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ROOT ABSORBING AND SEEPAGE MODEL IN WEIGHTLESS ENVIRONMENT AND SPACE

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Key words: Root model, Weightless environment, Seepage equation, Absorbent water

Abstract

The exterior stimulated growth and endogenous growth of plant roots have been the focus of the content of scientists' study over the years which has not reached a consensus. The research on the influence of gravity on root growth is one of the important parts of the study. In this paper, the study on the root water uptake from the perspective of soil moisture and set up a geometric mathematical model of roots and water seepage model under weight loss environment was carried out. Through numerical calculation and analysis, the relationship between distribution of soil moisture and root water uptake under gravity environment and weight loss environment has been obtained. It is concluded that gravity hinders the root absorption of water and the weightless environment is more conducive to the absorption of water while the weight loss also cause the loss of water. Previous studies only considered the effect of gravity and light on the distribution of biological molecular constituents of the plant roots. In this paper, the effect of gravity on the soil moisture distribution will also be studied. This study is helpful in research on the hydrotropism and muck-tropism gravitropism of plant and backlighting.

Introduction

There are a large number of reports on circumnutation and gravitropism of plant roots. A number of experts believe that the circumnutation is induced by the earth's gravity, others think that the motion is independent to gravity (Brown and Chapman 1984). There are more specific contradiction: in the classical biological evolutionism, Darwin believes that motion characteristics of plants are stimulated by the earth's gravity (Darwin and Darwin 1880) while some experts think the plants gravitropism cause circumnutation characteristics of root but not the gravity (Kiss 2006) which is in conflict with Darwin's view. It is unclear whether these oscillatory movements are an endogenous nastic movement or whether they are coupled to and depend on gravitropism (Kiss 2006). These studies are mainly related to molecular biology and planetology. The circumnutation of plant roots is relying on gravity-sensing columella cells inside the roots (Kitazawa *et al*. 2005, Kiss 2006). These cells contain amyloplasts that function as statoliths and move in response to the direction of the gravity (toward bottom).

Through the experimental study on agar soil, Okada and Shimura (1990) believe that the steering motion of the plant root system is caused by the impediment of the soil, hence, the roots of the plants continue to make steering motion.

Paul *et al*. (2012) also performance the seed germination and the root elongation growth test in the space to obtain the pictures of root elongation growth in space and on the ground as shown

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in Fig. 1. It is found that the growth of root on the ground and in the space both have the negatively phototropic characteristic. On the ground the root grows rapidly and has stronger negatively phototropic characteristic under the weightless condition. The root grows slower and has weaker negatively phototropic characteristic. The root growth is in disorder near the soil surface.

There is also a lot of related research about root water uptake in soil mechanics field. The effects of root suction on the soil slope stability. Vertical root distribution was measured using image analysis and soil density effect on suction was induced due to root water uptake investigated by *Schefflera heptaphylla* (Garg and Ng 2015). Water infiltration rate and hydraulic conductivity in vegetated soil on root was investigated by field experiments (Leung *et al*. 2015). The plant-induced suction distribution is investigated on a slope vegetated with multiple plants by a series of parametric study (Garg *et al*. 2012). Garget *et al.* (2015) quantified the effect of different vegetation species, root characteristics and transpiration reduction function on suction in slopes under natural variation. They investigated the suction distribution and root characteristics in recompacted slopes vegetated with two different species. These studies reinforce the people understanding the influence of the soil strength and root absorption.

The studies described above have positive significance in understanding the elongation especially the root circumnutation. In these situations researches mainly focused on plants, the gravity and light factors but the soil which is in direct contact with plant roots was ignored along with the water supply. Root elongation growth need moisture and nutrition from the soil. These influences on plant cannot be ignored. Explanation should be given on the study of soil from which plants absorb nutrient and water to solve these problems described above.

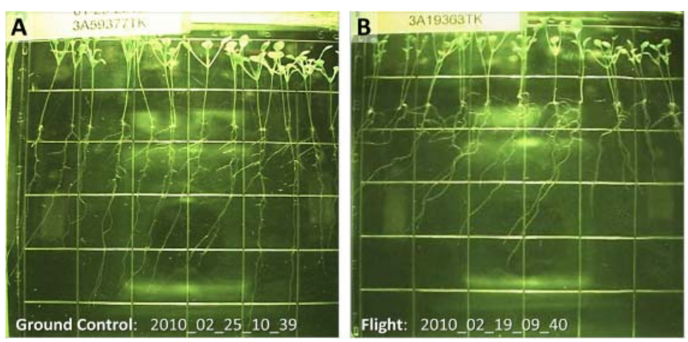

Fig. 1. Different extension of root on ground and space. (A) Root growth patterns of 9 days old plants from the ground control. (B) Flight experiment in space (Paul *et al*. 2012).

In the present investigation emphasis was given on the relationship between distribution of soil moisture and root water uptake. The direct observation and monitoring work is difficult. Therefore, the present work was conducted on the basis of numerical simulation to obtain the relevant law and mechanism and to explain the related phenomenon. Therefore, an attempt was made to solve two problems the mathematical modeling of plant root and the distribution of moisture in the unsaturated soil related to the process of root water uptake.

Materials and Methods

In the numerical calculation, it is necessary to obtain the outline curve of the root and carry on processing the actual photo group root (Fig. 2 A) to get the root contour curve (Fig. 2 B), with the software MATLAB. The process is as follows, (1) the image file is read, (2) binaryzation of the original value is done, (3) the root hollow is filled, (4) with the expansion function dilate (F, SE), the original graph is expanded. This can overstrike the small parts and then extract the contour. The SE is for the two-value structural element of function dilate. Then the proper value is selected in the function, not too big nor too small. If it is too big compared with the original graph, the isolated parts might mix together. If it is too small, the expansion effect is not obvious and small area still does not get to expand. (5) function bwperim in MATLAB was used, the root contour is extracted. (6) the color black and white is exchanged. (7) the image of the anticolor of graph is saved. The program statements are as follows:

```
Root = imread ('Root.bmp'); % Step 1
R1 = im2bw (Root);      % Step 2
R2 = bwfill (R1,'holes');   % Step 3
SE = ones(1);           % Step 4.1The number 1
% needs to be kept modified and adjusted
R3 = imdilate (R2,SE);    % Step 4.2
R4 = bwperim (R3);      % Step 5
R5 = ~im2bw (R4); % Step 6, % result picture
Imwrite (R5,'Root2.bmp'); % Step7
```

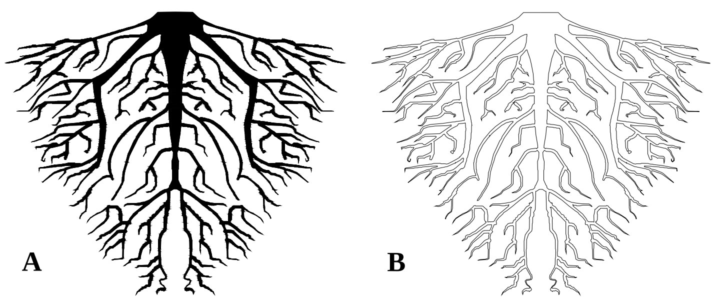

Fig. 2. The root contour curve.

Finally the diagram of root shown in Fig. 2.B is obtained, with the root height of 0.4506 m, width of 0.5428 m, area of 2 × 0.0198 = 0.0396 m^2 and the perimeter of 17.9408 m. The water seepage equation (Sun *et al*. 2006, Sun and Wang 2013, Sun and Wang 2010) is established for unsaturated soils (Sun *et al*. 2009) and sedimentation model of solid particles in porous media (Sun 2015) according to the mass balance equation, which is the evolution equation of water absorbent in gradient field, as follow:

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

In the formula, θ 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 θ; ϕ 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* ϕ takes "-"; at the time without considering the acceleration of gravity, namely flying in space, ϕ=-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, $v_x = -D(\theta)\partial\theta/\partial x$, $v_y = -K(\theta)-D(\theta)\partial\theta/\partial y$; in space flight, $v_x = -D(\theta)\partial\theta/\partial x$, $v_y = -D(\theta)\partial\theta/\partial y$. $D(\theta)$ is the water diffusivity of unsaturated soil.

In the surface of the earth, formula (1) can be simplified to,

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}[D(\theta)\frac{\partial\theta}{\partial x}] + \frac{\partial k(\theta)}{\partial\theta}\frac{\partial\theta}{\partial y} \quad (2)$$

In space, without considering the gravity, the above equation is changed into,

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}[D(\theta)\frac{\partial\theta}{\partial x}] + \frac{\partial}{\partial y}[D(\theta)\frac{\partial\theta}{\partial y}] \quad (3)$$

Results and Discussion

Half of the root is selected as the computational domain which is 1 m × 1 m. All units are of the standard international system. The initial water content in the research area is 0.2. Calculation parameters selected for the study are $D = 5\times10^{-4}$, $K = 2\times10^{-3}\theta^2$, $A = 0.25$, $h_c = 0.25/\theta$ of soil and $D = 5\times10^{-3}$, $K = 2\times10^{-3}\theta^2$, $A = 2.5$, $h_c = 2.5/\theta$ of the root.

The surface boundary condition is for the water content boundary condition. Because in a day, the evaporation of moisture is mostly during the day, the root absorption occurs during the day. The absorption of water in the day is from 6 o' clock to 18 o' clock, a total of 12 hrs. The sun-light is in the sine form, the water content of the root surface is,

$$\theta = 0.0008 \times \sin(t/3600/12 \times 3.1415926 + 3.1415926) + 0.1992 \quad (4)$$

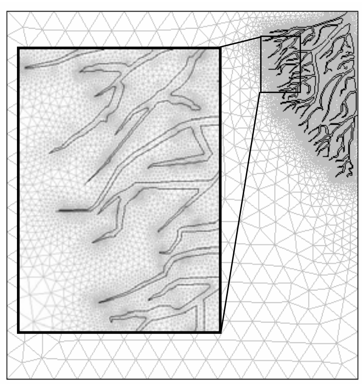

Fig. 3. The finite element mesh.

Change of the water content in this boundary is sinusoidal change. At t∈[0, 6h], it corresponds to the time from 6 o'clock to12 o'clock of earth time, boundary water content decreased to the lowest (0.1984), the water content of root surface is the lowest and the water absorption capacity is of the strongest at this time which corresponds to root water uptake increased stage in the morning; at t∈[6h,12h], it corresponds to the earth time from 12 o'clock to18 o'clock. Boundary water content is increased to the highest 0.1992, the water content of the root surface is at the highest and the water absorbing ability is of the weakest which corresponds to the decrease stage of root water uptake in the afternoon. Therefore, this boundary condition is consistent with the evolution of plant root water absorption time.

As the root system is symmetrical, so half of the root system was chosen for finite element method; the mesh is as shown in Fig. 3, in which the number of triangular meshes is 75887, boundary unit number is 6058. According to formula (2), (3) and (4), the calculation was made.

Fig. 4 is the top-down moisture distribution of the x = 0.5 straight in the computation domain. In Fig. 4 , t = 6G,12G are, respectively the water curve at the suction time of 6 hr and 12 hrs in the face of the earth.

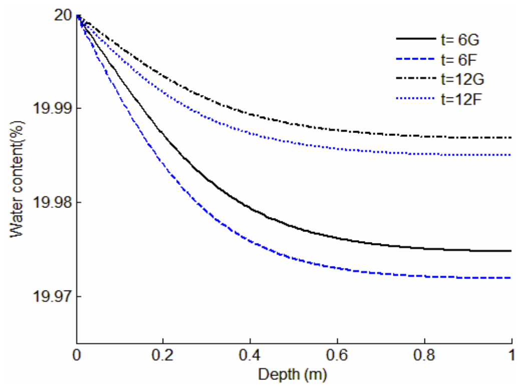

Fig. 4. The top-down moisture distribution of the x = 0.5 line.

The absorbing water characteristics under gravity are consistent with the conclusions in Leung *et al.* (2015), the grass and tree species having deeper root depth and greater root area index retained higher suction. The moisture distribution was similar to the result of Bufon *et al.* (2012) and Li *et al.* (2015). It can be seen from the graph that along with the increasing of the depth, moisture content is reduced; in t∈[6h,12h], along with the extension of time, water content is increased away from the surface.

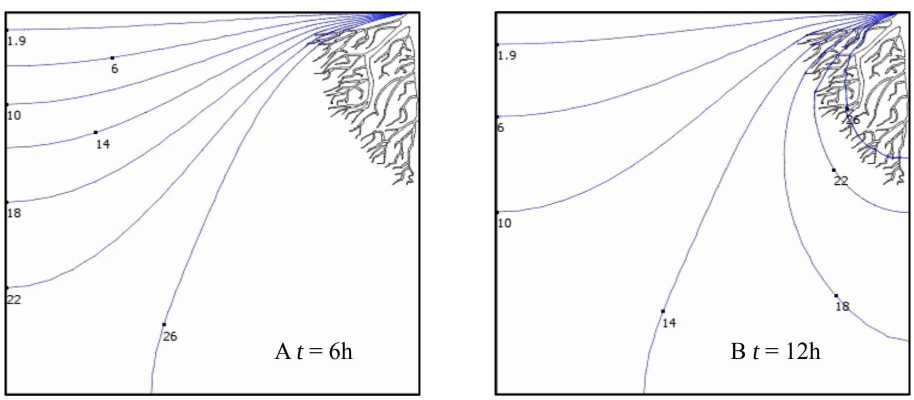

Fig. 5. The water content distribution in flight (The marked number is $\delta = -(\theta-0.2)\times10^5$, and θ is the water content).

Fig. 5 is the water distribution in the state of weightlessness, in which $\delta = -(\theta-0.2) \times 10^5$. It is a function of water content. It can be seen from the Fig. 5 that water content, taking the root for approximately the center, gets higher with distance increasing from the center (in Fig. 5 curve numbers and moisture are anti related). In the soil surface near the roots, the contour density is higher, which means that the water content gradient is bigger. The greater the depth, the lower the density of water content contours showing that the water content gradient is small, and the water content is close.

According to the Fig. 5B, further research was carried out on the characteristics of the center of root water uptake and got the roughly center of water closed contour. The contour of the center was defined, the cutting of water content of closed contour in the main root axis achieved the mid point of the contour which is the center of root water uptake. The center coordinates are as shown in Table 1.

There are two points appearing on the section cutting a certain contour, one of which is the center of the main root on the soil surface, the other of which is under the ground.

y in the Table 1 is the y coordinate of the under ground point on section. δ is $-(\theta - 0.2)\times10^5$, Dr is the distance of the two points and the diameter of the contour round and R is the radius of the contour round.

According to the data in Table 1, set up the equation of radius and moisture as follows,

$$R = -0.1285 \times (\delta\text{-}17.85)^{0.4} + 0.49 \quad (5)$$

The fitting mean variance of the formula 5 is 0.0017, $\delta \in [18, 26]$. The root evaporation and absorption capacity of formula 5 is related to soil permeability and initial water content. Formula 5 is a brief measurement. It can be seen that R is inversely related to δ and positively related to θ.

Table 1. Radius of root absorbing water contour.

$100\times\theta$	δ	y	$Dr=1-y$	$R=Dr/2$
19.974	26	0.619986	0.380014	0.190007
19.975	25	0.582945	0.417055	0.208528
19.976	24	0.546415	0.453585	0.226793
19.977	23	0.513512	0.486488	0.243244
19.978	22	0.476299	0.523701	0.261851
19.979	21	0.431018	0.568982	0.284491
19.98	20	0.372299	0.627701	0.313851
19.981	19	0.290015	0.709985	0.354993
19.982	18	0.13797	0.86203	0.431015

According to the definition of v_y on earth and in space flight in formula 1, $v_y = -2\times10^{-3}\theta^2 - 5\times10^{-3}\partial\theta/\partial y$ and $v_y = -5\times10^{-3}\partial\theta/\partial y$ are calculated by substituting parameters. Water absorption near the surface of the main root section is,

$$Q\Big|_{boudary-top} = \iint v_y\,dxdt \quad (6)$$

The integral interval of formula 6 is $x\in[0.971485113881926,1]$, $t\in[0,12h]$. According to formula v_y and 6, the time evolution of absorbing speed and weight was calculated, as shown in Fig. 6.

Fig. 6. A and B show that the absorbing speed and weight in the weightless environment are higher than root water uptake on earth but the basic law of water uptake is similar. Difference in absorption rate shows the basic arithmetic difference with the water uptake gradually increasing.

The reason is that water is not only affected by the matrix suction effect in the face of the earth but also by the direction of gravity, thus resulting in the difference.

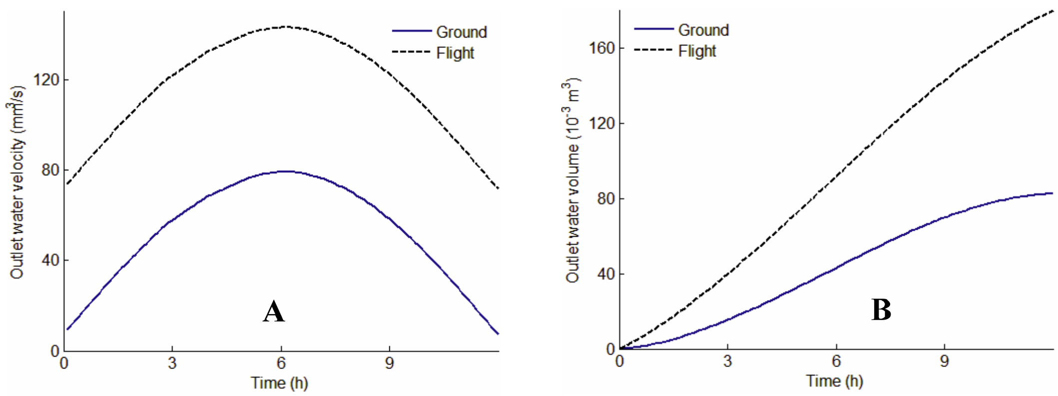

Fig. 6 Velocity and quantity of the root absorbing water with time going on. (A) One half velocity of the root absorbing water with time is performanced. (B) One half quantity of the root absorbing water with time is performanced.

Paul *et al.* (2012) made contribution on the growth elongation characteristics of root on the ground and in the space to gravity and light.

As shown in Fig. 5, contour lines are denser near the surface, showing larger gradient of distribution of soil moisture. In order to obtain more moisture, the root of the plant extends outwards and to the surface. While deep roots enter directly to the underground extension. Despite the large moisture gradient, the total supply of the water is small, so the root is not strong enough. There are lots of small roots and in the deep, fewer strong roots grow in one direction which well explains the phenomenon found by Paul *et al.* (2012) from the angle of soil nutrient.

The calculation and analysis show that the soil moisture gathers more in the bottom under the action of gravity, which forms a concentration gradient from the bottom to the top. The bottom roots easily absorb more moisture making the root extends to the bottom. In the weightless environment, water is more uniformly distributed in the soil and the main root's function is weakened, which is negatives its growth.

In conclusion, plants' ability of absorption of water and fertilizer in the weightless environment is better than that of in the earth. But in the weightless environment, a lot of water is evaporated easily (Paul *et al*. 2012). The growth of the plants in space experiment is slower than in the earth.

It might be further suggested that plant root growth is the result of many factors which are gravity, endogenous, phototropism and negative phototropism. A comprehensive consideration of these factors is necessary to uncover the mechanism of root elongation.

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