Applying Fractal Dimension to the Effects of Root System on Slope Soil Displacement

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Abstract. Based on the box-counting dimension method of fractal theory, a set of computing image fractal dimension software Fractal 1.0 was developed which can be used to determine the root fractal dimension of plants. By combining the theory of fractal with the finite element theory, the effects of root system fractal dimension on the amount of displacement taking place on the surface of slope were studied. By analyzing the relationship between them from different aspects, the results indicate that fractal dimension can be regarded as the parameter of root system, the effects of different root systems on the stability of soil in slope surface were quantitatively characterized through integrating fractal dimension with finite element method.

Keywords: fractal dimension; root form; slope stability

1. Introduction
Fractals are used to describe objects that are so irregular that they are not considered as classical geometry, through chaotic phenomena and irregular configuration, it tries to reveal the intrinsic relation and motion law between the local and the whole which is hidden behind the phenomenon, fractals can be measured with fractal dimension (Falconer 2007; Li and Huang 2001; Li and Ruan 2004). Mandelbert proposed the concept of fractal dimension firstly, and established the fractal geometry (Liao and Yu 2001). By using fractal dimension, the geometry complexity and capacity of fulling space can be quantified, as well as, the complexity of geometry which is characterized by the irregularity and self-similarity can be compared quantitatively (Xia et al. 2011).

Root system is a complex and irregular geometry structure, it is often considered to be a disordered meridional structure in euclidean geometry (Fattet et al. 2011; Hu et al. 2008; Hu et al. 2016). As a time-consuming job, it is difficult to be measured. Since now, an appropriate scheme of quantitatively describing the morphological features of the root system has not been propose (Bast et al. 2015). Aiming at the growth law and branch feature of plant root system, a set of studies is conducted, It is found that the root morphology has obvious statistical self-similarity on a certain scale, so the fractal geometry theory can be applied to explore the root morphology, then the parameter of root morphology will be measured and analyzed rapidly and accurately so that the reliability of parameter of root morphology will be promoted effectively (Eab et al. 2014; Gary and Sotir 1996). In this paper, the computer aided image analysis system and fractal theory are combined to be applied to the root morphology analysis. Basing on the Basing on the box dimension method of fractal theory, a software package (Fractal1.0) for calculating the fractal dimension of plant roots is developed, this software can be used to determine the dimension of plant roots while the effects of different root systems on the stability of soil in slope surface were quantitatively characterized through integrating fractal dimension with finite element method. The displacement of slope soil is closely related to the stability of slope. The slope soil produces
displacement with rainfall, and when the displacement increases to the limit value of soil, the slope slide occurs. Root-planted slope can effectively reduce the soil displacement and therefore improve the stability of the slope.

2. Development of Fractal Software

2.1. Development Thoughts

Fractal dimension computing software (Fractal1.0) is developed based on the method of box-counting dimension. The definition of box-counting dimension is, setting assembly \( A \in F(x) \), \( F(x) \) represents a set of all compact support sets on the metric space \( x \), \( \rho \) is a kind of measure, \( (x, \rho) \) is a metric space. As for every \( \delta > 0 \), the \( N_\delta(A) \) represent the minimum amount of closed ball whose radius is \( \delta > 0 \). If the \( \lim_{\delta \to 0} \frac{\log N_\delta(A)}{-\log \delta} \) is available, then this limit is box counting dimension of assembly \( A \), signed as \( \dim B(1-3) \).

2.2. Software Algorithm Implementation

The original grayscale image of root system \( f(x,y) \) was obtained by digital image acquisition device, the image is converted into a binary image \( f_2(x,y) \) by using a gray threshold value \( G \) so that every pixel point on the image is divided into black and white, in the process of binarization, try to keep the details which is relevant to the application in the image. There are many ways to choose the threshold value of binarization, the average gray value method which sets the average of all gray value as the threshold value is used in this software, then the binary image is represented by matrix of \( m \) by \( n \) (\( n \geq m \)), the matrix \( F \) is showed as follows:

\[
F = \begin{bmatrix}
F_{11} & F_{12} & \cdots & F_{1n} \\
F_{21} & F_{22} & \cdots & F_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
F_{m1} & F_{m2} & \cdots & F_{mn}
\end{bmatrix}
\]

Where \( F_{ij} \in \{0,1\} \), when \( F_{ij} = 1 \), it is the pixel of root system; when \( F_{ij} = 0 \), it is background pixel. As for the matrix of \( F \), it is covered by a square with length of \( L_{max} \) to assure all pixels are located in the square. By dividing the length \( L_{max} \) into equal proportions at the ratio of \( r \), multiple squares whose length of side is \( L = rL_{max} \) of the grid. It is assumed that the number of square which includes at least one pixel point in it is \( N \), the fractal dimension of root system is \( D \), then

\[
N = r^{-D}
\]  

(1)

So that the total area of all squares which includes at least one pixel point in it is:

\[
S = N \ast L^2
\]  

(2)

By applying the equation \( L = rL_{max} \) into equation (2) yields:

\[
S = N \ast L^2 = r^{-D} \ast r^2L_{max}^2
\]  

(3)

Take the logarithm of both ends of equation (3) yields:

\[
\log S = (2 - D) \log r + 2 \log L_{max}
\]  

(4)

Then:

\[
D = 2 + \frac{2 \log L_{max} - \log S}{\log r}
\]  

(5)

According to the equation (4), there is a linear relationship between \( \log S \) and \( \log r \), so the least square method is employed to estimate fractal dimension in practice, not use the equation (5) directly. By fitting multiple data points\( \{\log S, \log r\} \), the estimate of fractal dimension is obtained by the slope of the fitting line (Ghestem et al. 2011; Sonnenberg et al. 2010; Abe and Ziemer 2011).
2.3. Data Analysis and Experiment Result

The soil used in research was silty clay collected from field. The indexes are as followed:

**Table 1.** Physical and mechanical properties of testing soil

| Index                          | Value         |
|-------------------------------|---------------|
| Density (g/cm³)               | 1.80          |
| dry density (g/cm³)           | 1.41          |
| specific gravity of solids    | 2.72          |
| water content (%)             | 27.7          |
| liquid limit (%)              | 38.2          |
| plastic limit (%)             | 17.5          |
| Best water content (%)        | 16.9          |
| maximum dry density (g/cm³)   | 1.72          |
| void ratio (%)                | 0.93          |
| Saturation (%)                | 81            |

The depth of root system influencing the surface soil of slope is related to the length of root system. The bermuda root influenced soil at the depth of 200mm, 300mm and 400mm respectively, and the oleander root at the depth of 600mm.

The root samples were treated by using fractal calculation software, the root of bermuda grass and the root of oleander are showed in Figure.1 and Figure.2. Taking the root distribution in consideration, the test categorized the bermuda grass root system as 200mm, 300mm and 400mm according to the fibrous root amount and length, as showed in Figure.3. The root system of oleander was categorized as 30°, 45°, 60°, 90° according to the angle between main root and lateral root, as showed in Figure.4. Then fractal dimension of root system is calculated and the collected data is counted. By choosing the average of fractal dimension of root system, the fractal dimension of bermuda grass and oleander are 1.56753, 1.76572 respectively.

![Figure 1. Binary processing diagram of bermuda grass root system](image)

![Figure 2. Binary processing diagram of oleander root system](image)
3 fibrous roots  5 fibrous roots  7 fibrous roots

Figure 3. Bermuda grass root system distribution

Figure 4. Simplified oleander root forms with different main-lateral root angles

3. Application of Fractal Software

3.1. The Relationship between the Fractal Dimension of Root Model and Soil Displacement

Fractal dimension can show root system morphology and reflect the growth of root system. The root system with large fractal dimension is widely distributed and has strong ability of dividing. The larger the fractal dimension, the stronger the root growth; the stronger the entanglement of roots and soil, the better the solid soil effect (Ghestem et al. 2013; Ha et al. 2014). Bermuda grass and oleander, two widely used slope-protecting plants were focused as the example, and the paper explored how the root models related to slope soil displacement by means of numerical simulation software Abaqus (Hardin and Drnevich 1972), the quantitative calculation theory of the effect of root fractal dimension on Slope solid soil performance, this has significant meaning for the choice of plant in the process of ecological slope protection.

In numerical calculation, the root system was simplified in the process of model establishing. The actual morphology is much more complicated than modelling, but as there exists the intrinsic geometric regularity in root form which accord with the proportional self-similarity of fractal theory, fractal dimension can be used to measure and reflect the actual form of root system. The influence of plant roots on slope stability mainly depends on the rooting ability of plants. The greater root abundance, the more branches of plant roots, the greater contribution to soil stability. Based on the numerical calculation of the influence of different root systems on the surface displacement, the relationship curves between the fractal dimension and displacement field are established. The effect of root model fractal dimension on soil displacement is showed in Table.2 and Table.3.

| Fibrous root amount | 3    | 5    | 7    |
|---------------------|------|------|------|
| Length of root (mm) | 200  | 300  | 400  |
| Fractal dimension   | 1.003| 1.015| 1.032|
| Horizontal displacement(mm) | 1.252| 1.246| 1.237|
| Vertical displacement(mm) | 5.276| 5.264| 5.254|
| Total displacement(mm) | 5.374| 5.361| 5.355|

Table.2 Fractal dimension of numerical model of bermuda grass root system
Table 3: Fractal dimension of numerical model of oleander root system

| Main lateral root angle | Lateral root amount | Fractal dimension | Horizontal displacement (mm) | Vertical displacement (mm) | Total displacement (mm) |
|-------------------------|---------------------|-------------------|-------------------------------|---------------------------|------------------------|
|                         |                     | 0.986             | 1.867                        | 6.639                     | 6.808                  |
|                         | 2                   | 1.064             | 1.860                        | 6.632                     | 6.798                  |
|                         | 4                   | 1.088             | 1.852                        | 6.626                     | 6.788                  |
|                         | 6                   | 0.97              | 1.859                        | 6.633                     | 6.803                  |
| 30°                     | 2                   | 1.027             | 1.843                        | 6.621                     | 6.787                  |
|                         | 4                   | 1.704             | 1.826                        | 6.609                     | 6.772                  |
|                         | 6                   | 0.976             | 1.859                        | 6.635                     | 6.804                  |
| 45°                     | 2                   | 1.054             | 1.841                        | 6.624                     | 6.790                  |
|                         | 4                   | 1.097             | 1.822                        | 6.613                     | 6.776                  |
|                         | 6                   | 1.005             | 1.874                        | 6.645                     | 6.807                  |
| 60°                     | 2                   | 1.050             | 1.869                        | 6.644                     | 6.815                  |
|                         | 4                   | 1.112             | 1.865                        | 6.643                     | 6.805                  |

In order to show the relation between the fractal dimension of root system and the displacement of surface soil mass, according to the data in Table 1 and Table 2, curves of differences of horizontal slope soil displacement, vertical displacement and total displacement vary with fractal dimension were plotted out. The curves of effect of bermuda grass root system on soil displacement are showed in Figure 5, Figure 6, Figure 7. The curves of oleander root effects on soil displacement are demonstrated in Figure 8, Figure 9, Figure 10.

**Figure 5.** The effect of fractal dimension of bermuda root on horizontal displacement of soil

By data fitting and analyze, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

- Fibrous root length 200mm: \( y = 0.6339x^2 - 1.2339x + 1.3689 \) \( R^2 = 1 \) (6)
- Fibrous root length 300mm: \( y = 1.1008x^2 + 2.1888x + 1.8625 \) \( R^2 = 1 \) (7)
- Fibrous root length 400mm: \( y = 0.256x^2 - 0.3111x + 0.8324 \) \( R^2 = 1 \) (8)

Where: \( x \) means fractal dimension of root system, \( y \) means horizontal displacement reduction (mm)
Figure 6. The effect of fractal dimension of bermuda root on vertical displacement of soil
By data fitting and analysis, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

- Fibrous root length 200mm: \[ y = 0.0629x^2 - 0.0756x + 1.6375 \] \( R^2 = 1 \) (9)
- Fibrous root length 300mm: \[ y = 0.3905x^2 - 0.7831x + 2.0295 \] \( R^2 = 1 \) (10)
- Fibrous root length 400mm: \[ y = -0.0124 + 0.0923x + 1.565 \] \( R^2 = 1 \) (11)

Where: \( x \) means fractal dimension of root system, \( y \) means the vertical displacement reduction (mm)

Figure 7. The effect of fractal dimension of bermuda root on total displacement of soil
By data fitting and analysis, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

- Fibrous root length 200mm: \[ y = 1.3964x^2 - 2.8922x + 3.2062 \] \( R^2 = 1 \) (12)
- Fibrous root length 300mm: \[ y = 0.4351x^2 - 0.8585x + 2.1461 \] \( R^2 = 1 \) (13)
- Fibrous root length 400mm: \[ y = -0.2354x^2 + 0.6464x + 1.3105 \] \( R^2 = 1 \) (14)

Where: \( x \) means fractal dimension of root system, \( y \) means the total displacement reduction (mm)

Figure 8. The effect of fractal dimension of oleander root on horizontal displacement of soil
By data fitting and analyzation, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

**Main lateral root angle 30:**
\[ y = 0.1331x + 0.0221 \quad R^2 = 0.9844 \]  
(15)

**Main lateral root angle 45:**
\[ y = 0.3161x - 0.1454 \quad R^2 = 0.9936 \]  
(16)

**Main lateral root angle 60:**
\[ y = 0.2975x - 0.1298 \quad R^2 = 0.9885 \]  
(17)

**Main lateral root angle 90:**
\[ y = 0.2765x - 0.145 \quad R^2 = 0.9933 \]  
(18)

Where: \( x \) means fractal dimension of root system, \( y \) means the horizontal displacement reduction (mm)

**Figure 9.** The effect of fractal dimension of oleander root on vertical displacement of soil

By data fitting and analyzation, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

**Main lateral root angle 30:**
\[ y = 1.5243x^2 - 3.0346x + 1.7722 \quad R^2 = 1 \]  
(19)

**Main lateral root angle 45:**
\[ y = 0.4906x^2 - 0.772x + 0.5552 \quad R^2 = 1 \]  
(20)

**Main lateral root angle 60:**
\[ y = 0.933x^2 - 1.7527x + 1.0879 \quad R^2 = 1 \]  
(21)

**Main lateral root angle 90:**
\[ y = -0.9527x^2 + 2.1747x - 0.9763 \quad R^2 = 1 \]  
(22)

Where: \( x \) means fractal dimension of root system, \( y \) means vertical displacement reduction (mm)

**Figure 10.** The effect of fractal dimension of oleander root on total displacement of soil

By data fitting and analyzation, it was of more accuracy to regress the relationship between the bermuda root fractal dimension and slope horizontal displacement through polynomial fitting method. The following lists the fitting formula:

**Main lateral root angle 30:**
\[ y = 2.7507x^2 - 5.51x + 3.0346 \quad R^2 = 1 \]  
(23)

**Main lateral root angle 45:**
\[ y = 0.4461x^2 - 0.6137x + 0.4564 \quad R^2 = 1 \]  
(24)

**Main lateral root angle 60:**
\[ y = 1.1875x^2 - 2.2308x + 1.326 \quad R^2 = 1 \]  
(25)
Main lateral root angle 90: $y = 0.1017x^2 - 0.05577x + 0.2172 \quad R^2 = 1 \quad (26)$

Where: $x$ means fractal dimension of root system, $y$ means total displacement reduction (mm).

Based on the curves of the root fractal dimension and the slope soil displacement, both kinds of root systems showed the consistent relationships of root fractal dimension and displacement reduction, appearing polynomial fitting curve. The fractal dimension of bermuda grass root system increases with the increase of root length, for the plant root system with long root, the variation of slope displacement reduction with fractal dimension of root system is more obvious. The horizontal, vertical and total displacement of surface soil decrease as the fractal dimension of root system increases. The variation of fractal dimension impact the horizontal displacement less than vertical displacement and total displacement, this suggests the vertical soil displacement can be limited effectively with increase of fractal dimension of root system.

According to the variation curves of the root fractal dimension and the slope surface soil displacement, for different main lateral root angle of plant root system, the soil-reinforcement of root system is different. When the main lateral angle of oleander root system is 45 degrees and 60 degrees, the performance of reducing slope surface displacement is decent with the increase of fractal dimension of root system, and this change feature is corresponding to the result of digital simulation. The form of oleander root system with lateral root angle of 90 degrees is simple, the arrangement is regular, it is not conducive to forming a winding network structure in soil and the performance of reducing surface displacement is not so obvious (Danjon et al. 2008; Kaestner et al. 2006; Tasser and Tappeiner 2005).

For oleander root system with lateral root angle of 30 degree, because of the angle is small, the distribution in the soil is small, the contact with soil is not sufficient, so the performance of soil-reinforcement is bad (Liang 2015). According to the curve of relationship between soil-reinforcement performance and fractal dimension, the correlation between fractal dimension of root system and stability of slope surface can be identified, it also can be assured that the performance of reducing slope surface displacement become better with the increase of fractal dimension of root system (Pierret et al. 1999).

It is further verified that fractal dimension can be regarded as a parameter to scale root morphology through the relationship between slope surface displacement and fractal dimension of root morphology.

### 3.2. The Relationship between the Fractal Dimension of Natural State and Soil Displacement

The root system at natural state is more complex than that of numerical simulation, the fractal dimension is bigger, so the performance of reducing slope soil displacement and stabilizing soil is more obvious. According to the feature of bermuda grass root morphology and relationship between the fractal dimension of root digital model and slope soil displacement, the fitting formula of variation of displacement difference and fractal dimension of bermuda grass root model with root length of 300mm, was chosen to calculate the effect of fractal dimension of natural root system on the slope surface displacement. The equation of horizontal displacement with fractal dimension is: $y = 1.1008x^2 + 2.1888x + 1.8625$, The equation of vertical displacement with fractal dimension is: $y = 0.3905x^2 - 0.7831x + 2.0295$, The equation of total displacement with fractal dimension is: $y = 0.4351x^2 - 0.8585x + 2.1461$. The fractal dimension of bermuda grass root was calculated by using Fractal1.0 software, the value was 1.56753. After the root fractal dimension of the natural state is substituted into the fitting formula, it was observed that the root of bermuda grass can reduce the horizontal displacement of the surface soil by 0.975mm and vertical displacement by 1.41mm and total displacement 1.48mm, as well as, by implanting a naturally growing bermuda grass root, the horizontal displacement of slope surface can be reduced by 41.2%, vertical displacement can be reduced by 20.4%, total displacement can be reduced by 20.9%.

The fitting formula of displacement variation and fractal dimension of oleander root model with main lateral root angle of 45 degree was chosen as formula that is used to calculate impact of fractal dimension of natural root system on slope surface displacement. The equation of horizontal displacement with fractal dimension is: $y = 0.3161x - 0.1454$, The equation of vertical displacement with fractal dimension is: $y = 0.4906x^2 - 0.772x + 0.5552$. The equation of total displacement with fractal dimension is: $y = 0.4461x^2 - 0.6137x + 0.4564$. The fractal dimension of oleander root system was calculated by using Fractal1.0 software, the value was 1.76572. After the root fractal dimension of the
natural state is substituted into the fitting formula, it was observed that the root of oleander can reduce the horizontal displacement of the surface soil by 0.42mm and vertical displacement by 0.726mm and total displacement 0.767mm, as well as, by implanting a naturally growing bermuda grass root, the horizontal displacement of slope surface can be reduced by 20.7%, vertical displacement can be reduced by 10.5%, total displacement can be reduced by 10.8%.

4. Conclusion

In this paper, a software of root fractal dimension calculation Fractal1.0 was developed basing on morphological characteristics of plant root system. Theory of fractal with the theory finite element were combined together innovatively, he growth morphology of root system was characterized by fractal dimension. The relationship between fractal dimension of root system and displacement of surface of slopes was studied, by analyzing this relationship, the impact of morphological characteristics of plant root system to displacement of slope surface was reflected truly (Reubens et al. 2007). Research result indicates fractal dimension is capable to be regarded as parameter to describe growth morphology of root system, It is feasible to combine the fractal dimension of root system with the finite element method, but it need to be further investigated to be applied in practice. The influence factors of plant root to solid slope are multifaceted (Lin et al. 2010), but the root morphology of plants was simplified in the study (Stokes et al. 2009), it is a new attempt to apply the method in quantitative analysis of plant slope, further research is needed on the theory and practice of soil reinforced by root.

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