Not light or gravity but water guiding root to grow

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\textbf{A R T I C L E   I N F O}

\textbf{Article history:}
Received 7 July 2015
Accepted 5 December 2015

\textbf{Keywords:}
Random structured soil
Weightless environment
Backlit growth
Seepage

\textbf{A B S T R A C T}

The plant root elongation and growth-oriented mechanism is the research focus. The main viewpoints are three, which are the growth of backlight, to gravity and to water and fertilizer. This paper believes that the viewpoint of the root growth to water and fertilizer is more reasonable. The random structured soil model, and the soil water evaporation model in weightlessness and gravity environment are established. The numerical simulation is performed. The phenomena, that root faster grows on the earth’s gravity than in weightless environment, the root near the surface soils is more disorderly in weightless environment, the main root is more taproot growing faster in both environments than the lateral roots, and the roots have some bifurcation and tilt, are explained. The water evaporation near the surface causes the water gradient, and the water gradient drives root elongation and growth, which shows the illusion of the root elongating to gravity. This study can be referred in the subsequent root growth-oriented, random structured soil, soil cracking, and soil water seepage/evaporation.

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1. Hypothesis of root to water and fertilizer

About the elongation of plant roots in the soil, there are three viewpoints: one is that roots elongate opposite to the plant stem, which extends in the direction of the light source, while the roots grow opposite to the light. The second one is that the expansion of plant roots on the direction toward the earth gravity \cite{1}, namely growing toward downward. Some molecular biology experts support this viewpoints, and believe the gravity-sensing columella cells in roots can orient the root elongation \cite{2,3}. These cells contain amyloplasts that function as statoliths and move in response to the direction of the gravity (toward bottom). The third one is that the plant roots extend in the direction of the water and fertilizer in the soil, namely the roots grow to direction where there are more water and fertilizer, as shown in Fig. 1.

The above three viewpoints and hypothesis seem to be reasonable, and the plant roots seem to extend to the three hypotheses growth direction.

In Fig. 1, (A) Garlic vertically placed, (B) Garlic horizontally placed, (C) Garlic inverted, (D) Garlic vertically placed, (E) Garlic vertically placed. The center of garlic in A, B, C is regularly dropped water on. One side of garlic in D is regularly dropped water on. One side of garlic in E is regularly dropped water on, and at the same time the other side of garlic is regularly dropped fertilizer on. Phenomenon: after some time of the rooting, the root system of the garlic A extends to the bottom; the roots of the garlic B twistedly extend to the bottom; the roots of the garlic C stretch back to the bottom; the roots of the garlic D expand to the water drip side; the roots of the garlic E expand to the fertilizer drip side. Description: the growth of Garlic A, B, C root may explain roots elongate to the earth center direction, and to the backlight; Garlic D illustrate roots extend to the water direction; Garlic E describes roots grow more likely to the fertilizer direction than to the water direction.

Experiment shown in Fig. 1 cannot deny the three hypotheses about the root growth: away from the light, to gravity, in the direction of more water and fertilizer. Therefore, many scientists do many significant root growth experiments \cite{4,5}. But it is difficult to conduct the experiments the independent factor affecting on the earth. A lot of scientists expand the related root extension study by the experiments in space \cite{6}, as shown in Fig. 2.

These Phenomena can be found: (1) the roots grows to the bottom of soil; (2) On the earth, root growth speed is more than in space; (3) roots near surface in weightless environment are more disorderly; (4) The taproot grow fast and is thick, while the lateral root slow grows and is small; (5) the root has some bifurcation and tilt.

Many researchers have tried to explain such phenomena by the plant biological mechanism \cite{4,7,8}. Brown and Chapman \cite{9}
found the circumnutation in weightless environment, so Brown and Chapman [9] drew the conclusion that the phenomenon of plant growth is not related to gravity. But they ignore the fact that the plants growing in space is also in fertilizer and water soil, and therefore the water seepage in both environmental soil need to be fully considered. As shown in Fig. 3, the argument is expanded about the three hypothesis.

The first hypothesis (as shown in Fig. 3): the roots extending is depart from the plant stems and leaves growth. Is it right? From Fig. 1, garlic roots send forth prior to the stems and leaves. So the first hypothesis introduction is not appropriate. Root system shown in Fig. 2 was carried out in the agar, which is translucent. Is the conclusion drawn that the root growth of self-directed away from the light source? The root on the ground is grown in the soil, and the soil is opaque (as shown in Fig. 1). It is not appropriate, that roots grow away from the light, namely the light does not orient the root growth.

Therefore, we can say, the direction roots extending in is not directly related to the light, namely the first hypothesis is not appropriate. By the comparative experiments in the weightless and gravity environment (as shown in Fig. 2), the same phenomenon of the roots extending to the bottom of soils is found. Therefore root growth direction, we can say, is not connected with the gravity.

By comparing the three hypothesis, following conclusions are drawn: (1) Root growth is not directly connected with the gravity; (2) Roots extending to water and fertilizer may exist. The main aim of this paper is to explain based on the root growing to the water and fertilizer.

2. Seepage model of root absorbing water

The water seepage equation in the unsaturated soil is as follows [10–14]:

$$\frac{\partial \theta}{\partial t} + \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \tag{1}$$

In the formula, $\theta$ represents the volumetric water content, which is the volume of water contained in unit volume of soil (soil, pore and water); $v_x, v_y, v_z$ are flow velocities in three directions, $v_i = -K(\theta)\partial \phi / \partial i$, $i$ represents the $x, y$ or $z$ direction; $K(\theta)$ represents for permeability coefficient as a function of water content $\theta$; $\phi$ is soil matric potential in the face of the earth when considering the acceleration of gravity, $\phi = z - h_c$; $h_c$ is water pressure height (pore water pressure), $z$ is the coordinate in $z$ direction of the studied point. Because at this time, it is unsaturated soil, $h_c$ in $\phi$ takes “-”; at the time without considering the acceleration of gravity, namely flying in space, $\phi = -h_c$. Furthermore, according to the $D(\theta) = -K(\theta)\partial h_c / \partial \theta$. In the two-dimensional space on earth, Y axial direction is for positive, $v_y = -D(\theta)\partial \theta / \partial y$, $v_y = -K(\theta) - D(\theta)\partial \theta / \partial y$; in space flight, $v_y = -D(\theta)\partial \theta / \partial y$, $v_y = -D(\theta)\partial \theta / \partial y$. $D(\theta)$ is the water diffusivity of unsaturated soil.

2.1. Soil water seepage equation in weightlessness and gravity environment

There is water and pores in soils, and water is transported in pores, at last the water movement gets the balance. In space, there is no other external force, so water can run by the diffusion. On the earth, there is the gravity, so water can be influenced by the gravity. When the gravity is considered on the earth [15],

$$v_x = -D(\theta)\frac{d \theta}{dx} \tag{2}$$

$$v_y = -D(\theta)\frac{d \theta}{dy} \tag{3}$$

$$v_z = -K(\theta) - D(\theta)\frac{d \theta}{dz} \tag{4}$$

where, $v_i = -K(\theta)\partial \phi / \partial i$, $i$ is the $x, y$ and $z$. $\phi_x, \phi_y, \phi_z$ are $z - h_c$. $D(\theta) = -K(\theta)\partial h_c / \partial \theta$.

Therefore, Eq. (1) is simplified to,

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ D(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D(\theta) \frac{\partial \theta}{\partial y} \right] + \frac{\partial}{\partial z} \left[ D(\theta) \frac{\partial \theta}{\partial z} \right] \tag{5}$$

Eq (5) is the water seepage equation on the earth. If the $Z$-axis positive direction is upward, ‘+’ is taken, otherwise ‘-’ is taken.

Without the gravity in space, Eq. (4) is changed into,

$$v_z = -D(\theta)\frac{\partial \theta}{\partial z} \tag{6}$$

Eq. (2), (3), (6) into Eq. (1),

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ D(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D(\theta) \frac{\partial \theta}{\partial y} \right] \tag{7}$$
Eq. (7) is the seepage equation of unsaturated soils in space without gravity.

In two dimension, X, Y and Z-axis becomes X, Y axis, so Eqs. (5) and (7) change into,

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ D(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D(\theta) \frac{\partial \theta}{\partial y} \right] \pm \frac{\partial k(\theta)}{\partial \theta} \frac{\partial \theta}{\partial y} \]  

(8)

\[ \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ D(\theta) \frac{\partial \theta}{\partial x} \right] + \frac{\partial}{\partial y} \left[ D(\theta) \frac{\partial \theta}{\partial y} \right] \]  

(9)

Eq. (8) is the seepage equation of unsaturated soils on the earth with the gravity, while Eq. (9) is the seepage equation of unsaturated soils in space without gravity.

2.2. Evaporation conditions on soil surface

Whether the plant roots growth absorption experiments are on the earth or in space, the soil surface is open, so there is an evaporation interface on the soils.

There are some different boundary states on the evaporation interface of the slope [16]: (1) when the air humidity is small, the state of persistent drought, the soil surface can be considered to maintain a air-dry water content: \( \theta = \theta_s \), which also belongs to the first boundary condition. (2) In the early evaporation of soil water, when the outside weather conditions remain unchanged, the topsoil evaporation intensity remains essentially stable, that is \( D(\theta) \frac{\partial \theta}{\partial x} \sin \alpha + \partial \theta / \partial z \cos \alpha = E \), which also belongs to the second type of boundary condition. (3) In general, the evaporation strength will not remain stable for a long period. Because the intensity of surface evaporation is restricted by the soil water supply, it will transit to the case of the surface evaporation intensity reducing with water content decreasing, which is \( \frac{\partial}{\partial x} \left( \frac{\partial \theta}{\partial x} \sin \alpha + \frac{\partial \theta}{\partial z} \cos \alpha \right) = E(\theta) \) and is called the third boundary condition in soil water dynamics, where \( S(\theta) \) is the evaporation intensity function. Where \( \alpha \) is the slope angle, i.e. the tilt angle of the soil surface.

Three boundary conditions are there, not only in space and but also on the earth laboratory.

2.3. Numerical simulation

In order to better illustrate similarities and differences in soil water distribution in weightlessness and gravity, this paper makes a numerical calculation to describes these.

A half of the root area is selected as calculated area, that is 10 cm × 10 cm. The initial water content of the study area is 0.2. Since the soil is unsaturated, the soil permeability coefficient is a function of the water content \( \theta \). Research parameter selection: the diffusion coefficient chosen is \( 5 \times 10^{-6} \), and the permeability coefficient is \( 2 \times 10^{-3} \). Conditions in the two environments are the same, including the light irradiation, indoor humidity, etc. On the soil surface, the evaporation condition is exactly the same. The three evaporation boundary conditions are there. The focus of this paper is to take the third condition to study. The third boundary conditions, the function is \( E(\theta) = 1 \) - \( 8 \theta^3 \), the results as shown in Figs. 5–7.

So the water content is shown in Table 1. W is the water content and \( w = (W - 0.2973) \times 10^3 \). The time is the 24 h (1 day), 48 h (2 days), 72 h (3 days), 96 h (4 days), 120 h (5 days), 144 h (6 days), 168 h (7 days), 192 h (8 days) and 216 h (9 days). A, B, C, A', B', and C' are the six positions of Fig. 4. Ratio of Water Content is the ratio of water content in gravity environment and in the zero gravity environment.

As shown in Figs. 5 and 6, the water content gradually reduces from the top to the bottom. Because the surface soil water is first dissipated [16] due to the evaporation of surface water and the loss rate of bottom water is slow. The law of gravity on the earth and showed the same weightless environment deny rule.

The law in gravity environment is same to the one in weightlessness environment.

Fig. 7 show the water content difference along Line ab after 1 day placed in weightless environment and in gravity
As can be seen from the figure that water in the weightless environment is greater than the water content in the gravity environment, and this difference decreases with depth increasing.

\[ P_{gw} = \left( \frac{dW_g}{dy} \right) / \left( \frac{dW_z}{dy} \right) \]

where \( W_g \) and \( W_z \) are the water content in gravity and zero gravity environment. \( dW/dy \) is the water content gradient.

So the \( P_{gw} \) is shown in Table 2.

As can be seen from Table 1, at the same depth at three points \( A, B, C \), the water content in the gravity environment is less than the water content in the weightless environment, which can be found in Fig. 7. With time going on, the water on the surface gradually loses. As the depth increases, the evaporation rate of water loss decreases. The two water content ratio increases as the depth increases, that is, the two water content tends to the same with the depth increasing.

As can be seen from Table 2, at the same depth but different time, the ratio of the water content gradient is almost the same. With the depth increasing, the ratio increases.

In Tables 1 and 2, the water content at the same depth in the gravity environment is less than that in the weightless environment, but the water gradient in the gravity environment is greater than the water content in the weightless environment.

By this, many phenomena of the plant roots growth in space can be explained. As shown in Figs. 5 and 6, the water content increases with the depth increasing, so the root can be guided to the more deep (Phenomenon 1). In the same depth, the water content in gravity environment is less than that in the weightlessness environment, (for example, 2.398183 < 2.457961 of \( A \) and \( A' \) point in Table 1 in 24 h.), thus water in the gravity environment guides roots to stretch down to get more water. In the same depth, the water content gradient in the gravity environment is greater than that in the weightlessness environment (for example, 1.045316 > 1 of \( A \) and \( A' \) point in Table 2 in 24 h.). For the same roots, more water gradient can easier guide the roots, because roots are more sensitive to the larger water content gradient (Phenomenon 2).

The water content of the surface soil in weightless environment is more (for example, in Table 1, 2.398183 < 2.457961 of \( A \) and \( A' \) in 24 h.), while the water content gradient ratio on the surface is less than that in more deep (for example, in Table 2, 1.045316 < 1.200127 of \( AA' \) and \( CC' \) in 24 h.), namely the difference between the surface water gradient is small, here roots for water sensitivity to this gradient is weak, so superficial roots in the two environments are more disorderly, further, superficial roots in the weightless environment is more cluttered (Phenomenon 3).

When Root continues to grow when absorbing water, its taproot first grows to obtain the priority development opportunity. At the same time, the taproot continues to absorb water around, making the water around it be reduced. In order to get more water, the taproot needs grow out more lateral roots to absorb water in more distant soil. But this time the water is lower than the original water near the main root, the taproot grows fast and becomes thick, while the lateral root grows slow and becomes small (Phenomenon 4).

### 3. Root absorbing model in random structured soil

#### 3.1. Water and fertilizer distribution in random structured soil after evaporation and absorbing

The process of soils forming is complex [17], such as water and soil sediment seepage/transport [18], the mechanics/temperature [17], soil collapse [19–22] and other effects, so its components is wide vary. Soil has a large number of soil particles, rock granules, even a variety of impurities such as various kinds of glass, plastic and other components. The physical parameters of soil compositions are different, so these substances make the water seepage in soil very complex. Plant roots in the soil absorb water and the water near the root is absorbed, so roots gradually extend to the more water content. Between taproots, there appears more water content area, so the main roots grow the finer second root, as shown in Fig. 8.

The soil water from the meteoric water seeps downward to the bottom. When there is no rain for some time, the surface soil gradually dries due to the evaporation, the soil water will transport from
the bottom to the up, so a gradient from the top to the bottom is formed, as shown in Fig. 9A.

The water content of the upper part is small, that on the bottom is more. Roots grow downward to absorb more water, at that time the main root appears, as shown in Fig. 9B.

Plant roots absorb water in the soil. The water near the taproot becomes less. So the water content distribution and the water gradient field is changed. The taproot is the gradient center, the direction is from the center to around, and water seeps from around to the center.

At the same time, the effect due to the taproot absorbing water on the water distribution is superposed on the original water content field. The water becomes more inclined along the down direction, taking the taproot as the center. So the lateral roots along the taproot appear, as shown in Fig. 9C.

The taproot and lateral root absorbs water, making the water content decrease between the taproot and the lateral root, and between the lateral roots. At the same time, there is the water content gradient, so the second lateral root appears along the lateral roots, as shown in Fig. 9D

3.2. Random structured model of soil

Soil is composed of a large number of soil particles, the physical properties of each of the constituent particles are not identical, so the porosity, density, permeability, water content and other parameters are different. At the same time the root has the property of elongating to more water.

The paper established the random structured soils and seepage model. Calculation parameters: the random soil size is 1 m × 1 m, the root length is 0.2 m, the depth of the root is 0.2 m, root water uptake leads to near soil water distribution, $h = 0.1 + 0.5h$, where $h \in [0.0,2]$, the soil diffusion coefficient $D = 0.0005S$, permeability coefficient $K = -0.0025/2$, $S$ is the soil random physical parameters, $S \in [0.1]$, the initial water content is 0.3. The random structured soil model is shown in Fig. 10A, and the results is shown in Fig. 10B.

Generally, when the soil is composed of homogeneous matters, the water content contours in soil is smooth during the root absorbing water. But many of the water content contours in Fig. 10B are not smooth but curve, especially in the dotted line box, the reason is that the soil properties are not homogeneous in Fig. 10A. $S$ in the dotted line box changes from 0.01 to 0.76, that is, the permeability coefficient is from $1800 \times 10^{-6}$ m$^2$/s to $1368 \times 10^{-6}$ m$^2$/s, the diffusion coefficient is from $5 \times 10^{-6}$ m$^2$/s to $3.8 \times 10^{-6}$ m$^2$/s.

Therefore, the plant roots have bifurcation and tilt (Phenomenon 5). The main reason is the composite matter of soils is different and inhomogeneous, and thus the permeability and diffusion coefficient, water distribution appears different.

4. Conclusions

The random structured soils model and seepage model in weightless environment are established in this paper, and then numerical simulation is made. The case study reveals the mechanics and explains the difference of the plant roots growth between in the gravity and in the weightless environment. The following conclusions are obtained:

1. The soil composed of random soil particles has the random characteristics in physical properties. This random nature is difficult to analyze by experiments, especially in the condition that the plate used is very small in plant roots growing experiments. The numerical simulation is a good method to solve this problem. The random structured model of soils can be referred in the study of soil physical property.
2. Soil water seepage/evapotranspiration characteristics are different in the two environments. The seepage equation in weightless environment is established in the paper. By the model, the seepage can be better analyzed and studied in weightless environment.
3. There are many difference of the plant root growth between in the two environments. The growth differences are analyzed and the natural mechanism is revealed. Under the consideration of the boundary conditions and the soils’ random structure, the numerical simulation is made. It is obtained that the surface soils evaporation, the water content gradient and the random structure is the main reason.
4. This study can be referred in the subsequent root growth-oriented, random structured soil [23], soil cracking [11,14], and soil water seepage/evaporation.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 51179177), the Fundamental Research Funds for the Central Universities (No.: 2011YXL053), China State Scholarship Found (No.: 201208110444), and Beijing Higher Education Young Elite Teacher Project (No.:YETP0655).

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