all features with an accuracy of more than 50%.

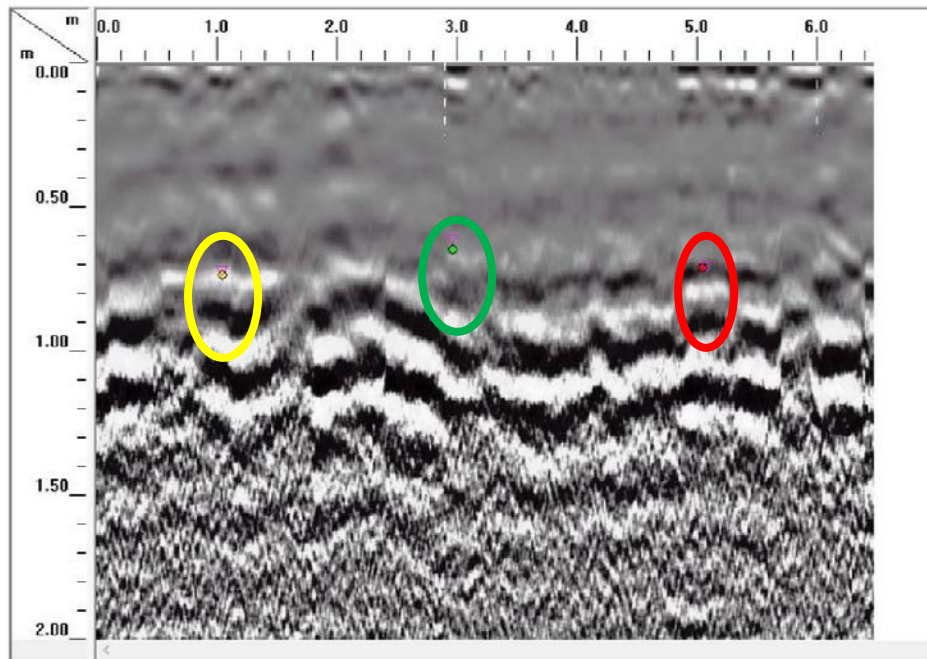


Figure 6-5 Phase4 - line 3 - 800MHz GPR in-ground verification experiment.

Yellow= plastic, green = void, red = MSW

Figure 6-5 shows an example of how this was done. The yellow, green, and red points were marked during data acquisition and analysis representing the actual location of plastic, voids, and MSW features, respectively. The revision of these locations during the mapping and digitizing (using MATLAB code) gives 90, 60, and 90 % detection accuracy values. The three successive colors vertically mean an anomaly in GPR analysis, in other words, detection. In the middle point of voids, the anomaly is a blur, but it was there, which means lower certainty than other points. Then these accuracies were converted to SUE codes as mentioned earlier to levels (A, B, and A, respectively).

Since the scanning was done in a grid using each device. This means that each feature will be scanned twice by each device. The grid scanning gives a redundant measurement to check the detection and produce a three-dimensional view. Also, it will be

scanned using each available sensor. For example, each feature was scanned at least six times in the ground verification experiment. After comparing the results from different scanning for the same features, it was noticed that the maximum difference in depth did not exceed 5 cm in general, and there is no noticeable trend in these differences.

To compare the same features with the same profile using the low-frequency band (300 MHz), shown in Figure 6-6. The figure shows that: plastic, voids, and MSW locations are a blur, with some anomalies shown in the first two locations. Although the detection accuracy was (50, 50, and 0), all these locations were categorized as (C, C, and D) levels, respectively. The D means no detection was found. The blurring in the first two locations is due to noise from the surface (background effect). Also, these locations are close to the blind area in the low-frequency band.

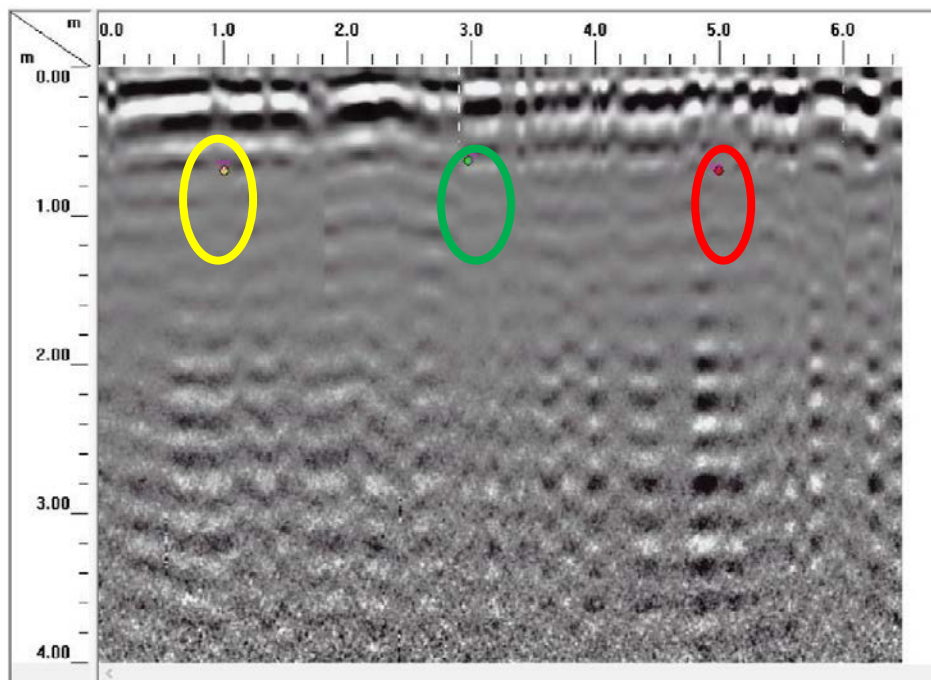


Figure 6-6 Phase 4 - line 3 - 300MHz GPR in-ground verification experiment.

Yellow= plastic, green = void, red = MSW

6.3.3 ISMS

The procedures of utilizing the results of experiments and the proposed system ISMS started by determining the subsurface feature's characteristics. These characteristics are obtained by an experiment similar to the main experiment. The results must be added to a specific database in the ISMS. The first step in the system is to define the user needs, as shown in Figure 5-16. Then based on user needs and the available database (similar to Table (2-9)), the system will guide the user to what to do and which technologies to utilize and integrate. For example, if the user wants to inspect and locate subsurface water (well exploration) less than 10m depth, the best technologies are the ERT and GPR. Many technologies could be used for dam investigation, such as ERT, Seismic Refraction, GPR, and Ultrasound. The results of mentioned experiments could be used based on the UML charts illustrated in the previous chapter to investigate the MSW in gravel, loamy, or sandy soil. These charts show that the integration of USW and GPR will detect the MSW in soil. Nevertheless, to find the plastic subsurface feature, an additional investigation and sensors must be utilized. Thus, the experiment should be repeated.

Although the ISMS procedures will facilitate the subsurface mapping, it requires an operator with some experience operating subsurface mapping devices. However, the ISMS was designed at this stage to delineate the subsurface location manually. The system will guide the user to decide the feature's type and extract it to a new shapefile. Besides, further experiments are required to investigate other features' characteristics or deploy more sensors in the system. That will increase the capability of accurate mapping.

In addition, ISMS delineates the procedure and requirements for subsurface feature mapping. Consequently, it could be a vital tool in the cost estimation for subsurface mapping processes, as illustrated in (A. Nashwan & Al-Joburi, 2021a). On the other hand, the ISMS provides a final product that complies with SUE standards.

Even though it could be noticed that there is a limitation in the new system (the shallow depth that was achieved and tested), it does not mean that the system will not work with increased depths. If the existing or new devices were designed, implemented, and calibrated to measure signals for a longer time in shear-ultrasound waves could obtain deeper penetration and find deeper features. On the other hand, one controller must operate the devices, and the collected data must be manipulated together for faster decisions. Besides, manufacturers avoid integrating the different technologies in one platform for commercial and marketing reasons. The cost could be a primary reason to avoid this integration. Although some academic projects tried to integrate several technologies during data collection, each analysis was done separately. In the industry, Screening Eagle company was recently established after merging Proceq company for NDT sensors and Software Lab for software and applications. The results are new products that the same controller can operate, and all the data can be sent on the cloud to other users. The results can be combined in new software, which they called Inspect. However, the user still has to use and analyze each device's data separately.

Chapter 7: Conclusions and Recommendations

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Chapter 7 Conclusions and Recommendations

7.1 Conclusions

The first conclusion provided through the achievement of the research objectives is as follows:

Objective 1

- *“Integrate various non-destructive remote sensing techniques and assess the interaction of targeted objects with them, then save these results in a central database called feature characteristics.”*

This research successfully developed a new technique and procedure to identify and locate the subsurface features based on defining the subsurface features' characteristics with the integrated RS sensors. These characteristics will enhance the locating and identifying process later instead of depending on analyst experience. Furthermore, the study designed a new system prototype called **ISMS**. This system will help the user know the procedures to locate and identify the targeted feature. Besides, the SUE levels will provide the level of confidence of the mapped features.

Objective 2

- *“Design the Integrated Subsurface Mapping System (ISMS) that produces a 3D digital map that incorporates spatial and nonspatial information to interpret subsurface features efficiently.”*

A new prototype for the ISMS was designed. This system will help the user know the procedures he should follow to locate and identify the targeted feature and produce a 3D spatial and nonspatial GIS layer. This

GIS layer will also contain information about the degree of certainty for locating the target based on the SUE standards.

The second conclusion about the ISMS is that this proposed system paves the way to build a universal scheme and database for the characteristics of subsurface features. In addition, this database enhances the locating and identification procedures for subsurface features.

Finally, the research results in the previous chapter demonstrated the following significant novelties: (1) Analysed and developed the first subsurface feature characteristics. (2) Designed, implemented, and tested a geodatabase and a system similar to the spectral signature for surface features in RS technologies. (3) Developed an algorithm that converts the subsurface scan images (GPR and USW) to a GIS-compatible theme layer that can easily be integrated with another GIS platform. (4) Ability to design a system and procedure to map subsurface MSW. This was never done nor analyzed. (5) Demonstrated that the GPR and USW integration represents the best combination to locate and identify subsurface MSW. (6) Mathematically modelled the object detection parameters that influence the degree of subsurface feature detection. (7) Demonstrated that terrestrial thermal imagery could be successfully utilized to map a bulky MSW. (8) Assessed the accuracy and certainty of mapping subsurface features using the SUE standards.

7.2 Recommendations and Future Works

From this thesis, the following are the recommendations and future works:

- As mentioned earlier, the first future work is to continue the programming for mapping the results directly on a GIS environment using the MapWinGIS open-source package.

- Design a new device that can utilize all sensors in one platform or be operated by one controller. In addition, the collected data could be integrated using ISMS to enhance the feature mapping. The communications are ongoing with Screening Eagle, a new subsurface mapping provider resulting from merging two companies in this field (Proceq -Switzerland: one of the best NDT manufacturers and Software Lab- Malaysia: specialized in software development). The recommendations are under review for possible implementation.
- In-depth analysis to mathematically and statistically model mapping accuracy from relative to absolute.
- Develop a protocol or standards for subsurface feature mapping that considers user needs, accuracy, and available devices.
- Develop a DSS for cost estimation of subsurface feature mapping procedures based on ISMS.
- Further experiments should be performed to create a comprehensive database of feature characteristics for more sensors, hosts, and materials. Such research is significant because it represents the backbone of the proposed ISMS.
- In-depth local research to study the effectiveness of using subsurface technology to map, analyze, and assess land-reclamation compliance with protocols and standards.
- Based on the experiment results, the ISMS can be implemented, developed, and published.
- For academic purposes to avoid bias, a separate host was used in each box. However, to obtain more accurate results, combinations of host mixes should be used to simulate the natural conditions. Also, the

material should be buried in the ground without any vertical's boundaries (instead of boxes). Which means a broader area will be required.

- A comprehensive study to examine and analyze the potential of close-range terrestrial, low altitude airborne, and space thermal imaging in mapping MSW, toxic waste, and other environmental hazards.
- The same procedures could be applied to other materials such as electronic waste, building debris, toxic waste, gasoline and other oil products, and black water dispersed in the soil to find their characteristics and facilitate their detection.
- Utilizing longitudinal ultrasound waves that are faster in soil could provide deeper penetration than the shear waves. This comment should be investigated in the future.
- The operation manual for the proposed prototypes and experiment works must be written well and published.

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Appendices

A. DIGITIZING AND SPATIAL MAPPING APPLICATIONS

B. EXTRA UML FEATURE DETECTION CHARTS

C. EXPERIMENT'S LAYOUT AND DIMENSIONS

A. Digitizing and Spatial Mapping Applications

This appendix includes the applications of API functions in the bridge design optimization algorithm. These examples were extracted from the algorithms developed for the tied-arch bridge.

A.1 Point Detection Code in MATLAB (Digitizing Code)

This code automatically reads the GSSI product images and automatically identifies the located features point. These points with their attribute data will be extracted in an Excel file. Also, it could be converted to shapefile using a MATLAB function or a GIS platform. The code for detecting all colors features are as follows:

```
clear;
clc;

%%% Initlisation
%ask user to select the path where his input data are located
path=uigetdir('D:\AllColors\');
files = dir(fullfile(path, '*.jpg'));
h=figure;
%Check if the Outputpolder os exist or not
if not(isfolder([path '\output\']))
    mkdir([path '\output\']);
end
%The coordinates of actual coordinates in array [X-cor Y-cor Z-Cor];
% the coordinate of phase four (Ground control Origion GCO)
GC01=[458950.080 2875059.570 10.000];
GC02=[458956.061 2875060.039 10.000];
GC03=[458955.592 2875066.021 10.000];
GC04=[458949.610 2875065.551 10.000];
Original=[GC01; GC02; GC03; GC04];
%Coordinate of phases 1 to 3 will be Ground control PRimary GCP
GCP1=[458900.0,2875000.0,10.0];
GCP2=[458920.0,2875000.0,10.0];
GCP3=[458920.0,2875020.0,10.0];
GCP4=[458900.0,2875020.0,10.0];
Original1=[GCP1; GCP2; GCP3; GCP4];
GridSpacing=0.1; % Grid spacing default value 5cm
TotalLines=14; %default value of total lines is 26

%create arrays for saving the posiylon vextor for x,y, and z
locations
pxv=[];
pyv=[];
```

```
pzv=[];

%Define arrays to save the Real coordinates of each lineand point
RXV=[]; % X-coordinate vector
RYV=[]; % Y-coordinate vector
RZV=[]; % Z-coordinate vector
PNI=[]; % Point number index
PType=[string]; % Object Type String Code
PTCode=[]; % Object Type Ingeger code


%create array t to save the color vector for the founded locations
colorv=[];
%Create arrays to save the file names for reading images, and their
index
FileName=[];
FileNamel=[]; % to save the file name for each founded points
Fileindex=[];
%Create an array to save the total points founded
Totalpoints=[];
% Parameters to convert the coordinates from pixel to centimeters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%These values tobe revised
Ystart=5;
Yincrement=10;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% X,Y Dimention Scale
XMinP=73;    % X axis minimum pixcel position      (Along B-scan)
XMinV=0;     % X axis minimum value                (Along B-scan)
XMaxP=313;   % X axis Maximum pixcel position      (Along B-scan)
XMaxV=60;    % X axis Maximum value                (Along B-scan)
ZMinP=46;    % Y axis minimum pixcel position      (Depth)
ZMinV=0;     % Y axis minimum value                (Depth)
ZMaxP=463;   % Y axis Maximum pixcel position      (Depth)
ZMaxV=80;    % Y axis Maximum value                (Depth)
% fill temporary variables to be used in calibration
PosOX(1)=XMinP;
PosOZ(1)=ZMinP;
PosXX(1)=XMaxP;
PosXY(1)=ZMinP;
PosZX(1)=XMinP;
PosZZ(1)=ZMaxP;
% % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % % %
%%% Processing

%To determine the position of origin and maximum x and depth scale
%by reading all images in the folder one by one,
%
%Prompt the user to check the images one by one, determine if the
image needs to be calibrated or not
%if need to be calibrated, then he must enter the correct minimum and
%maximum axis location and their values,
%the default values for the first time is 60 cm for the x-axis, and
80 cm for the y-axis (depth)
%%
% create acell array to save the index of files that no object
detected inside them
NoFile =[];
% Temporary counter for index of No objects files, and detected
points respectively
ii=1;iii=0;
```

```

for f=1:length(files)% For loop to read all images
    img = imread([path '\\' files(f).name]); %read the image and
save them to img variable
    imshow(img);
    FileName=[FileName; files(f).name];
    %Call the function FindFI to find the information as follows
    %1- Phase 2-Experiment time (day or night 3-Box No 4- Line
number 5- Gain value (G) 6- Dielectric constant (K)
    %7- Frequency used 8- Type of filter used except background
removal (it was a
    %default filter for all files)
    %Note: all previous information were saved as string
    TFN=FileName(f,:); %temporary array variable to save the file
name in string
    % TFN=TT{1}; %temporary variable to save the file name in
string
    FileInf=FindFI(TFN); % Call the find informartion from file
name
    FilesInfo(f,:)=FileInf'; %save the information in cell array
    % Starting a loop to find and calculate the real locations
and
    %%Call function to find the coordinates for the origion
point of the image
    %CR=Find_Coordinate(FileInf(3),FileInf(4));
    if FileInf(1)=='P4'
        GridSpacing=0.5; % Grid spacing default value 5cm
        TotalLines=26; %default value of total lines is 26

CR=Find_Real_Coordinate(FileInf(1),FileInf(3),FileInf(4),Original,GridSpacing,TotalLines);
    % coordinates for each point in the file.
    else

CR=Find_Real_Coordinate(FileInf(1),FileInf(3),FileInf(4),Original1,GridSpacing,TotalLines);
    end
    %FileCor{f} = CR; % save the Coordinates Record (Real) to
cell array
    hold on
    %Plot the default values of border and ask user to verify the
location if they ok or need to be calibrated
    plot(XMinP,ZMinP,'vm') %The top left corner
    plot(XMaxP,ZMinP,'vb') %The top right corner
    plot(XMinP,ZMaxP,'vr') %The bottom left corner
    plot(XMaxP,ZMaxP,'vy') %The bottom right corner
    %create dialog box to let the user choose if the image
contain detected
    %points
    %are there any points need to be detected and they need to be
detected
    %Automatically, or manually
    %Manually points usually for Proceq devices, in Phase 1,2,
and 3 only
    %if the image isempty the loop will pass to next image.
    Promp1='Would you like to calibrate this image, Click Yes to
proceed';
    Verf= questdlg(Promp1,'Y','N');
    if Verf(1) == 'Y'
        %prompt user to skip the origional points if it was
correct

```

```

        Promp2='If the original point is correct please enter
the maximum X, and Z point';
        Verf1= questdlg(Promp2, 'Y', 'N')';
        %uiwait(msgbox(Promp1));

        if Verf1(1) == 'Y'

            [xi,zi] = getpts;
            len=length(xi);
            %Check and change the values if the entries are less
than two points the
            %default values will take place
            if len<2
                uiwait(msgbox('You did not enter the required two
points of calibration, then the default values will be used'));
                PosOX(f)=XMinP;
                PosOZ(f)=ZMinP;
                PosXX(f)=XMaxP;
                PosXY(f)=ZMinP;
                PosZX(f)=XMinP;
                PosZZ(f)=ZMaxP;
                %default values will be entered, and go to next
photo
            else
                hold;
                prompt={'Enter the value(cm) of the Maximum X-
axis if not equal to 60 cm', 'Enter the value(cm) of the Maximum depth
Z-axis if not equal to 80cm'};
                dlgtitle = 'Input the dimension of profile';
                dlgdims = [1 35];
                definput = {'60', '80'};
                dims =
inputdlg(prompt,dlgtitle,dlgdims,definput);
                % Check if the default values had been changed or
not

                %kj=dims(1);
                kj=str2double(dims(1));
                if isnan(kj)
                    uiwait(msgBox('You didnt enter the Maximum X
value in centimeters, and didnt keep the default one, then default
will be set'))
                    kj=XMaxV;
                end
                XMaxV=kj;
                %%%
                %yj=dims(2);
                zj=str2double(dims(2));
                if isnan(zj)
                    uiwait(msgBox('You didnt enter the Maximum
depth (Z) value in centimeters, and didnt keep the default one,
then default will be set'))
                    zj=ZMaxV;
                end
                ZMaxV=zj;
                %Set the temporary variable by the new pixel
value of image

                %corners
                PosOX(f)=XMinP;
                PosOZ(f)=ZMinP;
                PosXX(f)=XMaxP;

```

```

        PosXY(f)=zi(1);
        PosZX(f)=xi(2);
        PosZZ(f)=zi(2);
        %End of entering new values
    end
else

    Promp3='Enter the first point as the top left
corner, then top right corner, and the last Bottom lest corner, Press
right-click to end';

    uiwait(msgbox(Promp3));
    [xi,zi] = getpts;
    len=length(xi);
    %Check and change the values if the entries are
less than two points the
    %default values will take place
    if len<3
        uiwait(msgbox('You did not enter the three
points of calibration, then the default values will be used'));
        PosOX(f)=XMinP;
        PosOZ(f)=ZMinP;
        PosXX(f)=XMaxP;
        PosXY(f)=ZMinP;
        PosZX(f)=XMinP;
        PosZZ(f)=ZMaxP;
        %default values will be entered, and go to
next photo
    else
        hold;
        prompt={'Enter the value(cm) of the Maximum
X-axis if not equal to 60 cm','Enter the value(cm) of the Maximum
depth Z-axis if not equal to 80cm'};
        dlgtitle = 'Input the dimension of profile';
        dlgdims = [1 35];
        definput = {'60','80'};
        dims =
inputdlg(prompt,dlgtitle,dlgdims,definput);
        % Check if the default values had been
changed or not

        %kj=dims(1);
        kj=str2double(dims(1));
        if isnan(kj)
            uiwait(msgBox('You didnt enter the
Maximum X value in centimenters, and didnt keep the default one,
then default will be set'))
            kj=XMaxV;
        end
        XMaxV=kj;
        %%%
        %yj=dims(2);
        zj=str2double(dims(2));
        if isnan(zj)
            uiwait(msgBox('You didnt enter the
Maximum depth (Z) value in centimenters, and didnt keep the default
one, then default will be set'))
            zj=ZMaxV;
        end
        ZMaxV=zj;
    end
end

```

```

                                %Set the temporary variable by the new pixel
value of image

                                %corners
                                PosOX(f)=xi(1);
                                PosOZ(f)=zi(1);
                                PosXX(f)=xi(2);
                                PosXY(f)=zi(2);
                                PosZX(f)=xi(3);
                                PosZZ(f)=zi(3);
                                %End of entering new values
                                end
                                end
                                %Reset the default parameters with the latest used one
                                XMinP=PosOX(f);
                                ZMinP=PosOZ(f);
                                XMaxP=PosXX(f);
                                ZMinP=PosXY(f);
                                XMinP=PosZX(f);
                                ZMaxP=PosZZ(f);
                                end

                                % to remove all black and white pixels and keep the colored ones
                                R=rgb2gray(img)-uint8(img(:,:,1)); %convert the colored image
                                tograyand then subtract the red color pixel from it
                                G=rgb2gray(img)-uint8(img(:,:,2)); %convert the colored image
                                tograyand then subtract the green color pixel from it
                                B=rgb2gray(img)-uint8(img(:,:,3)); %convert the colored image
                                tograyand then subtract the Blue color pixel from it
                                Rv=max(R); %return the maximum value in each column of the image
                                Gv=max(G); %return the maximum value in each column of the image
                                Bv=max(B); %return the maximum value in each column of the image
                                %%
                                %img2=max([R; G; B]);
                                img2=R+G+B; % combine all founded colors in one image (name it
                                img2)
                                img3=R+G+B; % combine all founded colors in one image (name it
                                img3)
                                img3=img3 *10; % magnify the numbers of image 3 ten times
                                xx=double(max(img3)); %find the maximum value in each row of
                                image3
                                xx = smooth(xx,13); %Smooth the pixel values to width of 13
                                pixels
                                xx(xx<150)=0; % set all DN values less than 150 to zero to remove

                                hold on;
                                % %   plot(max(R),'r-');
                                % %   plot(max(G),'g-');
                                % %   plot(max(B),'b-');
                                %plot(+max(G)+max(B),'m-');
                                [pks,locs] = findpeaks(xx); % Find the peaks value to determine
                                the colored points
                                %if the image didn't have point do nothing and check another file
                                if isempty(locs)
                                    %save the index of No object file
                                    NoFile(ii)=f;
                                    ii=ii+1;
                                else
                                    iii=iii+1;
                                end
                                end

```

```

    px=[]; % temporary array to save horizontal location of peaks
    pz=[]; % temporary variable to save vertical location of peaks
    py=[]; % temporary variable to save location of line of peaks
    RX=[]; % temporary variable to save the real x coordinate of the
location
    RY=[]; % temporary variable to save real y coordinate of the
location
    RZ=[]; % temporary variable to save real z coordinate of the
location
    PTy=[];% temporary variable to save the location type
    imshow(img);
    hold on

    %%for loops to search to search for type of objects in founded
peaks
    if length(locs) >0
        for i = 1:length(locs)
            px(i)=locs(i); % save the xlocation of each point
            py(i)=1; % put the default value for the line is line one
            pz(i)=find(img3(:,locs(i))>150,1,'first'); % the depth of
first founded peak that is more than 150 in each column
            %%%%%%%%%%
            FileName=[FileName; files(f).name]; % Save the file name
string into file name array
            Fileindex=[Fileindex; f]; % Save the file index
(integer) into file index array
            Totalpoints=[Totalpoints; length(locs) ]; % total points
founded location in each file were saved in totalpoints array
            %%%%%%%%%%
            Rmax=max(Rv([locs(i)-5:locs(i)+5]));
            Gmax=max(Gv([locs(i)-5:locs(i)+5]));
            Bmax=max(Bv([locs(i)-5:locs(i)+5]));
            if Bmax>150
                Color='P'; % Plastic is for Yellow color
            elseif Bmax>70 && Rmax>70
                Color='V'; % Void for Green color
            elseif Bmax>40 && Gmax>40
                Color='M'; % Municipal Solid Waste (MSW) for Red
color
            elseif Gmax>20 && Rmax>20
                Color='W'; %Water for Blue color
            else
                Color='S'; %Steal is for Brown or any other color
            end
            text(px(i),pz(i),[' ' Color]); % write the letter related
to type of feature near to it's location
            % y value
            ii=1; % counter to register of files with no features.

            while isempty(strfind(files(f).name,['P' num2str(ii)]))
&& (ii<100)
                ii=ii+1;
            end
            Emptyv=[Emptyv ii]; % register the index of emptyfiles
            colorv=[colorv ; Color]; %register the color to an array

            %%%%%%
            %%%%%%------

```

```

    %px(i)=locs(i);
    %py(i)=find(img2(:,locs(i))>150,1,'first');
    RposX=(px(i)-(XMinP-1)).*(XMaxV-XMinV)./(XMaxP-XMinP+1);
    RposZ=(pz(i)-(ZMinP-1)).*(ZMaxV-ZMinV)./(ZMaxP-ZMinP+1);

    %Calculatethe Real Coordiantes values for X, Y, and Z for
each point
    if str2num(FileInf(4))<14
        RX(i)=CR(1);
        RY(i)=CR(2)+RposX/100.0;
        RZ(i)=10-RposZ/100.0;
        PNT(i)=iii;
        py(i)=FileInf(4);
    else
        RX(i)=CR(1)+RposX/100.0;
        RY(i)=CR(2);
        RZ(i)=10-RposZ/100.0;
        PNT(i)=iii;
        py(i)=1;
    end
    %Delineate point type according to CR file in phases one
to three
    PTC(i)=CR(3);
    switch CR(3)
        case 0
            PTy(i)="Metal";
        case 1
            PTy(i)="MSW";
        case 2
            PTy(i)="Plastic";
        case 3
            PTy(i)="Void";
    end
    %Open a file index to save data
    Fileindex=[Fileindex; f];
    FileName1=[FileName1; files(f).name]; % Save the file
name string into file name array
    %Save the total points in each file with their location
    Totalpoints=[Totalpoints; length(locs) ];
end
    TT=pxv;
    pxv=Fill_Cell_array(TT,px); %save the horizontal locations to
cell array
    pzv=[pzv pz]; % save the vertical locations to cell array
    pyv=[pyv py]; % the line number
    RXV=[RXV RX];
    RYV=[RYV RY];
    RZV=[RZV RZ];
    PNI=[PNI PNT];
    PType=[PType PTy];
    PTCODE=[PTCODE PTC];
    imshow(img);
    hold on
end
    %plot(px,pz,'vm')
    %saveas(gcf,[files(1).folder '\output\' files(1).name], 'jpg')

    %%%%%%-----

```

```

        %%%%%%%%%

%end of loop
%end

        plot(px,pz,'vm')
        % figure
        % hold on
        % plot(max(R),'r-');
        % plot(max(G),'g-');
        % plot(max(B),'b-');
        saveas(gcf,[path '\output\' files(f).name], 'jpg') % save the
image to output folder
%end of loop
end

%%% Convert Pixel To CM
%posx=(pxv-(XMinP-1)).*(XMaxV-XMinV)./(XMaxP-XMinP+1);
%posz=(pzv-(ZMinP-1)).*(ZMaxV-ZMinV)./(ZMaxP-ZMinP+1);

%%% Convert Pass To CM
%posy=Ystart+ Emptyv * Yincrement;
%%% Save to excel

Colors={cellstr(colorv)}';
Fileindex={num2cell(Fileindex)};
FileName={cellstr(FileName)};
FileName1={cellstr(FileName1)};
Totalpoints={num2cell(Totalpoints)};
pxv={num2cell(RXV)};
pyv={num2cell(RYV)};
pzv={num2cell(RZV)};
Table=[{'Fileindex','FileName','Totalpoints','Color','X Coordinate','Y
Coordinate','Z
Coordinate'};Fileindex{1},FileName1{1},Totalpoints{1},Colors{1},pxv{1}
,pyv{1},pzv{1}];
if not(isfile([path '\output\DataAllcolors.xls']))
    xlswrite([path '\output\DataAllcolors.xls' ],Table); % save the
excel file to output folder
else
    Prompt5={'Thisfile is exist do you want to over write it'};
    Verf3 = questdlg(Prompt5,'Y','N');
    if Verf3(1)=='Y'
        xlswrite([path '\output\DataAllcolors.xls' ],Table); % save the
excel file to output folder
    end
end
%xlswrite([path '\output\DataAllcolors.xls' ],Table);
msgbox('Done');

%
```

This code is designed to find the actual coordinates for the extracted features. By finding the actual coordinates for the beginning and endpoint for each profile. The code of the real-coordinates function is as follows:

```
% Function to find the real coordinates of the corner of the Box.
function CordBxCorn = Find_Real_Coordinate(Phase,BxN,LiN,GC,GS,TL)
%GS: is the grid spacing
%BxN: is the Box number
%LiN: is the line number
%GC: is the array that contains the original grid coordinates
%TL: total ines in grid
% clear;
% clc;

BN=str2num(BxN); % converting the string to numbers
LN=str2num(LiN);
X0=GC(1,1);%left bottom corner x-cor
Y0=GC(1,2);%left bottom corner y-cor
XX=GC(2,1);%right bottom corner x-cor
XY=GC(2,2);%right bottom corner y-cor
XC=GC(3,1);%right top corner x-cor
YC=GC(3,2);%right top corner y-cor
YX=GC(4,1);%left top corner x-cor
YY=GC(4,2);%left top corner y-cor
DXH= XX-X0; %Delta X-coordinate in Horizontal direction for start
point
DYH= XY-Y0; %Delta Y-coordinate in Horizontal direction for start
point
DXV= YX-X0; %Delta X-coordinate in vertical direction for start point
DYV= YY-Y0; %Delta Y-coordinate in vertical direction for start point
DXHE= XC-XX; %Delta X-coordinate in Horizontal direction for End point
DYHE= YC-XY; %Delta Y-coordinate in Horizontal direction for End point
DXVE= XC-YX; %Delta X-coordinate in vertical direction for End point
DYVE= YC-YY; %Delta Y-coordinate in vertical direction for End point
GLH=sqrt(DXH^2+DYH^2); % calculate the length of the grid
horizontally
%DL=GLH/GS; %calculate the line increment horizontally
LD=TL/2; % Number of lines per direction
if Phase=='P4'
%     GS=0.5;
%     TL=26;
%     LD=TL/2;
    if LN<= (LD)
        Xc1=X0+GS*(DXH/LD)*(LD-LN);
        Xc2=YX+GS*(DXHE/LD)*(LD-LN);
        Yc1=Y0+GS*(DYH/LD)*(LD-LN);
        Yc2=YY+GS*(DYHE/LD)*(LD-LN);
    else
        Xc1=X0+(DXV/GS)*(LD-LN);
        Xc2=XX+(DXVE/GS)*(LD-LN);
        Yc1=Y0+(DYV/GS)*(LD-LN);
        Yc2=XY+(DYVE/GS)*(LD-LN);
    end
    XL1=Xc1;
```

```

        XL2=Xc2;
        YL1=Yc1;
        YL2=Yc2;
        Type=4; % HOST TYPE
    else
        Xc1=X0+4*floor(double(BN/4.1));
        BNtemp=floor(double(BN/4.1));
        %To check the strip where the box is located the boxes from 1-
4are in
        %one row, 5-8 in second row, and 9-12 in third row in order to
delineat
        %the coordinate of original point of the line in x direction
        if BNtemp==0
            BNY=BN;
        elseif (BNtemp==1)
            BNY=BN-4;
        else
            BNY=BN-8;
        end
        % calculate the y coordinate by delineting the exact box location
        % wherethe original point of the line is, and to find its y
        % coordinates
        TYC=double((floor(BNY/2)+floor(BNY/3)));
        Yc1=Y0+4*TYC;
        %The
        Type=(floor(BNY/2)+floor(BNY/3)); % HOST TYPE
        if LN >LD
            XL1=Xc1+20;
            XL2=Xc1+(GS*(LN-LD-1));
            YL1=Yc1+(LN-LD-1)*GS;
            YL2=YL1;
        else
            XL1=Xc1+(LN-1)*GS+20;
            XL2=XL1;
            YL1=Yc1;
            YL2=YL1+(GS*(LN-1));
        end
    end
    CordBxCorn =[XL1 YL1 Type XL2 YL2]'

return

```

There is another code to read the Proceq data profiles and extract their information. This code is as follows:

```

clc;
clear;
FileName=[];
path=uigetdir('D:\AllColors\');
files = dir(fullfile(path, '*.PNG'));
h=figure;
%Check if the Outputpolder os exist or not
if not(isfolder([path '\output_p\']))
    mkdir([path '\output_p\']);
end
%define temporary ariables
MsF=0;

```

```

VoF=0;
PlF=0;
StF=0;
WaF=0;
OtF=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Define variables to save file information
Phase='P1';      % The phase number
PTime='Day'      %time of acquisition default is Day
Box='01';        %The box Number
Line='01';       % The line number
Gain='00';       % Gain amount in the noriginal pitcure if know
Const='5.00';    %This constant either speed of wave or dielectric
constant
Device='SFCW';   %Device type GSSI-2700,300,800, SFCW, USW
Filter='';       %Type of filter used if any default is null
NOF='00';        %No of features;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Copy Parameters from All color file
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%
%The coordinates of actual coordinates in array [X-cor Y-cor Z-Cor];
% the coordinate of phase four (Ground control Origion GCO)
GC01=[458950.080 2875059.570 10.000];
GC02=[458956.061 2875060.039 10.000];
GC03=[458955.592 2875066.021 10.000];
GC04=[458949.610 2875065.551 10.000];
Original=[GC01; GC02; GC03; GC04];
%Coordinate of phases 1 to 3 will be Ground control Primary GCP
GCP1=[458900.0,2875000.0,10.0];
GCP2=[458920.0,2875000.0,10.0];
GCP3=[458920.0,2875020.0,10.0];
GCP4=[458900.0,2875020.0,10.0];
Original1=[GCP1; GCP2; GCP3; GCP4];
GridSpacing=0.1; % Grid spacing default value 5cm
TotalLines=14; %default value of total lines is 26

%create arrays for saving the position vextor for x,y, and z
locations
pxv=[];
pyv=[];
pzv=[];

%Define arrays to save the Real coordinates of each lineand point
RXV=[]; % X-coordinate vector
RYV=[]; % Y-coordinate vector
RZV=[]; % Z-coordinate vector
PNI=[]; % Point number index
PType=[string]; % Object Type String Code
PTCode=[]; % Object Type Ingeger code

%create array t to save the color vector for the founded locations
colorv=[];
%Create arrays to save the file names for reading images, and their
index
FileName=[];
FileName1=[]; % to save the file name for each founded points
Fileindex=[];
%Create an array to save the total points founded

```

```

Totalpoints=[];
% Parameters to convert the coordinates from pixel to centimeters
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
%       Processing
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for f=1:length(files)
    img = imread([path '\' files(f).name]); %read the image and save
them to img variable
    imshow(img);
    FileName=[FileName; files(f).name];
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    prompt00={'Phase No','Experiment time','Box No','Line
No','Gain','Constant','Technology','Filter Type','No of feature'};
    dlgtitle0 = 'Fill the file info';
    dims0 = [1 20];
    definput0 = {'P1','Day','01','01','00','5.00','SFCW','','0'};
    FileInf = inputdlg(prompt00,dlgtitle0,dims0,definput0);
    Phase=FileInf(1);
    PTime=FileInf(2);
    Box=FileInf(3);
    Line=FileInf(4);
    Gain=FileInf(5);
    Const=FileInf(6);
    Device=FileInf(7);
    Filter=FileInf(8);
    NoF=FileInf(9);
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    %Examine the Phase to determine the parameters
    if FileInf(1)=='P4'
        GridSpacing=0.5; % Grid spacing default value 5cm
        TotalLines=26; %default value of total lines is 26

CR=Find_Real_Coordinate(FileInf(1),FileInf(3),FileInf(4),Original,Gri
dSpacing,TotalLines);
        % coordinates for each point in the file.
        else

CR=Find_Real_Coordinate(FileInf(1),FileInf(3),FileInf(4),Original1,Gr
idSpacing,TotalLines);
        end
        %FileCor{f} = CR; % save the Coordinates Record (Real) to cell
array
        hold on
        %Plot the default values of border and ask user to verify the
location if they ok or need to be calibrated
        plot(XMinP,ZMinP,'vm') %The top left corner
        plot(XMaxP,ZMinP,'vb') %The top right corner
        plot(XMinP,ZMaxP,'vr') %The bottom left corner
        plot(XMaxP,ZMaxP,'vy') %The bottom right corner
        %create dialog box to let the user choose if the image contain
detected
        %points
        %are there any points need to be detected and they need to be
detected
        %Automatically, or manually
        %Manually points usually for Proceq devices, in Phase 1,2, and 3
only

```

```

    %if the image isempty the loop will pass to next image.
    Promp1='Would you like to calibrate this image, Click Yes to
proceed';
    Verf= questdlg(Promp1,'Y','N');
    if Verf(1) == 'Y'
        %prompt user to skip the original points if it was correct
        Promp2='If the original point is correct please enter the
maximum X, and Z point';
        Verf1= questdlg(Promp2,'Y','N');
        %uiwait(msgbox(Promp1));

        if Verf1(1) == 'Y'
            [xi,zi] = getpts;
            len=length(xi);
            %Check and change the values if the entries are less than
two points the
            %default values will take place
            if len<2
                uiwait(msgbox('You did not enter the required two
points of calibration, then the default values will be used'));
                PosOX(f)=XMinP;
                PosOZ(f)=ZMinP;
                PosXX(f)=XMaxP;
                PosXY(f)=ZMinP;
                PosZX(f)=XMinP;
                PosZZ(f)=ZMaxP;
                %default values will be entered, and go to next photo
            else
                hold;
                prompt={'Enter the value(cm) of the Maximum X-axis if
not equal to X-Maximum value cm','Enter the value(cm) of the Maximum
depth Z-axis if not equal to ZMaximum Value'};
                dlgtitle = 'Input the dimension of profile';
                dlgdims = [1 35];
                definput = {XMaxV,ZMaxV};
                dims = inputdlg(prompt,dlgtitle,dlgdims,definput);
                % Check if the default values had been changed or not
                %kj=dims(1);
                kj=str2double(dims(1));
                if isnan(kj)
                    uiwait(msgBox('You didnot enter the Maximum X
value in centimeters, and didnot keep the default one, then default
will be set'))
                    kj=XMaxV;
                end
                XMaxV=kj;
                %%%
                %yj=dims(2);
                zj=str2double(dims(2));
                if isnan(zj)
                    uiwait(msgBox('You didnot enter the Maximum depth
(Z) value in centimeters, and didnot keep the default one, then
default will be set'))
                    zj=ZMaxV;
                end
                ZMaxV=zj;
                %Set the temporary variable by the new pixel value of
image

                %                                %corners
                PosOX(f)=XMinP;

```

```

        PosOZ(f)=ZMinP;
        PosXX(f)=XMaxP;
        PosXY(f)=zi(1);
        PosZX(f)=xi(2);
        PosZZ(f)=zi(2);
        %End of entering new values
    end
else

    Promp3='Enter the first point as the top left corner,
then top right corner, and the last Bottom left corner, Press enter
to end';

    uiwait(msgbox(Promp3));
    [xi,zi] = getpts;
    len=length(xi);
    %Check and change the values if the entries are less than
two points the
    %default values will take place
    if len<3
        uiwait(msgbox('You did not enter the three points of
calibration, then the default values will be used'));
        PosOX(f)=XMinP;
        PosOZ(f)=ZMinP;
        PosXX(f)=XMaxP;
        PosXY(f)=ZMinP;
        PosZX(f)=XMinP;
        PosZZ(f)=ZMaxP;
        %default values will be entered, and go to next photo
    else
        hold;
        prompt={'Enter the value(cm) of the Maximum X-axis if
not equal to 60 cm','Enter the value(cm) of the Maximum depth Z-axis
if not equal to 80cm'};
        dlgtitle = 'Input the dimension of profile';
        dlgdims = [1 35];
        definput = {XMaxV,ZMaxV};
        dims = inputdlg(prompt,dlgtitle,dlgdims,definput);
        % Check if the default values had been changed or not
        %kj=dims(1);
        kj=str2double(dims(1));
        if isnan(kj)
            uiwait(msgBox('You didnt enter the Maximum X
value in centimeters, and didnt keep the default one, then default
will be set'))
            kj=XMaxV;
        end
        XMaxV=kj;
        %%%
        %yj=dims(2);
        zj=str2double(dims(2));
        if isnan(zj)
            uiwait(msgBox('You didnt enter the Maximum depth
(Z) value in centimeters, and didnt keep the default one, then
default will be set'))
            zj=ZMaxV;
        end
        ZMaxV=zj;
        %Set the temporary variable by the new pixel value of
image

```

```

        %corners
        PosOX(f)=xi(1);
        PosOZ(f)=zi(1);
        PosXX(f)=xi(2);
        PosXY(f)=zi(2);
        PosZX(f)=xi(3);
        PosZZ(f)=zi(3);
        %End of entering new values
    end
end
%Reset the default parameters with the latest used one
XMinP=PosOX(f);
ZMinP=PosOZ(f);
XMaxP=PosXX(f);
ZMinP=PosXY(f);
XMinP=PosZX(f);
ZMaxP=PosZZ(f);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Ask the user if he wants to digitize this image
Promp01={'Is ther any Object need to be digitized'};
Verf6= questdlg(Promp01,'Y','N');
if Verf6 (1) == 'Y'
    prompt02 = {'MSW objects','Voids objects','Plastic Objects',
'Steel objects', 'Water objects', 'Other objects'};
    dlgttitle = 'Input the number of opjects that you have in the
figures';
    dims = [1 20];
    definput = {'0','0','0','0','0','0'};
    Tot_No_Features = inputdlg(prompt02,dlgttitle,dims,definput);
    MsF=str2double(Tot_No_Features (1));
    VoF=str2double(Tot_No_Features (2));
    PlF=str2double(Tot_No_Features (3));
    StF=str2double(Tot_No_Features (4));
    WaF=str2double(Tot_No_Features (5));
    OtF=str2double(Tot_No_Features (6));
end
No_of_objects = MsF+VoF+PlF+StF+WaF+OtF;
i=0;
if No_of_objects>0
    for i=1:No_of_objects
        %1-Check the MSW points
        if MsF>0;
            prompt03={'Please specify the locations of MSW
objects. Then click Enter when finished'};
            uiwait(msgbox(prompt03));
            [xM zM]=getpts();
            len=length(xM);
            if len<MsF
                prompt04={'You did not digitized all points'};
                uiwait(msgbox(prompt04));
                hold on;
                plot(xM,zM,'vr') %The MSW points
            else if len>MsF
                prompt05={'You digitized points more than you
specified before'};
                uiwait(msgbox(prompt05));
                hold on;
                plot(xM,zM,'vr') %The MSW points
            end
        end
    end
end

```

```

end
hold on;
plot(xM,zM,'vr') %The MSW points
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Calculate the real coordinate for the digitized
points
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

RposX=(xM-(XMinP-1)).*(XMaxV-XMinV)./(XMaxP-
XMinP+1);
RposY=(py(i)-(YMinP-1)).*(YMaxV-YMinV)./(YMaxP-
YMinP+1);
RposZ=(pz(i)-(ZMinP-1)).*(ZMaxV-ZMinV)./(ZMaxP-
ZMinP+1);

%Calculated the Real Coordinates values for X, Y,
and Z for each point
if str2num(FileInf(4))<14
    RX(i)=CR(1);
    RY(i)=CR(2)+RposX/100.0;
    RZ(i)=10-RposZ/100.0;
    PNT(i)=1;
    py(i)=FileInf(4);
else
    RX(i)=CR(1)+RposX/100.0;
    RY(i)=CR(2);
    RZ(i)=10-RposZ/100.0;
    PNT(i)=1;
    py(i)=1;
end

end
Promp00='Are the points you entered Ok';
Verf0= questdlg(Promp00,'Y','N');
if Verf0 (1) == 'Y'
    i=i+ MsF;
    MsF=0;
else
    uiwait(msgbox('This part will be repeated'));
end
end
%2-Check the voids points
if VoF>0;
    imshow(img);
    hold on;
    prompt06={'Please specify the locations of Voids
features. Then click Enter when finished'};
    uiwait(msgbox(prompt06));
    [xV zV]=getpts();
    len=length(xV);
    if len<VoF
        prompt07={'You did not digitized all points'};
        uiwait(msgbox(prompt07));
        plot(xV,zV,'vg') %The Voids points
    else if len>VoF
        prompt08={'You digitized points more than you
specified before'};
        uiwait(msgbox(prompt08));
        plot(xV,zV,'vg') %The vVoids points
    end
end

```

```

        end
        plot(xV,zV,'vg') %The Voids points
    end
    Promp00='Are the points you entered Ok';
    Verf0= questdlg(Promp00,'Y','N');
    if Verf0 (1) == 'Y'
        i=i+VoF;
        VoF=0;
    else
        uiwait(msgbox('This part will be repeated'));
    end
end
%3-Check the Plastic points
if PlF>0
    imshow(img);
    hold on;
    prompt10={'Please specify the locations of Plastic
objects. Then click Enter when finished'};
    uiwait(msgbox(prompt10));
    [xP zP]=getpts();
    len=length(xP);
    if len<PlF
        prompt11={'You did not digitized all points'};
        uiwait(msgbox(prompt11));
        plot(xP,zP,'vy') %The Plastic points
    else if len>PlF
        prompt05={'You digitized points more than you
specified before'};
        uiwait(msgbox(prompt05));
        plot(xP,zP,'vy') %The Plastic points
    end
    plot(xP,zP,'vy') %The Plastic points
end

Promp00='Are the points you entered Ok';
Verf0= questdlg(Promp00,'Y','N');
if Verf0 (1) == 'Y'
    i=i+ PlF;
    PlF=0;
else
    uiwait(msgbox('This part will be repeated'));
end
end
%4-Check the steels points
if StF>0
    imshow(img);
    hold on;
    prompt06={'Please specify the locations of Steels
features. Then click Enter when finished'};
    uiwait(msgbox(prompt06));
    [xS zS]=getpts();
    len=length(xS);
    if len<StF
        prompt07={'You did not digitized all points'};
        uiwait(msgbox(prompt07));
        plot(xS,zS,'vm') %The Steels points
    else if len>StF
        prompt08={'You digitized points more than you
specified before'};
        uiwait(msgbox(prompt08));
    end
end

```

```

        plot(xS,zS,'vm') %The Steel points
    end
    plot(xS,zS,'vm') %The Steels points
end
Promp00='Are the points you entered Ok';
Verf0= questdlg(Promp00,'Y','N')';
if Verf0 (1) == 'Y'
    i=i+StF;
    StF=0;
else
    uiwait(msgbox('This part will be repeated'));
end
end
%5-Check the Water points
if WaF>0
    imshow(img);
    hold on;
    prompt10={'Please specify the locations of Water
objects. Then click Enter when finished'};
    uiwait(msgbox(prompt10));
    [xW zW]=getpts();
    len=length(xW);
    if len<WaF
        prompt11={'You did not digitized all points'};
        uiwait(msgbox(prompt11));
        plot(xW,zW,'vb') %The Water points
    else if len>WaF
        prompt05={'You digitized points more than you
specified before'};
        uiwait(msgbox(prompt05));
        plot(xW,zW,'vb') %The Water points
    end
    plot(xW,zW,'vb') %The Waater points
end
%Check if the points need to be repeated or not
Promp00='Are the points you entered Ok';
Verf0= questdlg(Promp00,'Y','N')';
if Verf0 (1) == 'Y'
    i=i+ WaF;
    WaF=0;
else
    uiwait(msgbox('This part will be repeated'));
end
end
%6-Check the Other features points
if OtF>0
    imshow(img);
    hold on;
    prompt06={'Please specify the locations of Other
features. Then click Enter when finished'};
    uiwait(msgbox(prompt06));
    [xO zO]=getpts();
    len=length(xO);
    if len<OtF
        prompt07={'You did not digitized all points'};
        uiwait(msgbox(prompt07));
        plot(xO,zO,'vc') %The Other points
    else if len>OtF
        prompt08={'You digitized points more than you
specified before'};
        uiwait(msgbox(prompt08));

```

```

        plot(x0,z0,'vc') %The Other points
    end
    plot(x0,z0,'vc') %The Other points
end
%Check if the points need to be repeated or not
Promp00='Are the points you entered Ok';
Verf0= questdlg(Promp00,'Y','N');
if Verf0 (1) == 'Y'
    i=i+OtF;
    OtF=0;
else
    uiwait(msgbox('This part will be repeated'));
end
end

% check if all points was digitized, end the loop
chk=MsF+VoF+PlF+StF+WaF+OtF;
if chk==0
    i=No_of_objects;
end
RposX=(px(i)-(XMinP-1)).*(XMaxV-XMinV)./(XMaxP-XMinP+1);
RposZ=(pz(i)-(ZMinP-1)).*(ZMaxV-ZMinV)./(ZMaxP-ZMinP+1);

%Calculatethe Real Coordinantes values for X, Y, and Z for
each point
if str2num(FileInf(4))<14
    RX(i)=CR(1);
    RY(i)=CR(2)+RposX/100.0;
    RZ(i)=10-RposZ/100.0;
    PNT(i)=iii;
    py(i)=FileInf(4);
else
    RX(i)=CR(1)+RposX/100.0;
    RY(i)=CR(2);
    RZ(i)=10-RposZ/100.0;
    PNT(i)=iii;
    py(i)=1;
end
%Delineate point type according to CR file in phases one
to three
PTC(i)=CR(3);
switch CR(3)
    case 0
        PTy(i)="Metal";
    case 1
        PTy(i)="MSW";
    case 2
        PTy(i)="Plastic";
    case 3
        PTy(i)="Void";
end
%Open a file index to save data
Fileindex=[Fileindex; f];
FileName1=[FileName1; files(f).name]; % Save the file
name string into file name array
%Save the total points in each file with their location
Totalpoints=[Totalpoints; length(locs) ];

end

```

```
        end
    end
    %combine file infor together to construct new image output
    FF= strcat(Phase,'-',PTime,'-B',Box,'-L',Line,'-G=',Gain,'-',Const,'-
    ',Device,'-',Filter,NoF,'.JPG');
    fileName=FF{1};
    saveas(gcf,[path '\output_p\' fileName], 'jpg') % save the image to
    output folder
```

Appendix B

B. Extra UML Feature

Detection Charts

B. Extra UML Feature Detection Charts

The chart in Figure B. 7 to Figure B. 3 shows the detecting results probability depending on changing two independent variables, moisture content and host type. The charts in Figure B. 10, Figure B. 11, and Figure B. 12 represent the available detection depending on host type dry, saturated, wet, respectively. Thus, these charts show the likelihood of detecting features in each host.

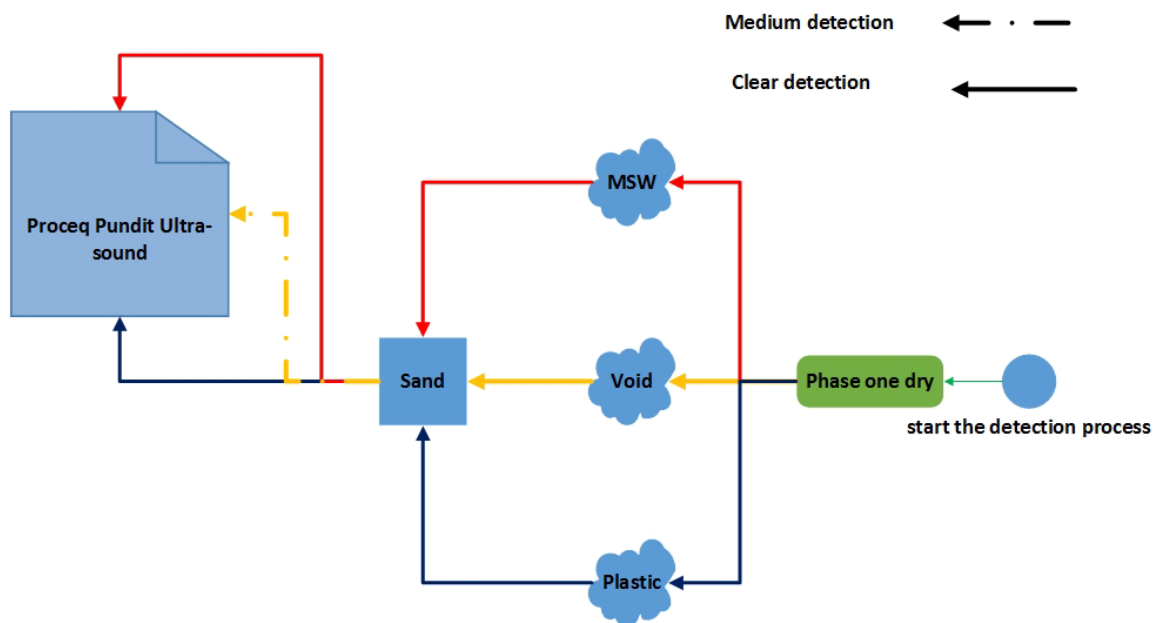


Figure B. 1 Detection results in dry sand

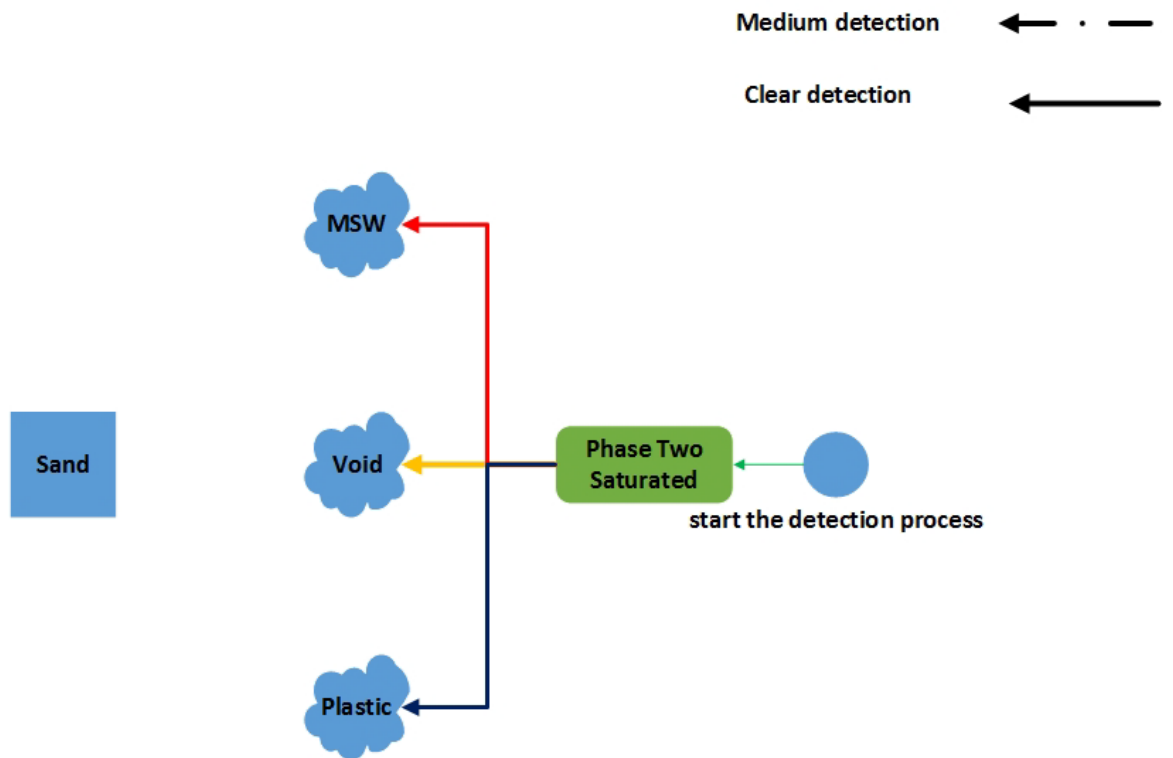


Figure B. 2 Detection results in saturated sand

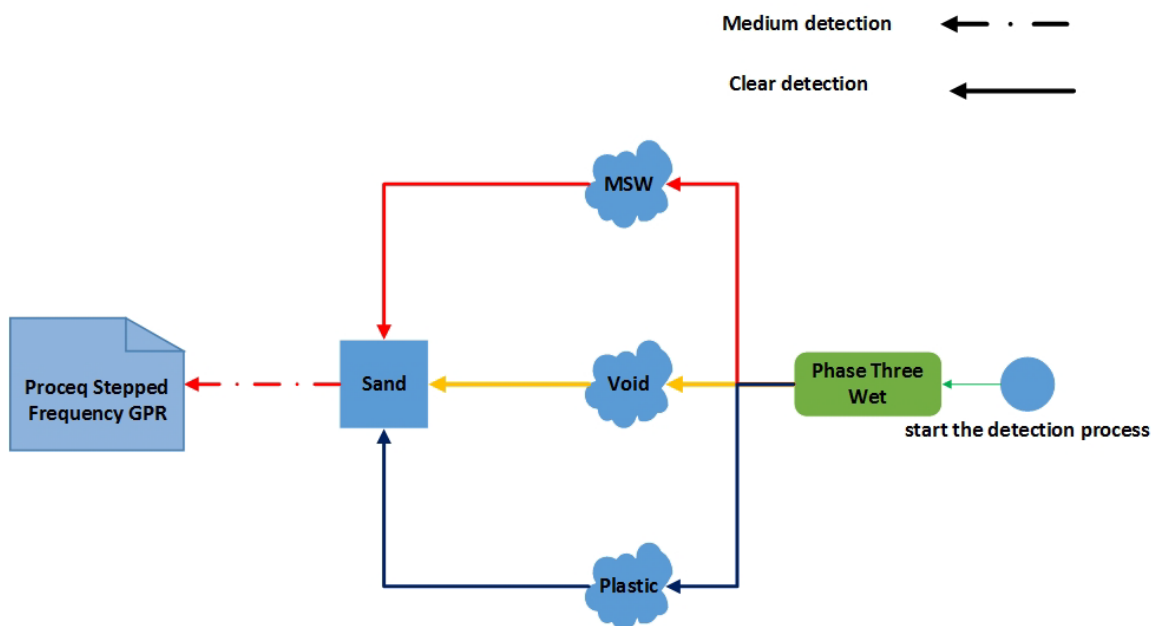


Figure B. 3 Detection results in wet sand

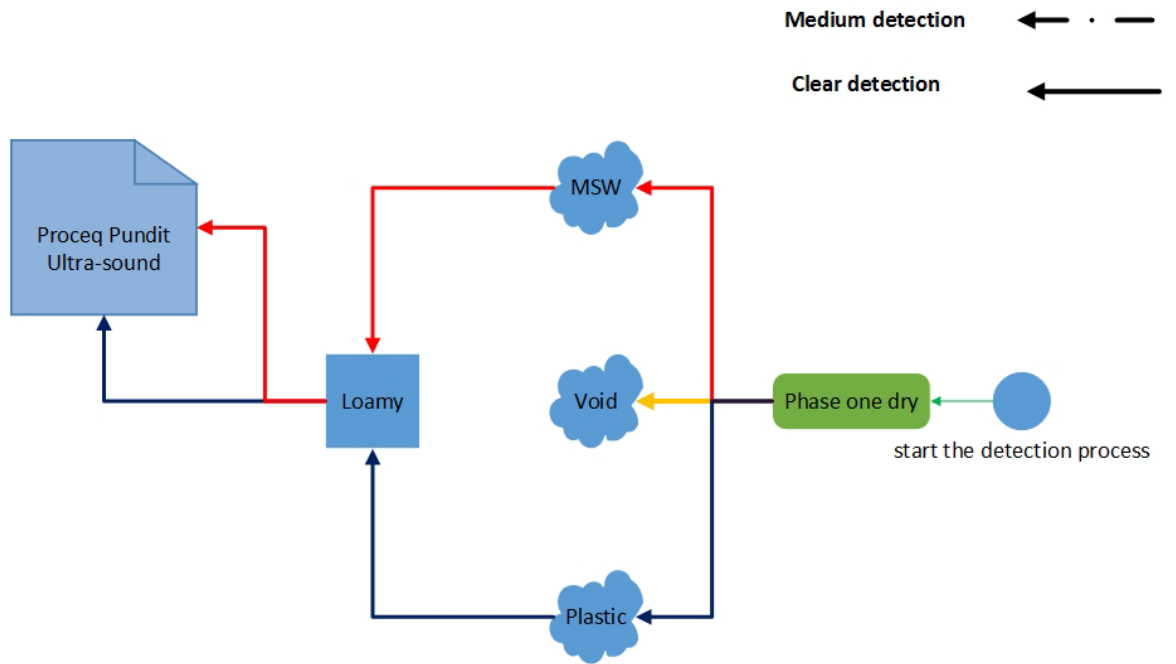


Figure B. 4 Detection results in dry loamy

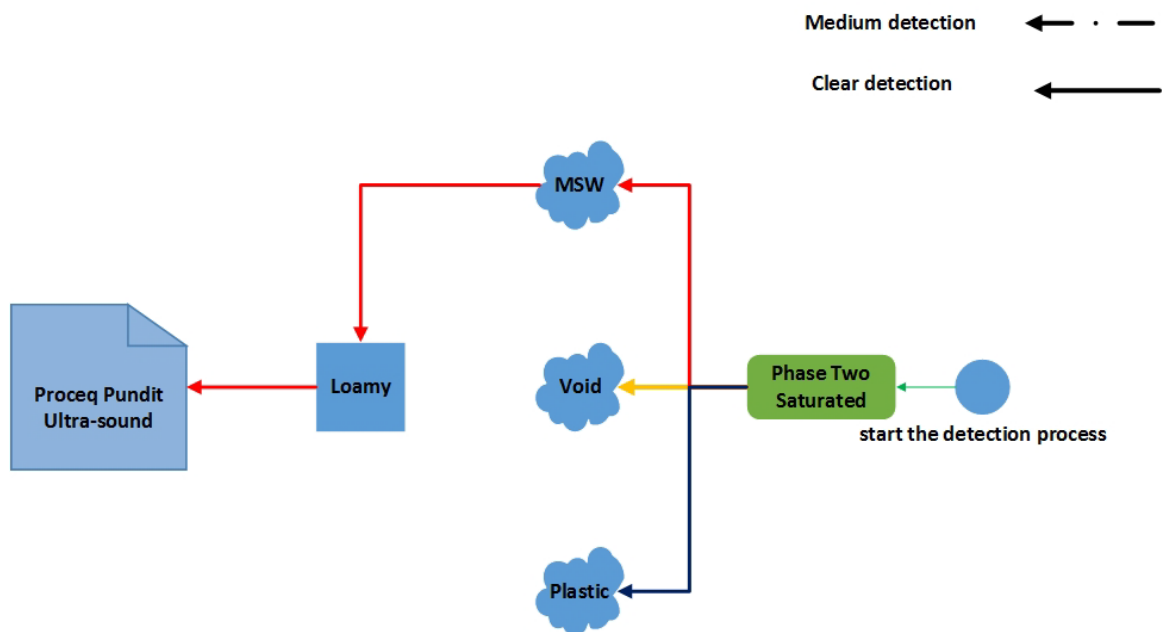


Figure B. 5 Detection results in saturated loamy

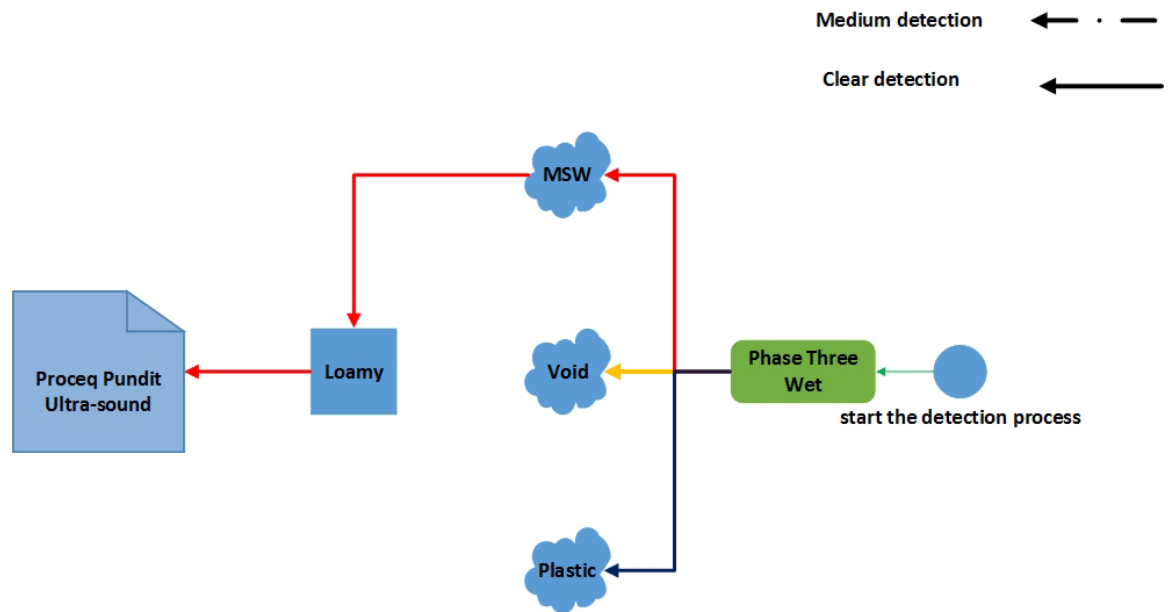


Figure B. 6 Detection results in wet loamy

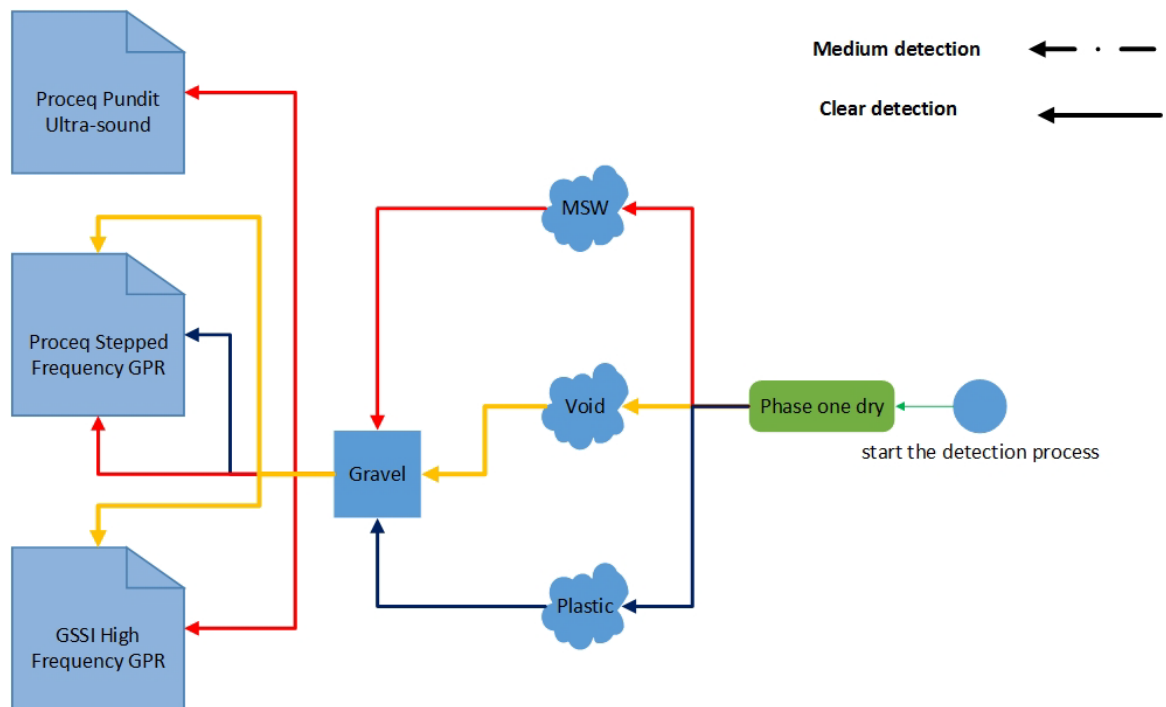


Figure B. 7 Detection result in dry gravel

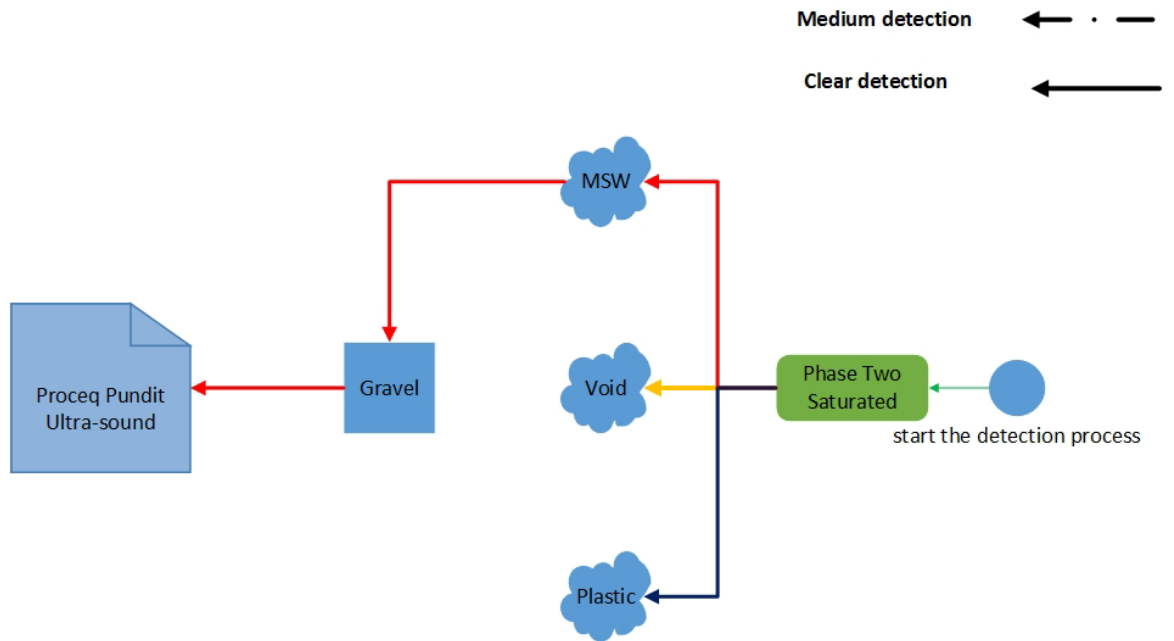


Figure B. 8 Detection results in saturated gravel

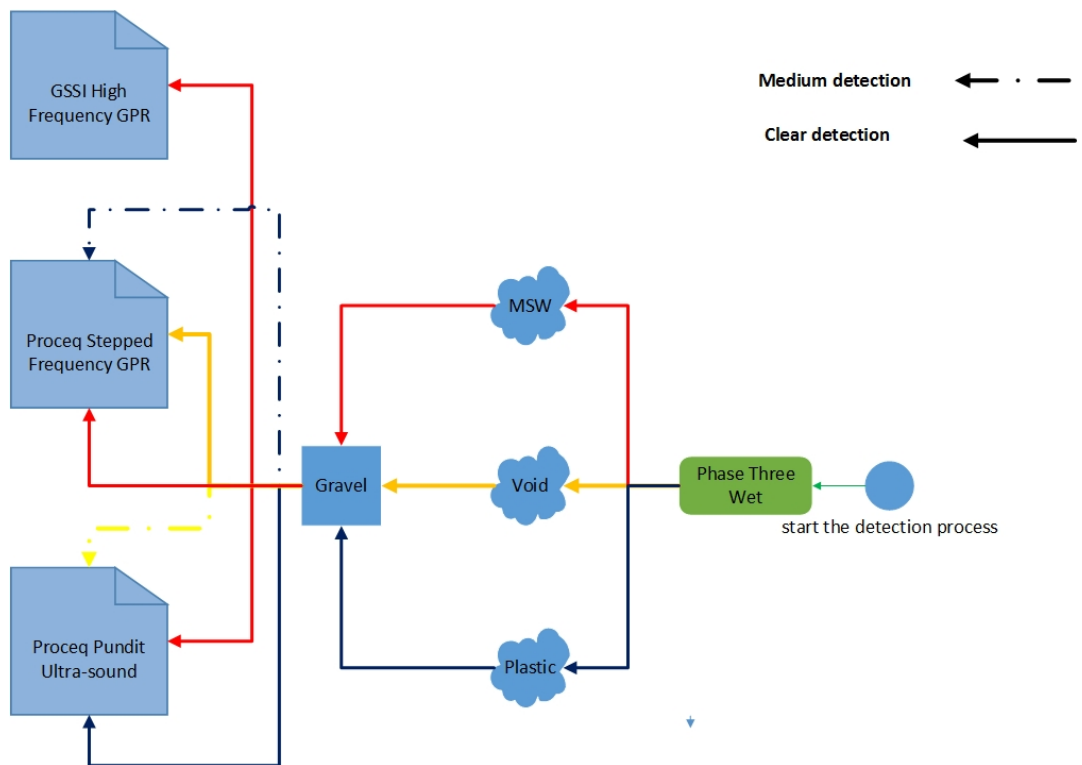


Figure B. 9 Detection results in wet gravel

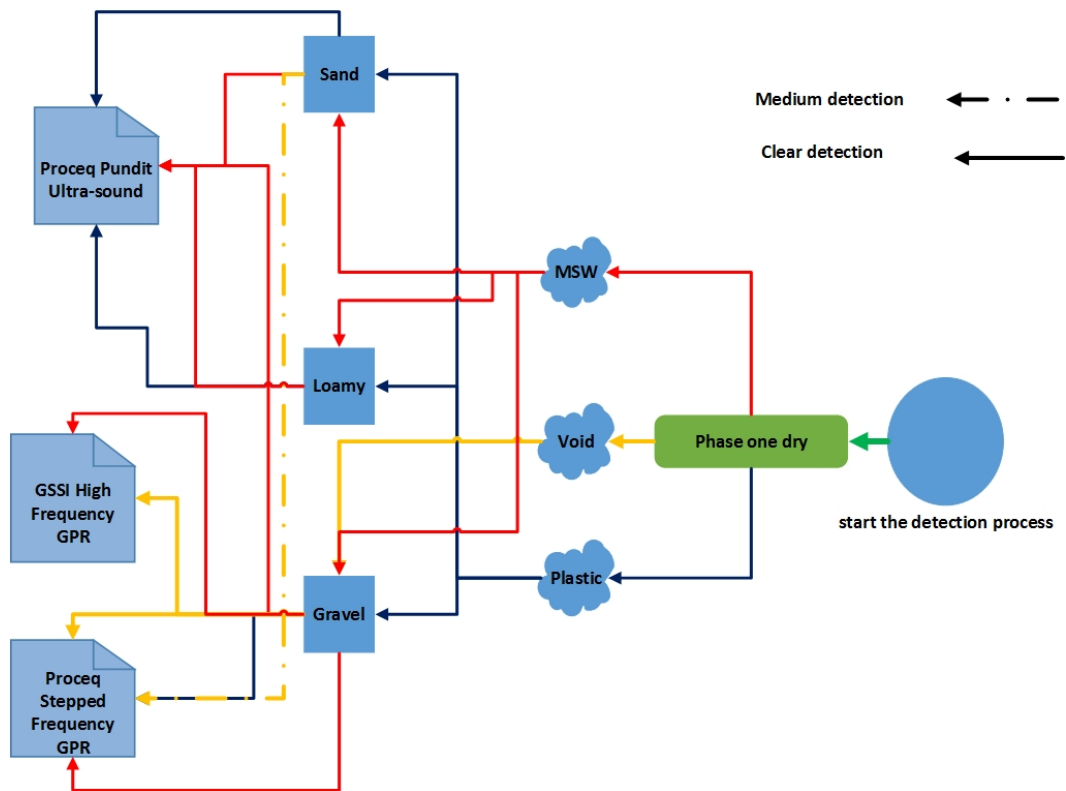


Figure B. 10 Dry host detection chart

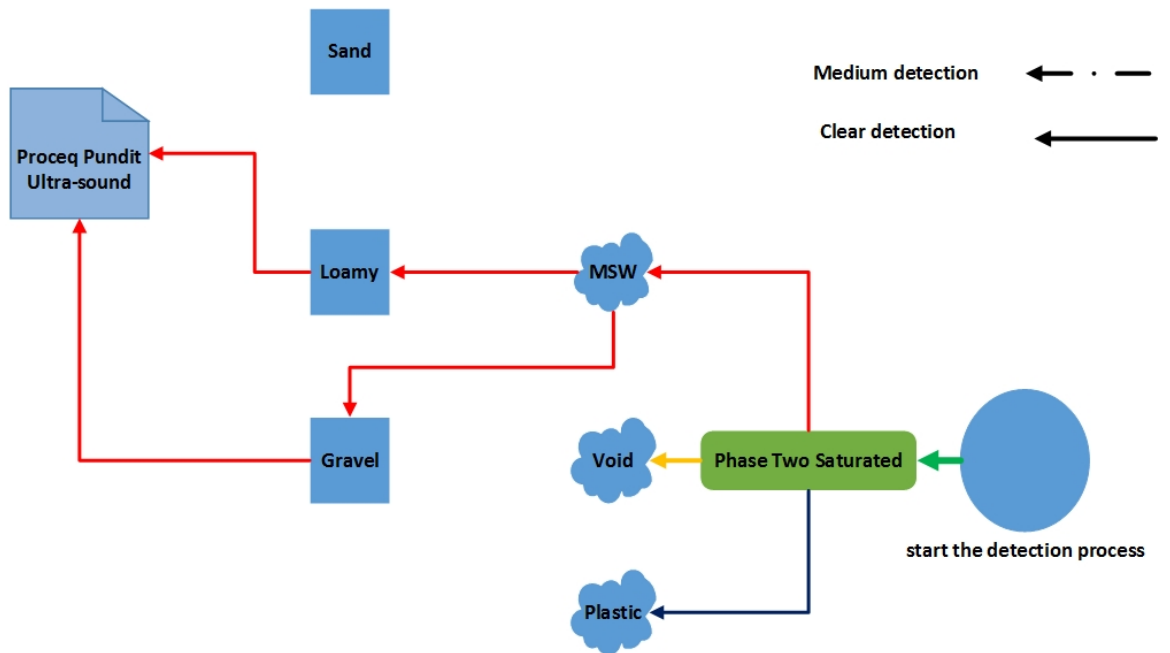


Figure B. 11 Saturated host detection chart

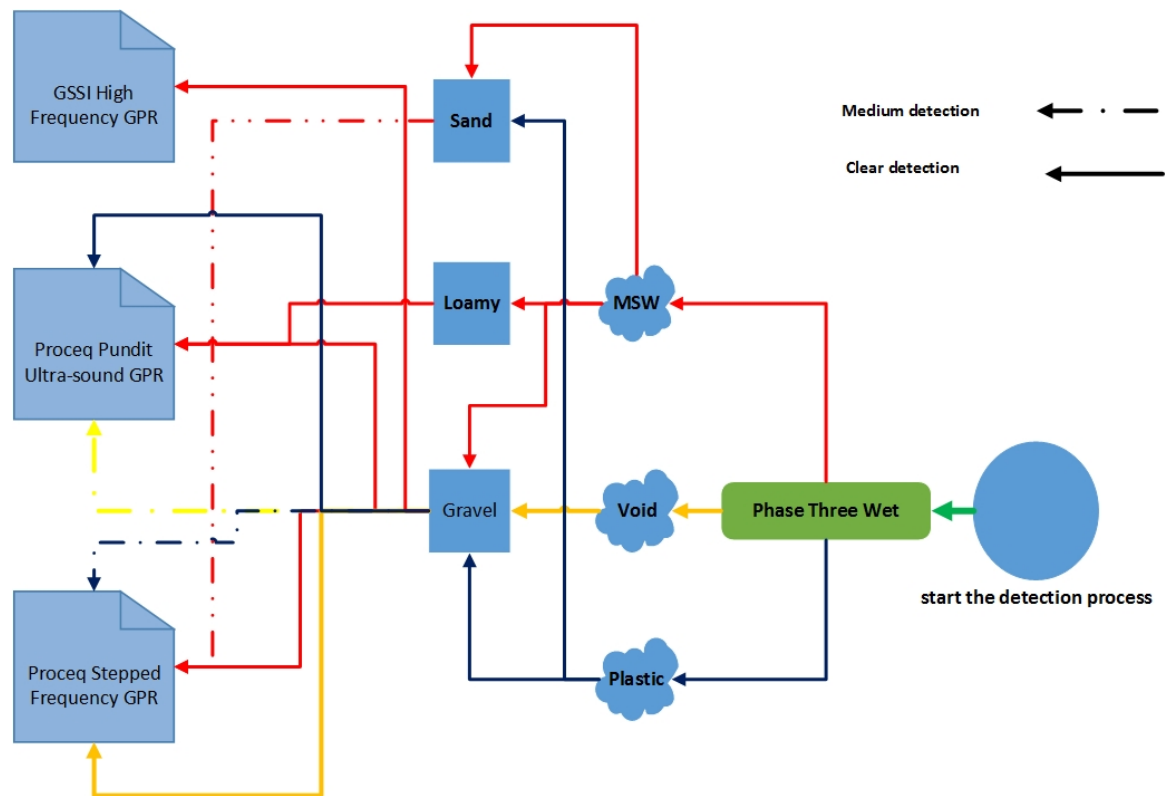


Figure B. 12 Wet host detection chart

After defining the behavior, the general SIMS flowchart in high-level UML shown in Figure 5-16 could be applied. This flow chart represents the steps the user might follow to detect the targeted features. The designed prototype will state the steps that the user must follow to locate a specific feature. Alternatively, to determine if he can be detected or not. Also, it gives him the capability to know the best practice procedures of detecting. The |SIMS, after compilation in a programming language such for subsurface feature detection.

This system does not require any experience from the user on geophysical engineering as the traditional case. However, he needs to have this experience if he will do the feature locating by himself.

The system products will be feasible in cost estimating the subsurface mapping project because it gives the user the information about the requirements to detect the features.

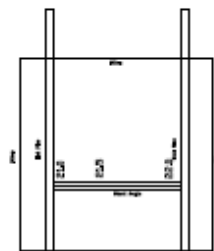
Appendix C

Experiment's Layout and Dimensions

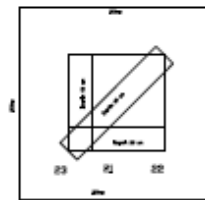
C. Experiment's Layout and Dimensions

This appendix includes the experiment's dimensions and layout for all phases.

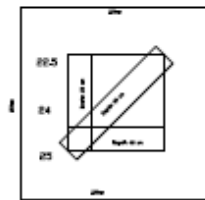
C.1 Phase one (dry host phase)



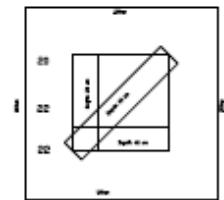
Box 9 GC



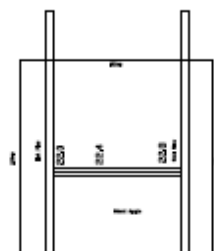
Box 10 GW



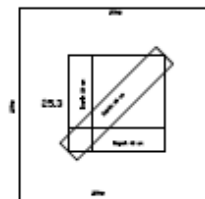
Box 11 GP



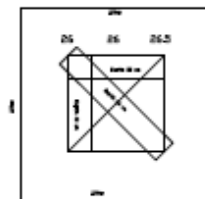
Box 12 GV



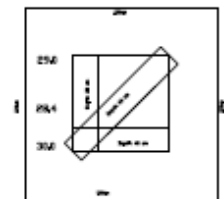
Box 5 LC



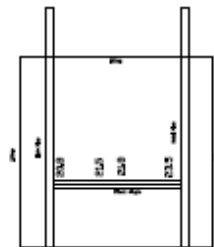
Box 6 LW



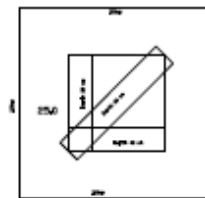
Box 7 LP



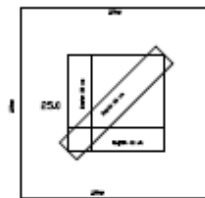
Box 8 LV



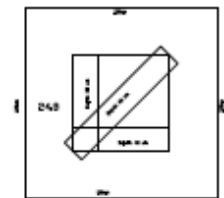
Box 1 SC



Box 2 SW

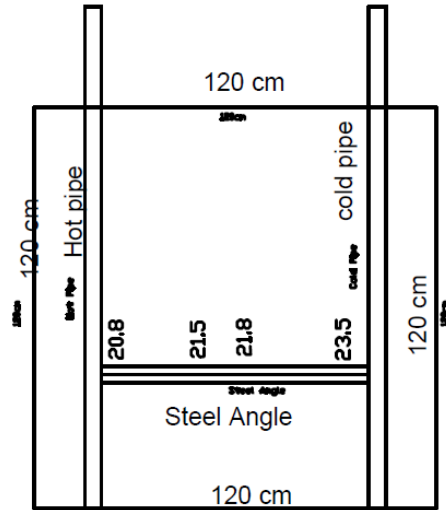


Box 3 SP

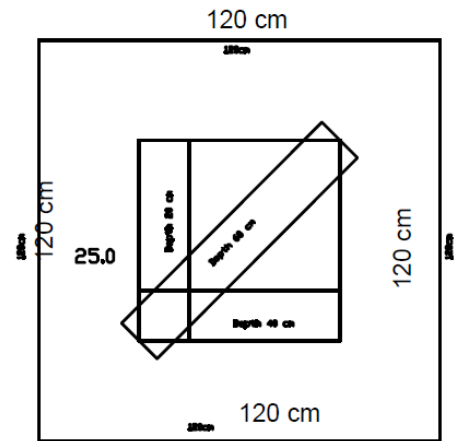


Box 4 SV

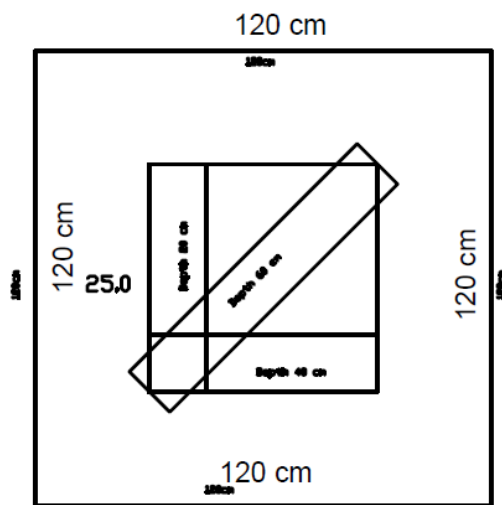
Phase 1



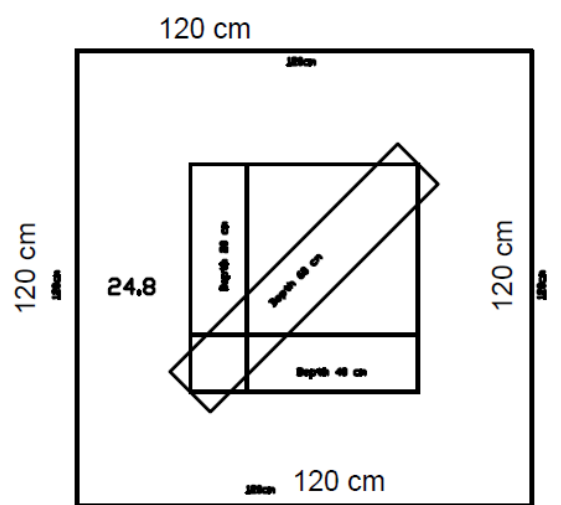
Box 1 SC



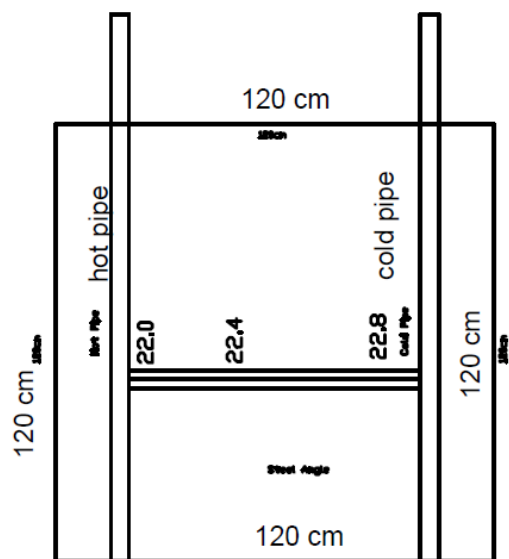
Box 2 SW



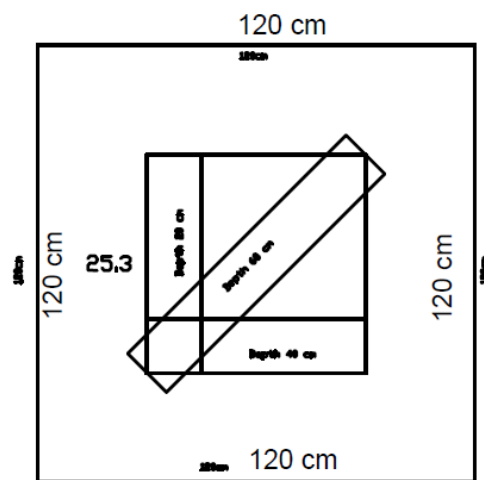
Box 3 SP



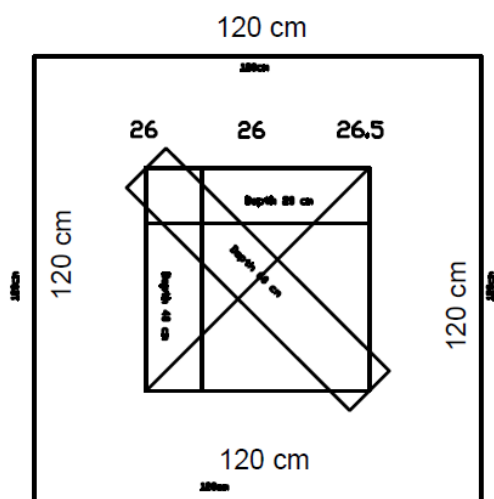
Box 4 SV



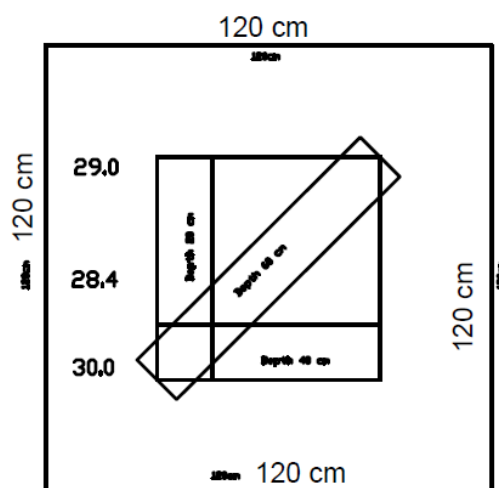
Box 5 LC



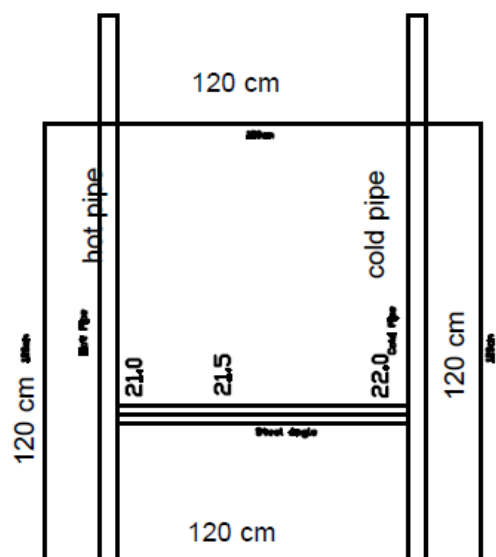
Box 6 LW



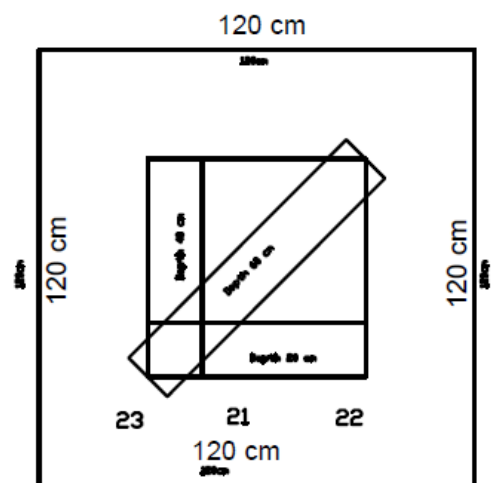
Box 7 LP



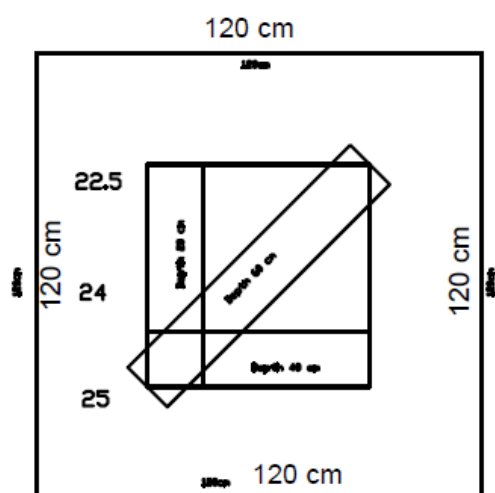
Box 8 LV



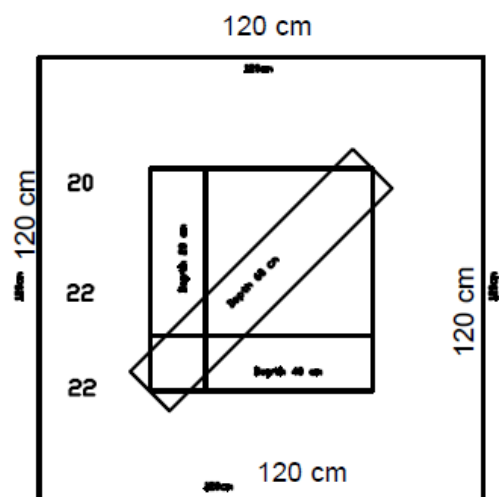
Box 9 GC



Box 10 GW

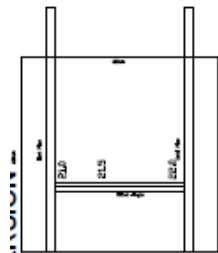


Box 11 GP

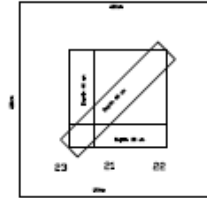


Box 12 GV

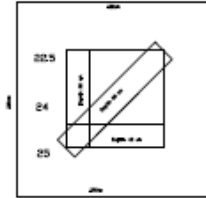
C.2Phase two (Saturated host phase)



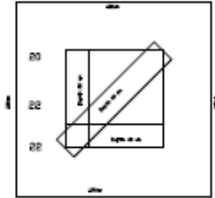
Box 9 GC



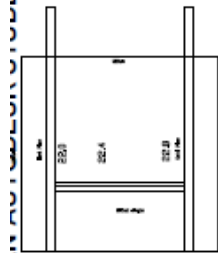
Box 10 GW



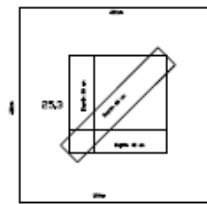
Box 11 GP



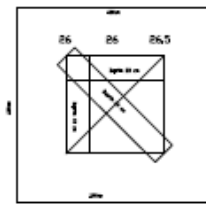
Box 12 GV



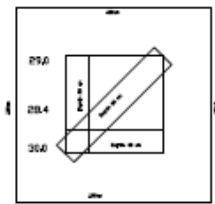
Box 5 LC



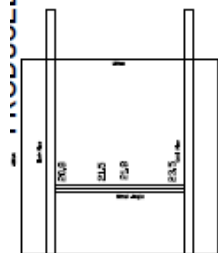
Box 6 LW



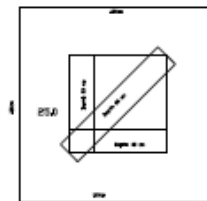
Box 7 LP



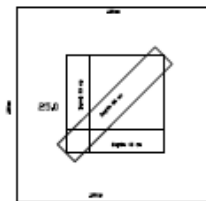
Box 8 LV



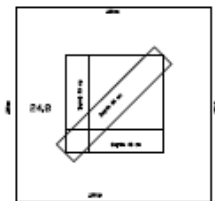
Box 1 SC



Box 2 SW

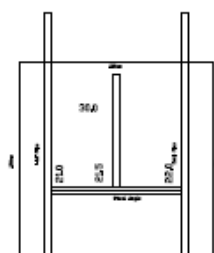


Box 3 SP

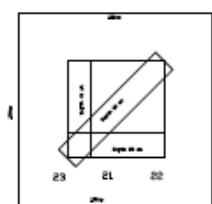


Box 4 SV

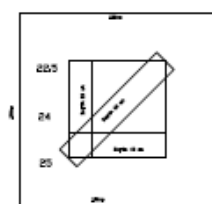
C.3Phase three (wet host phase)



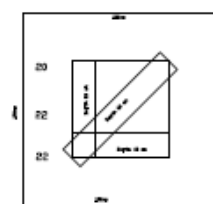
Box 9 GC



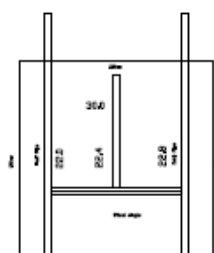
Box 10 GW



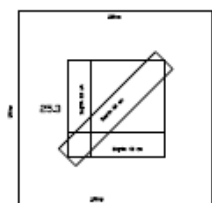
Box 11 GP



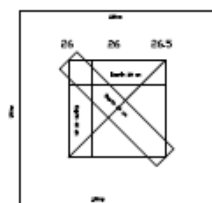
Box 12 GV



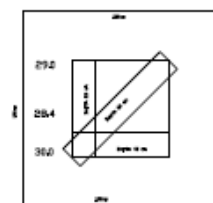
Box 5 LC



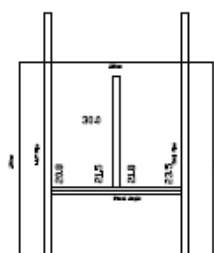
Box 6 LW



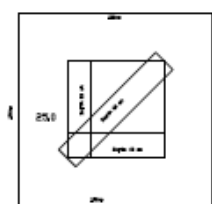
Box 7 LP



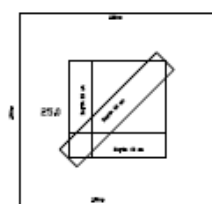
Box 8 LV



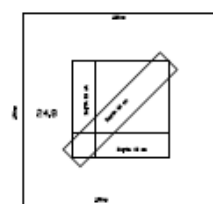
Box 1 SC



Box 2 SW



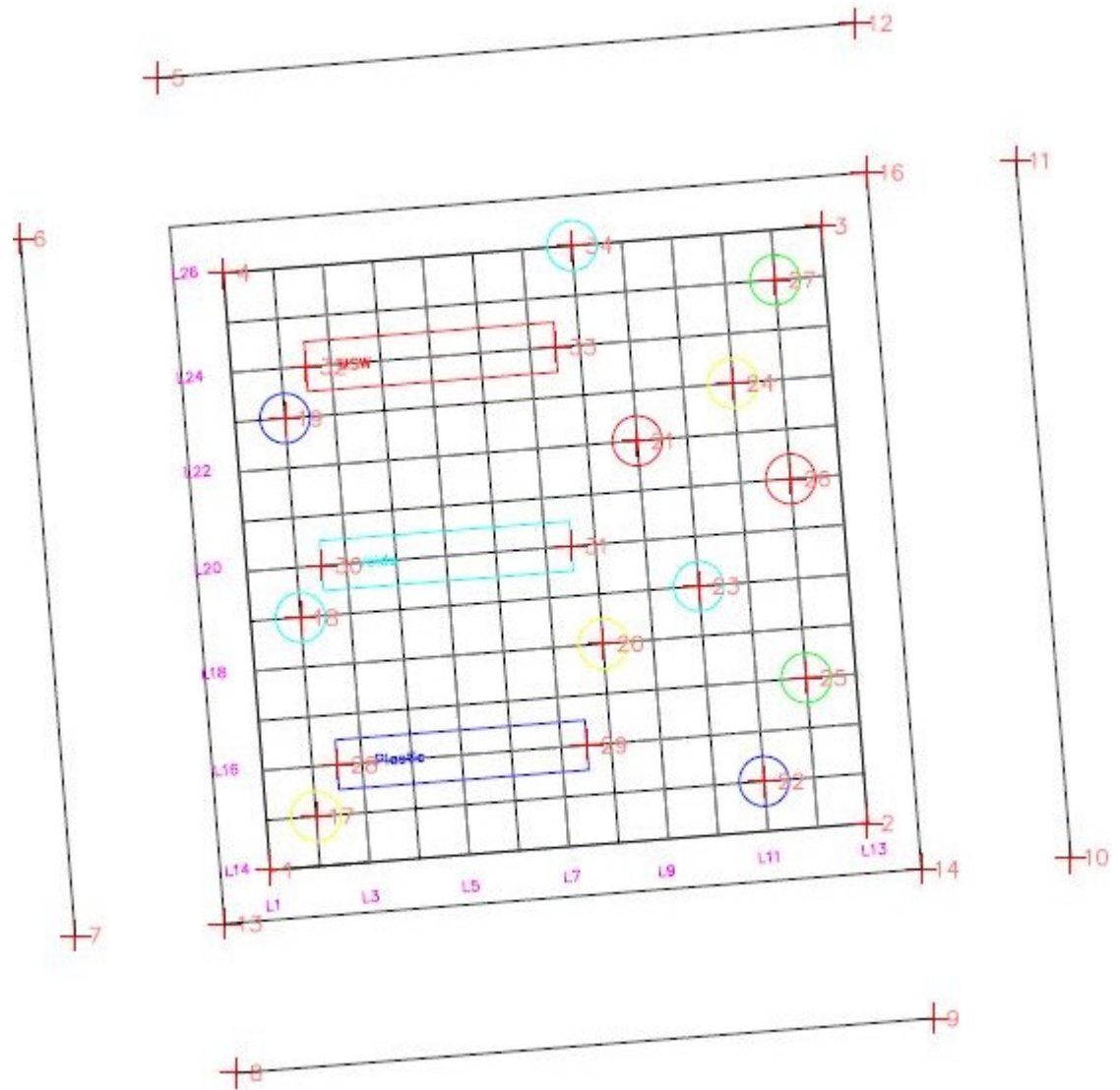
Box 3 SP



Box 4 SV

Phase 3

C.4 Phase four (extending phase|)



الملخص

هناك طرق عديدة لتحديد نوع ومكان الأجسام تحت الأرض وتعد الحفر الاستكشافية أدق طريقة فحص ولكنها تحمل مخاطر كثيرة وكبيرة وكلفتها عالية. لذلك يصار إلى استخدام تكنولوجيا المسح الجيوفيزيائي ثل أجهزة الرادار و الرنين الصوتي وغيرهما. ولقد تبين من خلال بحث مكثف في كل من الابحاث العلمية والصناعات الهندسية الآتي: أنه على الرغم من التطور الكبير في عملية كشف ومسح الأشياء تحت الأرض، إلا أنه مازال هنالك الكثير من التحديات التي لم تحل إلى الآن، على سبيل المثال لا الحصر لا يوجد أي مسافات أو قواعد او نظم متفق عليها لتحديد أفضل طرق المسح تحت الأرض. وكذلك فإن مخرجات التقنيات الموجودة حالياً لا زالت لا تتوافق مباشرة مع بيانات نظم المعلومات الجغرافية والمكانية خصوصاً عند استخدام أكثر من تقنية معاً. وأيضاً فإنه لا يوجد أي جهاز أو تقنية تستطيع ان تحدد نوع الأجسام تحت الأرض. وأخيراً فإنه قلما يتم التعاطي والبحث في عملية ترسيم النفايات الصلبة والتجاويف والنفايات الخطرة ومخلفات البناء. لذلك تسعى هذه الأطروحة لتحقيق هدفان أساسيان: الأول "دراسة وفهم كيفية تفاعل الأجسام تحت الأرض مع التكنولوجيا الحديثة المدمجة ضمن تربة وظروف معينة ، وجمع هذه البيانات في قاعدة بيانات تستخدم في كشف اماكن الأجسام وتحديد نوعها. والثاني هو: "وضع التصميم الهيكلي لنظام ترسيم الأجسام تحت الأرض (نتجت) الذي يسهل عملية إختيار كيفية دمج أكثر من مستشعر معاً، وإنتاج خريطة مكانية رقمية ثلاثية الأبعاد سهلة الفهم، وقابلة للتوافق والدمج مع الخرائط المكانية الأخرى في برمجيات نظم المعلومات الجغرافية."

طالما انه لا يوجد في الصناعات الهندسية ولا في البحوث العلمية السابقة أي بيانات حول خصائص النفايات العضوية الصلبة والتجاويف وقطع البلاستيك المدفونة تحت الأرض عند مسحها بواسطة المستشعرات فوق الصوتية والرادار والكاميرات الحرارية، ولتحقيق للهدف الأول فقد تم تصميم وتنفيذ نموذج تجربة علمية لفهم خصائص هذه المواد مع التقنيات المذكورة، وفي أنواع تربة مختلفة. كما أنه يمكن تطويره لاحقاً لدراسة مواد أخرى لم تدرس مسبقاً مثل النفايات الخطرة والبتروول ومشتقاته والمياه العادمة التي تسربت للتربة وغيرها. وتوفر هذه الخصائص يفضي إلى إمكانية تطوير نموذج لنظام جديد لمسح وتحديد المواد تحت الأرض. وهذا النظام يرسم خارطة الطريق لوضع خطوات لترسيم المواد بخرائط مكانية ثلاثية الأبعاد وهذا تحقيق للهدف الثاني. ومن أجل التأكد من تحقق هذا الهدف فقد تم تصميم خوارزمية باستخدام برنامج الماتلاب. هذه الخوارزمية تقوم بدمج كل البيانات المجمعة وتنتج خريطة رقمية مكانية ثلاثية الأبعاد متوافقة مع نظم المعلومات الجغرافية.

وأخيراً فأ، أهم توصيات هذا البحث أولاً استكمال أعمال دراسة خصائص الأجسام والتي تعتبر حجر الأساس للنظام الجديد، كذلك ضرورة استكمال عملية تحضير وبرمجة النظام الجديد، بالإضافة إلى كتابة دليل الاستخدام وخطوات العمل بهذا النظام والتجارب المطلوبة. وأخيراً فإن هذا البحث يوصي بدراسة أجسام جديدة وظروف معيارية أخرى لتعزيز قاعدة البيانات التي تم انتاجها في هذا البحث.

جامعة البحرين

قسم الهندسة المدنية

كلية الهندسة



استخدام نظام المعلومات الجغرافية لمسح تحت الأرض: طريقة ثلاثية الأبعاد

أطروحة مقدمة كجزء من متطلبات الحصول على درجة

دكتوراه الفلسفة في الهندسة المدنية

إعداد

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إشراف

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مملكة البحرين

أكتوبر، 2021