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A Smart Sensing Platform to Study Moisture Content and Soil Texture

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Abstract

Soil moisture is one of the important indexes of soil character; it is of great significance and greatly influences agricultural geology, climate, and surface hydrology. Therefore, we should carry out a series of studies on the measurement of soil moisture. We first investigated how two core parameters of soil, soil texture and moisture content, affect the power absorption of the 2.45 GHz electromagnetic wave emitted by the sensor, this paper set up the eight different types of soil samples, including five to be established in accordance with the real soil texture that constitutes the proportion of the soil model. The three of them are single ideal soil texture model, as a comparison, and set up five different volumetric moisture content in the soil, and then use the MATLAB calculation of the related physical parameters of the soil dielectric model, combining with COMSOL software was used to carry out the simulation experiment. The influence of water content and soil texture on the electromagnetic wave power absorbed by soil was obtained, which was expressed intuitively by graph and further discussed. After the influence of soil moisture content and soil texture on microwave power absorption is obtained, the possibility of ceramic as the probe of the soil moisture sensor mentioned in this paper is proposed. Like the soil, the dielectric constant is calculated and the porous ceramic model is established. Then, the relation curve between the moisture content of the porous ceramic and the absorbing electromagnetic wave power is established. Finally, it is concluded the power absorption of porous ceramic after water absorption is similar to that of soil moisture.

Keywords

Electromagnetic Wave; Soil Moisture; Soil Texture; Power Absorption; Porous Ceramics.

1. Introduction

1.1. Background

1.1.1. Significance of soil moisture measurement

Soil moisture is one of the most critical factors affecting climate change. Abnormal changes in soil moisture will cause surface radiation flux and sensible and latent heat fluxes of the ground-atmosphere system, and change the balance between energy and water, thus altering the climate. In 1994, according to the US National Research Council its influence on climate change is only lower than that of sea temperature. [49] In meteorology, soil moisture determines that net radiation is divided into latent heat and sensible heat, while in some inland regions, The influence on climate even exceeds that of sea temperature [48]. For example, the climate of Serbia has changed dramatically in the past six years due to the influence of soil moisture, which has led to many similar landslides and floods. [12] According to the 2014 Serbia Flood Recovery Assessment Report, the damage caused by floods alone is estimated at 1.525 billion euros, and many houses were destroyed in the disaster. In addition, the influence of soil moisture on the agricultural sector is also considerable, [7] it can be defined as the earth's surface shallow water of temporary storage, compared with those of the world's total water very insignificant. However, it is only a small amount of this water that controls our whole agriculture, [8] for example, soil drought is currently one of the costliest natural disasters in China; it directly led to the direct loss of us $37.9 billion in the 25 years from 1978 to 2003. Soil drought caused 23.9 million hectares of land and 35.6% of the agricultural area affected in northern China. [9,10,11] The difficult situation of soil drought in northern China has been fully described in different literature materials. In hydrology, soil surface water content also significantly influences the distribution of rainfall, infiltration, and runoff components. [13] In the case of increasing dependence on soil moisture data in hydrology, meteorology, and agriculture, soil moisture measurement is very important now. If we want to measure the soil moisture, we must do further analysis and research on the soil parameters.

At present, there have been various kinds of methods for measuring soil moisture; this article first summarise existing soil moisture measuring methods, then through the simulation experiment of two core parameters of soil water content and soil texture were studied, the simulation experiment is based on the method of measuring soil moisture with 2450 MHz electromagnetic wave, that is, the method of measuring soil moisture with 2.45 GHz electromagnetic wave which is absorbed by water. Finally, according to the relationship between the moisture content of porous ceramics and the electromagnetic wave power absorbed by porous ceramics, the conclusion is drawn that porous ceramics are suitable for 2.45 GHz frequency sensor probe.

1.1.2. Composition and characteristics of soil water

Moist soil is a mixture of soil particles, air gaps, and liquid water. [17] A Briggs study in 1897 showed that soil has three types of moisture: gravitational, capillary, and hygroscopic. Gravity moisture is the free water existing in the soil with large pores that moves very quickly in well-drained soil. [5,17] These water molecules are distributed in the molecular layer far away from the soil particles, called "free water". The farther with water molecules are from the surface of the soil particles, the lower the influence of the matrix force and penetration force; generally speaking, after 2–3 days of rain, gravity water will be discharged from the soil. [18] The capillary moisture resists gravity with adsorption force and exists in the micropores of the soil. These water molecules exist in the molecular layers of the first few layers of soil particles, also called "bound water", while the hygroscopic moisture exists on the soil's surface, it is not in the soil's pores meaning that clay can hold more moisture than sand. In 1985, Dobson's semi-empirical model was also established based on the definition of free water and bound water. [45]

1.2. Porous ceramic properties

In 1978, the United States researchers developed porous ceramics made of alumina kaolin and other ceramic materials; these are used in aluminium alloy casting filtration, significantly improving the casting quality and reducing scrap rates. Nowadays, porous ceramics are used in all aspects and have become a new industry. [28] The relative density of porous ceramic materials is small, the specific surface area is large, the thermal conductivity is low, and the strength is high, and compared with the general porous materials, the mechanical strength and stiffness is high, the porosity is high, and the heat resistance is good. More importantly, porous ceramic materials are non-toxic and tasteless and do not produce secondary pollution. [29] Gupta et al. studied the infiltration characteristics of porous ceramics and found that the water movement of soil will change with the change of soil moisture content, so the higher the soil moisture content, the more water will enter the porous ceramics until the moisture content of the porous ceramics and the soil moisture content reached equilibrium. [30] Because of the high porosity and permeability of the porous ceramics, the electrical resistance method, the tensiometer and time domain reflection (TDR) methods all use the porous ceramic probes to measure soil moisture. The electrical resistivity method measures soil moisture according to the soil and the ceramic's electrical conductivity. The tensiometer method measures soil moisture according to the water in the soil, and the water in the detector pipeline reaching the water potential equilibrium, the porous probe of TDR is used to detect the change of dielectric constant in soil. [3, 31] The most fundamental principle in porous ceramics is that water can infiltrate into the soil. Water from the soil can also penetrate the porous ceramics, making the porous ceramics and the soil integrated. However, the conductivity and penetration depth of some soils with high salinity or special texture will be greatly affected, ultimately impacting soil moisture results. However, when porous ceramics are used as a probe and 2.45 GHz electromagnetic wave is emitted to the soil, the principle remains that the water in soil or ceramics will absorb electromagnetic wave energy, so any change of soil texture will not affect the test results.

2. Literature Review

2.1. Methods for Measuring soil Moisture

2.1.1. Drying method

The traditional method of measuring soil moisture is to remove water from the soil by evaporation or chemical reaction, also known as drying. [4] The drying method is the most direct and commonly used. This method removes the moisture in the soil, usually at 105 ℃, for 12 hours. The sample weights are compared before and after drying to determine the moisture content. In 1970, Reynolds further improved the accuracy and efficiency of the drying method. When the soil moisture was measured by gravity method, aluminium foil was selected as the measuring container because of its high efficiency, low cost and convenient transportation. When measuring soil moisture, the best temperature is 8–18 ℃. The drying rate of test soil was proposed to reduce the error of results. In this way, this drying method has the advantages of being intuitive, having a wide measurement range, and providing accurate, intensive reading. [33] Nevertheless, the drying method still has many deficiencies. Drying the soil takes time, labour and requires equipment. This method can only dry soil particles between the free water; the adhesive layer between the irreducible water is difficult to remove. Moreover, A Klute study in 1986 showed that the quality of the measured soil would decline after drying at 105 ℃ for a few days. [34] Under normal circumstances, the required accuracy can be reached only after drying for 6–8 hours, but it is still far from meeting the needs of modern soil moisture detection and rapid measurement. In 1981, Gee and Dodson proposed to use a microwave to dry soil materials quickly, and the total measurement time only needed 3–6 minutes. [35] Likewise, this method would destroy the organic matter in the soil and make it oxidised and volatile, which was not beneficial to the subsequent soil research, so this method could not be widely promoted. When the drying method is used, the volume of the measuring equipment is large, and the temperature in the measured program is not uniform. Finally, the drying method is a measurement method applied in the laboratory, and attention should be paid to the disturbance of soil samples sampled earlier. However, the coefficient of variation of field samples is as high as 10%, and the factor of human error is very large.

2.1.2. Tension meter method

In 1922, Gardner proposed using a tensiometer, also known as a negative manometer, to measure soil moisture, also known as negative pressure measurement. It mainly measures the tension of water in wet soil and then measures the soil moisture content and soil matrix potential. [36] Porous ceramic probes, gas-tight tubes and hydraulic gauges, are the main components of the tension gauge. First, one needs to detect that water in air-tight pipe can seep smoothly into the soil through the porous ceramics and water in the soil can infiltrate into the

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air-tight pipe. After some time, the soil and water of the airtight tube can achieve the water balance of a state. In this state, by reading the value in the tension meter, the matrix potential of water value (suction) can be determined. Finally, the volumetric water content of the soil can be determined by the relationship between soil volumetric water content and matrix potential. Deans designed an automatic recording system in 1978 that combined a tensiometer with a pressure sensor based on the tensiometer method. [37] However, using the tensiometer by measuring soil moisture content under the influence of soil is considerable. When measuring the permeability of poor clay, negative pressure must be greater than 0.8, but it can be affected by so many factors and soil water content that there is no linear relationship between suction and the soil moisture content. Overall there will be some significant measurement errors. The measuring range of the tensiometer method is affected by the probe; the measuring range is not extensive, its measuring speed still cannot fully meet the needs of rapid soil moisture measurement.

2.1.3. Resistance method

Schlumberger, in 1992 further cited Meyer de Stadelhofen's idea in 1991 of using resistivity to measure underground rocks. [5] The principle of using resistivity to measure soil is to place a resistance block embedded with an electrode in the measured soil, and the water potential in the resistance block is balanced with the soil water potential. The resistance of the resistance block is measured, and the soil water potential is obtained from the resistance. Porous media (such as gypsum, nylon, and fibreglass) are made into so-called resistors, which measure soil moisture using the properties of their resistance relative to water content. Compared with traditional methods of soil moisture measurement, the resistivity method is non-destructive and will not change the soil structure, and the soil resistivity will not be changed by random drilling and sampling disturbance. However, its disadvantages are also apparent. The resistivity method has a hysteresis effect, and the measurement can only reach 100 kPa at most, with low sensitivity. In addition, the drying resistance block will produce the phenomenon of poor contact, and any change in soil conductivity will affect the final result (such as fertilisation). The resistance method is very susceptible to the change of soil properties.

2.1.4. Neutron probe method

In 1972, M Visvalingam, JD Tandy summarised the theory and practice of the neutron scattering method, which improved the sensitivity and accuracy of soil measurement and became the second standard method after the drying method. [38] Since the most significant hydrogen compound in the soil is water, the water content in the soil can be estimated by measuring the content of hydrogen in the soil. The idea is that fast neutrons are emitted from a source, collide with other atoms, thus losing energy and changing direction. Because the hydrogen molecule has the same mass as the fast neutron, it is most effective to make the fast neutron suffer more severe energy loss and slow down the fast neutron. After the collision, by losing energy, the fast neutron becomes a slow neutron. The higher the water content in the soil, the more hydrogen and the higher the density of the slow neutron cloud, so the water content in the soil can be detected by measuring the strength of the slow neutron cloud after the collision [39]. The neutron probe can quickly and accurately measure soil water content. This method does not destroy the soil structure, which can realise fast fixed-point measuring soil moisture over a long time. The neutron probe can be up to 15 cm to 50 cm across, and a wide range of requirements for determining soil moisture content can be met. [1,40] However, the price of neutron detectors ranges from $3,500 to $4,500, the cost of the instruments is high, and their operation is complicated. Because the measuring instruments have radioactive sources, they can only be used after permission, training and testing. Although the measurement range is large, it is difficult to measure the shallow soil water content, and it is difficult to be widely used.

2.1.5. Dielectric method

The principle of soil moisture measurement with the dielectric method is that the change of soil moisture will directly affect the dielectric constant of soil. After detecting the dielectric constant of soil, the soil moisture content can also be calculated. In 1933, Smith–Rose demonstrated the relationship between soil moisture and soil dielectric constant at the frequency of 1 kHz to 10 MHz [41], but due to the incomplete dielectric theory of soil at that time, this study could not be directly converted into a practical sensor. In 1973, Kraszewski introduced the principle of measuring grain water content by microwave. After different instrument tests, he further analysed the data and obtained the “density irrelevance” theory. [19] The experimental principle measures the amplitude and phase changes after microwave attenuation and finally calculates grain water content according to the relation, but it is not applied to the soil. Trop et al. determined that the propagation velocity of the electromagnetic wave is a deterministic monomial relation of the dielectric constant of the medium in which the electromagnetic wave is propagated. [3] More and more methods of measuring the dielectric type appear. Figure 1 summarises the measurement methods of these sensors.

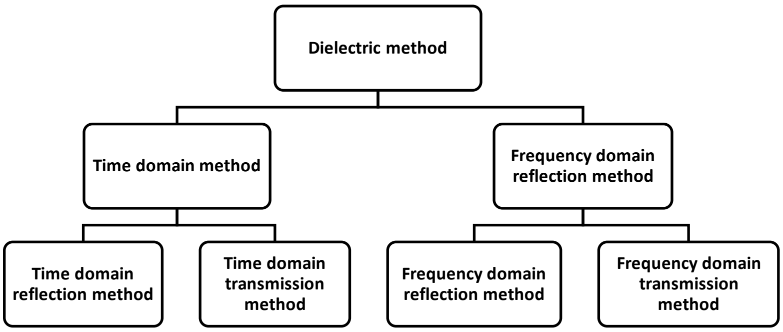


Figure 1. Classification of soil moisture measurement methods based on the dielectric theory

The two most commonly used methods to measure soil moisture are time-domain reflectometer (TDR) and frequency domain reflectometer (FDR). In 1975, Davis and Chudobiak first used TDR to measure soil water content, i.e. electromagnetic waves, because materials have a response to electromagnetic pulses. [21] The principle of this method is to calculate the time spent by electromagnetic waves passing through the soil to determine the content of free water. Because the dielectric constant of water is much greater than that of soil, different water contents have different effects on the electromagnetic pulse. TDR is a remote sensing testing technology based on the principle of time-domain reflectometry. [20] At the earliest, it was used to locate the defects of communication cables. The device transmits transverse high-frequency electromagnetic waves from one probe through a cable and then reaches another probe through the soil. [1] Instruments record the transmitted pulse and receiving time of the reflection wave, with cable length, and the length of the waveguide of electromagnetic wave propagation speed is calculated; the faster the speed, the lower the soil moisture. TDR is a portable device, so convenient when soil surface measurements are to be made in position, it is easy to access the shallow roots of plants on the ground, The moisture measured by TDR is the average of the length of the waveguide, so when measuring 10 cm of soil, the waveguide should be placed horizontally in soil to the same depth. [2] The accuracy of soil moisture measurement by this equipment is more accurate than that by neutron instrument, and it is non-destructive to raw materials. Soil type, density and temperature do not affect the measurement result, but the measurements are only affected by soil bulk density and properties. However, due to the complex circuit design, the method is too expensive ($8,000) to be widely used in farmland water monitoring systems and must be graphed to show the time it takes to emit electromagnetic waves and calculate the soil moisture in response.

FDR completely solves this problem when measuring soil moisture and has most of the advantages of TDR and the probe is more flexible. FDR has an oscillating circuit and a sensor in the soil. [4] Using the principle of an electromagnetic pulse, the soil is used as the medium to complete a capacitance circuit. The dielectric constant of soil is determined according to the propagation frequency of the electromagnetic wave in the medium because the dielectric constant of soil determines the operating frequency of the electromagnetic wave. Finally, the volumetric water content of the soil is obtained. The oscillator and capacitor form a tuned circuit and work together. FDR technology often requires calibration before use, but its cost is far lower than TDR technology.

In this paper, a single frequency of 2.45 GHz is used to measure the moisture content instead of the frequency domain because 2.45 GHz is the same as the natural frequency of water, so the water will absorb this high-frequency electromagnetic wave, which solves the problem of calibration in specific soil before the use of FDR technology. As a result, the measurements are more accurate and are not affected by the soil composition. In order to further study the core parameters of soil sensors, it is critical to determine the influence of different volume moisture content and different soil materials on power absorption.

2.1.6. Other methods

In addition to the methods mentioned above, many scientific techniques can measure soil moisture, including nuclear magnetic resonance, thermal, and separation tracer methods. [14,42,43] These three methods can measure soil water content, but they are not suitable for real-time soil water detection due to the large detection equipment and low measurement accuracy.

3. Methodology

This chapter first embarks from the soil dielectric theory, analysing the principle of high-frequency electromagnetic waves to measure soil moisture. First, an analysis of the former research literature of different soil dielectric models, based on building moisture content from 0% to 50% is given. Then, the Dobson soil model, three kinds of ideal soil model, to calculate soil dielectric constant is introduced. Finally, the dielectric properties are studied to obtain the influence of soil texture on the absorption of electromagnetic wave power in soil, and the possibility of using porous ceramics as a soil moisture sensor probe is explored.

3.1. Rationale

Due to the heterogeneity of soil topography and soil cover, soil moisture is different in space and time, so it is complicated to measure the overall soil moisture. [7] Therefore, most soil moisture measurements can only represent one point, so the average value measured by many soil points should be used to describe the soil moisture in an area. Since the 1960s, microwave remote sensing technology has become one of the most important methods for measuring soil moisture due to its all-weather measurement ability and accuracy. [15] The dielectric constant of soil is closely related to soil moisture, and the soil's dielectric properties determine the soil's microwave radiation characteristics. [14,15] Therefore, before using a microwave to detect soil water content, the first step is to establish the soil's dielectric model and calculate the soil's dielectric constant. Different soil materials and soil moisture will significantly influence the dielectric constant and affect the soil's energy absorption when electromagnetic waves pass through. Therefore, it is of great significance to study the absorption of microwave energy by different soil materials with differing water contents.

According to Chernyak in 1967, the complex dielectric constant describes the interaction between the electric field and a material and is represented by a complex number. [23] The complex dielectric constant consists of two parts, namely the real part (representing the storage of charge) and the imaginary part (representing the loss of charge), which can be expressed as:

$$k = \varepsilon_m = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_m' - j\varepsilon_m'' \tag{4}$$

ε_m' is the real part of the dielectric constant
ε_m'' is the imaginary part of the dielectric constant.

It can be seen from the above formula that the dielectric constant is the complex dielectric constant K, which can be expressed by ε_m. [23] Generally speaking, the real part of the dielectric constant represents how much energy is stored in the material by the external electric field. At the same time, the imaginary part of the dielectric constant, also called the loss factor, represents how much energy is dissipated into the external electric field.

The soil itself is also a kind of dielectric, so it satisfies the above theory of dielectric constant, and the dielectric constant of soil also consists of the real part ε_m' and the imaginary part ε_m''. The real ε_m' shows the ionic polarisation of the soil, which is mainly composed of displacement polarisation and relaxation plane, while the imaginary ε_m' shows the total energy consumption of the soil, which is composed of electrical loss and ionic conductivity loss. Therefore, the imaginary part of the dielectric constant of wet soil plays a very important role in this paper.

3.2. Selection of soil texture

Several kinds of soil were investigated sandy loam, loam, silt loam, silty clay, pure sand, pure silt, pure clay. The last three soils are soils with a single texture, which are ideal soil models established in this simulation experiment. The first five soils are mixed with different proportions of soil texture according to the actual soil. Because the permittivity model here is modelled using the semi-empirical model developed by Dobson in 1985, it is also blended for convenience according to the proportions of the five soil textures in the soil model. [22]

As shown in Table 1, since simulation was adopted in this experiment, three groups of ideal soils were set for comparison, namely soil with a sand ratio of 100%, soil with clay ratio of 100% and soil with a sand ratio of 100%, to explore the influence of soil texture sand further silt and clay on electromagnetic wave power absorption.

Table 1. The percentage of eight different soil textures sand, silt and silt in the total soil weight

Code	Textural class	Sand%	Silt%	Clay%
1	Sandy Loam	51.51	35.06	13.43
2	Loam	41.96	49.51	8.53
3	Silt Loam	30.63	55.89	13.48
4	Silt Loam	17.16	63.84	19.00
5	Silty Clay	5.02	47.06	47.38
6	Pure Sand	100%	0%	0%
7	Pure Silt	0%	100%	0%
8	Pure Clay	0%	0%	100%

3.3. Construction of soil Dielectric model

The value of the dielectric constant of the soil mixture lies between the dielectric constants of the substances, neither greater than the value of the largest dielectric constant, such as that of water, nor less than the value of the smallest. When the water content of the mixture is higher, its complex dielectric constant will be greater. The basic principle of using electromagnetic waves with a frequency of 2.45 GHz to measure soil moisture content is also on the dielectric constant of the wet soil mixture. Before the microwave soil sensor model simulation is established, different dielectric constants of several soil materials need to be obtained. In this paper, several permittivity models are analysed first, and the corresponding permittivity is calculated and compared with the previous studies on the permittivity of soil.

Several models of permittivity have been established and can be divided into empirical ones (Topp et al., 1980; Hallikainen et al., 1985; Ledieu, 1986), semi-experience (Dobson et al.,1985; Wang and Schmugge, 1980) and physical models (Dobson et al., 1985; Mironv et al.,2004). Topp's empirical model is the simplest, which only analyses a single type of soil material; it considers the influence of soil moisture on the dielectric constant and establishes the empirical relationship between dielectric constant and water content. Moreover, it is only applicable to the frequency band of TDR technology. [3] In 1985, Hallikainen et al. established the empirical relationship with variables of different soil materials on this basis. In 1985, Dobson established the physical and semi-empirical models and defined the free water based on data of Hallikainen et al., where air and soil particles together constituted wet soil.[45] This semi-empirical model is based on the mixed model of empirical and theoretical dielectric media in the frequency range of 1.4–18 GHz, so it is suitable for the calculation of the dielectric constant of different types of soil because the variables of Dobson's semi-empirical model are water content, different soil materials and soil bulk density. In 2004, Mironv created a physical model, but the basic data were challenging to obtain and required maximum bound and free water data, such as the static dielectric constant and conductivity of bound water. These data need to be in different water content and frequency of soil materials and do not apply to widely different soil types. [46]

This paper compares the effects of different soil texture types on the absorption of electromagnetic wave power, so the most suitable Dobson semi-empirical model is chosen to calculate and analyse different soil types' permittivity and moisture content.

3.4. Calculation of soil parameters by MATLAB

3.4.1. Calculation of Permittivity of soil

In order to better understand the influence of soil texture and water content on microwave power absorption, 48 groups of soil conditions were set up. The real and imaginary parts of the complex dielectric constant were calculated for each soil with eight different soil textures and five different water contents at a frequency of 2.45 GHz.

The dielectric constant of wet soil should be the weighted sum of the different materials in proportion by volume, and the sum of the total volume should be 1.

$$\varepsilon^{a} = V_S\varepsilon_s^{\alpha} + V_a\varepsilon_a^{\alpha} + V_{fw}\varepsilon_{fw}^{\alpha} + V_{bw}\varepsilon_{bw}^{\alpha} \tag{5}$$

Where V is the volume ratio of different soil materials, and ε is the dielectric constant of soil. Subscripts s, a, fw and bw are used to refer to soil substrate, air, free water, and bound water. α is the shape factor, and in the Dobson model, is taken to be 0.65,

Apply the following transformation to the above equation:

$$V_S = \frac{\rho_b}{\rho_s} \tag{6}$$

$$V_a = 1 - V_S - \theta_v \tag{7}$$

$$V_{fw}\varepsilon_{fw}^{\alpha} + V_{bw}\varepsilon_{bw}^{\alpha} = \theta_v^{\beta}\varepsilon_{fw}^{\alpha} \tag{8}$$

Where ρb is bulk density, which means the dried weight of soil per unit volume (g·cm−3); ρs is the specific gravity, is the density of soil matrix particles; θ_v is the volume water content of the soil. By substituting Equations 6, 7, and 8 into 5, the mixing model of Dobson's dielectric constant can be obtained, and its relation is as follows:

$$\varepsilon_m = \varepsilon_m' - j\varepsilon_m'' \tag{9}$$

$$\varepsilon_m' = [1 + \frac{\rho_b}{\rho_s}(\varepsilon_s^{\alpha} + m_v^{\beta'}\varepsilon'^{\alpha}_{f\omega} - m_v)]^{\frac{1}{\alpha}} \tag{10}$$

$$\varepsilon_m'' = [m_v^{\beta''}\varepsilon''^{\alpha}_{f\omega}]^{\frac{1}{\alpha}} \tag{11}$$

By simplifying the soil model, Dobson combined free water and bound water in the soil into one term because the dielectric constants of bound water in the soil are difficult to obtain. Instead, they are connected by a β coefficient, and the two β coefficients can be calculated by the following relationship:

$$\beta' = 1.2748 - 0.519S - 0.152C \tag{12}$$

$$\beta'' = 1.33797 - 0.603S - 0.166C \tag{13}$$

The real part ε_f' and the imaginary part $\varepsilon_{f\omega}''$ of the relative permittivity of free water can be expressed by the following relation,

$$\varepsilon_{f\omega}' = \varepsilon_{\omega\infty} + \frac{\varepsilon_{\omega 0} - \varepsilon_{\omega\infty}}{1 + (2\pi f \gamma_\omega)^2} \tag{14}$$

$$\varepsilon_{f\omega}'' = \frac{2\pi f \gamma_w (\varepsilon_{\omega 0} - \varepsilon_{\omega\infty})}{1 + (2\pi f \gamma_\omega)^2} + \frac{\sigma_{eff}(\rho_s - \rho_b)}{2\pi \varepsilon_0 f \rho_s m_v} \tag{15}$$

ε_0 is the dielectric constant of free space, and $\varepsilon_{\omega\infty}$ is the limit of the high frequency of the imaginary part of the dielectric constant of free water, where the value is 4.9. $\varepsilon_{\omega 0}$ is the static dielectric constant of water at room temperature 20 ℃, here is 80.1. γ_ω is the relaxation time for water at room temperature 20 ℃, where $2\pi\gamma_\omega = 0.58 \times 10^{-10}$. [25]

From Equation 12, it can be seen that the conductivity term (the second term of Equation 12) depends on $\frac{1}{f}$. When the frequency is 2.45 GHz, this term has very little influence on the calculation of $\varepsilon_{f\omega}''$. Therefore, when the frequency increases, the conductivity term will decrease rapidly with the increase of frequency, thus developing $\varepsilon_{f\omega}''$ based on soil texture and bulk density σ_{eff} of empirical expression. This expression cannot be used for frequencies below 1.4 GHz, The calculated value of $\varepsilon_{f\omega}''$ cannot be basically consistent with the measured value:

$$\mathrm{\sigma_{eff}} = -1.645 + 1.939\mathrm{\rho_b} - 0.02013\mathrm{S} + 0.01594\mathrm{C} \tag{16}$$

where the mass fraction of S is sand, C is clay's mass fraction (i.e., 0\leqS, c ≤ 1).

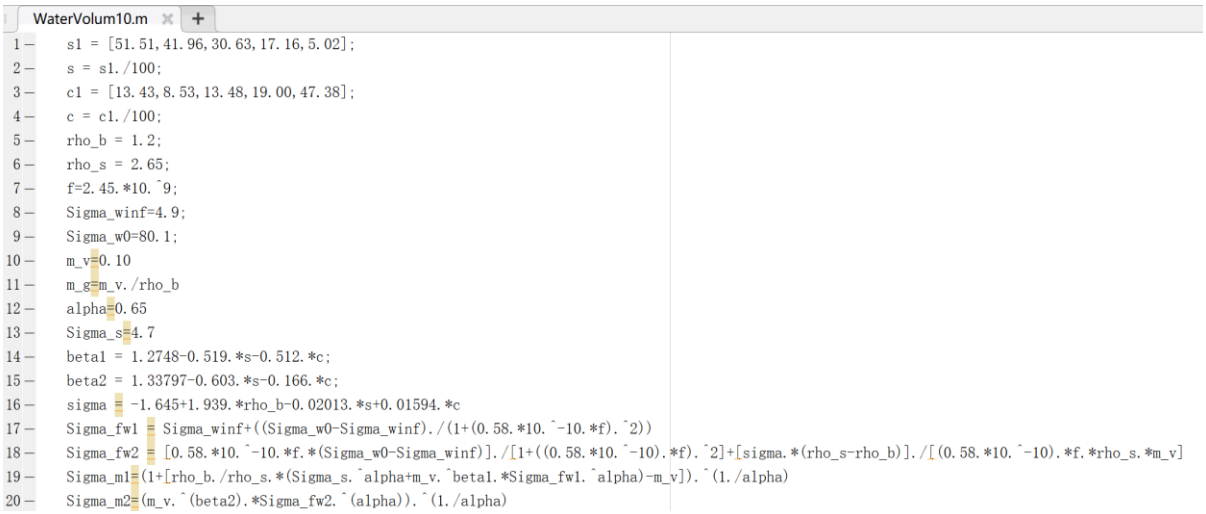
In this paper, the volume water content θ_v is used for calculation from 10% to 50%, and the effects of soil moisture content from the minimum to the maximum on energy absorption are compared. Taking the volume water content equal to 10% as an example, the detailed properties of soil materials are calculated, and the bulk density is set as 1.2 $\mathrm{g/cm^3}$, and the specific gravity is 2.65 $\mathrm{g/cm^3}$, the ambient temperature is 20 ℃.

Dielectric function calculation of five conventional soils

In this paper, the parameters of five soil textures with different volume water content were calculated in detail by MATLAB, and the calculation process of soil with 10% volume water content was taken as an example. First, the proportions of sand and clay in five different types of soils were input into MATLAB. The mass fraction of sand was 51.51%, 41.96%, 30.63%, 17.16% and 5.0%, and the mass fraction of clay was 13.43%,8.53%, 13.48%, 19.00% and 47.38, respectively.

Thus, the empirically determined constants β' and β'', which are related to soil types, are calculated, and the real and imaginary parts of the relative permittivity of free water, $\varepsilon_{f\omega}'$ and $\varepsilon_{f\omega}'''$, can be obtained by inserting the values of each parameter mentioned above. Finally, the volume water content is expressed as M_V in MATLAB and set as 0.1. Then the real part ε_m' and imaginary part ε_m'' of the dielectric constant of five soil materials can be calculated when the volume water content θ_v is 10%. The results are shown in the Figure 2, and the real part is 5.4986, respectively. The imaginary parts of 5.1109, 4.9604, 4.7905 and 5.1450 were 1.0351, 0.8211, 0.6658, 0.5177 and 0.4755, respectively. So the complex dielectric constant of soil ε_m is:

$$\varepsilon_{m1} = 5.4986 - 1.0351j$$
$$\varepsilon_{m2} = 5.1109 - 0.8211j$$
$$\varepsilon_{m3} = 4.9604 - 0.6658j$$
$$\varepsilon_{m4} = 4.7905 - 0.5177j$$
$$\varepsilon_{m5} = 5.1450 - 0.4755j$$



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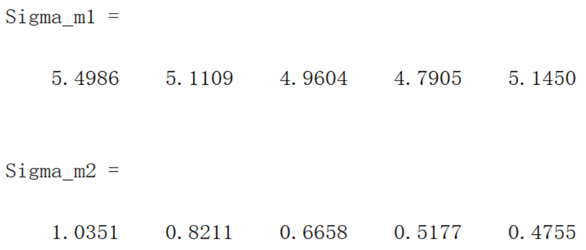
s1 = [51.51,41.96,30.63,17.16,5.02];
s = s1./100;
c1 = [13.43,8.53,13.48,19.00,47.38];
c = c1./100;
rho_b = 1.2;
rho_s = 2.65;
f=2.45.*10.^9;
Sigma_winf=4.9;
Sigma_w0=80.1;
m_v=0.10
m_g=m_v./rho_b
alpha=0.65
Sigma_s=4.7
beta1 = 1.2748-0.519.*s-0.512.*c;
beta2 = 1.33797-0.603.*s-0.166.*c;
sigma = -1.645+1.939.*rho_b-0.02013.*s+0.01594.*c
Sigma_fw1 = Sigma_winf+((Sigma_w0-Sigma_winf)./(1+(0.58.*10.^-10.*f).^2))
Sigma_fw2 = [0.58.*10.^-10.*f.*(Sigma_w0-Sigma_winf)]./[1+((0.58.*10.^-10).*f).^2]+[sigma.*(rho_s-rho_b)]./[(0.58.*10.^-10).*f.*rho_s.*m_v]
Sigma_m1=(1+[rho_b./rho_s.*(Sigma_s.^alpha+m_v.^beta1.*Sigma_fw1.^alpha)-m_v]).^(1./alpha)
Sigma_m2=(m_v.^(beta2).*Sigma_fw2.^(alpha)).^(1./alpha)
```

Figure 2 The calculation process of soil dielectric constant under 10% water content in MATLAB



```
Sigma_m1 =

    5.4986    5.1109    4.9604    4.7905    5.1450


Sigma_m2 =

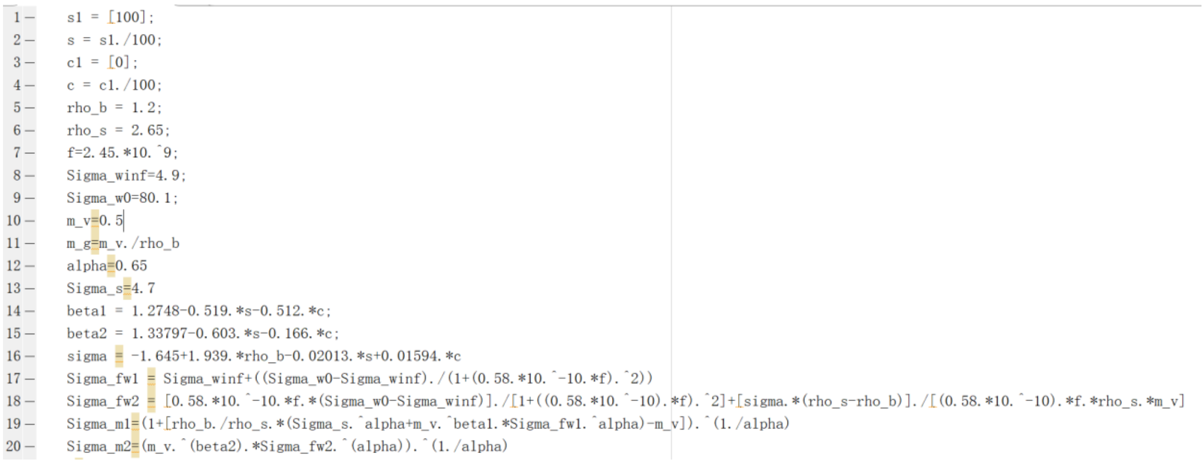
    1.0351    0.8211    0.6658    0.5177    0.4755
```

Figure 3. Calculated results of soil dielectric constant under 10% water content in MATLAB

Calculation of dielectric function of three ideal soils

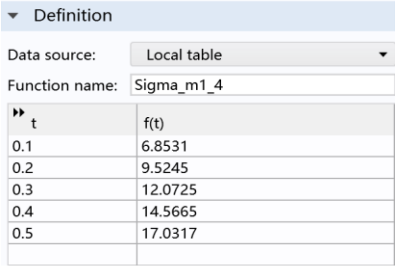
The mass fraction of sand was 100%,0%, 0%, the mass fraction of silt was 0%, 100%, 0%, and the mass fraction of clay was 0%,0%, 100%, respectively.

First of all, for pure sand soil, since its sand mass fraction is 100%, we can ignore the value of C and only calculate S when we only calculate β, whereas, for pure clay, we can ignore the value of S; the same is true for pure clay, it ignores S and C, that is to say, S and C are equal to 0, and then the relevant dielectric constant is calculated. Take pure sand as an example with S=1; the calculation process of dielectric constant in MATLAB and the result of filling in COMSOL are shown in Figure 4, 5, and 6.



```
s1 = [100];
s = s1./100;
c1 = [0];
c = c1./100;
rho_b = 1.2;
rho_s = 2.65;
f=2.45.*10.^9;
Sigma_winf=4.9;
Sigma_w0=80.1;
m_v=0.5
m_g=m_v./rho_b
alpha=0.65
Sigma_s=4.7
beta1 = 1.2748-0.519.*s-0.512.*c;
beta2 = 1.33797-0.603.*s-0.166.*c;
sigma = -1.645+1.939.*rho_b-0.02013.*s+0.01594.*c
Sigma_fw1 = Sigma_winf+((Sigma_w0-Sigma_winf)./(1+(0.58.*10.^-10.*f).^2))
Sigma_fw2 = [0.58.*10.^-10.*f.*(Sigma_w0-Sigma_winf)]./[1+((0.58.*10.^-10).*f).^2]+[sigma.*(rho_s-rho_b)]./[(0.58.*10.^-10).*f.*rho_s.*m_v]
Sigma_m1=(1+[rho_b./rho_s.*(Sigma_s.^alpha+m_v.^beta1.*Sigma_fw1.^alpha)-m_v]).^(1./alpha)
Sigma_m2=(m_v.^(beta2).*Sigma_fw2.^(alpha)).^(1./alpha)
```

Figure 4. Calculation of dielectric constant of pure sand in MATLAB



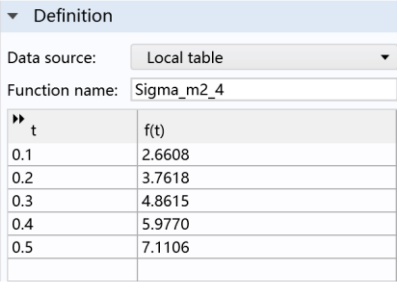
Definition

Data source: Local table

Function name: Sigma_m1_4

t	f(t)
0.1	6.8531
0.2	9.5245
0.3	12.0725
0.4	14.5665
0.5	17.0317

Figure 5. The real part of the dielectric constant of pure sand at different water contents



Definition

Data source: Local table

Function name: Sigma_m2_4

t	f(t)
0.1	2.6608
0.2	3.7618
0.3	4.8615
0.4	5.9770
0.5	7.1106

Figure 6. The imaginary part of the dielectric constant of pure sand at different water contents

3.4.2. Calculation of other soil parameters

Calculation of soil density

Generally, soil density refers to soil mass per unit volume after removing the pores between the soils, i.e., specific gravity. In this case, it is 1.6 g/cm^3.

Calculation of thermal conductivity of soil

In the following, the thermal conductivity of the measured soil is studied. Here, the soil thermal conductivity model proposed by Campbell in 1985 is applied in this paper. [47] The main structure of this model in calculating the thermal conductivity of soil is as follows:

$$\lambda = A + B\theta_v - (A - D)exp[-(C\theta_v)^E] \tag{14}$$

$$A = 0.65 - 0.78\rho_b + 0.60\rho_b^2$$

$$B = 1.06\rho_b$$

$$C = 1 + 2.6/m_c^{0.5}$$

$$D = 0.03 + 0.1\rho_b^2$$

$$E = 4$$

Where, values of A, B, C, D and E all depend on soil bulk density and clay content, ρ_b is soil bulk density, m_c is clay content in the soil, and θ_v is the volume moisture content. Through Campbell's empirical model, we can calculate the thermal conductivity of the soil. Taking the soil with 5% volume moisture content as an example, there should be five different thermal conductivity coefficients, 0.2483, 0.2612, 0.2482, 0.2435 and 0.2389.

Soil constant pressure heat capacity calculation

The constant pressure heat capacity of the soil is calculated, the heat capacity of the water for about 1 cal/g, five times of the heat capacity of soil is dry, dry soil generally 0.2 cal/g, the specific heat of the moist soil compared with the dry soil, heat capacity, higher temperature rise more slowly. Under the condition of constant pressure, the constant pressure heat capacity is obtained by simple analysis. Set C_S for the heat capacity of the soil, when the volumetric water content θ_v was 10%, through $\theta_v = \theta_g \times \rho_b$, water content is converted to a weight θ_g and is equal to 4.2%. The hypothesis is 100 g, soil water is 4.2 g, giving a total of 104.2 g, and can be simplified as soil 1 ℃ increased calories needed for $100\ \mathrm{g} \times 0.2\ \mathrm{cal/g} = 20\ \mathrm{cal}$, Of water by 1 ℃ for $4.2\ \mathrm{g} \times 1\frac{\mathrm{cal}}{\mathrm{g}} = 4.2\ \mathrm{cal}$, is needed in the volumetric moisture content $\theta\ v$ for 5% of the cases, elevated 1 ℃, needs 24.2 calories. In this case, the specific heat of the soil is equal to $\frac{24.2cal}{104.2g}$ or 972.366212 J/Kg.

A series of validation concluded that the density of different specific heat and thermal conductivity for launching 2.45 GHz did not affect the energy loss of electromagnetic waves with different soil composition, no matter if it is set to 0 or calculated value of the above. Figure 7 shows the image in the same way; the power of soil to absorb electromagnetic waves did not change, so one does not need to fill in these parameters when modelling, and the model can only be used as a reference.

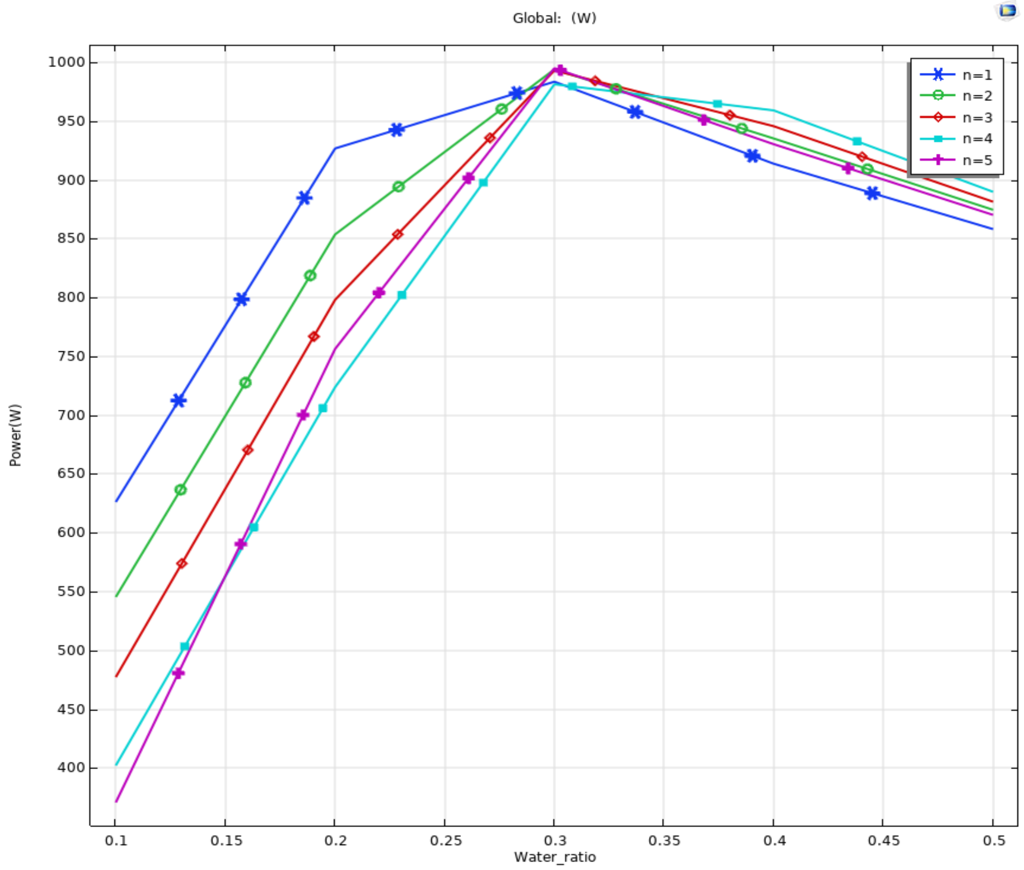


Figure 7. The soil model produces a peak that exceeds 1/4 of the microwave wavelength

3.5. Simulation experiment in COMSOL

3.5.1. Soil model establishment

After calculating the basic parameters of the soil material, COMSOL software was used for modelling. In this paper, the basic model takes a model of a 2.45 GHz microwave device heating potatoes as a reference, defining the solved equation, and then solving the electromagnetic field in the resonant cavity. Next, the initial model is further modified and modelled. A rectangular waveguide with a length, width and height of 0.078 m × 0.05 m × 0.018 m is set as the entrance for microwaves to enter the cavity, and then a length, width and height of 0.27 m × 0.267 m × 0.188 m is established. A cube is used as the resonant cavity. In the middle of the resonant cavity, a glass container with a length, width and height of 0.03 m is constructed, and there is an opening directly above the glass container to fix the soil. Next, a cube-shaped material with a length of 0.0112 × 0.0112 × 0.0206 m in length, width and height and a volume of 2.58 cm^3 is placed inside for testing. The wavelength of the microwave is 12.24 cm, and the size of the material could not be greater than 1/4 λ. If the material is more than a quarter the size of the microwave wavelength, shown below, will happen at 30% moisture content when a power absorption peak, the reason is that the electromagnetic wave will material model is more than in the space outside 1/4 λ part of certain points, resonance occurs, causing electric field enhancement, and creating unnecessary errors. The next step is to define the material properties. First, the material is selected. [16] Here, metal copper is selected as the metal wall of the resonant cavity, playing the role of Faraday cage, and then the power absorption of the whole soil is obtained by integrating the soil in the most central cube. Since the resonant frequency is related to the geometric shape, the simulation assumes that the medium is filled, and further comparison is carried out without the influence of the geometric shape. As shown in Figure 8, the coloured cube in the centre is the soil part.

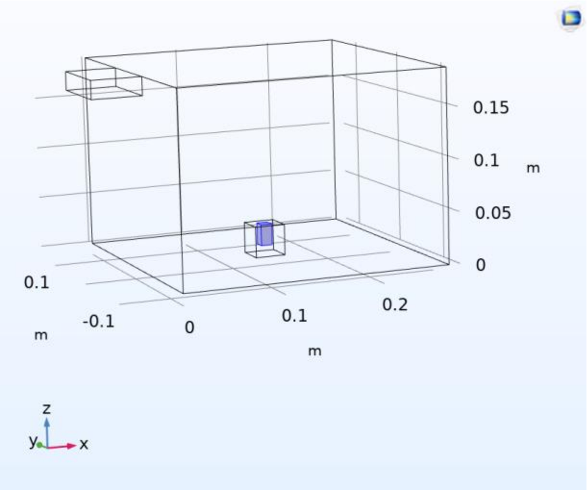


Figure 8. Models built in COMSOL

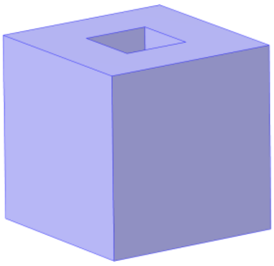


Figure 9. Upper half-open glass container

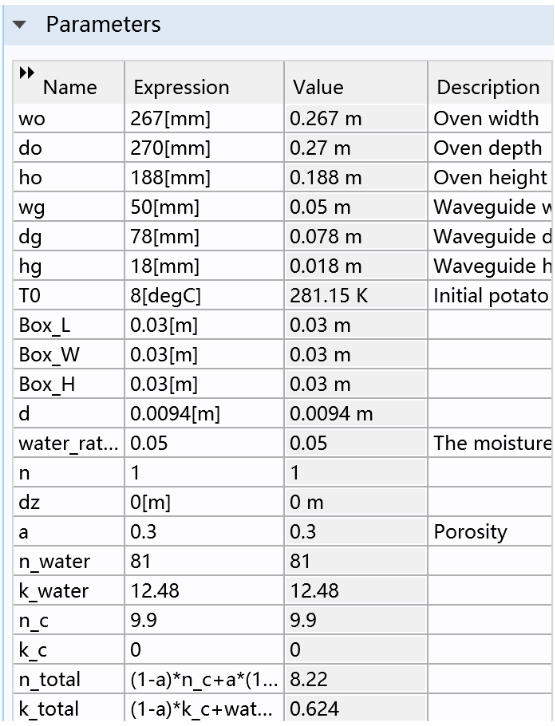
3.5.2. Ceramic model establishment

This procedure is to explore the consistency between the soil and ceramics for microwave power absorption, so the design of the model should be consistent with soil, cavity, glass shell and the material being measured dimensions and soil; the only difference is the glass container material is replaced by a different material, a 99.6% alumina ceramic. Since porous ceramics are needed to simulate soil, the porosity is set as 0.3, and the porosity for air and water, that is, the total volume of air and water, is 0.3, and the dielectric constant of alumina ceramic is 9.9. In this experiment, the composite dielectric constant of water at room temperature is 81-12.48*j, while the dielectric constant of air is 1. For convenience, according to the porosity and water content, the weighted average of the dielectric constants of the three substances is used to describe their dielectric constants by the proportion of each substance, and a uniform dielectric constant is obtained. The expressions of the real and imaginary parts of the weighted average dielectric constant constructed are as follows. For the real part of the weighted average, the first term in the expression is the dielectric constant of the ceramic part of the material, the second term is the dielectric constant of the air part, and the third term is the dielectric constant of the water part. For the imaginary part, because it is pure ceramic and dry air, only the dielectric constant of the water part can be calculated.

$$\varepsilon'_{total} = (1\text{-}a)\times \varepsilon_c + a\times [1\text{-}\theta_v\text{-}(1\text{-}a)]\times \varepsilon_{air} + a\times \theta_v \times \varepsilon'_{water} \tag{15}$$

$$\varepsilon''_{total} = \theta_v \times \varepsilon''_{water} \tag{16}$$

Here, ε'_{total} is the real part of the dielectric constant after the weighted average of the material, ε''_{total} is its imaginary part, a is the porosity of the material, θ_v is the volumetric water content of the material, and ε'_{water} is the water at room temperature. The real part of the dielectric constant, ε''_{water} is its imaginary part, ε_c is the dielectric constant of ceramics, ε_{air} is the dielectric constant of air, here is 1. Figure 10 shows the parameter settings and model in COMSOL.



Name	Expression	Value	Description
wo	267[mm]	0.267 m	Oven width
do	270[mm]	0.27 m	Oven depth
ho	188[mm]	0.188 m	Oven height
wg	50[mm]	0.05 m	Waveguide w
dg	78[mm]	0.078 m	Waveguide d
hg	18[mm]	0.018 m	Waveguide h
T0	8[degC]	281.15 K	Initial potato
Box_L	0.03[m]	0.03 m	
Box_W	0.03[m]	0.03 m	
Box_H	0.03[m]	0.03 m	
d	0.0094[m]	0.0094 m	
water_rat...	0.05	0.05	The moisture
n	1	1	
dz	0[m]	0 m	
a	0.3	0.3	Porosity
n_water	81	81	
k_water	12.48	12.48	
n_c	9.9	9.9	
k_c	0	0	
n_total	(1-a)*n_c+a*(1...	8.22	
k_total	(1-a)*k_c+wat...	0.624	

Figure 10. Parameter setting of porous ceramic material model

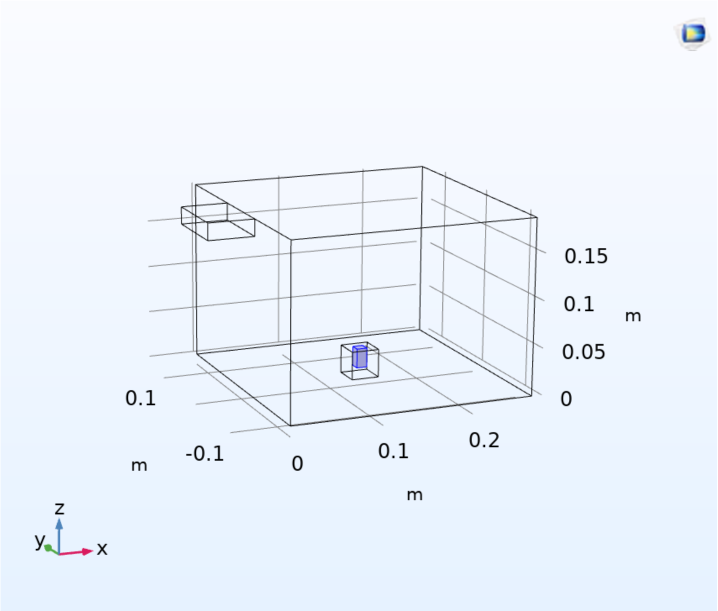


Figure 11. Construction of the porous ceramic model

3.5.3. Grid generation

Finite element discretisation was used for the cavity volume because the grid is only precise enough to parse medium electromagnetic wavelengths, and a triangle unit was selected for the grid type due to reduced dispersion error. However, the material properties are unchanged during the simulation process, so we choose the automatic subdivision mesh model, as shown in Figure 12.

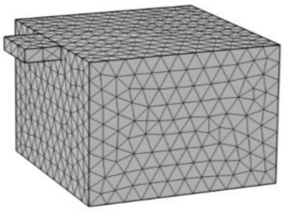
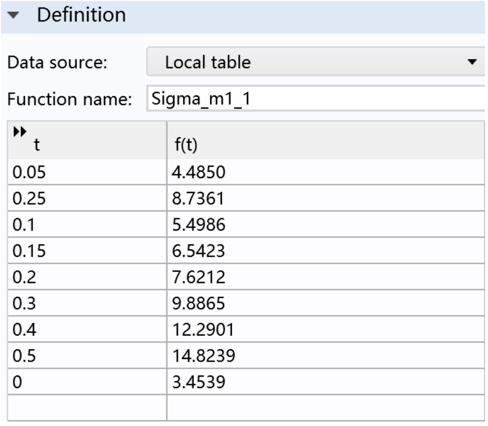


Figure 12. COMSOL grid generation model

3.5.4. Soil parameter setting

After the modification of the soil modelling is completed, the initial soil temperature is set to 8°C and the initial soil volumetric water content to 10%, the soil's absorption of electromagnetic wave power is set as a variable in the definition of Component in COMSOL, and then the five soil material dielectrics are set. The constant and water content function takes the real part of the first soil material with 10% water content as an example, as shown in Figure 13. The function is named Sigma_m1_1, and its imaginary part is named Sigma_m1_2, the variable t is the water content, f(t) is the real or imaginary part of the dielectric constant. Next, the data under different water content and soil materials is filled in sequence. The ceramic parameters have been set above.

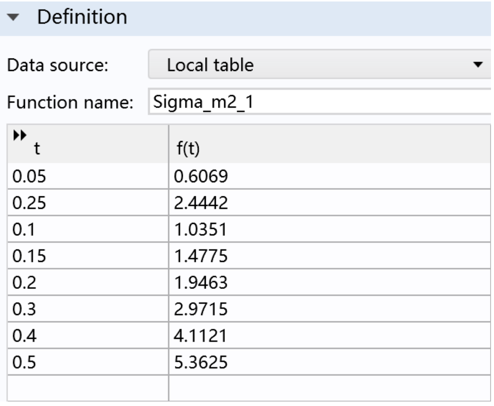


Data source: Local table

Function name: Sigma_m1_1

t	f(t)
0.05	4.4850
0.25	8.7361
0.1	5.4986
0.15	6.5423
0.2	7.6212
0.3	9.8865
0.4	12.2901
0.5	14.8239
0	3.4539

Figure 13. The setting of the real part of the dielectric constant in COMSOL



Data source: Local table

Function name: Sigma_m2_1

t	f(t)
0.05	0.6069
0.25	2.4442
0.1	1.0351
0.15	1.4775
0.2	1.9463
0.3	2.9715
0.4	4.1121
0.5	5.3625

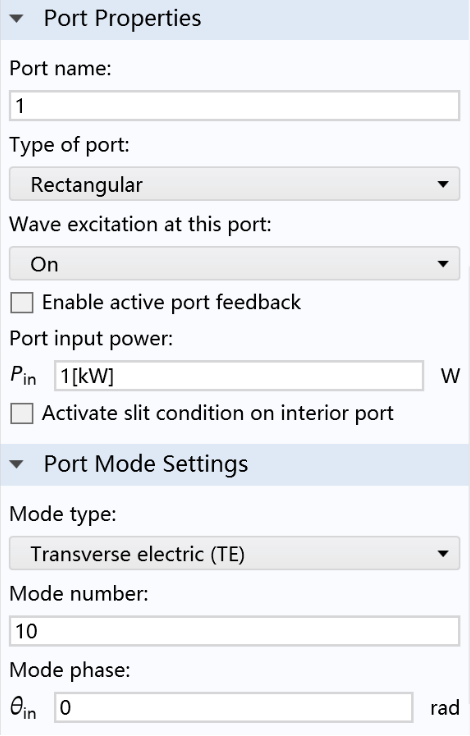
Figure 14. The setting of the imaginary part of the dielectric constant in COMSOL

3.5.5. Solving

In order to solve the linear equation of electromagnetic field described in this model, the soil and ceramics remained the same; the electromagnetic wave in radio frequency and the physical field in frequency domain were established in Component, using the wave equation. Then the electromagnetic field in the resonant cavity was solved. The initial value of the electric field in the Initial Values was set to 0. Next, the impedance boundary was set in the boundary conditions. The impedance boundary condition set in the metal case for an excitation source emits electromagnetic waves that can cause reflection to a metal shell and a shell induced current, hence the need for simulation of this kind of circumstance to reduce the error of the simulation results. The impedance of the metal shell of the copper boundary of the relative dielectric constant is 1, its permeability is 1, and its conductivity 5.998×10^7 S/m. The port excitation source power is set to 1 kW in Port, and the rectangular waveguide mode TE10, the main mode of the rectangular waveguide and its lowest frequency transmission mode, is selected. The setting of the port is shown in Figure 15.

The equation for volatility is as follows

$$\nabla \times \mu_r^{-1}(\nabla \times E)\text{-}k_0^2(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0})\mathrm{E}=0 \tag{17}$$



Port Properties

Port name:
1

Type of port:
Rectangular

Wave excitation at this port:
On

☐ Enable active port feedback

Port input power:
P_{in} 1[kW] W

☐ Activate slit condition on interior port

Port Mode Settings

Mode type:
Transverse electric (TE)

Mode number:
10

Mode phase:
θ_{in} 0 rad

Figure 15. Parameter Settings of Port

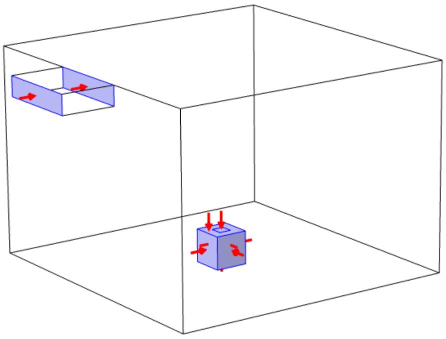


Figure 16. A legend of electromagnetic waves entering a rectangular waveguide

Next, a series of parameter scans were set in the study. First, *n* was set as the number of materials for *n* = 1–5. Next, the water content starts at 0% and increases by 0% until 50%. Finally, the frequency of the electromagnetic waves is set at 2.45 GHz.

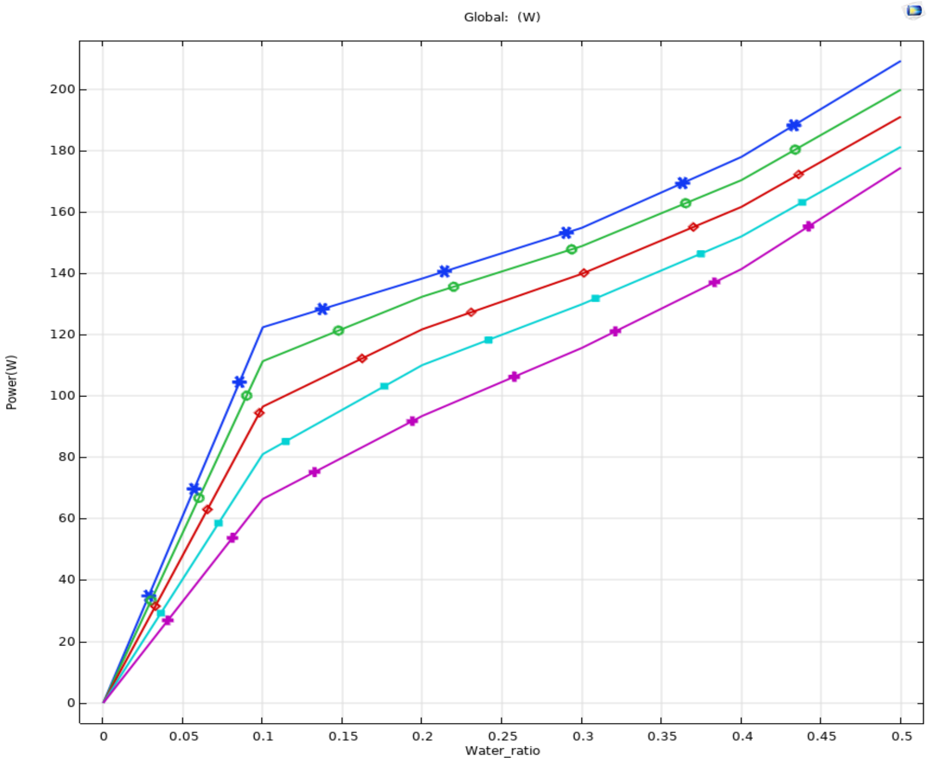


Figure 17. Power absorption of 2.45 GHz microwaves in five soil textures at 0–50% water content

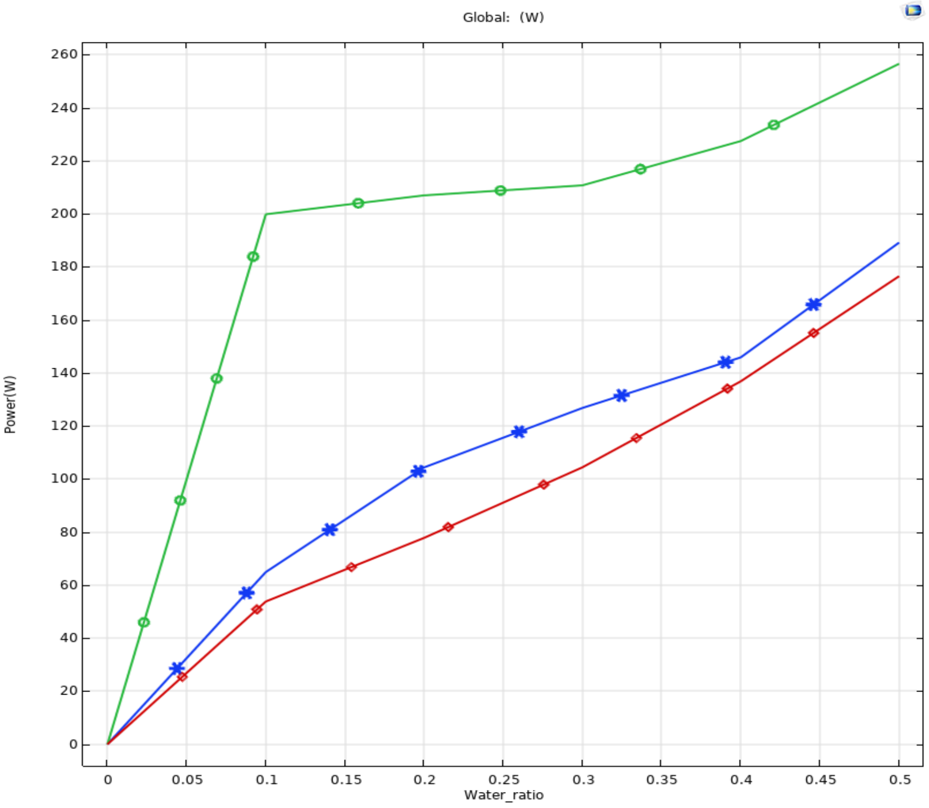


Figure 18. Power absorption of 2.45 GHz microwaves in soils of a single texture at 0–50% water content

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3.5.6. Post-processing

As shown in Figures 17 and 18, the results can be derived for the following two images with respect to water content and soil texture, which are core soil parameters that affect the soil's absorption of electromagnetic wave power. In Figure 17, the blue curve is soil 1, the green curve is soil 2, the red curve is soil 3, the cyan curve is soil 4, and the purple curve is soil 5. In Figure 18, the green curve represents 100% sand, 100% silt in blue, and 100% clay in red. For porous ceramics, shown in Figure 19, the power absorption curves are more consistent with the soil under different water contents.

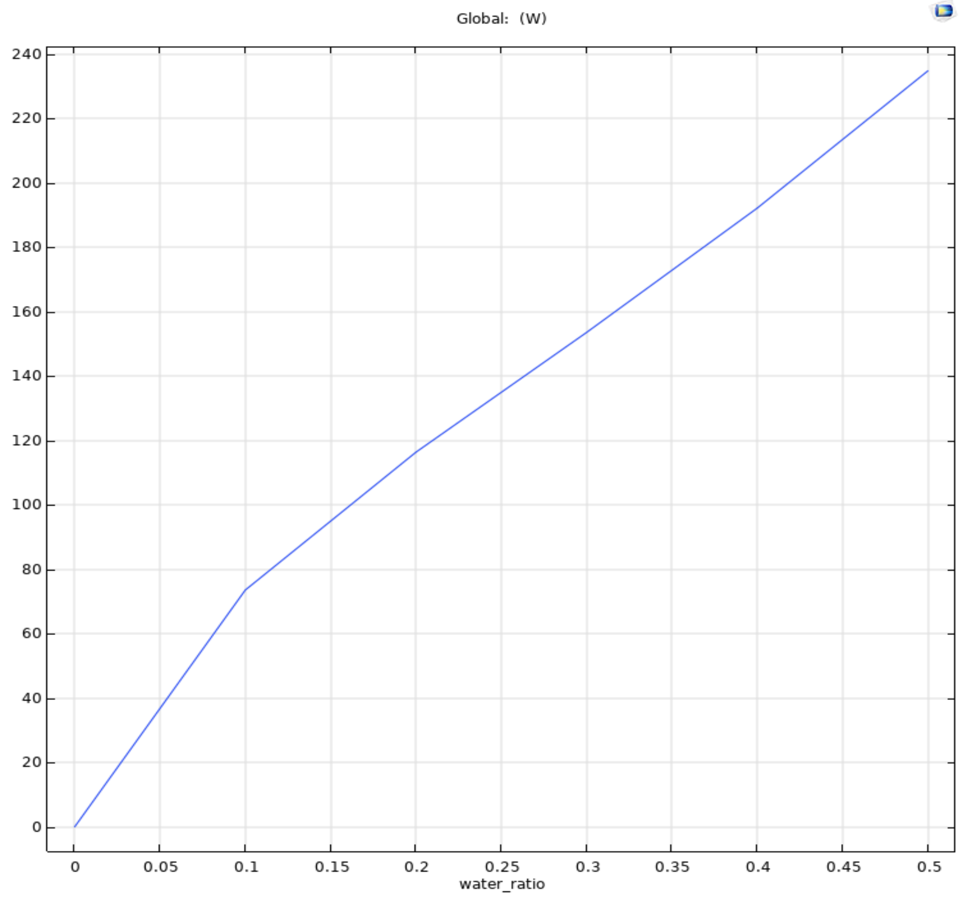

Figure 19. Power absorption of 2.45 GHz microwave in porous ceramics under 10–50% water content

4. Conclusions

1. The results simulated by COMSOL modelling in Figure 1 shows that there are a total of five curves. When the soil moisture increases, the power of the five soil materials to absorb 2.45 GHz electromagnetic waves increases accordingly.

2. By combining the images of the mixed soil model and a single soil texture model, it can be found that when different soil materials contain the same volumetric water content, the higher the proportion of sand, the stronger the ability to absorb power. This is especially true in the soil of a single sand soil texture with a water content of up to 10%; as the water content increases, the electromagnetic wave power absorption by the soil increases rapidly and then slowly rises. Silt and clay increase with the water content. The power absorption also slowly increases.

3. When the water content is 0%, no matter the type of soil or ceramic, electromagnetic waves are not absorbed.

4. From Figure 17, 18 and 19, it can be seen that the power absorption changes for porous ceramics and soil models are the same. Therefore, a ceramic with no water content does not absorb energy, so porous ceramics can be used as a frequency of 2.45 GHz—the conclusion of the sensor for measuring soil moisture with GHz electromagnetic wave.

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