INVESTIGATION ON DATA COLLECTION AND FRACTAL CHARACTERISTICS OF SOIL SURFACE ROUGHNESS

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土壤表面粗糙度数据采集及分形特性研究

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ABSTRACT

It is of great significance to acquire the soil surface roughness accurately for the study of the interaction between tractors and soil. Based on the laser sensor, this paper proposed the non-contact measuring instrument of the soil surface roughness with the data acquiring system by using Lab-View software. By using W-M theory, three commonly used fractal dimension calculation methods are compared and analyzed.. The result showed that the Root-mean-square method has the highest accuracy and clear physical meaning, which is ideal method to calculate the soil surface roughness characteristics. When the fractal dimension is between 1.4 and 1.6, the acquired data is analysed by the Root-mean-square method to obtain the fractal features of the soil surface roughness. The experiment results indicated that the fractal dimension of the ploughed surface is 1.39, that of disc harrow surface is 1.550, and that of rolled surface is 1.46-1.54. Obviously, the fractal dimension can accurately distinguish the soil surface roughness with the different treatments. However, the fractal dimension selected from different scales showed an obvious instability during calculations. The surface roughness index combined with the two parameters can effectively represent the soil surface roughness, and the larger the surface roughness index is, the greater the surface roughness is.

摘要

准确获取土壤表面粗糙度对于研究拖拉机与土壤的相互作用具有重要意义。基于激光传感器，利用软件Lab View的数据采集系统，提出了一种非接触式土壤表面粗糙度测量仪。利用W-M理论的分形曲线对3种常用的分形维数计算方法进行了比较分析。结果表明，均方根法具有较高的精度和明确的物理意义，是计算土壤表面粗糙度特性的理想方法。当分形维数在1.4~1.6之间时，用均方根法对采集的数据进行分析，得到土壤表面粗糙度的分形特征。试验结果表明，犁耕表面的分形维数为 1.390，圆盘耙耕作表面的分形维数为 1.550，驱动耙耕作表面的分形维数为 1.460-1.540。可见，分形维数可以准确区分不同处理的土壤表面粗糙度。然而，选取不同尺度得到的分形维数在计算过程中表现出明显的不稳定性。结合分形维数与标准差这两个参数的表面粗糙度指数可以有效地表征土壤表面粗糙度，且表面粗糙度指数越大，表面粗糙度越大。

INTRODUCTION

Soil surface roughness plays an important role on the formation of soil particles, soil surface abrasion, wind erosion (*Shu, 2016; Lin, 2019*).Through the soil surface roughness analysis, predictions of soil erosion and soil moisture and distribution maps of soil moisture content can be drawn (*Zeng, 2017*). In addition, the interaction between the soil and the tire and the soil deformation can be simulated according to the surface roughness (*Mark, 2015; Hambleton, 2008*). Therefore, the soil roughness is the object the agricultural engineers and the automotive engineering personnel have studied since long (*Per, 2010*). This indicates that research to characteristic of soil surface irregularity has the great significance.

Since the 1980s, fractal theory has been widely used in surface topography feature recognition, which has good applicability for describing the natural phenomena of scale rate characteristics (*Altun, 2016; Fernández, 2016*). Therefore, regarding the randomness of spatial and temporal variability of agricultural soil, the use of fractal analysis can better describe the soil surface irregularities and supply the information that the traditional parameters cannot provide. So far, it has introduced a number of different methods of calculating fractal dimension, such as the box counting method, variation method, power spectrum method, the Root-mean-square method and the structure function method, these methods have their own characteristics and the applicable scope (*Alsaidi, 2015; Tao,2020*). If the fractal dimension calculated and the actual types of fractal sets are incompatible, big calculation errors will be caused.

In this paper, several commonly used methods to calculate the fractal dimension of the rough surface are compared and studied to find a suitable characterization method for the fractal characteristics of the soil surface roughness.

MATERIALS AND METHODS

METHODOLOGY

Fractal, as a novel mathematical concept, is widely applied in processing and analysing natural phenomena of the complex minutiae characteristic. In the process of fractal attribute of surface roughness, the first step is to choose the appropriate fractal dimension calculation method. If the calculated fractal dimension is not compatible with the actual fractal set type, it will cause a large calculation error.

Measuring the spectral index β of a section is a common method to measure the fractal dimension. Fractal dimension D can be evaluated by plotting the power spectrum P in a logarithmic graph.

$$\left.\begin{aligned} P(\omega) &= B\cdot\omega^{-\beta} \\ D &= (5-\beta)/2 \end{aligned}\right\} \tag{1}$$

where: D-the fractal dimension, [-];
β-the slope, [-]
ω-the frequency, [Hz];
B-a constant, [-];

Hurst method is a simple and direct method applied to self-affine profile data. This method finds the maximum difference R (τ) in the window τ, and displays the difference in a *log–log* plot as a function of 'window' width. R (τ) is calculated as follows.

$$R(\tau) = \max_{1\langle t\langle\tau} X(t,\tau) - \min_{1\langle t\langle\tau} X(t,\tau) \tag{2}$$

X (T, τ) is the data set. By dividing R (τ) by 'window' width S (τ), the R/S value will be a dimensionless number, which can be used to compare different phenomena and data sets. The slope H will give the fractal dimension according to $D = 2\text{-}H$. However, one disadvantage of this method is that transient noise may hide "real" data, although Hurst method has been proved to be one of the more accurate methods when tested on simulated isotropic noise-free sections.

The Root-mean-square (*RMS*) surface roughness describes the variation in surface elevation. It is also known as the standard deviation of the surface height. The *RMS* is the most basic form of profile description. The method of *RMS* height statistics h_{RMS} is as follows:

$$h_{RMS} = \sqrt{\frac{1}{n}\sum_{x=0}^{n}[s(x)-\bar{s}(x)]^2} \tag{3}$$

Where: n-the observation times of each sample, [-];
$S(x)$-the height of the surface, the point X in the surface contour, [m];
$\bar{s}(x)$-the average height of the surface contour, [m];

The fractal dimension is obtained from the *log–log* plot of the *RMS* /variance values versus the perimeter length or box size. In this study we divide the profiles or the surfaces into equal-sized lengths or boxes, and calculate the variance or the square of the *RMS*, as:

$$\begin{aligned} S(h) &= \frac{1}{N_h}\sum_{u=1}^{N_h}\left\langle \frac{1}{m_h}\sum_{i\in h}\left[z(x_i)-\bar{z}(h)\right]^2\right\rangle^{1/2} \\ &= ch^{2-D_{RMS}} \end{aligned} \tag{4}$$

Where: N_h-the total number of boxes of size h, [-];
m_h-the number of points in a box of size h, [-];
$z(x_i)$-the measured value of profile curve that correspond to the x_i position, [m];
$\bar{z}(x)$-average elevation value for all points in its box, [m];
c-scale parameter, [-];
D_{RMS}-fractal dimension, [-];

Changing equation (4) into the logarithm style, the form of linear equation is as follows:

$$\log S(h) = \log c + (2 - D_{RMS}) \log h \tag{5}$$

Assuming fractal behaviour, the slope of the *log*-*log* plot of the structural function, $S(h)$, against the distance, h, gives an estimation of the D_{RMS}.

The *RMS*/variance method is useful since it combines traditional roughness measurements with fractal analyses, and emphasizes the fact that *RMS*/variance values are scale dependent and can only be used as qualitative measurement.

W-M function

The soil surface roughness has statistical self-affine property, which can be simulated by the ideal fractal curve W-M which is continuous everywhere but not differentiable everywhere and has self-affine property. Its expression is as follows (*Deng, 2017*):

$$Z(x) = G^{D-1} \sum_{n=n_1}^{M} \frac{\cos(2\pi \ \gamma^n x)}{\gamma^{(2-D)n}} \quad (1 < D < 2 \ , \ \gamma > 1) \tag{6}$$

Where: $Z(x)$-random surface profile height, x-profile position coordinates, [m];

G-amplitude correction, reflecting the amplitude of $Z(x)$, which determines the specific size of $Z(x)$, [-];

D-fractal dimension, [-];

γ^n-profile spatial frequency, to determine the surface roughness spectrum, [-];

In this paper, calculating methods of the fractal dimension of surface roughness were compared using the standard functions. The fractal dimension of four W-M function curve was tested by using software programming of Matlab 7.0 (taking $D = 1.2, 1.4, 1.6, 1.8$; $G = 0.01$, $\gamma = 1.5$); the results are shown in Table 1.

Comparison with four methods **Table 1**

Theoretical dimension	RMS method		Power spectrum method		Variation method		Weighted RMS method	
	Fractal Dimension	Accuracy	Fractal Dimension	Accuracy	Fractal Dimension	Accuracy	Fractal Dimension	Accuracy
	[-]	[%]	[-]	[%]	[-]	[%]	[-]	[%]
1.2	1.317	90.3	0.703	58.6	1.262	94.8	1.086	94.9
1.4	1.457	95.9	1.078	77.0	1.342	95.8	1.455	96.2
1.6	1.592	99.0	1.433	89.6	1.469	91.8	1.597	99.8
1.8	1.619	89.9	1.761	97.8	1.501	83.4	1.794	98.9

Analysis of results

It can be seen from the above computed results, for the simulated profile curve, that power spectrum method increases its precision unceasingly along with the rise of fractal dimension. When the fractal dimension is 1.8, the precision is higher than other methods. Variation method has the high precision when the fractal dimension is small compared to other calculation methods, but the precision drops sharply along with the rise of fractal dimension; the method is suitable for dimension analysis of less than 1.4 in profile curves. Root-mean-square method has high computational accuracy in the theory fractal dimension of 1.4 to 1.6.

As physical meaning of the Root-mean-square method is clear, this method has very good function of characterization to the surface profile curve. Simultaneously, pass through calculation of each kind of soil data, it can be found that its fractal dimension value is smaller than 1.6, therefore the root-mean-square method was used to calculate soil surface roughness in this article.

Root-mean-square weighting method

In the computational analysis, it is found that the fractal curve in the scale domain of the measure does not strictly meet the fractal scaling rates. In different scale domain estimate of the fractal dimension, there are still some differences, which makes difficult to eliminate subjective defects of fractal dimension.

It is observed from Equation (5) that, (2-D) is the slope of the straight line obtained from the statistical regression in the double logarithmic graph, so that (2-D) is equal to ε, which is called the fractal dimension scale factor. If the time series strictly satisfies the fractal scaling rate, the scaling factor should be constant. However, in the actual calculation of the fractal dimension of soil surface roughness, if the calculation of time-domain value is known as the growth measure, and because calculation of the selected growth scale is different, it will lead to the difference between the corresponding scale factors. Their standard deviation can be expressed as:

$$\sigma_c = \mathrm{E}\left(\varepsilon - \bar{\varepsilon}\right)^2 \tag{7}$$

The smaller the value of δ_C is, the closer the scale coefficient ε is, the higher the precision of fractal dimension is. On the other hand, if the value of δ_C is larger, the deviation of fractal dimension scale factor ε will increase, and the accuracy of fractal dimension will be lower. In a certain confidence level, the confidence limit of scale coefficient of these growth measure is:

$$\varepsilon_u = \bar{\varepsilon} + K\sigma_c \tag{8}$$

K is the ratio of scale factor, when K is discrete normal distribution and confidence level is 0.995 in the case, K=2.99. The value of ε_u is substituted into (5), obtaining:

$$\log S(\tau) = \log c + \varepsilon_u \log \tau \tag{9}$$

See Table 1 for the standard fractal dimension value calculated by standard function W-M method. The results show that the accuracy of this method is obviously higher than that of the original Root-mean-square method.

RESULTS AND DISCUSSIONS

Surface roughness testing device Design Solutions

The testing device of road surface asperity designed in this paper. This device uses laser distance measuring sensor to collect the data information about the distance between the uneven ground and sensor. From a light source L, a light beam is issued onto the surface of measured object O_1 in Fig.1. The light beam will hit the surface of the measured object at point A. The scattered light reflection is focussed through a lens at a point A' on the detector. If the distance from the gauge probe to the measured surface is changed by X, the light beam from the light source will hit the source O_2 of the measured object at a new point B. The image of point B on the detector at point B' is displaced from the previous point A' by X'. The relation between the distance change X and the translation of X' by the light spot on the detector is determined by the geometrical arrangement between the light source and the detector. This relation is not linear. Since the light source, the lens and the detector are mechanically and solidly attached together, the relation between X and X' is known and can be used to linearize the measured results.

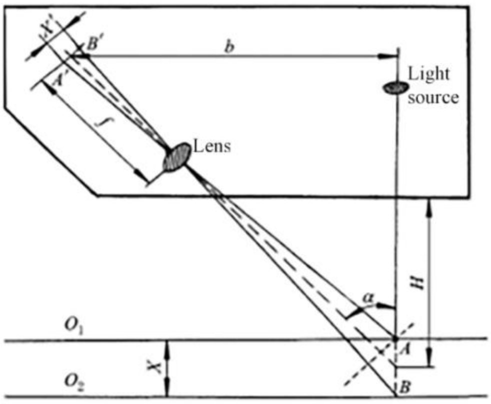


Fig. 1 - The measurement principle of the laser profiler

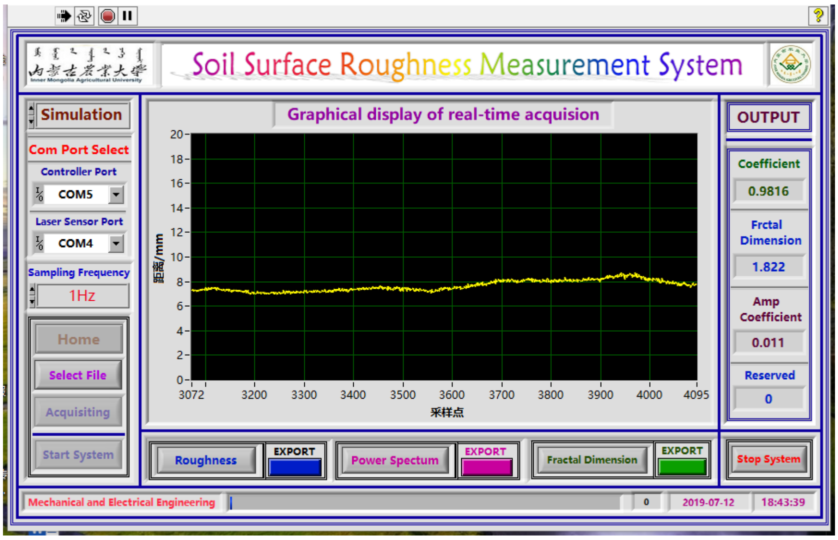
The test system consists of the hardware control and software data processing in Fig.2. The hardware control system is established on the ball screw slipway with the length of 1.2 m and lead of 5 mm. The rack is 0.6 to 1 m higher above the ground, which is equipped with 42HD1403 two phase four-wire stepping motor and high-subdivision stepper motor drives 2HD403 with a stepping angle of 1.8°. The laser distance measuring sensor has a range of measurement of 0.2m to 2m with a resolution rate of 1mm and data interface of RS232 USB. In the process of measuring, the laser sensor is fixed on the sliding block and moves back and forth along with the screw on the horizontal direction. The data transmission interface is connected with the USB interface. The controller adopts STC89C52 single-chip as the central processing unit and programming adopts the integrated development environment of Keil-μVision4. The serial port break method is utilized to receive the control order from the upper monitor and control the working condition of stepper motor driver module. The working voltage of stepper motor driver is DC 24V (external power source) and that of the single-chip control system is direct current 5V (computer serial port power supply).

Fig. 2 - The test equipment

A laser profiler was applied to measure agricultural soil roughness. The profiler is capable of acquiring roughness profiles of up to 1 m long at one time. The spatial resolution of the instrument is 1 mm. The instrument is thus well suited for capturing accuracy roughness information. The software control system adopts the virtual instrument software development platform LabVIEW2014 and the modular design method. The module is independent, and realizes the functions of parameter setting, control instruction sending, data acquisition and analysis processing, graph drawing and data display. The data processing software interface and system flow chart are shown in Fig.3 and Fig.4.

Under the “measurement mode”, first, it is demanding to reset the laser sensor location and click on the button of “Start Calibration”. Send “3” to the single-chip controller through the software. After receiving the instruction, the controller will reverse the stepping motor and the sliding block drives the laser sensor to move left to the “zero”. Click on this button after it reaches “zero” and the software system will send “zero” to the single-chip controller. The stepping motor will enter the “forward state”, indicating the completion of calibration and entry into the state of waiting for the instructions.

Click on the button of “start processing”. The software will send “0x4F” to the laser sensor; after the laser sensor is started, “0x43” is sent after 3s so as to place it under the continuous collection mode (at this time, the laser sensor has already started sending the collected data to the serial port; however, the software system does not read this data). At last, click on the button of “collecting data”. After setting the save path, the stepping motor is driven for operation according to the parameter that has been set’ meanwhile, the upper computer software reads the data collected by laser sensor and exercises the real-time display and storage. When the measuring point reaches 1024, the software system stops data storage. At the same time, the MCU names a new measuring file according to the time and stores the data in the file. The single-chip controller is also started to drive the stepping motor.



Controller Port: COM5
Laser Sensor Port: COM4
Sampling Frequency: 1Hz
Coefficient: 0.9816
Frctal Dimension: 1.822
Amp Coefficient: 0.011
Reserved: 0
0
2019-07-12
18:43:39

Fig. 3 - Data processing interface

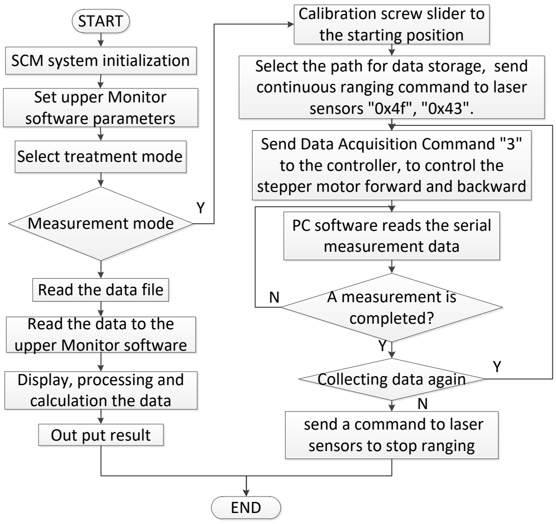
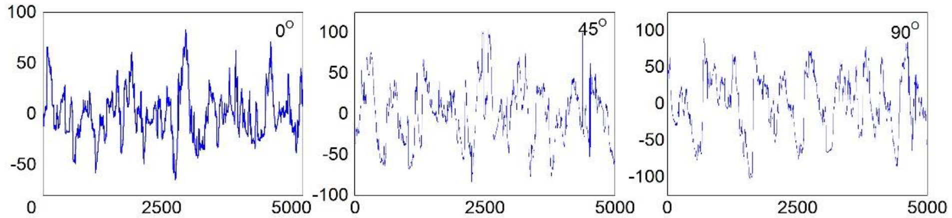
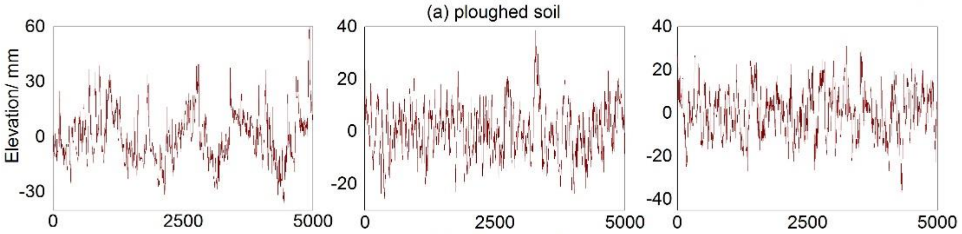


Fig. 4 - The system work flow chart

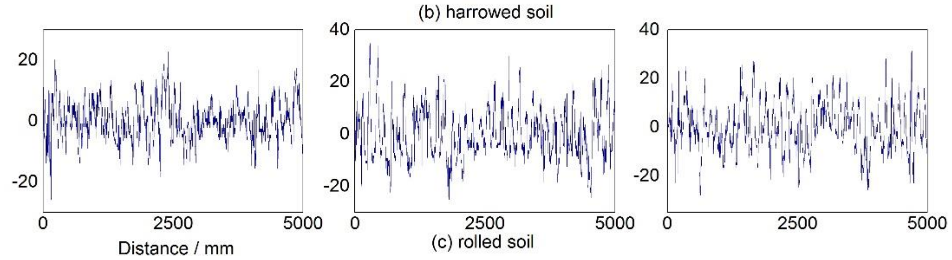
Three types of tillage surfaces, that is ploughed, harrowed and rolled surface, are tested, details concerning this database are showed in Fig.5. Profiles are acquired at 0 (parallel), 45 and 90 (perpendicular) degrees with respect to the tillage direction. The measuring length is 5 m.



(a) ploughed soil



(b) harrowed soil



(c) rolled soil

Fig. 5 - Profiles of different tillage soil surface

Calculation of fractal dimension

Three kinds of soil surface roughness are analysed with root-mean-square weighting method and the result is shown in Table 2. The fractal features of the three soil surface asperity of the data are presented in Fig.6.

RMS height, fractal dimension and surface roughness parameter **Table 2**

Tillage method	Ploughed soil			Harrowed soil			Rolled soil		
	0°	45°	90°	0°	45°	90°	0°	45°	90°
D	1.340	1.391	1.362	1.471	1.534	1.497	1.622	1.552	1.578
RMS	22.395	37.294	40.773	11.941	9.014	10.214	6.689	10.984	8.485
R^*	103.55	181.86	231.59	29.13	17.58	22.30	10.42	21.94	15.03

Table 2 shows that fractal dimension can distinguish the different tillage states. There is a good correspondence between tillage state and fractal dimension. For instance, the ploughed surface exhibit D less 1.40, rolled surfaces exhibit D more than 1.55, whereas the harrowed surfaces have D values between 1.40

and 1.55. So, fractal dimension can be considered as a reliable parameter to describe local irregular structure of soil surface. The more non-uniform the surface roughness profile, the higher the fractal dimension.

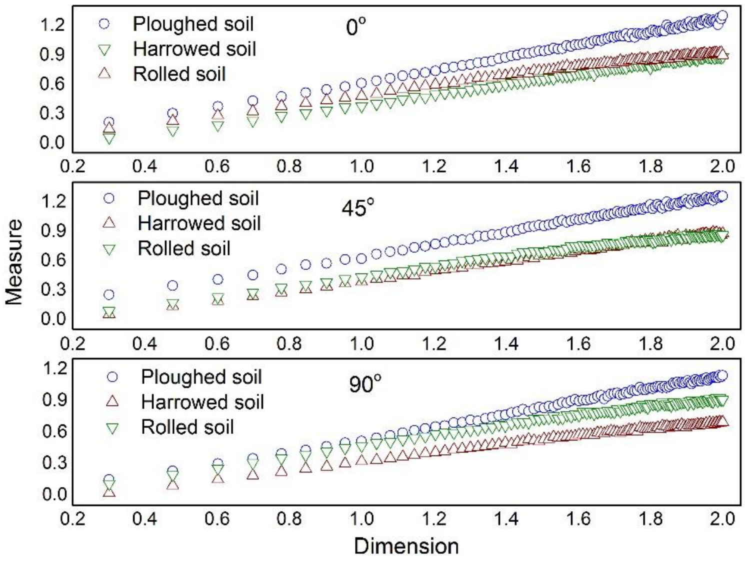


Fig. 6 - Fractal features of different soil surface

Fig. 6 shows that measure $S(\tau)$ and scale τ display good linear relation in the bi-logarithmic diagram, a phenomenon that eloquently demonstrates that the curve of soil surface asperity is of typical fractal features. The irregularity of the soil surface could be described by the fractal dimension.

At the same time, it can be found that fractal dimension is the slope coefficient of the straight line between $logS(h)$ and $log(h)$. If two scale lines are parallel, it can be gotten the equal fractal dimension. Surface with the same profile shapes but with different profile heights have the same fractal dimensions. However, properties of such surfaces are completely different. In general, only the fractal dimension cannot express the character of soil surface's roughness. Therefore, a new parameter is still necessary. In the following, we will show that combining local fractal structure with classical parameters (RMS height) leads to satisfying description of soil surfaces. The overall statistics for RMS height as a function of fractal dimension are summarised in Fig.7.

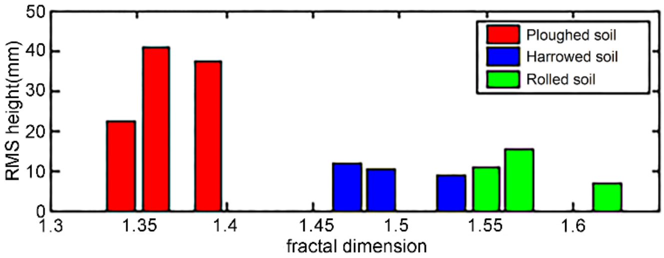


Fig. 7 - Effect of vibration frequency on the quality of pelleting

The Fig.7 shows that the linear relationship of RMS height h_{RMS} and fractal dimension D_{RMS} is not very obvious. For our database, the greater the RMS height is, the smaller the fractal dimension is. In fact, observation of our test soils show that for small RMS height, local structure is often described by small clods and then introduces a very high variability in the surface leading to a high fractal dimension.

The Equation(5) indicates that when the size of h is a unit, the dimension parameter $logC$ is the intercept of the regression line in $logS(h)$ -$logh$ plot. In other words, it is the height deviation of the profile in unit scale, and it has the same physics sense with the profile mean root square deviation value h_{RMS}. Therefore, we defined roughness index as a combinative parameter of fractal dimension D and mean root square deviation h_{RMS}, with the form as following:

$$R^{*}=h_{RMS}{}^{\frac{1}{D_{RMS}}} \tag{10}$$

When D_{RMS} keeps invariable, the increase or decline of h_{RMS} reflects the flat grade of the surface. increases or declines with h_{RMS} changes. So, we can apply to identify the complexity roughness surface. For instance, Table 2 shows that h_{RMS} value between the harrowed and rolled surfaces is basically the same. But value of the ploughed soil, harrowed soil and rolled soil has a big difference. So, roughness index has high resolution capability to express the soil surface roughness.

CONCLUSIONS

1) The self-made soil surface asperity tester is utilized to collect the relevant information, which could provide a rapid and efficient method for the engineers to collect the data information about the soil surface asperity.

2) For cultivated soils, the fractal dimension is 1.3 to 1.6; calculating its fractal dimension using Root-mean-square method has high precision; Root-mean-square measure directly reflects the dynamic level of the surface profile roughness in the different scales, its physical meaning is clear, the fractal attribute is intuitive, after all, it is an effective way for soil surface fractal.

3) Calculating fractal dimension by modified Root-mean-square method can get right dimensions of division ratio with the growth measure; any scale of the fractal dimension has little influence on the results, so it is very stable and accurate to calculate fractal dimension of soil surface using this method.

4) The relationship between RMS height of the traditional statistical parameters and the farming way is not as obvious as the relationship between the fractal dimension and farming way of soil. Linear relationship between D and RMS is not very obvious, but as a whole, RMS height decreases as the fractal value increases gradually.

5) Describing the surface roughness with surface roughness index has higher resolution power than with RMS; it retains not only the characteristics of multi-scale fractal measurement, but also retains the advantages of traditional roughness parameters intuitive and simple. The greater the surface roughness index, the greater the surface roughness, and vice versa.

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