3D FE–DEM Simulation of a Thickening Growth Model for Japanese Radish Root

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Abstract: The mechanical impedance of soil is well known to influence the shape formation of storage roots of root vegetables strongly. Contact interaction between the root and soil become important in the growth and shape formation of the storage root. This study was aimed at construction of a numerical model for thickening growth of radish tap roots based on the root–soil contact interaction. However in 2D simulation, the height of the soil Discrete Elements increased greatly compared with experimental observations. To solve this problem, 3D simulation was extended and improvements in the shape representation of soil Discrete Elements were made. Soil Discrete Elements with non-spherical shape were generated such that several spherical Discrete Elements were joined together to create a model particle. In this report, the results of preliminary simulation obtained for a small scale are discussed. For the 3D simulation, the shape of root Finite Elements was reproduced based on growth velocities. No distortion occurred in root Finite Elements. Additional examinations of the mechanical properties of radish roots and parameter settings for root Finite Elements are needed. Furthermore, results confirmed that the extension of FE–DEM for the root–soil system in 3D was able to decrease the final height of surface soil Discrete Elements from 18 mm to approximately 14 mm. Clumped Discrete Elements decrease the height to about 13 mm.

Keywords: Radish, Root, Thickening growth, 3D FE–DEM, Non-spherical discrete elements, Plants, Numerical simulation

1. INTRODUCTION

It is generally recognized that the growth of plant roots can be affected adversely by high mechanical impedance imposed by their ambient soil environment. Generally, highly compacted soil interrupts root growth. Especially for root vegetables, storage roots must move the surrounding soil particles to make space as they grow in a soil medium. Consequently, the hardness, density, and structure of the soil strongly influence the development and shape formation of the storage root. Radish roots used to be evaluated according to their shape and size from the view of efficiency in transport and processing. This might also affect competitiveness on the market. Usually, straight and cylindrical shapes are desired. Although the shape patterns of storage roots of radish plants are basically programmed in their genetic DNA sequence, physical soil conditions alter these traits dramatically through vegetative growth. For example, soil layers that are heavily compacted by wheels and tracks of heavy agricultural machines and continuous tillage operations at the same depth would produce irregular shapes of storage roots in Japanese Radish. Therefore, root–soil contact interaction plays an important role in the radish root shape formation.

This study specifically examines the effects of the mechanical impedance in the radish root shape formation in terms of the contact problem. The study was designed to develop a thickening growth model of a radish tap root based on the root–soil contact interaction.

As for modeling of root growth, with the increasing speed of computers, numerical methods such as Discrete Element Method (DEM) and Finite Element Method (FEM), are gradually becoming more effective techniques for the analysis of granular materials and contact problems between soil and agricultural machine devices (Horner et al. 2001; Nakashima et al. 2009). Based on the idea of cone penetration, when the root elongates in soil, development of a stress field in the soil medium has been analyzed using FEM (Faure 1994). In this study, root deformation was not considered. Similarly, the effects of the radial division and enlargement in the meristematic zone on the root tip and the deformation and stress field in the vicinity of the root tip have been analyzed using FEM (Richards and Greacen 1986). Recently, modeling of the root elongation growth based on the dynamic contact interaction between root and ambient soil environment using DEM was proposed (Nakashima et al. 2008). Furthermore, in a previous study, the basis of the thickening growth model of radish root based on the root–soil contact interaction was constructed in 2D (Fujita 2010). In this developed model, the DEM and the FEM were applied, respectively, to the modeled soil and root. Furthermore, root–soil contact interaction was analyzed using the Finite Element – Discrete Element Method (FE–DEM). The calculated shape of root Finite Elements mostly agreed with the experimental results. However, the behavior of the soil Discrete Elements caused larger displacements. Particularly, the height measured at the surface of soil Discrete Elements was considerably greater. Figure 1 shows numerical results in 2D simulation obtained at the initial and final growth stages. Furthermore, Fig. 2 shows changes of the height in soil Discrete Elements with time. In Fig. 1 and Fig. 2, T(day) is the time elapsed in the experiment and t(s) is that which elapsed in the simulation. Because of the extremely long calculation time of DEM simulation, a virtual time scale was introduced. The correspondence between the time scale in the simulation and in experiment was explained in previous reports (Fujita 2010). The root Finite Elements thickened laterally; soil Discrete Elements were largely deformed. Also, the height of soil Discrete Elements increased from 130 mm to approximately 155 mm. Therefore, the soil Discrete Elements had almost no compressibility, which was against the observation that the soil used in the experiment was compacted. Furthermore, in the previous model, the elongation of the hypocotyls could not be simulated apparently. To solve this unnatural increase of soil Discrete Elements, extension of FE–DEM to model root–soil systems in 3D was done and improvements in the shape of soil Discrete Elements were made.

The main objective of this study is to construct a 3D thickening growth model of radish root by application of 3D FE–DEM.

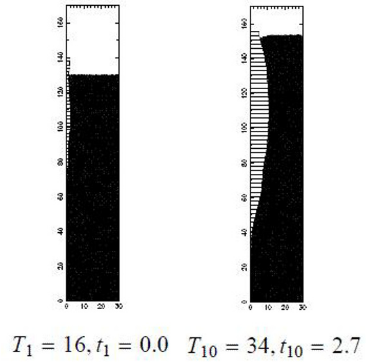

Fig. 1. Results of the 2D simulation of thickening growth of radish root (left, initial growth stage; right, final growth stage, T_i(day), t_i(s)).

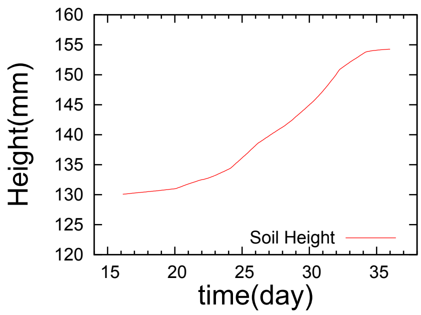

Fig. 2. Height of the soil Discrete Elements shown versus time.

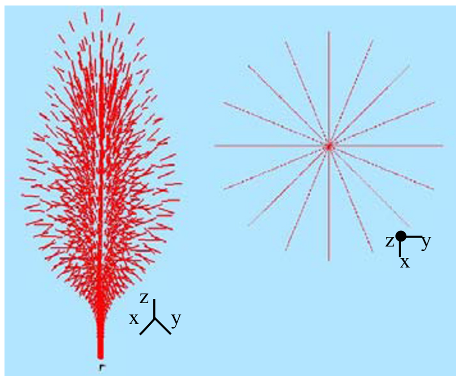

Fig. 3. Setting growth rule for root Finite Elements in 3D.

2. MATERIALS AND METHODS

In this section, the 3D thickening growth model is described. Then, numerical methods used in the previous 2D model, FEM, DEM, and FE–DEM were extended to a 3D model. Furthermore, improvement in the shape of Discrete Elements was made. As in the previous 2D analysis, to reproduce the growth of root Finite Elements, a simplified assumption for mechanism of the thickening growth of radish root was made under which root Finite Elements would obey the experimental growth rule of “Growth Velocity” data obtained by virtual marking method in this radish experiment. The radish outline was obtained by projection onto a plane. Furthermore, the root shape was assumed to be axisymmetric. The root shape was expressed as the radius and the distance from the proximal end. Furthermore, in the 3D case, the radish growth was assumed to be the same for all radial directions (Fig. 3). Figure 3 shows the assumed direction and magnitude of growth in the radish root.

2.1 Root Model

A radish root was modeled using FEM. When the storage root grows radially, the root exerts a force to displace the soil particles; it is simultaneously reacted upon by the soil particles. The deformation and development of the stress fields within the root were calculated using FEM. The basic shape of the radish root was assumed to be axisymmetric and a quarter of the target domain was modeled. The root Finite Elements consist of standard hexahedral eight-node isoparametric elements (Fig. 4). For