

Digging Trajectory Optimization by Soil Models and Dynamics Models of Excavator

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ABSTRACT

Researches for automated construction machinery have been conducted for labor-saving, improved work efficiency and worker's safety, where a tracking control function was proposed as one of the key control system strategies for highly automated productive hydraulic excavators. An optimized digging trajectory that assures as much soils scooped as possible and less energy consumption is critical for an automated hydraulic excavator to improve work efficiency.

Simulation models that we used to seek an optimized digging trajectory in this study consist of soil models and front linkage models of a hydraulic excavator. We developed two types of soil models. One is called wedge models used to calculate reaction forces from soils acting on a bucket during digging operation, based on the earth pressure theory. The other is called Distinct Element Method (DEM) model used to analyze soil behaviors and estimate amounts of soils scooped and reaction forces quantitatively. In this simulation, we calculated generative forces and energy consumptions of hydraulic cylinders by solving inverse dynamics of the linkages.

Firstly, we used wedge models that enable extremely high-speed calculations, to look for numerous combinations of trajectory parameters and select ones with less energy consumption. Then, we used DEM models that enable detailed analysis by combining with the front linkage models to evaluate digging efficiencies of the selected trajectories. The results show that the trajectories with the highest efficiency generated in this research exceeds the efficiency level of a skilled operator by 6.6%.

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INTRODUCTION

Hydraulic excavators are widely used for earth-moving works as the leading construction machine to increase productivity. Current general problems in excavation works are to be dirty, dangerous, demanding and difficult. Moreover, the number of highly skilled operators is limited. Productivity in excavation works can be significantly impacted by these reasons. To solve these problems, we studied automatic digging system, remote control, simplified operation, digging assistance and so on [1, 2, 3, 4, 5], focusing on automatic digging system which can significantly contribute to increase productivity with as much soils scooped as possible and less energy consumption in digging operation.

We proposed a tracking control function as one of control system strategies for automated hydraulic excavators, where our study focused on tracking control function that allows to generate optimum digging trajectory. For this purpose, we looked for digging trajectories which could improve energy efficiency for automated hydraulic excavators. Productivity of excavation work depends largely on ground shapes and soil properties. In order to generate a highly efficient digging trajectory, we had to evaluate the energy efficiency for each digging trajectory that varies with ground shapes and soil properties. Since such evaluation using an actual machine would take significant cost and time, we developed simulation models that enable to calculate the energy efficiency, where we defined the mass of scooped soils per consumption energy as a performance index for the digging

efficiency. To identify a highly efficient digging trajectory by this simulation was the main purpose of this research.

Simulation models that we used to seek an optimized digging trajectory in this study consist of soil models and front linkage models of hydraulic excavator. In order to simulate reaction forces from ground, we developed and used two types of soil models depending on applications. In addition, we calculated generative forces and energy consumptions of hydraulic cylinders by solving inverse dynamics of the linkages.

In this study, first, we validated wedge models that allow extremely high speed calculations, where we set up four parameters designed for the geometry of a digging trajectory. Then, by taking advantage of high speed calculation of wedge models, we could quickly select appropriate parameters that might realize less energy consumptions. We selected 150 trajectories from 100,000 trajectories and then analyzed them in details together with the front linkage models using DEM models to evaluate the digging efficiency.

SIMULATION MODELS

Summary of Digging Simulation Models

Simulation models that we used to seek an optimized digging trajectory consist of front linkage models of an excavator and soil models selected from two types of soil models. One of soil models is called wedge models, used to calculate reaction forces from soils acting on a bucket during digging operation, based on the earth pressure theory [6]. The other is models created by Distinct Element Method (DEM) [8], which allows to analyze soil behaviors and estimate scooped soil volumes and reaction forces quantitatively. Wedge models are used for iterative analysis, allowing to calculate digging reaction forces more quickly than 2D-DEM models. On the other hand, DEM simulation models that take longer allow to accurately calculate reaction forces and analyze scooped soil volumes in details using the function to reproduce soil behaviors. Figure 1 and 2 show wedge and 2D-DEM simulation models during digging operation respectively. In addition, we calculated generative forces and energy consumptions of hydraulic cylinder by solving inverse dynamics of front linkages of an excavator.

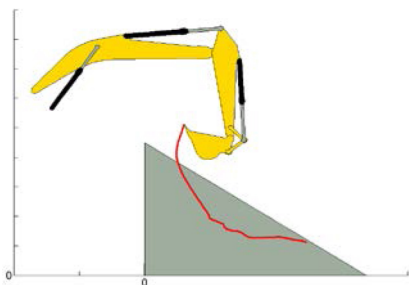


Figure 1. Illustration of wedge model simulation

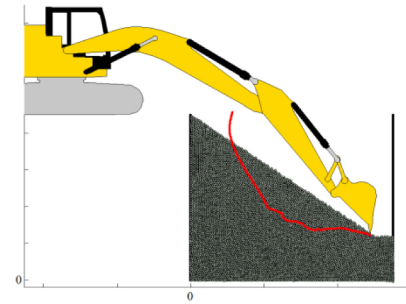


Figure 2. Illustration of 2D-DEM model simulation

Soil Models (Wedge Models)

Wedge models [6] allow to calculate reaction forces acting on the bucket using the amount that the bucket penetrates into soils, under an assumption that soils fracture in the shape of a wedge. The force acting on the bucket during digging motion is divided into 5 component forces, as shown in figure 3.

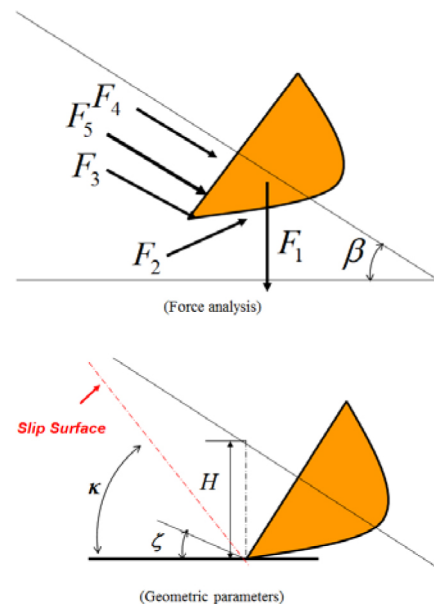


Figure 3. Analysis of force acting on bucket during digging operation

F_1 is the weight of soils scooped into the bucket. F_2 is the resistance force at the bottom of the bucket. F_3 is the penetration force at the bucket tip during digging operation. F_4 is the frictional force between bucket and soils scooped into the bucket. The weight of soils in the bucket F_1 is shown as follows:

$$F_1 = Mg = \frac{1}{2} \gamma d^2 \cos^2 \xi (\tan \beta - \tan \xi) g$$

(1)

where M is the mass of soils in the bucket, g is the acceleration of gravity, γ is the density of soil, β is the angle of soil surface and ζ is the angle between the horizontal axis and the bottom of the bucket.

$$F_2 = 0 \quad (2)$$

This study assumes that, after bucket starts moving upward, no contact of bucket bottom and soils will occur, which makes $F_2 = 0$.

$$F_3 = (K_0 \cos \kappa + \sin \kappa) \gamma H S g \quad (3)$$

Where K_0 is coefficient related penetration resistance for each material, κ is the angle between the horizontal line and the moving direction of the bucket tip, H is the depth of the bucket tip from the slope surface, and, S is cross sectional area of the bucket tip.

$$F_4 = \mu F_1 \cos \zeta + \mu F_5 \sin(\beta \mp \zeta) \quad (4)$$

Where μ is the coefficient of static friction, ζ is the angle between the horizontal axis and the bottom of the bucket, and β is the slope angle of the soil surface.

F_5 is called passive earth pressure that varies with the digging angle and the amount that the bucket penetrated into soils. F_5 can be calculated based on the Coulomb earth theory [7], that allows to estimate the force required for the retaining wall to support soils. As shown in figure 4, a slip surface is generated in front of the bucket.

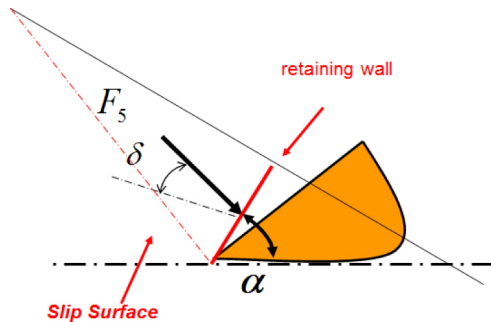


Figure 4. Passive force during digging operation

Now, F_5 is calculated as follows:

$$F_5 = \frac{H^2 \gamma}{2} K_p = \frac{H^2 \gamma}{2} \frac{1}{\sin^2 \alpha \sin(\alpha + \delta)} \left[\frac{\sin^2(\alpha - \phi)}{1 - \frac{\sin(\phi + \delta) \sin(\phi - \beta)}{\sin(\alpha + \delta) \sin(\alpha + \beta)}} \right]^2 \quad (5)$$

Where K_p is the passive force coefficient, H is the height of the retaining wall, γ is the density of soils, α is the angle of the bucket with respect to the horizontal axis, β is the slope angle of the soil surface, δ is the friction angle between soil and tool, and ϕ is the friction angle between soils.

Motion Equation of Distinct Element Method [8]

Distinct element method theory allows to calculate the forces in the normal and tangential directions that act on particle i caused by contacting with particles. These resultant forces are regarded as forces acting on particles. Behavior of each particle can be calculated by the following motion equation:

$$m \frac{d^2 \mathbf{w}_i}{dt^2} = m \mathbf{g} + \Sigma \mathbf{F}_n + \Sigma \mathbf{F}_s \quad (6)$$

Where m is the mass of particle, $\mathbf{w}_i$ is the position vector of particle, and $\mathbf{g}$ is gravity vector.

In this simulation program, the force represented by the right side of the above equation was solved in horizontal and vertical directions and behaviors of the particles were reproduced by solving the motion equation in each direction.

Force working between particles

Forces between particles acting in the normal and tangential directions are calculated based on the Voigt model [9] shown in figure 5. η is the coefficient of viscosity and K is the stiffness coefficient, where n subscript shows the normal direction of particles, and s subscript shows the tangential direction.

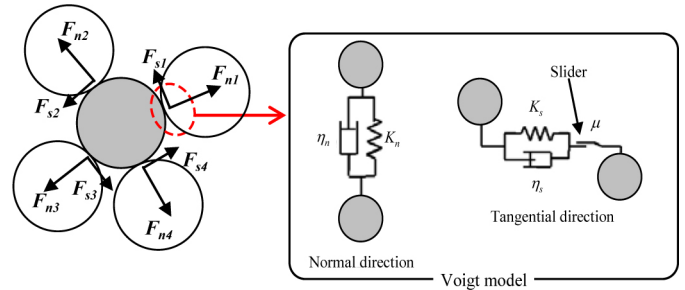


Figure 5. Modeling of particles

When particles contact, the reaction and damping forces act in the normal direction. The reaction force is calculated by Hooke's law. Stiffness K_n in the normal direction of particles i and j is determined by the Hertz contact theory [10]:

$$K_n = \frac{4}{3} \frac{1}{\left(\frac{1 - \nu_i^2}{E_i^2} + \frac{1 - \nu_j^2}{E_j^2} \right)} \sqrt{\frac{\delta}{\left(\frac{1}{r_i} + \frac{1}{r_j} \right)}} \quad (7)$$

Where ν is the poisson's ratio of particle, δ is penetration of particles, E is Young's module of particle, and r is radius of particle, K_n and the time step of the simulation affect the convergence of the solution of Eq. (6). The coefficient of viscosity η is calculated as follows:

$$\eta_n = 2\zeta\sqrt{mK_n} \quad (8)$$

where ζ is the damping ratio. Force F_n acting in the normal direction is calculated as follows:

$$F_n = K_n u_n + \eta_n \frac{du_n}{dt} \quad (9)$$

u_n is the relative displacement in the normal direction of two particles.

Shear forces are calculated by shear coefficient s , which is converted from a coefficient of rigidity using the coefficient of transformation.

$$K_s = K_n s \quad (10)$$

$$\eta_s = \eta_n \sqrt{s} \quad (11)$$

$$s = \frac{G}{E} = \frac{1}{2(1+\nu)} \quad (12)$$

where G is shear module of rigidity. The friction force acts among the particles. When the particles move in the shearing direction, the friction force is calculated. When the force generated by a spring and a dashpot exceeds the maximum static friction force, the friction slider acts. Therefore, shear force F_s is calculated by the following conditional expression using the coefficient of friction μ :

$$F_s = \begin{cases} \mu F_n & (\mu F_n < \eta_s \frac{du_s}{dt} + K_s u_s) \\ \eta_s \frac{du_s}{dt} + K_s u_s & (\mu F_n \geq \eta_s \frac{du_s}{dt} + K_s u_s) \end{cases} \quad (13)$$

Calculation of payloads

Each time a simulation finished, we calculated payload M_d based on particles n_p over the bucket. Because this digging simulation is based on two-dimensional modeling, the following equation provides a payload equivalent to bucket width w_b and density of soil γ :

$$M_d = \pi r^2 w_b \rho n_p \quad (14)$$

DYNAMICS MODELS OF EXCAVATOR

Definition of coordinates

Backhoe type excavators have a closed loop mechanism consisting of three hydraulic cylinders. In this study, we defined a serial link consisting of a boom link, arm link and bucket link as the main link system. Then, we defined the boom closed loop as a serial link of upper structure, boom and boom cylinder, the arm cylinder loop as a serial link of boom, arm and arm cylinder, and the bucket cylinder loop as a serial link of arm, bucket, power link, idle link and bucket cylinder.

In this simulation models, a coordinate system is located at each linkage part, as shown in figure 6, 7, 8, 9, 10. In these figures, circled numbers show call-out numbers of parts. $\{i\}$ shows coordinate system of part number i . In order to simulate motions of an excavator, a coordinate system is located at each link based on Denavite-Hartenberg method [11]. Table 1 shows call-out number of coordinate system and joint number of the origin on each part. The intersection of the ground and the pivot at the swing center of the upper body is defined as the origin of coordinate system $\{0\}$. Swing motion of upper body is not considered in these models because this study mainly focuses on digging motions.

By Denavite-Hartenberg method, dynamic problems mentioned later are recursively solved, where motion equations can be derived easily. Denavite-Hartenberg parameters of a hydraulic excavator shown in table 2 are defined as follow.

$a_{(i-1)i}$: Distance from axis z_{i-1} to z_i along axis x_i

α_{i-1} : Angle about axis x_{i-1} , formed by axis z_{i-1} and z_i

d_i : Distance from axis x_{i-1} to x_i along axis z_i

θ_{i-1} : Angle about axis z_{i-1} , formed by axis x_{i-1} and x_i

In the case of an excavator, α_{i-1} becomes either value of $-90, 0$ or 90 [deg]. d_i shows a cylinder length.

Table 1. Arrangement of coordinate systems

Parts	Parts No.	Coordinate No.	Joint number of coordinate origin
Uppur body and crawler	0	0	0
Boom	1	1	1
Arm	2	2	2
Bucket	3	3	3
Boom cylinder tube	4	4	4
Boom cylinder rod	5	5	12
Arm cylinder tube	6	6	6
Arm cylinder rod	7	7	13
Bucket cylinder tube	8	8	8
Bucket cylinder rod	9	9	10
Power link	10	10	10
Idle link	11	11	11
Bucket tip	3	E	E



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