Application of ground penetrating radar technology in moisture content detection of stored grain

Fan Cui,[1,2] Guoqi Dong,[1] Baiping Chen,[1] Penglin Yong,[3] Suping Peng[1,2]

[1]School of Geosciences and Surveying Engineering, China University of Mining and Technology, Beijing;
[2]State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Beijing;
[3]Shandong TUDI Group Yellow River Delta Co., Ltd, Dongying, China

Abstract

How to detect grain moisture content storage inefficiently, non-destructively, and quickly is a critical task in the storage process of the modern grain industry. The influence of media with different moisture content on the propagation and attenuation of electromagnetic wave energy is the premise and basis for applying electromagnetic wave technology in detecting grain moisture content. To explore the applicability of electromagnetic wave technology in detecting grain moisture content, we used ground penetrating radar (GPR) technology and autoregressive and moving average (ARMA) power spectrum analysis method to detect and study the moisture content of the typical national grain depots and local grain depots. The results show that GPR technology could realise the moisture content of stored grains and solve the problems of detection distance, non-destructive, and detection dead ends. Compared with the actual test data, the correlation is above 90%, the error can be controlled within 0.5%, and the measurement accuracy is higher, within ±0.3%. Furthermore, the continuous distribution profile of stored grain moisture content was obtained using the ARMA method. The moisture content distribution range of the rice barn was 10-14%, showing the regularity of the moisture content distribution in the middle layer > upper-middle layer > lower-middle layer > bottom layer > grain surface layer. It indicates that the GPR technology has particular advantages in food safety detection and provides data support for real-time detection of food storage safety.

Correspondence: Guoqi Dong, School of Geosciences and Surveying Engineering, China University of Mining and Technology, Beijing, 100083, China.
E-mail: bqt2000202016@student.cumtb.edu.cn

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Introduction

Food security is a widespread major strategic issue of national economic development, social stability, and self-reliance. In China's latest "14th Five-Year Plan", ensuring food security is included as a binding target, which is also the first time that the implementation of food security strategies has been included in China's five-year plan (Zhu *et al*., 2021). There are differences in moisture content requirements for different grain uses (Hemhirun and Bunyawanichakul, 2020). The detection and control of grain moisture content is the fundamental guarantee of grain safety and quality, which is of great significance to grain production, storage, processing, and marketing (Chen, 2001; Nelson *et al*., 2001; Lewis *et al*., 2019; Flor *et al*., 2022).

Currently, many tasks in grain storage management are based on samples and single-point measurements (Gibson, 2007; Ramli *et al*., 2021), which are cumbersome, time-consuming, labour-intensive, and costly. They can be mainly divided into direct measurement methods and indirect measurement methods. The direct measurement method is to detect the absolute moisture content of the sample through experiments, including drying, distillation, gravimetric analysis, *etc*. (Lim *et al*., 2003; Lian *et al*., 2012). The indirect measurement method uses portable rapid measurement equipment, including resistance, capacitance, infrared spectroscopy, *etc*. (Kandala *et al*., 1987; Kim *et al*., 2006; Liang and Ji, 2006; Flor *et al*., 2022). Although these detection technologies meet the application requirements to a certain extent but do not represent the level of detection of the entire grain storage. They have apparent shortcomings and are unable to detect the whole grain of the granary, have dead ends, and cannot meet the detection distance and non-destructive requirements. As well as the managers with rich experience to help detect the judgment of abnormal grain situations, experience-dependent grain detection methods have problems such as low accuracy, low efficiency, and large consumption of human resources.

Compared with the traditional and typical point measurement of humidity sensors, the time domain reflectometry, the electromagnetic method has certain advantages in moisture content detection. Especially in real-time continuous measurement, it has the benefits of fast, non-destructive, and non-contact (Kim *et al*., 2006; Bu and Han, 2007). It fills the blank of invasive detection and point-based measurement and solves the difficulties of complex detection technology and easy aging. At the same time, it also creates a new idea of real-time electromagnetic wave detection for non-destructive detection of grain situations. In recent years, ground penetrating radar (GPR) has made remarkable achievements in physical parameters such as moisture content of the medium and has been widely used in effective engineering practices (Lunt *et al*., 2005; Zheng *et al*., 2019; Anbazhagan *et al*., 2020). However, there are few applied studies on the moisture content of stored grains. In addition, there are specific differences in the distribution characteristics of the moisture content of different grain media in different seasons.

Herein, based on GPR technology, combined with the current situation of grain moisture content detection, taking typical national grain depots as the research object, the experimental study of grain moisture content detection was carried out. As a result, the feasibility of GPR technology was discussed, and the distribution law of stored grain moisture content was further analysed based on the detection of stored grain moisture content, which provided technical support for continuous and accurate content inversion and food storage safety.

Materials and Methods

Study area

A local grain reserve in the southern Jiangsu Province of China was selected as the study area, located in central China's grain storage area, and stored wheat and rice in a typical bungalow building shape (Figure 1). The grain storage is 17.4m in length, 17.4m in width, and 5-6m in height. The storage method is bulk storage, and the designed tonnage of grain storage is 1295t. It has a steel ground ridge ventilation system, circulation fumigation system, air conditioning cooling system, and other facilities. The study area belongs to a subtropical warm moist monsoon climate, with abundant rainfall and an annual average relative air humidity of 70-85%. The annual rainfall is 1084mm, which fluctuates synchronously with the temperature. In summer, the temperature is the highest, rain is the most, and the average annual temperature is 16°C.

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Figure 1. Schematic diagram of bungalow warehouse grain reserve.

Table 1. Technical parameter information of ground penetrating radar.

Equipment	Technical parameters	
GR series radar hosts	Overall dimension	300 mm×200 mm× 65 mm
	Weight	＜3 kg
	Battery design	Snap-on type
	A/D conversion	16-bit
	Display modes	Curve, variable area, colour section
	Data acquisition modes	Continuous, single point, range wheel control
	Sampling time window	5~3000 ns
	Minimum Resolution	5ps
	Sampling points	512， 1024， 2048 available
	Pulse repetition frequency	100KHz
300Mhz shielded antenna	Overall dimension	660 mm×460 mm ×220 mm
	Weight	8 kg
	Antenna types	Transceiver integrated type (transmitter and receiver are enclosed in the same antenna housing)
	Shielding modes	Shielded coupled TE polarised antenna
	Front-end analogue noise amplifier	–20 dB~+40dB

Testing equipment

The GPR experiment of moisture content detection was carried out in the local grain reserve rice barn, and the grain storage height was 5.1m. According to the field detection conditions, the GR series of portable radar hosts and 300 MHz shielded antenna independently developed by the China University of Mining and Technology (Beijing) are selected as testing equipment (Figure 2). Specific instrumentation information is shown in Table 1.

According to the propagation law of electromagnetic waves in the grain medium and the detection requirements for the height of stored grain, the sampling time window of the instrument parameter is set to 180ns, sampling points for 1024, and the sampling frequency for 100k, using the time-triggered method is used for continuous detection.

Data acquisition

Two radar survey lines, A and B, and probe rod sampling test points 1 to 8 were arranged in the rice barn (Figure 3A). The GPR measurement method uses manual dragging for continuous scanning detection test (Figure 3B), with the detection antenna moving along the direction of the measurement line scanning detection. When the antenna starts moving detection, probe sampling test point detection, special position detection, and end pause detection, the position can be calibrated by marking, which provides convenience for subsequent data processing and analysis.

The actual detection antenna moves along the direction of the grain surface measurement line, and the pulse signal is continuously transmitted and received. The Radar display system will be obtained by the A/D conversion of the data signal according to a certain way of coding arrangement and processing in a two-dimensional form (one dimension is the spatial coordinates, corresponding to different horizontal positions on the grain surface; one dimension is the time coordinates, indicating that the echo signal propagation time delay, corresponding to different depths) in order to give continuous longitudinal profile imaging results of the grain pile. Data acquisition results in the vertical direction correspond to the position of measuring line A and line B of the rice bin. Immediately after the GPR detection, the sampling probe is used for sampling, and the moisture content of the sampling point is measured for comparison and analysis with the later moisture content inversion data. The sampling position is to take and arrange 8 sampling points at equal intervals on survey lines A and B, which are sampling points 1-8 (Figure 3A). Grain samples within the depth range of 1-4m were taken from each sampling point, and one test sample was taken every 1m depth, with a total of four samples per sampling point. The moisture content of 32 samples was measured on-site with the grain moisture metre “LDS-1G” (Figure 3C).

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Figure 2. Physical map of detection equipment host, antenna, and data connection line.

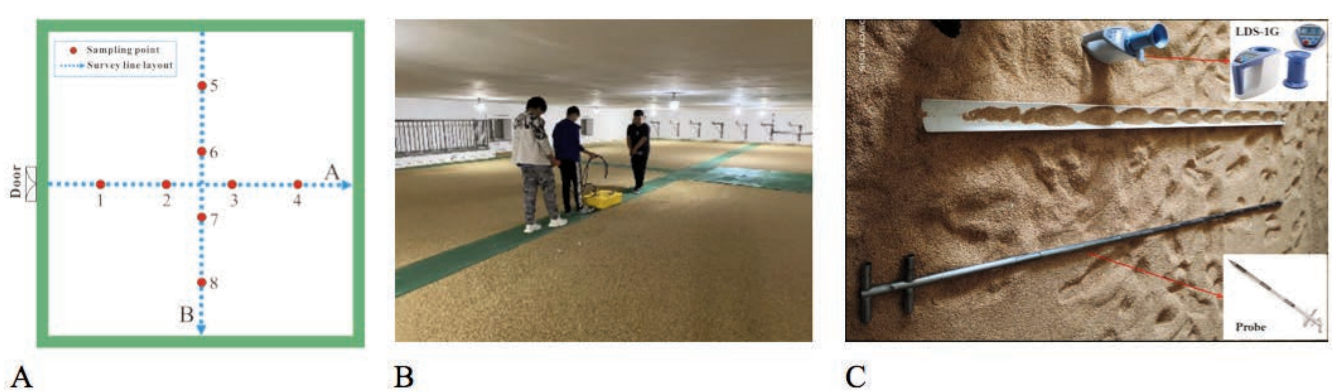

Figure 3. Data collection: A) schematic diagram of sampling point and survey line layout; B) ground penetrating radar detection experiment; C) the measured data of the sampling point is collected. After the probe is sampled, the moisture content is tested with the grain moisture meter “LDS-1G”.

The measurement range of this instrument is 3-35%, and the measurement error is ±0.5%. The measurement time is less than or equal to 10s, and it can work in an environment of 0-40°C, which is convenient, rapid, and accurate for measuring the moisture content of grains and avoids measurement errors caused by the loss of grain moisture.

Water content inversion method

GPR is a fast, efficient, and non-destructive means of geophysical exploration (Zhou *et al*., 2003). The detection of abnormal areas is realized by transmitting high-frequency broadband electromagnetic wave pulse signals to the detection medium by the transmitting antenna and receiving the electromagnetic wave echo signals by the receiving antenna (Figure 4). Among them, the radar reflected wave method, the ground wave method, the borehole radar method, and other methods have been widely used in the detection of physical properties such as the water content of the medium, and they all belong to the "wave velocity-dielectric constant" method (Huisman *et al*., 2003; Weihermüller *et al*., 2007; Bian *et al*., 2009).

Compared with the "wave velocity dielectric constant" method for calculating radar signals in the time domain, the spectrum analysis method converts radar data from the time domain to the frequency domain. Different media and their physical properties can cause the distribution of frequency-domain signals in energy, amplitude, amplitude envelope, and other information (Zhang, 1999) to achieve the purpose of inversion of media moisture content. Autoregressive and moving average (ARMA) is a frequency-domain spectral analysis method that can extract signal features at low signal-to-noise ratios and has the characteristics of high resolution (Cui *et al*., 2014).

ARMA spectrum analysis is based on a stationary linear signal process to estimate power spectrum density (Khanshan *et al*., 2010; Cui *et al*., 2015). The spectral density is obtained by performing ARMA spectral analysis on the stationary digital radar signal (Li, 1997) and then calculated by the Cadzow spectral analysis method (Cadzow, 1980), which reduces the estimation of spectral density parameters and uses logarithm to express the spectral density. To obtain the moisture content at different depths, a Gaussian time window function is added to the radar signal (Wang *et al*., 2021). Pick a rolling time window of length Δt(ns) and roll down from the start of the signal. The entire radar time signal is divided into several time windows, and each time window corresponds to the corresponding detection depth. The radar-reflected energy at this depth could be converted into the mean value of the spectral density energy in the corresponding window, and the rolling profile formed is as follows (Cui *et al*., 2018):

$$G(m) = (m)(\sum_{t=0}^{T_m} Q(t)) \quad (m = 1,2,3\ldots) \tag{1}$$

where Q(t) is the spectral mean in the time window; T_m is the selected rolling time window, unit ns; m is the number of time windows.

Since the power spectrum energy corresponding to each frequency signal is centred on each frequency and distributed in the form of an energy envelope. The different moisture content of the medium will affect the energy distribution of the received radar echo signal in different frequency ranges. By calculating the power spectrum energy value of the envelope in each time window and the percentage of the whole spectrum energy in the high and low-frequency ranges, the relationship model between the power spectrum energy and the moisture content described by formula (2) is used to inverse the volumetric moisture content of the corresponding depth (Cui *et al*., 2014, 2018; Wu *et al*., 2020):

$$\theta_V = k\frac{1}{F_a}\int_0^m p(f)df \times 100\% \tag{2}$$

where θ_V is volumetric moisture content, %; m is the segmentation point of high and low-frequency envelopes in the frequency domain, MHz; f is the frequency value of continuous distribution;

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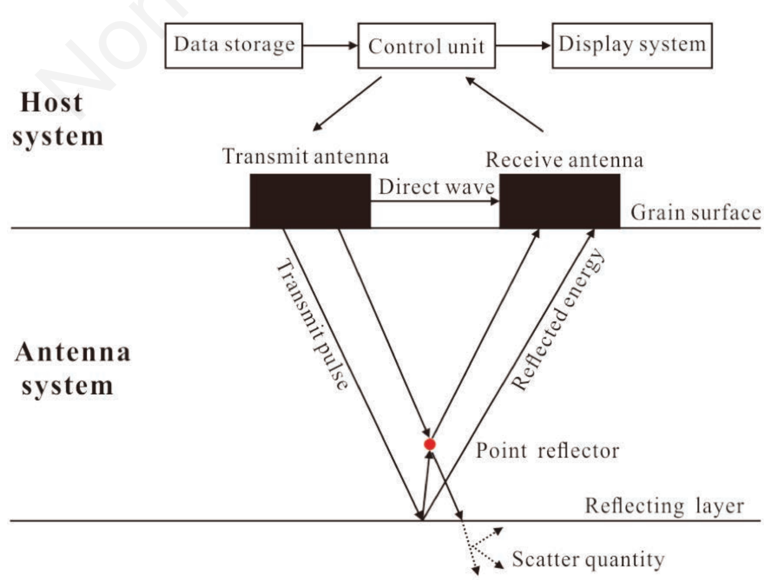

Figure 4. Schematic diagram of data acquisition of ground penetrating radar host system and antenna system.

p is the power spectrum value; F_a is the total energy of the full-frequency power spectrum; k is the linear correction parameter of the moisture content model.

Data analysis method

Analysis of the correlation between the GPR moisture content inversion and the use of probe sampling to test the moisture content with the grain moisture meter "LDS-1G" and the correlation coefficient will be calculated by the Correl function. The higher the correlation degree, the closer the correlation coefficient is to -1 or 1; the positive sign is a positive correlation, the negative sign is a negative correlation, and the closer to 0, the lower the correlation.

$$Correl(M,M_0)=\frac{\sum(M-\overline{M})(M_0-\overline{M_0})}{\sqrt{\sum(M-\overline{M})^2(M_0-\overline{M_0})^2}} \quad (3)$$

where $Correl(M, M_0)$ is the correlation between the inversion moisture content and the measured moisture content; $\overline{M_0}$ is the inversion moisture content; M_0 is the measured moisture content; is the average value of the inversion moisture content; $\overline{M_0}$ is the average value of the measured moisture content. To verify the accuracy and measurement accuracy of moisture content inversion by GPR, data analysis was carried out: i) calculate the mean error $\overline{X}$ and standard error σ; ii) given the confidence coefficient, look up the table to find the probability degree t, take the confidence probability P=0.95, then t=1.96; iii) calculate the average limit error $\Delta_{\overline{X}}$ based on the probability degree t and the sample root mean squared error σ; iv) the overall error of the measurement is calculated from the mean error $\overline{X}$ and the average limit error $\Delta_{\overline{X}}$, which is the measuring accuracy Δ*M*.

$$\overline{X}=\frac{\sum_{i=1}^{n}|M-M_0|}{n} \quad (4)$$

$$\sigma=\sqrt{\frac{\sum_{i=1}^{n}|M-M_0|^2}{n}} \quad (5)$$

$$\Delta_{\overline{X}}=\frac{t\sigma}{\sqrt{n}} \quad (6)$$

$$\Delta M=\pm\left(\overline{X}+\Delta_{\overline{X}}\right) \quad (7)$$

where M is the inversion moisture content; M_0 is the measured moisture content; n is the number of measurement groups.

Results and Discussion

Data comparison and analysis

According to the power spectrum data detected by the experiments, the correlation between the ratio of low-frequency energy to total energy L/(H+L) and the moisture content is analysed when different frequencies are used as high-low frequency dividing points. For example, it is found that when the frequency of the dividing point is 670MHz, the correlation coefficient between the corresponding L/(H+L) and moisture content reaches the maximum value of 0.952, as shown in Figure 5 and Table 2.

The grain medium's high and low-frequency dividing point m=670MHz is determined by analysing the moisture content and power spectrum data. The correction parameter of the moisture content model is determined to be 0.7-1.1 for the calibration of the test sample. The dielectric constant of the rice medium is taken as 4.5 and combines the moisture content calculation formula (2) to obtain the moisture content of the corresponding depth by inversion.

Table 3 shows the results of moisture content inversion of GPR and the use of probe sampling to test the moisture content with the grain moisture meter "LDS-1G" on survey lines A and B.

From the results in Table 3, we can see that inverse moisture content distribution range is 12.25-13.18%, and the measured moisture content distribution range is 12.1-13.0%. The errors of the inverse moisture content and the measured moisture content were 0.04%-0.38%, and the errors were all controlled within 0.5%. The correlation between the inversion moisture content and the measured moisture content of measurement lines A and B is analysed, as shown in Figure 6. The inversion moisture content has a certain similarity with the measured moisture content. The calculated values are = 0.946 and = 0.907, and the correlations are above 0.9. The average difference between the moisture content obtained by the two methods is 0.162%, indicating that the GPR inversion grain medium moisture content is feasible.

Using Eqs. (4)-(7), the mean error $\overline{X}$ and standard error σ, and measurement accuracy Δ*M*. are calculated for the data in Table 3. Where the measurement line A, the mean error $\overline{X}$ is 0.168%, the standard error σ is 0.186%, and the measurement accuracy Δ*M*. is ± 0.259%; in measurement line B, the mean error $\overline{X}$ is 0.181%, the standard error σ is 0.202%, the measurement accuracy Δ*M*. is ± 0.28%. It can be seen that the mean error $\overline{X}$ and standard error σ are within 0.3%. Therefore, the measuring accuracy Δ*M*. can be controlled within ±0.3%, which meets the National Standard Measurement Specification requirements of the People's Republic of China (GB\T 18314-2009). Errors are unavoidable, which may come from the measurement equipment itself, uneven grain density, foreign objects in the grain pile, insect pests, the ambient temperature in the warehouse, and other factors.

Distribution characteristics of moisture content in rice barns

GPR technology has a controllable error and high precision in the inversion of rice moisture content, which can well reflect the volumetric moisture content of the medium in the granary. Combined with the shielding measures already in place for the

Table 2. The correlation coefficient between *L*/(*H*+*L*) and moisture content under different high and low-frequency boundary conditions.

Segmentation frequency /MHz	400	500	600	660	670	800	900	1100	1300	1500	1700
Correlation coefficient	0.624	0.789	0.895	0.941	0.952	0.885	0.790	-0.704	-0.774	-0.600	-0.402

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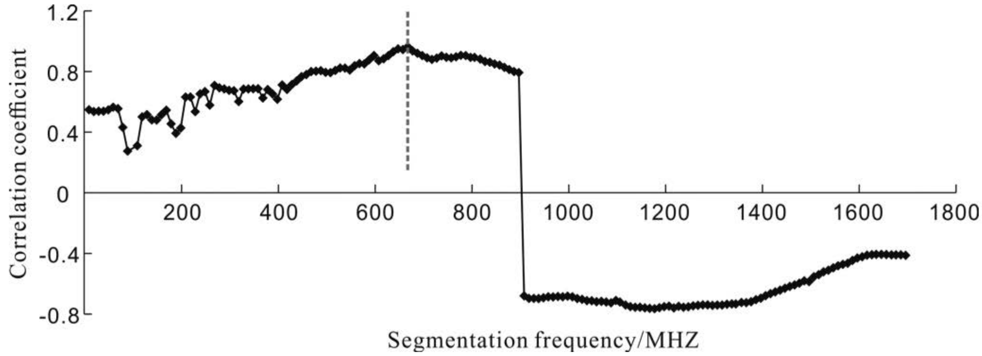

Figure 5. Correlation analysis of segmentation frequency distribution and moisture content.

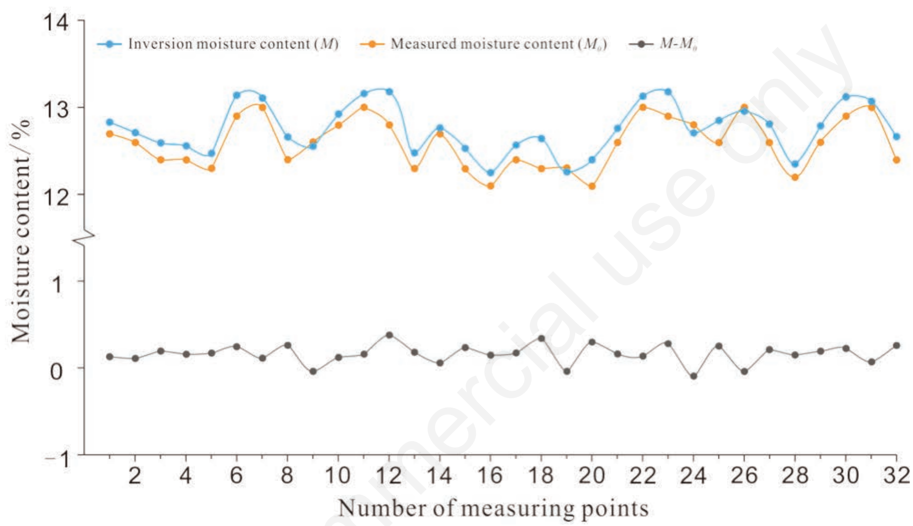

Figure 6. Comparison of measured moisture content and inversion moisture content.

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Table 3. Comparison of inversion moisture content and measured moisture content.

Line A Sampling point	Depth/m	Inversion data M/(%)	Measured data M_0/(%)	$\mid M-M_0 \mid$	Line B Sampling point	Depth/m	Inversion data M/(%)	Measured data M_0/(%)	$\mid M-M_0 \mid$
Sample1	1	12.83	12.7	0.13	Sample 5	1	12.57	12.4	0.17
	2	12.71	12.6	0.11		2	12.64	12.3	0.34
	3	12.59	12.4	0.19		3	12.26	12.3	0.04
	4	12.56	12.4	0.16		4	12.4	12.1	0.3
Sample 2	1	12.47	12.3	0.17	Sample 6	1	12.76	12.6	0.16
	2	13.14	12.9	0.24		2	13.13	13	0.13
	3	13.11	13	0.11		3	13.18	12.9	0.28
	4	12.66	12.4	0.26		4	12.71	12.8	0.09
Sample 3	1	12.56	12.6	0.04	Sample 7	1	12.85	12.6	0.25
	2	12.92	12.8	0.12		2	12.96	13	0.04
	3	13.16	13	0.16		3	12.81	12.6	0.21
	4	13.18	12.8	0.38		4	12.35	12.2	0.15
Sample 4	1	12.48	12.3	0.18	Sample 8	1	12.79	12.6	0.19
	2	12.76	12.7	0.06		2	13.12	12.9	0.22
	3	12.53	12.3	0.23		3	13.07	13	0.07
	4	12.25	12.1	0.15		4	12.66	12.4	0.26

GPR itself, the electromagnetic wave signal propagation path characteristics, and the digital filtering method for the later data processing, it is considered that the walls will not affect the data collected by the GPR system. In turn, the continuous distribution profile of rice moisture content can be obtained according to the ARMA power spectrum analysis method. Figures 7 and 8 show the profile distribution of the constant moisture content change in the granary with depth from 0 to 5.1 m when survey lines A and B are detected. It can be seen from the figure that the overall distribution range of grain moisture content is between 10% and 14%. In the vertical direction, the moisture content of rice from the surface to the bottom showed a trend of increasing first and then decreasing. Therefore, the distribution law of moisture content can be expressed as middle layer > upper-middle layer > lower-middle layer > bottom layer > grain surface layer, which is consistent with the actual measurement results of the granary (Figure 9) and previous granary management experience. Figure 9 shows the moisture content with the grain moisture meter "LDS-1G" at a depth of 1-4m. In the vertical direction of the central storage area (2m and 3m), the moisture content is higher than in the upper and lower

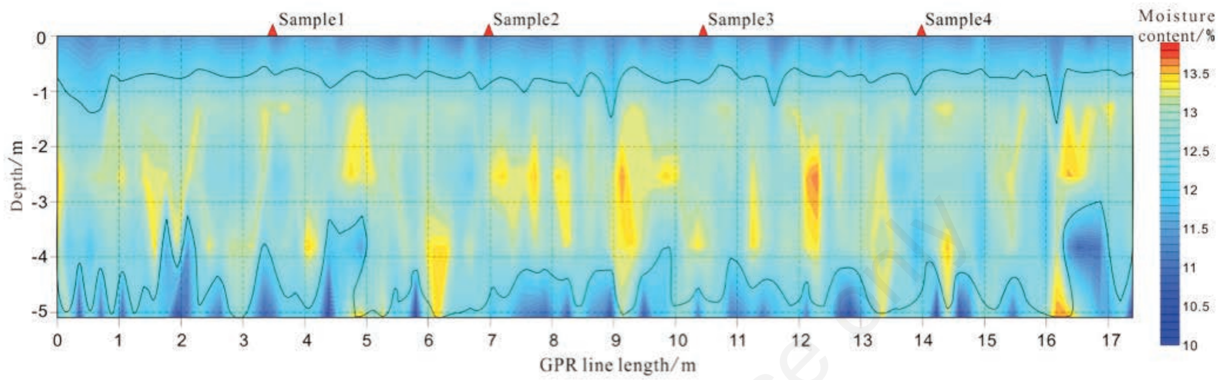

Figure 7. Moisture content distribution profile of radar survey line A.

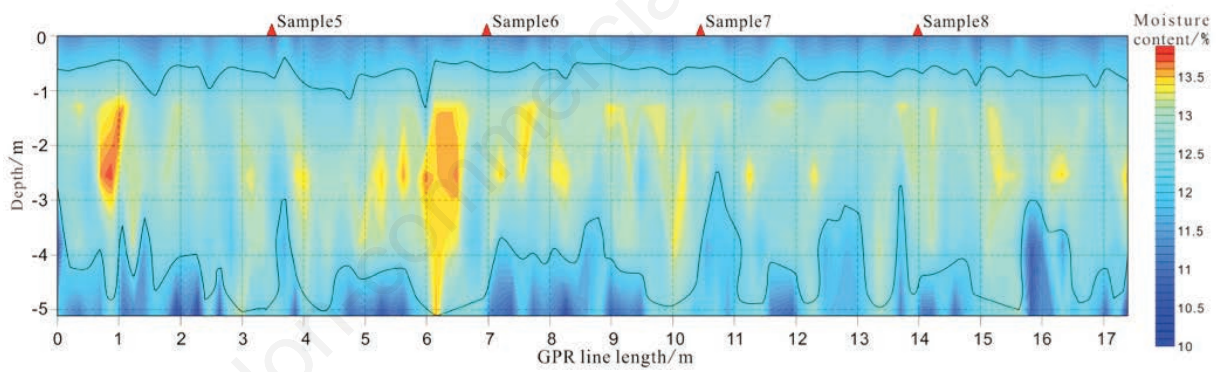

Figure 8. Moisture content distribution profile of radar survey line B.

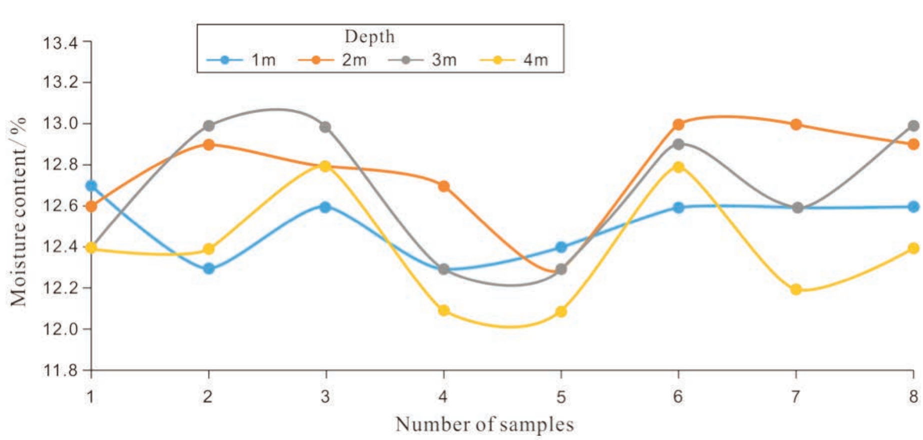

Figure 9. Comparison of measured moisture content at different depths

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zones (1m and 4m). The red and grey lines are on the blue and yellow lines.

According to the variation range of water content, there are changing bands of grain surface layer (0~-1m), middle layer (-1~-4m), and bottom layer (-4~-5.1m) in the vertical direction. The surface layer of the grain is in contact with the air, and the moisture content distribution is relatively uniform, in the range of 11.5-12%. The bottom of the granary is equipped with a ventilation system to remove rice's moisture content, resulting in lower moisture content in some areas of the bottom grain, in the range of 10-12%. The grain in the middle layer does not directly contact the air between the two regions and is less affected by the atmosphere. As a result, the moisture content is significantly high, primarily distributed in 12.5-13.5%, and there is a high moisture content value in individual regions.

The distribution characteristics of moisture content in the middle layer (-1~-4m) can be further divided into the upper-middle layer (-1~-2m), middle layer (-2~-3m), and lower-middle layer (-3~-4m). The areas with high moisture content were mainly distributed in the middle layer, and the upper-middle and lower-middle layers were relatively low, which may be caused by the surface and bottom ventilation cages' effect on reducing grains' moisture content. Among them, there are two high-value moisture content areas near the middle layer of 9m and 12m on survey line A (Figure 7) and two high-value moisture content areas near the middle layer of 1m and 6m on survey line B (Figure 8), both reaching 13.7%. In addition, under the action of the ventilation cage for a long time, the low moisture content area of the bottom layer affects the lower middle layer areas, such as the 2m, 4-5m, 16-17m areas of survey line A (Figure 7); Survey lines B near the 1-2m, 8-9m, 11m, 13m, and 16m areas (Figure 8).

It should be noted that there are abnormal situations with high or low moisture content, and it may also be that the presence of foreign objects in the grain pile medium causes the dielectric properties of the region to change during detection. Therefore, the inversion moisture content is different from the actual one.

Conclusions

This paper presents a grain moisture content detection system based on GPR technology. The system is based on energy attenuation, power change, and change of electromagnetic wave signal parameters during the propagation of electromagnetic waves in grain media. It uses the ARMA power spectrum method to detect moisture content in grain silos and piles. The main findings include the following: i) comparison and analysis of grain moisture content inversion based on electromagnetic wave and actual point measurement data. The correlation is high, the correlation is above 90%, and the error is within 0.5%, consistent with the actual detection results, and has high detection accuracy. Therefore, it can realise the application of GPR in grain condition detection; ii) the detection of GPR technology in grain storage moisture content can effectively solve the problems of detection distance, non-destructive, and the existence of detection dead ends. Therefore, it plays a positive role in reducing grain loss and the investment of human and material resources; iii) the moisture content distribution in rice ranges from 10% to 14%. In the vertical direction from the surface layer to the bottom layer, the moisture content generally increases first and then decreases. Therefore, the distribution law can be expressed as middle layer > upper-middle layer > lower-middle layer > bottom layer > grain surface layer; iv) based on the advantages of GPR technology application, it provides a prospect for developing instruments for online monitoring of foreign matter in stored grain, bad grain, hollow grain, granary structure, and underground space of grain storage. Further positive contribution to sustainable economic development and green grain storage process to maintain safe, pollution-free, high quality, and nutritious grain storage methods is required.

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