

Article

Optimizing Excavation by Excavators Based on an Analysis of Digging Resistance Characteristics

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Abstract

Accurately determining digging resistance during bucket–soil interaction is crucial for optimizing excavator working devices and power systems. To address measurement difficulties, a numerical simulation model based on the arbitrary Lagrangian–Eulerian (ALE) method was established and verified through excavation tests. Through orthogonal experiments, the influence of excavation parameters was studied, and the optimal compound digging trajectory was determined. The results show that increasing the excavation angle from 36° to 48° decreases the X-direction resistance and moment by 39.48% and 38.85%, respectively, though specific energy consumption (*SE*) increases. Additionally, optimizing arm movement speed reduces the X-direction resistance and moment. While ensuring the bucket load factor is suitable, reducing arm speed and a horizontal soil push during compound excavation effectively decreases *SE*. Finally, the optimal balance of digging resistance and *SE* can be achieved with a 300 mm bucket hydraulic cylinder displacement, a 1.5 s interval for initial arm and bucket movements, and an arm-to-bucket speed ratio of 5.5 for hydraulic cylinders.

Keywords: excavator; digging resistance; arbitrary Lagrangian–Euler; excavation parameter; digging trajectory

1. Introduction

With their strong adaptability and high flexibility in harsh and changeable working environments, excavators have become indispensable pieces of equipment in earthmoving projects, such as urban renewal, exploitation of mineral resources, and track construction [1,2]. The actions an excavator carries out mainly include moving, swinging the rotating platform, and extending and retracting the boom, arm, and bucket cylinders. The combination of these actions allows the completion of different earthwork operations, such as grading, slope trimming, and swing loading (which is the most common). Based on earthmoving (e.g., excavating, loading, hauling, and dumping soil) completed through the combination of actuator actions, the process of swing loading can be divided into four segments, namely, digging, hauling, dumping, and swinging [3–5]. The digging segment is a bucket–soil interaction process, and determining digging resistance is critical for the study of statics, dynamics, fatigue life, and trajectory optimization regarding the working components of an excavator [6].

A great deal of research has been conducted on digging resistance during bucket–soil interaction using theoretical modeling, field or laboratory tests, and numerical simulation.



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In terms of establishing the mathematical model for the prediction of digging resistance, based on the Mohr–Coulomb soil failure criterion and passive earth pressure theory pertaining to retaining walls, Hemami and Daneshmand [7] established a digging resistance calculation model composed of five components with clear physical significance by projecting the obstructive effect of the soil on the bucket onto the symmetry plane of the working devices. As shown in Figure 1a, it includes the gravity of the bucket and soil (in the bucket) F_1 , compression resistance (soil outside the bucket) F_2 , friction F_3 , cutting resistance F_4 , and the inertia of the soil in the bucket F_5 . However, Hemami’s model lacks an explicit expression for each component. Balovnev, V.I. et al. [8] established cutting force models for predicting different parts of the bucket and soil. All the components were decomposed and recomposed in the horizontal and vertical directions, as shown in Figure 1b. The method consisting of joining “bucket structure decomposing–cutting force modeling–digging resistance composing” is more suitable for trajectory planning studies pertaining to the bucket. Based on the tool–soil static equilibrium equations proposed by McKyes, Sun et al. [9] established a dynamic digging resistance prediction model that can reflect the influence of ore gravity, friction, excavation speed, and materials on both sides of the bucket. It was applied to optimize excavation parameter control for a material pile with different angles. Overall, it is extremely difficult to establish a unified, accurate, and universally applicable analytical model because of the changeable operation modes, unstructured topographic features, uncertain excavation objects, and irregular bucket geometry relevant in this situation.

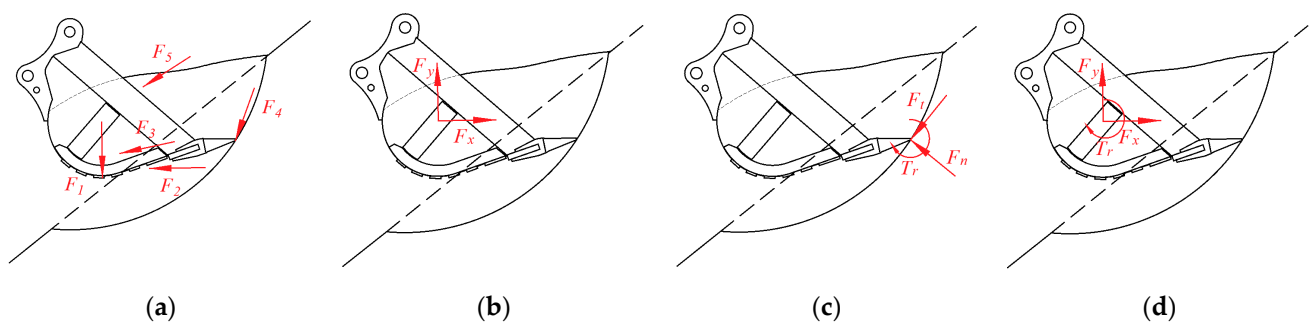


Figure 1. Bucket–soil interaction models: (a) Hemami’s model; (b) Balovnev’s model; (c) Zou’s model; and (d) the model proposed in this paper.

Additionally, many researchers have attempted to perform real vehicle tests or build indoor test benches to analyze digging resistance in the excavation process using statistical theories and methods [10–12]. Zou et al. [11] converted the output forces of the boom, arm, and bucket hydraulic cylinders into the comprehensive effect of tangential, normal resistances and the moment acting on the tip of the bucket through an established dynamic model of an excavator, as shown in Figure 1c. The principal interval and probability density of the coefficient of resistance and the moment, resistance angle, and difference angle were statistically analyzed. In another of their studies, they proposed a compound digging force calculation model based on the principal interval of the resistance, the difference angles and the safety requirements for the whole machine [12]. Balovnev, V.I., Zou et al. [8,10] established a comprehensive evaluation system for excavator performance that can quantify excavation ability, the efficiency of the working components, the degree of matching between mechanisms and hydraulic cylinder output forces, and the influence of limiting factors on excavation ability. On this basis, working-component structures and digging trajectory were optimally designed using a genetic algorithm. However, the high cost and poor repeatability of the actions and the need for a secondary transformation for

the digging resistance results prevented real vehicle and laboratory tests from being the first choice for researchers.

With the rapid development of computer technology, researchers are increasingly turning to commercial or self-developed software for the numerical simulation of the excavation process using approaches such as the discrete element method (DEM), finite element method (FEM), and arbitrary Lagrangian–Eulerian (ALE) method [13,14]. Wang et al. [15] used a surrogate model to accurately simulate the soil accumulation angle, cohesion, and internal friction angle by optimizing the particle radius, static, and rolling friction factors. The results showed that the average error of soil stress was 5.1% during rolling with a tire, and the optimized soil discrete element model can be approximated to replace the real soil for analysis. Fang et al. [16] analyzed the macroscopic and mesoscopic movement behaviors of soil during the rotary tillage process by establishing a discrete element model of the rotary tillage tool and soil. In addition, the displacement of soil was verified using the tracer method. The ALE method incorporates the advantages of both the Lagrangian and Eulerian methods. It can accurately track the free boundary of meshes and effectively solve the problem of mesh distortion during the simulation process, making it more suitable for numerical simulation studies featuring high soil deformation [17,18]. Li et al. [13,14] used the ALE method to simulate foundation reinforcement under single-tamping and continuous dynamic compaction replacement conditions. The optimal rammer diameter and height/diameter ratio were found to be 2.5 m and 0.3–0.5, respectively.

To address the low applicability of mathematical models and poor repeatability of actual vehicle and laboratory tests, firstly, digging resistance was decomposed and recomposed into three components acting on the centroid of the bucket according to the theorem of the translation of a force, namely horizontal resistance F_x , vertical resistance F_y , and the resistance moment T_r , as shown in Figure 1d. In this way, the direction and amplitude of the components of digging resistance are directly related to the translational and rotational motion of the bucket. The results can be directly used to guide efforts to control the trajectory of the bucket under real-life conditions. Secondly, a numerical model of the bucket–soil interaction process was established and experimentally verified to study the characteristics of digging resistance. Thirdly, the relationship between excavation parameters, methods, and the digging resistance was analyzed based on the parameterized characterization of the bucket excavation trajectory. Lastly, the optimal compound digging trajectory was determined.

2. Kinematics and Kinetic Models of Excavator Working Devices

2.1. Kinematics Model

Figure 2 shows a structural diagram of a backhoe excavator. According to the positional relationship between the hinge points of the excavator, Equations (1) and (2) can be obtained:

$$\begin{bmatrix} X_B \\ Y_B \\ X_G \\ Y_G \\ X_J \\ Y_J \end{bmatrix} = \begin{bmatrix} L_{AB} \times \cos \theta_1 \\ L_{AB} \times \sin \theta_1 \\ X_B + L_{BG} \times \cos(\theta_1 + \theta_2) \\ Y_B + L_{BG} \times \sin(\theta_1 + \theta_2) \\ X_G + L_{GJ} \times \cos(\theta_1 + \theta_2 + \theta_3) \\ Y_G + L_{GJ} \times \sin(\theta_1 + \theta_2 + \theta_3) \end{bmatrix} \quad (1)$$

$$\left\{ \begin{array}{l} \theta_1 = \arccos \frac{L_{AF}^2 + L_{AC}^2 - L_1^2}{2L_{AF}L_{AC}} - \angle BAC - \alpha \\ \theta_2 = \angle ABD + \arccos \frac{L_{BD}^2 + L_{BH}^2 - L_2^2}{2L_{BD}L_{BH}} + \angle HBG - \pi \\ \theta_3 = \angle NGB + \arccos \frac{L_{GN} - L_{NK} \cos \angle KNG}{L_{GK}} + \angle LGJ - \pi + \arccos \frac{L_{NK}^2 + L_{NG}^2 - 2L_{NK}L_{NG} \cos \angle KNG + L_{GL}^2 - L_{KL}^2}{2L_{GL} \sqrt{L_{NK}^2 + L_{NG}^2 - 2L_{NK}L_{NG} \cos \angle KNG}} \\ \angle KNG = \angle ENG - \arccos \frac{L_{NE}^2 + L_{NK}^2 - L_3^2}{2L_{NE}L_{NK}} \end{array} \right. \quad (2)$$

where θ_1 is the angle between the connecting line of boom hinge points A and B and the horizontal plane; θ_2 is the angle between the connecting line of arm hinge points B and G and the connecting line of boom hinge points A and B ; θ_3 is the angle between the connecting line of bucket hinge points G and J and the connecting line of boom hinge points B and G ; L_1 , L_2 , and L_3 are the total lengths of the boom, arm, and bucket hydraulic cylinders, respectively; L_{IJ} is the distance between hinge points I and J ; $\angle IJK$ is the angle between the connecting line of points I and J and the connecting line of hinge points J and K ; and α is the angle between the connecting line of hinge points A and F and the horizontal plane.

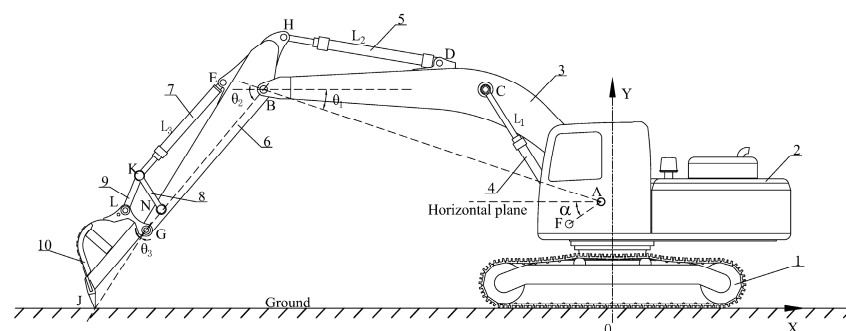


Figure 2. Structural diagram of a backhoe excavator: 1—substructure, 2—upper structure, 3—boom, 4—boom hydraulic cylinder, 5—arm hydraulic cylinder, 6—arm, 7—bucket hydraulic cylinder, 8—rocker arm, 9—connecting rod, and 10—bucket.

For a specific type of excavator, the digging trajectory of the bucket, which is the trajectory of the tooth-tip point J , can be expressed as follows: $(X_J, Y_J) = f(L_1, L_2, L_3)$. In this study, we employ the digging segment in swing loading with more complex changes in digging resistance as an example. To facilitate the following analysis of the characteristics of digging resistance as well as the optimization of digging trajectory, combined with the operation specifications of the excavators and the operating habits of the operators, the following simplifications and assumptions were made regarding the excavation process:

1. The tips of the bucket's teeth are just in the horizontal ground at the beginning of excavation, and the connecting line between points G and J is parallel to the horizontal plane at the end of excavation. The boom remains stationary during excavation.
2. The compound excavation process starts with the action of the arm hydraulic cylinder and ends with the cessation of the operation of the bucket hydraulic cylinder. The total time consumed by excavation is set to T .
3. The hydraulic cylinders remain stationary or move at a constant speed until they reach the set displacements during the excavation process.

According to the first assumption, the bucket's digging trajectory can be further expressed as $(X_J, Y_J) = g(L_2, L_3)$. According to the second and third assumptions, the

total lengths of hydraulic cylinders of the bucket and arm at any time can be expressed as follows:

$$L_2 = \begin{cases} l_{20} + k_v \times \frac{\Delta L_3}{T - \Delta t} \times t & , 0 \leq t < t_{arm} \\ L_2 & , t \geq t_{arm} \end{cases} \quad (3)$$

$$L_3 = \begin{cases} l_{30} & , t < \Delta t \\ l_{30} + \frac{\Delta L_3}{T - \Delta t} \times (t - \Delta t) & , t \geq \Delta t \end{cases} \quad (4)$$

where l_{20} and l_{30} are the initial total length of the arm and bucket hydraulic cylinders determined by the initial excavation attitude; k_v is the arm-to-bucket hydraulic cylinder speed ratio; ΔL_3 is the displacement of the bucket hydraulic cylinder; Δt is the time interval from the start to the moment that the bucket hydraulic cylinder starts to move; and t_{arm} denotes the time consumed during the arm hydraulic cylinder moves.

When the initial excavation attitude is determined, the bucket's digging trajectory can be further expressed as $(X_J, Y_J) = h(\Delta L_3, \Delta t, k_v)$. That is, the digging trajectory can be described through a combination of the displacement of the bucket hydraulic cylinder, the time interval from the start to the moment that the bucket hydraulic cylinder starts to move, and the arm-to-bucket hydraulic cylinder speed ratio. The parameterized characterization of the bucket excavation trajectory will be used in the study of the optimal digging trajectory in Section 5.3.

2.2. Kinetic Model

According to the robot kinematics and kinetic analysis method, the excavator can be regarded as a plane linkage mechanism composed of key hinge points. Figure 3 shows the Denavit–Harterberg (D–H) coordinate system of the excavator's working devices. O_0, O_1, O_2, O_3 , and O_4 are the coordinate systems of the substructure, upper structure, boom, arm, and bucket. The kinetic equation of the excavator system established with the Lagrangian method is as follows:

$$T_i = \frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = \frac{d}{dt} \frac{\partial K}{\partial \dot{q}_i} - \frac{\partial K}{\partial q_i} + \frac{\partial P}{\partial q_i}, \quad i = 1, 2, \dots, n \quad (5)$$

where T_i denotes the moment acting on the coordinate system O_i ; L denotes the Lagrangian function, where $L = K - P$; K and P denote the kinetic and potential energy of the system, respectively; $\dot{q}_i$ denotes angular velocity; q_i denotes angle; and n denotes the number of equivalent plane-connecting rods for the excavator, with $n = 4$.

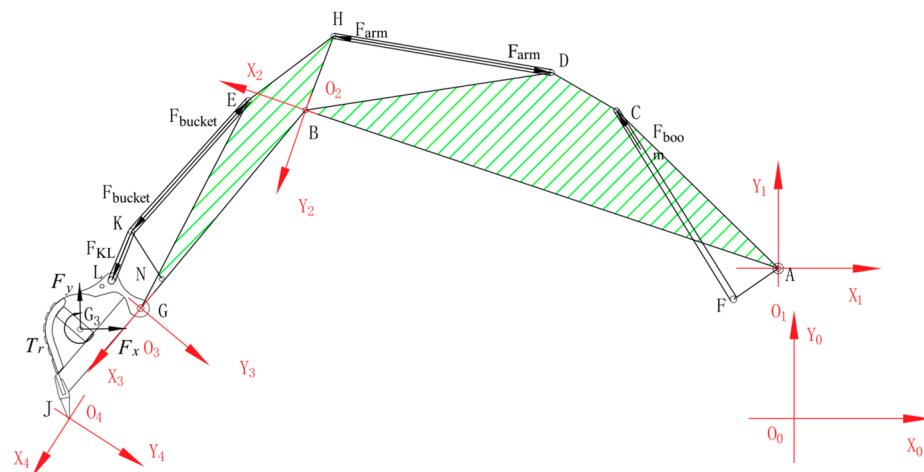


Figure 3. Denavit–Harterberg coordinate system of the excavator's working devices.

Suppose that p is a point on the equivalent connecting rod i of the excavator; let

$${}^0r_p = H_i {}^i r_p \quad (6)$$

where ${}^0r_p$ denotes the position vector of p in the base coordinate system O_0 ; ${}^i r_p$ denotes the position vector of p in the local coordinate system O_i ; and H_i denotes the transformation matrix from the local coordinate system O_i to the base coordinate system O_0 .

The velocity of point p can be expressed as follows:

$${}^0V_p = \frac{d}{dt}({}^0r_p) = \dot{H}_i {}^i r_p = \left(\sum_{j=1}^i \frac{\partial H_i}{\partial \theta_j} \dot{\theta}_j \right) {}^i r_p = \left(\sum_{j=1}^i U_{ij} \dot{\theta}_j \right) {}^i r_p \quad (7)$$

where U_{ij} denotes the derivative of the transformation matrix H_i with respect to the i -th generalized coordinate.

Suppose that the mass of point p is d_m . The translational kinetic energy of equivalent connecting rod i relative to the base coordinate system and the rotational kinetic energy of equivalent connecting rod i relative to the local coordinate system can be obtained as follows:

$$\begin{cases} K_i = \int_i \frac{1}{2} ({}^0V_p)^2 d_m = \int_i \frac{1}{2} \text{Trace} \left[({}^0V_p) \cdot ({}^0V_p)^T \right] d_m = \frac{1}{2} \text{Trace} \left[\sum_{j=1}^i \sum_{k=1}^i U_{ij} I_i (U_{ik})^T \dot{\theta}_j \dot{\theta}_k \right] \\ K_{ai} = \frac{1}{2} I_{ai} \dot{\theta}_i^2 \end{cases} \quad (8)$$

where I_i denotes the pseudo-inertia matrix of the equivalent connecting rod i ; U_{ik} denotes the derivative of the transformation matrix H_i with respect to the k -th generalized coordinate; and I_{ai} denotes the equivalent moment of inertia of the equivalent connecting rod i .

According to König's theorem, the total kinetic and potential energy of the excavator system are as follows:

$$\begin{cases} K = \frac{1}{2} \sum_{i=1}^4 \sum_{j=1}^i \sum_{k=1}^i \text{Trace} \left[U_{ij} I_i (U_{ik})^T \right] \dot{\theta}_j \dot{\theta}_k + \frac{1}{2} \sum_{i=1}^4 I_{ai} \dot{\theta}_i^2 \\ P = - \sum_{i=1}^4 m_i g^T (H_i {}^i r_p) \end{cases} \quad (9)$$

Thus, the kinetic model of the excavator system based on the Lagrangian method can be obtained as follows:

$$\begin{cases} T_i = \sum_{j=1}^4 D_{ij} \ddot{\theta}_j + I_{ai} \ddot{\theta}_i + \sum_{j=1}^4 \sum_{k=1}^4 D_{ijk} \theta_j \theta_k + D_i, \quad i = 1, 2, 3, 4 \\ D_{ij} = \sum_{p=\max(i,j)}^n \text{Trace} (U_{pj} I_p U_{pj}^T) \\ D_{ijk} = \sum_{p=\max(i,j,k)}^n \text{Trace} (U_{pj} I_p U_{pj}^T) \\ D_i = \sum_{p=i}^n -m_p g^T U_{pj} {}^p r_p \end{cases} \quad (10)$$

where U_{pj} denotes the second-order derivative of the transformation matrix H_p with respect to the two generalized coordinates of j and k ; and T_i denotes the external moment acting on the i -th coordinate system.

Based on the principle of simplification and equivalence, digging resistance can be simplified into the comprehensive effect acting on the centroid of the bucket, constituting

the resistances in the X and Y directions and the moment, as shown in Figure 3. Thus, the kinetic model of the excavator based on the Lagrangian method can be obtained:

$$\left\{ \begin{array}{l} \vec{AC} \times \vec{F}_{boom} + \vec{AG}_3 \times \vec{F}_x + \vec{AG}_3 \times \vec{F}_y + T_r = \sum_{j=1}^4 D_{2j} \ddot{\theta}_j + I_{aj} \ddot{\theta}_2 + \sum_{j=1}^4 \sum_{k=1}^4 D_{2jk} \dot{\theta}_j \dot{\theta}_k + D_2 \\ \vec{BH} \times \vec{F}_{arm} + \vec{BG}_3 \times \vec{F}_x + \vec{BG}_3 \times \vec{F}_y + T_r = \sum_{j=1}^4 D_{3j} \ddot{\theta}_j + I_{aj} \ddot{\theta}_3 + \sum_{j=1}^4 \sum_{k=1}^4 D_{3jk} \dot{\theta}_j \dot{\theta}_k + D_3 \\ \vec{GL} \times \vec{F}_{KL} + \vec{GG}_3 \times \vec{F}_x + \vec{GG}_3 \times \vec{F}_y + T_r = \sum_{j=1}^4 D_{4j} \ddot{\theta}_j + I_{aj} \ddot{\theta}_4 + \sum_{j=1}^4 \sum_{k=1}^4 D_{4jk} \dot{\theta}_j \dot{\theta}_k + D_4 \end{array} \right. \quad (11)$$

where G_3 denotes the centroid of the bucket, and F_{KL} denotes the output force of the connecting rod acting on the bucket. According to the law of the transmission of forces, $F_{KL} = f(F_{bucket})$. F_{boom} , F_{arm} , and F_{bucket} denote the output forces of the boom, arm, and bucket hydraulic cylinders, and F_x , F_y and T_r are the components of digging resistance when it is decomposed and recomposed horizontally and vertically with respect to point G_3 , as shown in Figure 3.

Equation (11) shows that determining the excavator's digging trajectory allows the determination of the kinematic parameters of each working device according to the excavator kinematics model; that is, the right side of Equation (11) is known. Furthermore, the ascertained digging resistance can be converted into the hydraulic cylinders' output forces, which are easy to measure, and the results can be experimentally verified. The kinetic model established based on the Lagrangian method is applied in the experimental verification of the simulation results in Section 4.

3. Numerical Simulation of Bucket–Soil Interaction

3.1. Establishment of Simulation Model

In the analysis of nonlinear continuum mechanics, researchers generally adopt the Lagrangian method for solid media. This method can accurately describe the state of deformation of the material boundary. To analyze fluid media, researchers generally adopt the Eulerian method, which can ensure accurate results are obtained when the structure has been heavily deformed. The ALE method introduces a reference coordinate system to represent finite element mesh nodes based on Lagrangian and Eulerian coordinate systems. The ALE method allows one to reasonably select the equation describing the way in which the finite element mesh moves, ensuring the state of deformation of the material boundary and results featuring heavy deformation are accurately described [14,17,18].

In view of the superiority of the ALE method in simulating the heavy deformation of the structure, a numerical model for studying the characteristics of digging resistance is established in this section. To effectively balance the relationship between calculation accuracy and efficiency, the bucket is regarded as rigid, and the soil is assumed to be an isotropic material; that is, physical parameters such as the density, elastic modulus, and shear modulus of each part are the same.

As only the bucket is in contact with the soil during the actual excavation process, the excavator's other structures are ignored. According to the spatial range of bucket movement during the excavation test in Section 4, a rectangular parallelepiped measuring 5 m × 2.4 m × 0.83 m was used to simulate the infinite volume of the soil, and the dimensions of the flow region above the soil were 5 m × 2.4 m × 2.67 m. The relative positions of the bucket and existing soil were determined according to the initial excavation attitude of the excavator. Tetrahedral and regular hexahedral meshes were used to mesh the bucket and soil models, respectively. Considering both computational efficiency and accuracy, the final total number of computational grids after grid independence verification was 709,450, as shown in Figure 4.

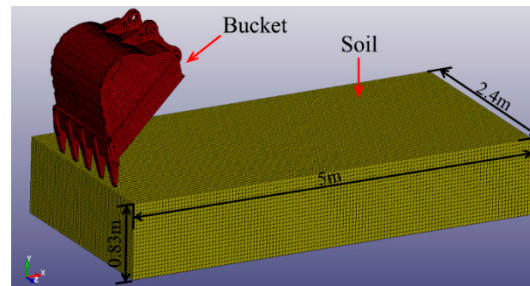


Figure 4. Meshes of the bucket and soil models (the flow region is not shown).

The material parameters of the bucket are shown in Table 1. For the soil model, as the earthwork operations for which excavators are used are mainly focused on clayey soil, the stress state of the soil is approximately plane strain and subject to shear failure. Therefore, the Mohr–Coulomb model that fits the shear failure mechanism of clay, that has easily obtainable parameters, and that is easy to calculate was selected [17,18]. Based on the results of a geotechnical investigation report [19], the specific parameters of the soil model are shown in Table 2. The constant-stress-element algorithm was adopted for the bucket. Additionally, the element algorithm of soil and flow region was set to the one-point integration with a single material, that is, the ALE unit algorithm.

Table 1. Material parameters of the bucket.

Density (kg/m ³)	Elastic Modulus (Pa)	Poisson's Ratio	Limit of Yielding (Pa)
7850	2.06×10^{11}	0.3	6×10^8

Table 2. Material parameters of the soil model.

Density (kg/m ³)	Shear Modulus (Pa)	Poisson's Ratio	Internal Friction Angle (rad)	Cohesion (Pa)
2020	8.7×10^6	0.3	0.323	26,000

The digging segment can be divided into three excavation methods according to the differences in working devices that are involved in this segment: bucket excavation (only the bucket rotates around point G), arm excavation (only the arm rotates around point B), and compound excavation (both the bucket and ram rotate). To uniformly describe the trajectory of the bucket under different excavation conditions, based on the results in Section 2, the combination of translation along the X and Y axes and rotation around the centroid is used to describe the trajectory of the bucket driven by the hydraulic cylinders. Figure 5 shows the displacements of the hydraulic cylinders in the actual tests and the transformed movement curves of the bucket centroid. Notably, since only the bucket for the excavator has been established, the origin of the coordinate system in Figure 2 was translated from point O to point G to facilitate description. The displacement and angular velocity values of the centroid of the bucket in Figure 5b are the result of the translation. The soil model is a zero-degree-of-freedom system, limiting the bottom nodes' degrees of freedom in all directions. The established flow region was defined as a void field, which is used as the mesh transfer of the soil finite element when heavy deformation occurs. The gravity field environment was defined according to the actual situation.

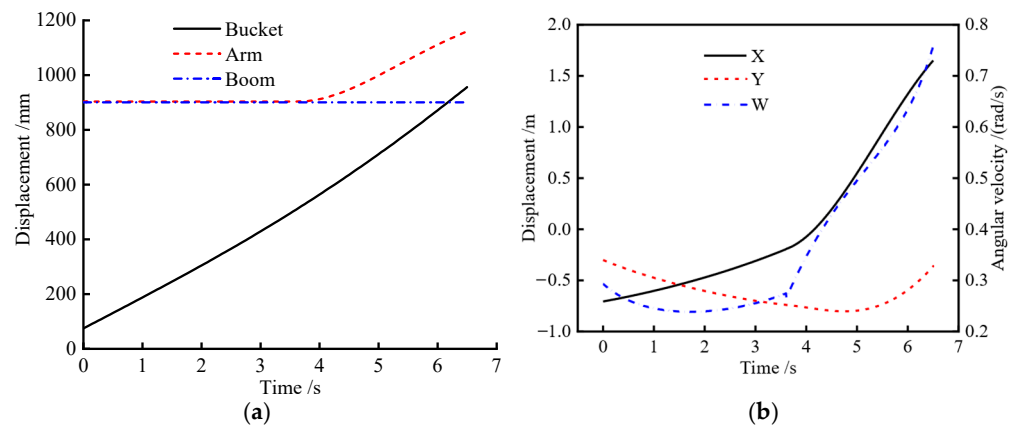


Figure 5. Movement curves of the bucket centroid: (a) displacement of the hydraulic cylinders, and (b) the transformed movement curves of the bucket centroid.

To accurately reflect the variations in contact area and interaction forces between the bucket structure (the inner and outer walls, bucket teeth, etc.) and soil during digging, a symmetric penalty function algorithm was used to simulate the dynamic contact process in the numerical model. The interaction forces between the bucket and soil during the excavation process were output according to the components defined in Figure 1d. The total simulation time was set to 6.5 s.

3.2. Analysis of the Results from the Simulation

Figures 6 and 7 show the simulated excavation process and digging resistance, respectively. From 0 to 0.585 s, the bucket penetrates and squeezes the soil in the positive X-axis direction and negative Y-axis direction, resulting in a rapid increase in digging resistance in these two directions. The bucket excavation angle, which is the angle between the connecting line of bucket hinge points G and J and the horizontal plane, gradually increases to 90° from 0.585 s to 1.95 s. Digging resistance in the Y direction basically remains relatively high—with an average of 23.73 kN—because of the small change in the displacement of the tips of the teeth in the Y-axis direction. With the accumulation of the built-up edge in front of the bucket, the resistance to the pushing of the soil in the X direction continues to increase. The digging resistance in the X direction reaches the maximum value of 71.44 kN at 2.6 s. Afterwards, the built-up edge is slowly loaded into the bucket under the retracting action of the bucket and arm, resulting in a decrease, and the gravitational force of the soil in the bucket becomes the main component of digging resistance in the Y direction. At 4.6 s, the tips of the bucket teeth separate from the upper surface of the soil. The cohesion between the built-up edge of the bucket teeth and the soil becomes the main component of digging resistance, and digging resistance in the negative Y direction increases rapidly. As the bucket continues to rotate, the built-up edge completely separates from the soil, and digging resistance in the Y direction gradually decreases, finally equaling the gravity of the soil in the bucket, that is, 12.27 kN. The digging resistance in the Z direction is basically zero without lateral movement. The variation in the moment is consistent with the digging resistance, which plays a major role in the corresponding moment.

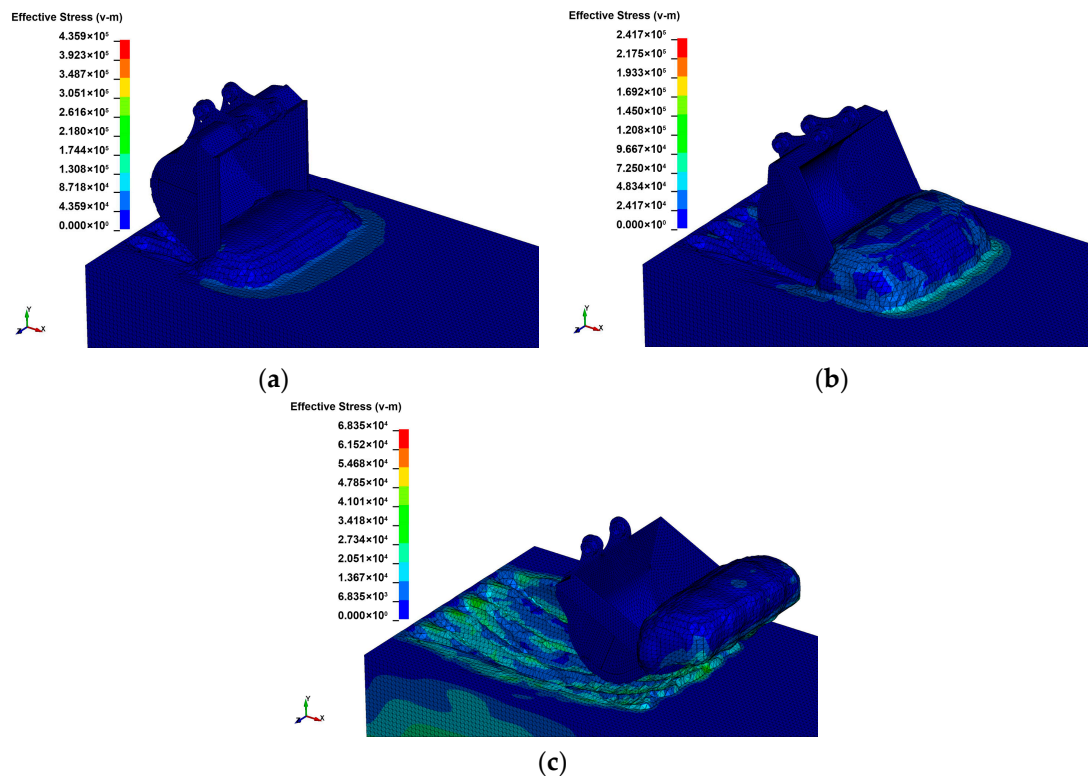


Figure 6. Results of the simulation of the excavation process: (a) $T = 2.6$ s, (b) $T = 4.6$ s, and (c) $T = 5.85$ s.

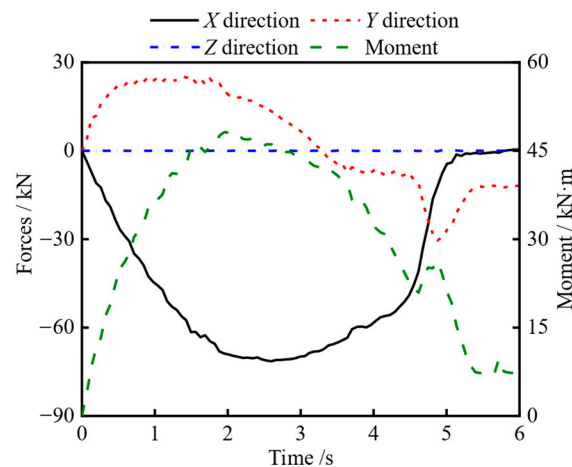


Figure 7. Digging resistance during excavation.

Figure 6 shows that the soil meshes can still maintain regularization and move effectively when the soil undergoes heavy deformation, so simulation analysis can be effectively carried out. We have proven that the ALE method can effectively solve the large deformation problem in the bucket–soil interaction process and simulate the real state of the soil in the digging segment.

4. Experimental Validation of Model Effectiveness

4.1. Details of the Experiment

A series of excavation tests was carried out using the ZE215E-10 medium-sized hydraulic excavator (Zoomlion Earthmoving Machinery Co., Ltd., Changsha, China). It exhibits good operational performance, with a digging distance of 9830 mm, a digging height of 9615 mm, and a digging depth of 6610 mm. The bucket's capacity is 1.1 m^3 . Six

pressure sensors and three displacement sensors are used to collect information on the pressure and displacement of three kinds of hydraulic cylinders, as shown in Figure 8. The signal acquisition frequency was set to 100 Hz. The soil slated for excavation was mainly composed of clayey soil, lime soil, and a small amount of sand and ash. The specific parameters of the soil are shown in Table 2.

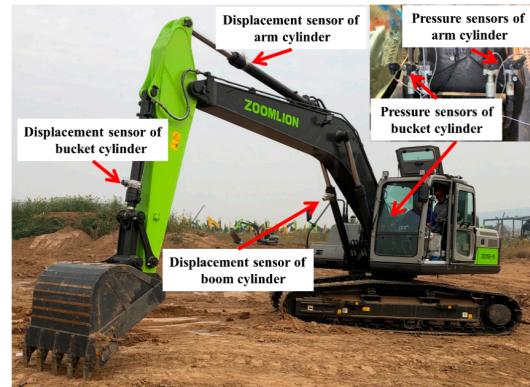


Figure 8. Schematic diagram of sensor installation.

To ensure the excavation tests were repeatable, unified operating rules were formulated based on the operation specifications of the excavator loading on flat ground. Before the test, the excavator was parked on a flat, unexcavated soil surface. The displacements of the boom, arm, and bucket hydraulic cylinders were 900.71 mm, 903.87 mm, and 74.90 mm, respectively, so the boom was horizontal, and the tips of the bucket teeth just made contact with the surface of the soil. In the beginning, the handle that controls the retraction of the bucket was pushed to 50% of the maximum stroke. When the bucket excavation angle increased to 90° , the handle that controls the retractions of the arm was also pushed to 50% of the maximum stroke. Soil excavation ended when the bucket excavation angle reached 0° . The displacement curves of the boom, arm, and bucket hydraulic cylinders during excavation are shown in Figure 5a. It should be noted that this situation is slightly different from the compound digging trajectory defined in Section 2, which is more in line with real-world operations, because the fixed-axis rotation of the bucket in the early stage of excavation helps excavator operators judge the change in the excavation angle more accurately, thus ensuring the test is repeatable. The adjustment of the digging trajectory has no influence on the simulation model's ability to characterize the main cause of digging resistance.

4.2. Results and Validation

The contact area and loads between the bucket and the soil dynamically change during excavation, so digging resistance cannot be directly measured or verified using simple instruments. Therefore, the digging resistance obtained from the simulation model under the same digging trajectory was converted into the output forces of the hydraulic cylinders based on the kinetic models of the hydraulic excavator. The detailed theoretical derivation and the specific procedure for converting these resistance forces via the kinetic model are elaborated in Section 2.2. The digging resistance shown in Figure 7 was applied to the centroid of the bucket, and three hydraulic cylinders of the excavator were driven according to the displacement shown in Figure 5a. Thus, the output forces of the hydraulic cylinders were obtained.

A comparison of the test and simulation results is shown in Figure 9. The bucket penetrates and squeezes the soil at the beginning of excavation, and the increase in digging resistance leads to a rapid uptrend in the output forces of the hydraulic cylinders. The arm

hydraulic cylinder that does not perform any actions is also subjected to a great deal of backpressure due to force transmission. When the excavation angle reaches 90° at 2.6 s, the output forces of the bucket and arm hydraulic cylinders reach their maximum values, which are 233.76 kN and 403.90 kN, respectively. Afterwards, the output forces of the two hydraulic cylinders decrease rapidly. Because of the shortening of the arm of forces, the output forces of the two hydraulic cylinders slowly rise again after 5.2 s. Overall, since the soil in the simulation analysis is assumed to be an ideal isotropic material, the output force curves of the hydraulic cylinder are smoother. The average errors of the output forces of the bucket and arm hydraulic cylinders obtained through the experiments and the conversion of the results of the numerical simulation are 9.72% and 14.56%, respectively, proving that the analysis results regarding digging resistance based on ALE are correct and accurate.

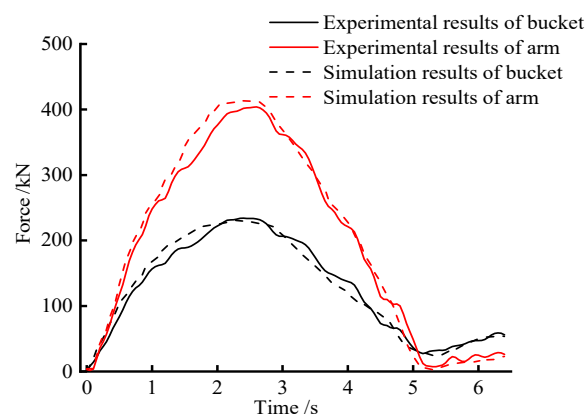


Figure 9. Output forces of the hydraulic cylinders determined via experiments and numerical simulation.

Although the results of model validation are satisfactory, as the ALE method was used to describe the heavy deformation of soil under the action of the bucket, model calculation requires an accurate representation of the soil's constitutive behavior. Therefore, the proposed model exhibits higher accuracy in the validated cohesive soil environments. Its application in other scenarios that require recalibrating medium parameters or modifying the constitutive model is subject to certain limitations.

5. Results of Optimizing the Excavation Process

5.1. Characteristics of Digging Resistance Under Different Excavation Parameters

With bucket excavation as an example, bucket excavation speed (i.e., the angular velocity of the bucket) and the excavation angle (i.e., the angle between the connecting line of bucket hinge points G and J and the horizontal plane) are important factors that determine bucket digging trajectory and, in turn, affect the magnitude of digging resistance. Theoretically, there are countless combinations of these two excavation parameters. Considering the requirements of hydraulic system performance and construction progress, the excavation angle and excavation speed have a principal interval. According to the assumption made in Section 2.1 regarding the excavation process, excavation speed is represented by the amount of time taken to reach a bucket excavation angle of zero, starting from the moment the bucket starts cutting into the soil. The range of excavation speed is [4 s, 10 s]. Additionally, the load factor, which is the volume of soil excavated by the bucket as a proportion of its capacity, is used as the limitation with which to define the bucket excavation angle. The principal interval of the load factor is set to [0.4, 1.1], and the corresponding bucket excavation angle is $[36^\circ, 48^\circ]$.

Figure 10 shows the characteristics of digging resistance under different excavation parameters. As the bucket excavation angle increases from 36° to 48° , digging resistance in the X direction decreases approximately linearly from 81.94 kN to 49.59 kN, a 39.48% reduction, as shown in Figure 10a. This is mainly due to the decrease in load factor and digging depth as per Rankine's earth pressure theory. However, with the increase in excavation time from 4 s to 10 s, the digging resistance in the X direction only decreased by 0.71 kN (on average). This is because the inertial effect of the clayey soil is not obvious even when the excavation time is 4 s [20]. The decrease in digging depth reduces digging resistance in the positive Y-axis direction when the bucket squeezes the soil, and the decrease in load factor reduces digging resistance in the negative Y-axis direction when the centroid of the bucket rises. Therefore, digging resistance in the Y direction slightly fluctuates under the combined effect of two factors noted above as the excavation angle increases. Digging resistance in the Y direction is basically constant with the increase in excavation time. As shown in Figure 10c, the moment is 54.31 kN·m when the excavation angle is 36° . It decreases by 38.85% when the excavation angle increases to 48° due to the decrease in digging resistance in the X direction. Overall, the excavation angle is the main factor that determines the resistance and moment acting on the bucket. Digging resistance in the Y direction is no longer the focus of this study because of the small fluctuation.

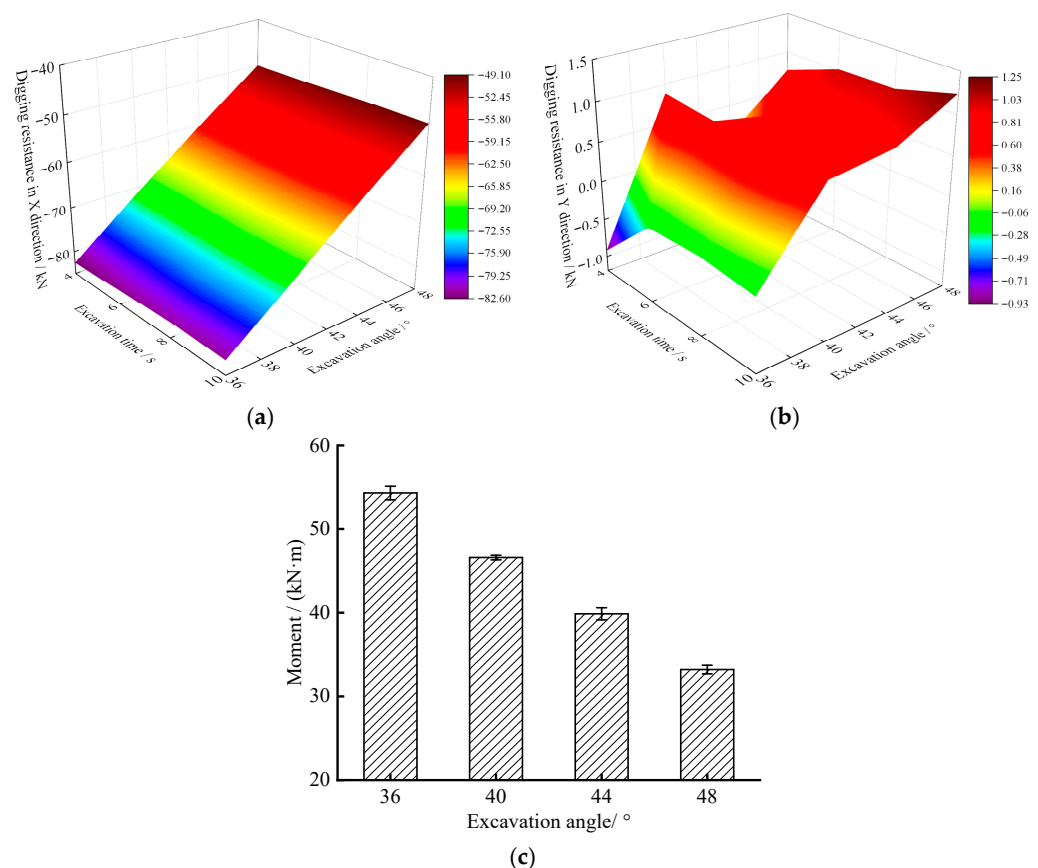


Figure 10. The characteristics of digging resistance under different excavation parameters: (a) digging resistance in the X direction, (b) digging resistance in the Y direction, and (c) moment.

With reference to the concept of rock-breaking mechanics, the energy consumed to excavate per unit volume of soil with a bucket, that is, specific energy consumption (SE), is used as an indicator to characterize excavation efficiency. The greater the SE , the greater

the amount of energy required to excavate the same volume of soil, and the lower the excavation efficiency [21,22]. The SE is calculated as follows:

$$SE = \frac{W}{V} = \frac{\int F_x dl_x + \int F_y dl_y + \int T_r d\varphi}{\eta V_m} \quad (12)$$

where W is the work carried out by the bucket to excavate the soil; V is the volume of excavated soil; F_x , F_y , and T_r are the resistances and moment acting on the bucket; l_x , l_y , and φ are the displacement and rotation angle of the centroid of the bucket; η is the load factor of the bucket; and V_m is the bucket's capacity, which is 1.1 m^3 .

Although the digging resistance in the X direction, the moment acting on the bucket, and the load factor of the bucket significantly decrease with an increase in the excavation angle, the variation in soil volume is more obvious. When the excavation angle increases from 36° to 48° , the SE gradually increases from 0.1671 MJ/m^3 to 0.2123 MJ/m^3 , as shown in Figure 11. Therefore, a high load factor in the digging segment is favorable for meeting excavation efficiency and construction progress requirements. Notably, concerning the final fuel consumption of the excavator power system, one needs to further consider the energy consumed to move all the working devices.

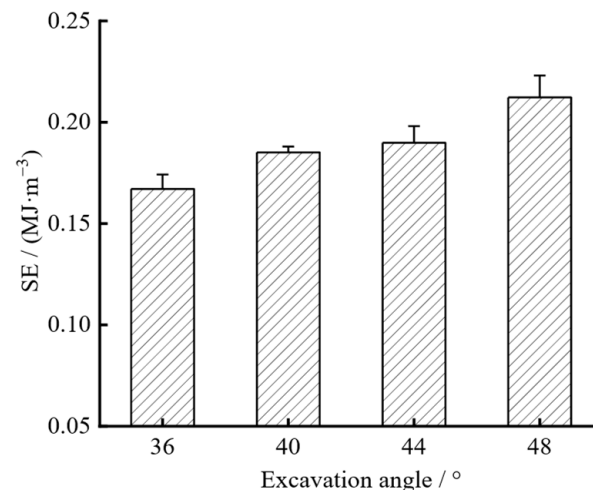


Figure 11. The relationship between specific energy consumption and excavation angle.

5.2. Characteristics of Digging Resistance Under Different Excavation Methods

As mentioned earlier, three excavation methods—bucket excavation, arm excavation, and compound excavation—can be employed to adapt to the complex and changeable excavation conditions. According to the principal interval of the load factor, the arm excavation angle, i.e., the angle between the connecting line of B and J and the horizontal plane, is $[65^\circ, 71^\circ]$. For compound excavation, the digging trajectory can be described through a combination of the displacement of the bucket hydraulic cylinder, the time interval from the start to the moment that the bucket hydraulic cylinder starts to move, and the arm-to-bucket hydraulic cylinder speed ratio, according to the analysis in Section 2.1. Based on statistical analysis of the numerous excavation results, a three-factored, four-leveled orthogonal experiment regarding compound excavation was carried out to study the characteristics of digging resistance under different excavation methods, as shown in Table 3.

Table 3. The results of the three-factored, four-leveled orthogonal experiment regarding compound excavation.

Cases	Factor A (mm)	Factor B (s)	Factor C	Digging Resistance in the X Direction (kN)	Moment (kN·m)	SE (MJ/m ³)
1	1(200)	1(0)	1(4.9)	−92.12	26.39	0.1589
2	1	2(0.5)	2(5.1)	−84.27	26.94	0.1898
3	1	3(1)	3(5.3)	−73.56	27.02	0.1676
4	1	4(1.5)	4(5.5)	−62.46	26.31	0.1654
5	2(250)	1	2	−67.41	25.06	0.1612
6	2	2	1	−66.97	26.27	0.1640
7	2	3	4	−52.53	26.35	0.1680
8	2	4	3	−50.74	25.68	0.1651
9	3(300)	1	3	−49.28	30.54	0.1664
10	3	2	1	−47.30	31.41	0.1574
11	3	3	4	−37.60	31.63	0.1618
12	3	4	2	−38.71	31.77	0.1681
13	4(350)	1	4	−33.71	27.91	0.2546
14	4	2	3	−33.28	29.29	0.2147
15	4	3	2	−33.20	29.85	0.1999
16	4	4	1	−33.83	31.29	0.1932

Note: Factor A denotes the displacement of the bucket hydraulic cylinder; Factor B denotes the time interval of the initial movement of the arm and bucket; and Factor C denotes the arm-to-bucket hydraulic cylinder speed ratio.

Figure 12 shows the results of digging resistance in the X direction under different excavation methods. For arm excavation, digging resistance in the X direction increases from 33.09 kN to 54.70 kN when the load factor increases from 40% to 100%, mainly because the excavation angle decreases with an increase in digging depth as the load factor increases. The soil pressure that needs to be overcome when the bucket pushes the soil increases. However, bucket excavation features greater digging resistance in the X direction relative to that of arm excavation under the same load factor. Taking a load factor of 100% as an example, because of the larger turn radius under arm excavation, the digging trajectory has a smaller digging depth (0.422 m) as well as a greater digging length (3.759 m), which is approximately flat. The bucket digging trajectory is approximately semicircular (0.623 m in depth and 2.432 m in length), and the greater digging depth means a higher level of pushing is required when shoveling the soil. As for compound excavation, the digging resistance in the X direction has a weak correlation with the load factor. Further analysis shows that when the displacement of the bucket hydraulic cylinder is small, the overall absolute value of digging resistance in the X direction is large, such as in Cases 1 and 2, and vice versa, such as in Cases 11–16. Digging resistance in the X direction has a negative correlation with the displacement of the bucket hydraulic cylinder. Take Case 1 and Case 10 as examples: there are similar digging depths and lengths, as shown in Figure 13. The time interval between the adjacent connecting lines of bucket hinge points G and J is 0.2 s. The movement speed of the arm hydraulic cylinder in Case 10 is greater under the greater displacement, the reduced movement time of the bucket hydraulic cylinder, and the same speed ratio. The rapid rotation of the arm shortens the duration of contact between the tips of the bucket teeth and the soil, a phenomenon illustrated by the sparser digging trajectory in Case 10. When the tips of the bucket teeth separate from the upper surface of the soil, Case 10 has a denser trajectory, and the bucket slowly retracts around point G. Due to the rapid movement of the arm in Case 10, the duration of the peak value is greatly shortened, while the duration of the small digging resistance after the tips of the teeth leave the soil is increased, resulting in a significant reduction in the overall amplitude

of the digging resistance in the X direction. Overall, increasing the movement speed of the arm is conducive to reducing the average digging resistance in the X direction.

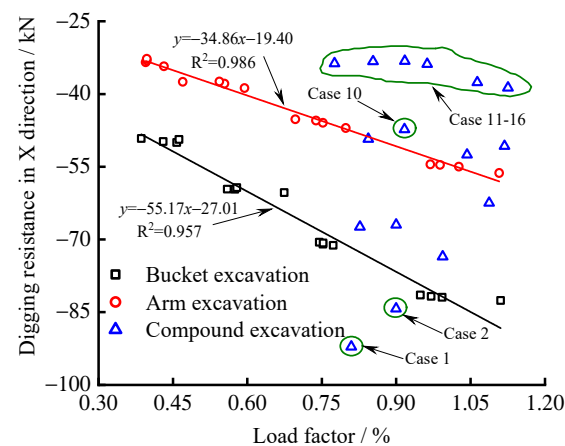


Figure 12. Digging resistance in the X direction under different excavation methods.

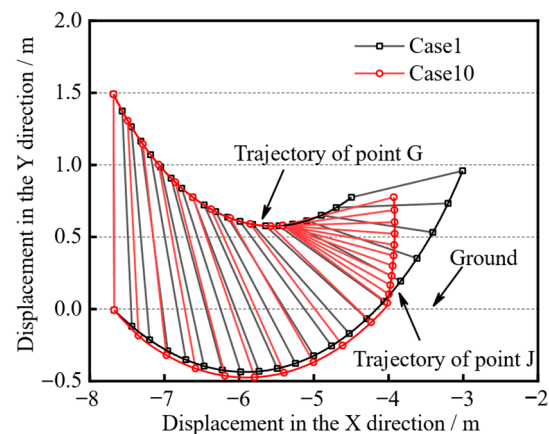


Figure 13. Digging trajectories of Case 1 and Case 10.

Figure 14 shows the variations in the moment when different excavation methods are used. As the load factor increases, the excavation angle decreases, while the digging depth increases. The resistance to horizontal pushing of the soil with the tips of the teeth increases, leading to an increase in the moment. Under arm excavation, the moment increases from 18.37 kN·m to 29.63 kN·m when the load factor increases from 40% to 100%. Bucket excavation leads to a greater digging depth under the same load factor, resulting in a greater moment than that for arm excavation. In terms of compound excavation, the overall magnitude of the moment is like that of arm excavation, mainly because the movement of the arm greatly reduces digging resistance in the X direction. With the increase in the load factor, the moment of compound excavation presents two kinds of variations. For Cases 1–8, the displacement of the bucket hydraulic cylinder is relatively small, resulting in generally slow movement of the arm. During the long contact time between the bucket and the soil, the digging resistance in the negative X-axis direction and the positive Y-axis direction is mutually suppressed when converted into a moment acting on the centroid of the bucket. The moment is basically unchanged in Cases 1–8. For Cases 9–16, the movement speed of the arm is generally high, and the gravity of soil in the bucket when the tips of the teeth separate from the surface of the soil becomes the main component of digging resistance. Therefore, under the same load factor, the moment in Cases 9–16 is greater than that in Cases 1–8. Furthermore, the moment in Cases 9–16 shows an uptrend with an increase in

the load factor. In summary, a reasonable arm movement speed is conducive to further reducing the moment.

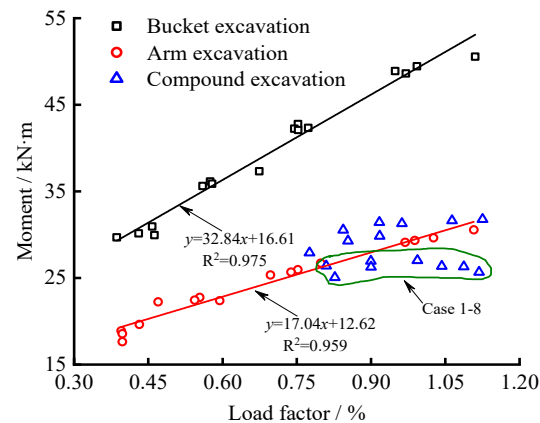


Figure 14. The moment under different excavation methods.

Figure 15 shows the variations in the *SE* under different excavation methods. The *SE* for arm excavation is 0.2616 MJ/m³ at a load factor of 40%, and it reduces by 17.39% when the load factor increases to 100%. This is the result of the combined effect of the simultaneous increase in the digging resistance in the X direction and the amount of excavated soil. Under the same load factor, the arm excavation method leads to a shallower digging depth and a greater digging length than those for bucket excavation, resulting in an obvious horizontal push effect on the soil and a higher *SE*. As for compound excavation, the *SE* shows an overall downtrend as the load factor increases. However, there are two extreme specific energy consumption distributions under similar load factors, such as in Cases 1 and 13. On the one hand, the high movement speed of the arm in Case 13 shortens the duration of digging resistance in the X direction near the peak value, but it does not reduce the *SE* for soil excavation. On the other hand, in Case 13, the displacement of the bucket hydraulic cylinder is larger, while the displacement of the arm hydraulic cylinder is smaller, as shown in Figure 16. Thus, the bucket rotates around point G prematurely, and the excavation volume is smaller than in Case 1. Overall, there is an increase in the *SE* in Case 13. In addition, comparing Case 1 with Case 10 reveals that the load factor has a higher degree of influence on the *SE* of compound excavation. In summary, under the premise of ensuring the bucket load factor is stable, reducing arm speed and a horizontal soil push during compound excavation is beneficial to decreasing the *SE*.

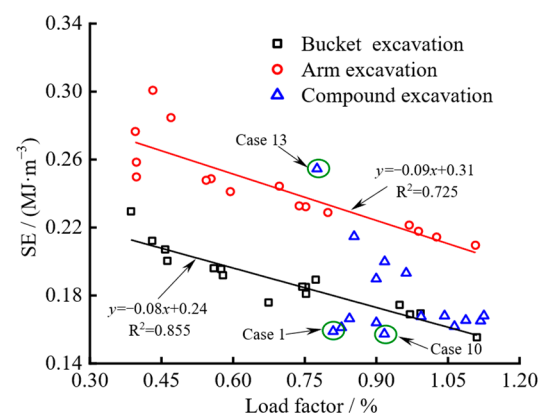


Figure 15. The *SE* under different excavation methods.

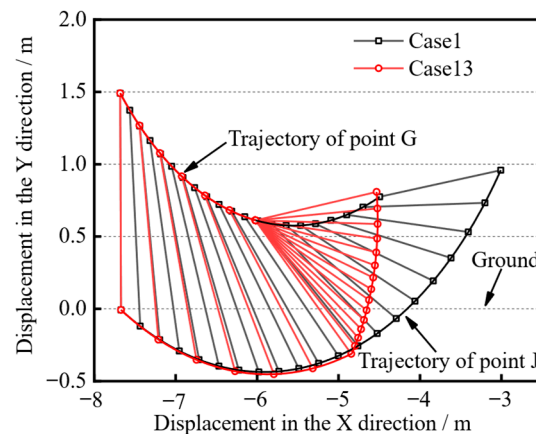


Figure 16. Digging trajectories in Cases 1 and 13.

5.3. Determination of the Optimal Digging Trajectory

Analysis of the results of the orthogonal experiment shows that the selection of optimal excavation parameters and methods under different evaluation indicators is often inconsistent. Moreover, based on the existing limited cases, it is impossible to determine the main factors that influence the change in the evaluation indicators and the potential optimal combination. Therefore, using compound excavation as an example, we conducted range and variance analysis on the orthogonal experiment results to determine the optimal digging trajectory. Due to the small variation range of the moment and digging resistance in the Y direction, the evaluation indicators for the range and variance analysis of the orthogonal experiment focus on specific energy consumption and digging resistance in the X direction.

Tables 4 and 5 present the results of the range and variance analysis of specific energy consumption. The most important factor is the displacement of the bucket hydraulic cylinder, while the least important factor is the time interval for the initial movement of the arm and bucket. Evidently, the displacement of the bucket hydraulic cylinder is a significant influencing factor. From the perspective of *SE*, the optimal combination of excavation parameters is $A_3B_4C_1$ —that is, a 300 mm displacement of the bucket hydraulic cylinder, a 1.5 s interval for the initial movement of the arm and bucket, and an arm-to-bucket hydraulic cylinder speed ratio of 4.9. Similar results were obtained with respect to digging resistance in the X direction: the optimal combination is $A_4B_4C_4$ —that is, a 350 mm displacement of the bucket hydraulic cylinder, a 1.5 s interval for the initial movement of the arm and bucket, and an arm-to-bucket hydraulic cylinder speed ratio of 5.5.

Table 4. The results of the range analysis of the *SE*.

	Factor A (mm)	Factor B (s)	Factor C
$\bar{K}_1$	0.1705	0.1853	0.1684
$\bar{K}_2$	0.1646	0.1815	0.1798
$\bar{K}_3$	0.1634	0.1743	0.1785
$\bar{K}_4$	0.2156	0.1730	0.1875
R_i	0.0522	0.0123	0.0191

The integrated balance method was used to analyze the optimal compound digging trajectory under the two indicators. The most significant factor influencing the two indicators was the displacement of the bucket hydraulic cylinder, but there is a difference in the optimal level. When A_3 is selected, the *SE* is 31.95% lower than that of A_4 (a favorable change), and the digging resistance in the X direction increases by 22.47% (an adverse

change). However, when A_4 is selected, the SE increases by 24.21% (an adverse change) relative to A_3 , and the digging resistance in the X direction reduces by 28.98% (a favorable change). Considering these favorable and adverse changes, A_3 should be selected. Since the other factors have no significant influence on SE , the selection is based on the optimal level of digging resistance in the X direction. Therefore, the optimal digging trajectory of compound excavation is $A_3B_4C_4$: a 300 mm displacement of the bucket hydraulic cylinder, a 1.5 s interval for the initial movement of the arm and bucket, and an arm-to-bucket hydraulic cylinder speed ratio of 5.5.

Table 5. The results of the variance analysis of the SE .

Source of Variation	SS (10^{-3})	df	MS (10^{-3})	F	$F_{0.05} (3,6)$
Factor A	7.45	3	2.48	8.42	4.76
Factor B	0.41	3	0.14	0.47	
Factor C	0.74	3	0.25	0.83	
Error	1.78	6	0.30		
Variation	2.59	15			

6. Conclusions

In this study, a numerical simulation model of bucket–soil interaction based on ALE was established and verified through excavation tests. The influence of excavation parameters and methods on digging resistance was also studied. The optimal compound digging trajectory was determined through an orthogonal experiment. The results can serve as the basis for designing the structure and power system of an intelligent excavator and controlling its trajectory. The specific results are as follows:

1. As the excavation angle increases from 36° to 48° , digging resistance in the X direction and the moment decrease by 39.48% and 38.85%, respectively, but the specific energy consumption increases by 27.05%. The influence of excavation speed on digging resistance can be ignored.
2. Under the same load factor, arm excavation results in a shallower digging depth and a greater digging length, resulting in a greater SE . For compound excavation, the rapid rotation of the arm can effectively shorten the duration of the peak value of digging resistance. Under the premise of ensuring the bucket load factor is suitable, reducing the movement speed of the arm is beneficial in decreasing the specific energy consumption.
3. The optimal combination of digging resistance and SE for compound excavation consists of a 300 mm displacement of the bucket hydraulic cylinder, a 1.5 s interval for the initial movement of the arm and bucket, and an arm-to-bucket hydraulic cylinder speed ratio of 5.5.

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Abbreviations

The following abbreviations are used in this manuscript:

ALE	Arbitrary Lagrangian–Euler
SE	Specific energy
DEM	Discrete element method
FEM	Finite element method

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