

Comparative analysis study of resistance characteristics of backhoe hydraulic excavators

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Received: 28 March 2023 / Accepted: 23 October 2024

Abstract. Resistance characteristics research lays a foundation for establishing and improving excavator performance evaluation. Therefore, a thorough understanding of the general laws governing excavation resistance is particularly significant. Based on experimental data from 8 sets of excavation conditions involving two types of a 20 t backhoe hydraulic excavator, this paper first conducted a comparative analysis of the distribution trends and concentration of resistance coefficients, resistance moment coefficients, resistance angles, differential angles, and component rotation angular velocities. Subsequently, employing the response surface optimization theory, the main value intervals of relevant data under different conditions were obtained, and the impact of excavation scenarios and type variations on the distribution of these intervals was explored. Finally, the principal value intervals under different conditions were applied to calculate and verify the theoretical digging force. The results indicate differences in the general laws of resistance characteristics under different conditions, with the machine type having a more significant influence on the main value intervals than the excavation condition. Variations in the main value intervals lead to changes in the performance evaluation metrics of the excavator. Under different conditions, the front-end working unit of the excavator maintains a stable operational speed.

Keywords: Excavators / numerical simulation / optimization / statistics

1 Introduction

Hydraulic excavator refers to a vital engineering machinery and equipment that exhibits excellent manoeuvrability and operability, excavation force and other properties. It has been extensively employed in several aspects (e.g., industrial and agricultural construction and mining). The excavation resistance encountered by hydraulic excavators during operation significantly affects both the operational stability and efficiency of the equipment. Specifically, accurately understanding and systematically summarizing the distribution patterns of excavation resistance is a critical factor in advancing the development and manufacturing of excavator equipment. Accordingly, the regular characteristics of the excavation resistance should be explored in the practical working process.

Extensive research has been conducted on excavation resistance, and numerous results have been achieved in practical tests, numerical simulations, as well as simulation analysis. Wang's team [1,2] developed a data-driven

algorithm to create a soft sensing model for excavation resistance, which effectively characterizes the resistance by using hydraulic cylinder pressure and dynamic parameters as model inputs while utilizing nearby bucket strains as outputs. The experimental results demonstrate that this method can effectively capture the operational resistance. However, it is essential to note that while the strain near the bucket reflects the resistance trend, it does not accurately represent the actual value of the working resistance. Additionally, Li and his collaborators [3] combined a mechanism model that integrates the kinematics and dynamics of the excavator's working device with a machine learning algorithm to establish a soft sensing model for the excavator's working resistance based on the Physics-Informed Machine Learning (PIML) method. This model provides accurate estimates of the working resistance encountered by the excavator during the excavation process.

The existing sensors face difficulty directly testing the excavation resistance. Yu et al. [4] developed a pin sensor to examine the pin force at the bucket rod-bucket hinge. They determined the bucket force in accordance with the examined force data and bucket working attitude. Chen

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et al. [5] built a bucket-soil model in LS-PREPOST software with the experimental bucket trajectory as the simulation running trajectory and compared the simulation with the excavation resistance load spectrum. Mathematical analysis is capable of indicating tool-soil interaction. In previous research [6,7], inertial forces caused by the increased soil portion in the bucket from static to incorporated into the bucket following bucket motion were introduced to the soil wedge force model, so as to deepen the tool-soil interaction force analysis model. Lipsett et al. [8] reviewed the formulation of tool-soil interaction forces and modified the excavator dynamics model to estimate soil parameters through soil damage forces using Newton's iterative method. Lee et al. [9] modified the fundamental soil equation under the force balance condition to address the discontinuity of loader bucket forces when digging a huge, sloped soil pile. Ni et al. [10] developed a PC-based multidisplay virtual reality system to teach operators and assess excavator management tactics using revised basic earth equations to predict excavation forces. Tsuchiya et al. [11] examined the spatiotemporal deformation of excavated soil using vision techniques to predict bucket forces. Based on the experimental measurements of soil deformation, the bucket-soil interaction model was updated in real-time by introducing correction variables that varied with the cutting angle. Jovanović et al. [12–14] initially defined the simulated components of excavation resistance through an analytical mathematical model. Subsequently, they developed a comprehensive mathematical model for a hydraulic excavator to delineate the boundaries of possible excavation resistances and to assess the equivalent loads acting on the bearings of the slewing platform drive mechanism throughout the excavator's entire operational range. Furthermore, the study thoroughly examines the influence of both position and excavation resistance on the bearing loads of the slewing platform drive mechanism of the excavator.

Furthermore, computer simulation techniques have been progressively employed in soil force analysis. In previous research [15,16], the tool-soil interaction forces were simulated by combining the Lagrangian-Eulerian method with the finite unit method, and the simulation results are well consistent with the practical test results (e.g., the soil plastic deformation and tool forces). Obermayr [17] built a finite element model of a cohesionless material to determine the internal friction angle of the material through triaxial compression experiments and analyze the change of resistance during excavation operations in depth for different cut depths and excavation widths. MaK [18] built a cohesion model using a PFC analysis program to account for the interaction between the soil mound and the bucket and to calibrate the stiffness parameters of the mound model. Bi et al. [19] simulated and calculated the excavation resistance through a joint simulation of the excavation process based on the dynamics software ADAMS and the discrete element software EDEM. Skonieczny [20] investigated the effect of soil wedge build-up on tool forces during excavation using the DEM and then modified the McKyes tool-soil interaction force analysis model. Tekeste et al. [21] simulated the

Norfolk sandy loam soil using the discrete element simulation software EDEM and developed the proportional relationship between soil reaction forces and the length scale of the bulldozer blade. Huo et al. [22] proposed an intelligent prediction method for excavation load leveraging a radial basis function (RBF) neural network, specifically tailored to the characteristics of excavation loads encountered in typical excavation tasks. This work establishes a foundation for predicting excavation loads in intelligent excavators. Similarly, Chen et al. [23] calibrated an interaction model for soil and bucket by integrating the discrete element method (DEM) with multi-body dynamics (MBD). He further introduced a Hardware-in-the-Loop (HIL) test rig to simulate real load conditions, resulting in a prediction accuracy with an error margin of no more than 12% when compared to actual excavation tests. Jiang et al. [24] analyzed the factors influencing the resistance of excavating lunar soil under harsh lunar environmental conditions using the DEM. As indicated by the results, the cutting resistance and energy consumption are linearly correlated with the gravity value, and the cutting resistance, energy consumption, and bending moment characteristics are significantly affected by van der Waals forces in low gravity fields. Furthermore, the values are increased significantly with the increase of the soil strength.

Normal excavation resistance and tangential excavation resistance take on a critical significance to the research on practical operations, and the research [25] assumed that the ratio of the two is a constant with respect to the flat wedge edge model. Ren [26] devised two numerical indicators (i.e., the resistance coefficient and the resistance moment coefficient) to quantify the complicated force system present during excavation. However, more detailed and generalized characteristics of resistance remain to be explored. Building upon a substantial volume of experimental data, this study investigates the distributional characteristics of the excavation resistance law, the impact of excavation conditions and machine types on this distribution, and the efficacy of its application. Based on statistics, the relationship between resistance force value, resistance direction, and resistance itself was considered comprehensively. Moreover, response surface optimization was used to construct the main value interval of resistance-associated coefficients and analyze the interval variation under different conditions. The interval was then applied to the theoretical digging force model to verify the influence of resistance characteristics on the evaluation of excavator performance.

2 Force characteristics of digging resistance

Excavation resistance indicates the excavation performance of excavators, and the study of its change law has been confirmed as one of the basic bases for excavator design optimization calculation. Numerous uncertain factors (e.g., the difference of operator's operating habits and the adaptation of different machines to different operating environments) cause the excavation resistance to show the same outstanding random characteristics.

The test machines were two different types of 20 t backhoe hydraulic excavators, and a total of eight sets of tests were performed on the soil field for surface excavation (e.g., loose soil surface, normal soil surface, and hard soil surface), 1 M digging, as well as 2 M digging. The tests were expressed as the completion of several excavations with selected composite excavation method (i.e., nonactive operation of the boom hydraulic cylinders and active operation of the arm and bucket hydraulic cylinders). The correlation between the components of excavation resistance was studied by analyzing and processing the cylinder and hydraulic data obtained from the tests. The test excavation conditions were described in detail as follows:

- The surface excavation test necessitates several consecutive work cycles. The specific digging mode is characterized by initiating excavation at a designated point on the earth's surface. During this process, both the arm and bucket engage in active work, with the lengths of their hydraulic cylinders gradually extending, while the hydraulic cylinder of the boom shortens in a passive working state. This working mode is maintained until further digging becomes impractical. At this point, the boom hydraulic cylinder is extended, and the cutting angle is adjusted to actively contribute to the excavation process, thus completing a work cycle. The test pilot then adjusts the cutting depth, relying on empirical measurement, to complete multiple work cycles while measuring cylinder pressure and displacement data.
- 1 M digging test follows the same specific excavation method as surface excavation, but with a cutting depth of approximately 1 meter. During this test, the experienced operator adjusts the cutting depth to complete several consecutive work cycles, concurrently measuring cylinder pressure and displacement data.
- 2 M digging test employs the same specific excavation method as surface excavation, but with a cutting depth of approximately 2 meters. In this case, the experienced operator adjusts the cutting depth to complete multiple consecutive work cycles while also measuring cylinder pressure and displacement data.

2.1 Statistical analysis of force characteristics

The tangential resistance corresponding to the tangential force was selected as the reference object for analysis since the tangential force refers to a vital component and key performance index of theoretical digging force. The change characteristics of the normal resistance F_n and the resistance moment T_r were explored with the tangential resistance F_t as a reference.

Set $\varepsilon = F_n/F_t$, $\delta = T_r/F_t$ where ε denotes the resistance coefficient and δ represents the resistance moment coefficient. This method facilitates a comprehensive understanding of the relationship between the components of excavation resistance during the excavation process, thereby elucidating the change rule of excavation resistance.

Figure 1 illustrates the change of the resistance coefficient with time during multiple excavations. The black dotted line in the figure represents the resistance coefficient values of multiple excavations at the corresponding point in time. As depicted in the figure, most of the values of the resistance coefficients of the different types of excavation of the 2 machines were located from -0.5 to 0.5 , with a few data peaks at the first end of the single excavation process. The thick solid line represents the average value of all resistance coefficients at the respective point in time. The average value of all diverse types of excavation resistance coefficients was located above the zero-value line and fluctuated around a straight line with a positive slope due to the peak value. Likewise, as depicted in Figure 2, most of the values of the excavation resistance moment coefficients were located from -0.5 to 0.5 , with a larger peak at the first end of the excavation data. The average value of the surface digging resistance moment coefficient fluctuated at the zero-value line and tended to be elevated in the opposite direction, whereas the average values of the 1 M and 2 M digging resistance moment coefficients were below the zero-value line and increased in the opposite direction compared with the surface digging.

The calculation of the resistance coefficient comprises the tangential resistance, normal resistance, which was initially described by scholars with a fixed ratio. However, the excavation resistance can serve as a complex and dynamic indicator, and the resistance coefficient should also be a dynamic and changing value. To reveal the real excavation resistance in the excavation process, the existence of the resistance moment should not be ignored, and the ratio of the resistance moment to the tangential resistance should vary with time. Tangential resistance is recognized as the main component of excavation resistance. Under the effect of tangential resistance, the value of the resistance coefficient and that of the resistance moment coefficient fluctuated in a small ratio range.

Besides, the bucket contacted the excavation object to exert the instantaneous impact, while the active action of arm and bucket hydraulic cylinder was weakened with the completion of bucket turning and loading action, and the active action of boom hydraulic cylinder was adopted to lift the material. At this stage, the tangential force was small. Thus, the coefficient value reached a relatively large peak at the beginning and end of the excavation process. The study of resistance coefficient and resistance moment coefficient aims to gain insights into the law of resistance change, and the trend of change presented by a considerable number of statistics confirms that the law of both is indeed traceable. To be specific, this pattern will be clearer if more comprehensive data analysis is conducted. Moreover, the fluctuation of data may be caused by various inconsistencies in the practical measurement process. For instance, hard soil surface whose soil is not necessarily all hard soil exhibits inconsistent soil properties, the true excavation depth of 1 M digging is less than 1 M digging test range inconsistencies, and so forth.

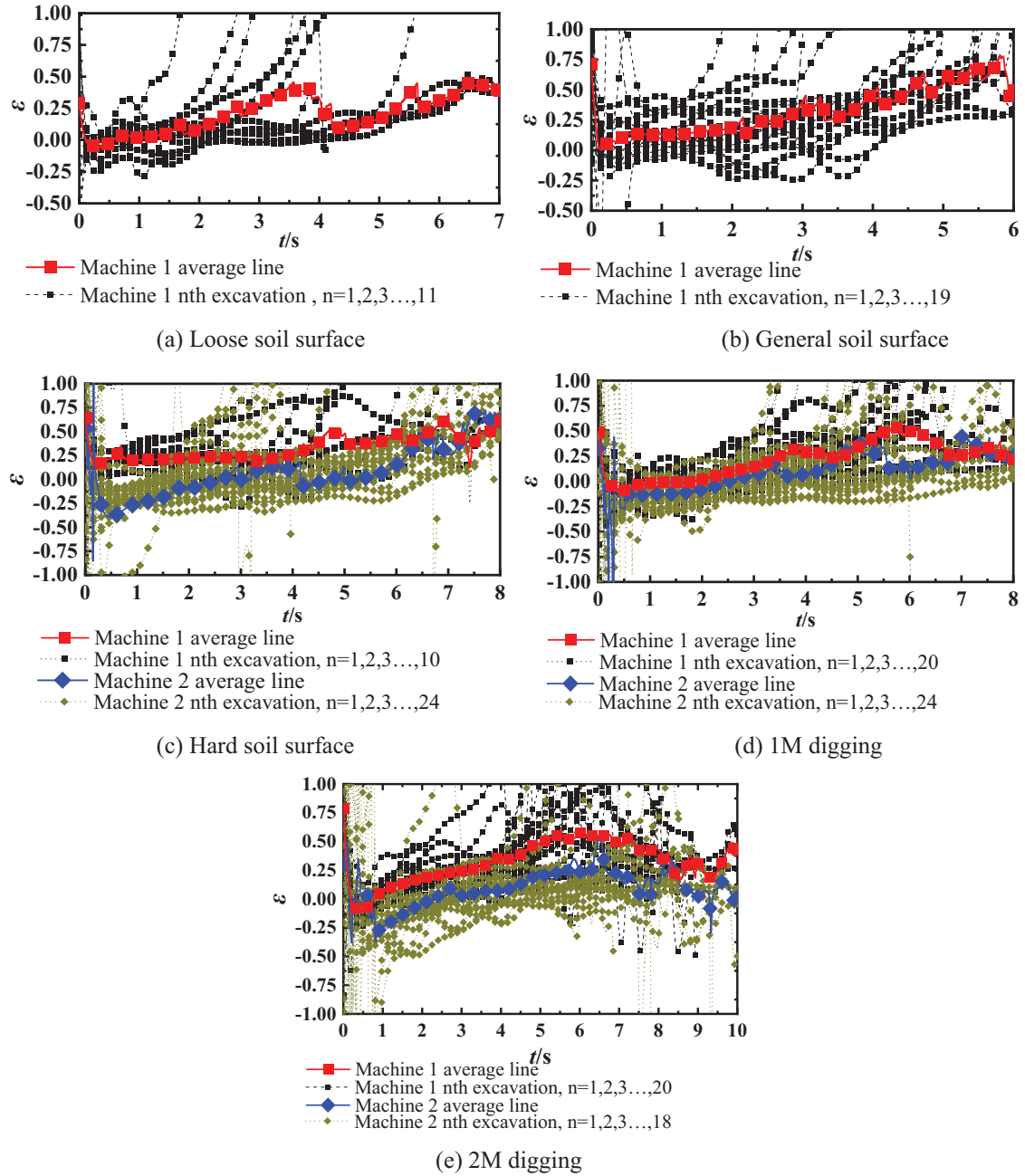


Fig. 1. Resistance coefficient curve ε with time.

The numerical statistics of resistance coefficient and resistance moment coefficient involve surface digging, 1 M digging, and 2 M digging, which belong to the main working areas of excavators and will appear in the practical digging operation. One of the machine type surface excavation tests selected three different soil properties of the experimental excavation object to a greater extent to restore the excavator usually face the operating environment. Besides, the 1 M and 2 M digging belong to a relatively wide operating area, where the soil is complex and variable, and may be soft or hard or even contain sand and gravel. A statistical method was adopted to calculate the probability of the distribution of the resistance coefficient and the resistance moment coefficient

in the corresponding intervals to obtain more detailed distribution characteristics of the resistance-associated coefficients.

2.2 Response surface optimization

The coefficients of the resistance force values followed a similar normal distribution, and a change in the length of the interval resulted in a significant increase in the probability of the interval distribution as it was expanded from the base of the zero point in certain steps toward the ends of the interval, whereas this effect tended to diminish. The above-described results suggested that a main interval

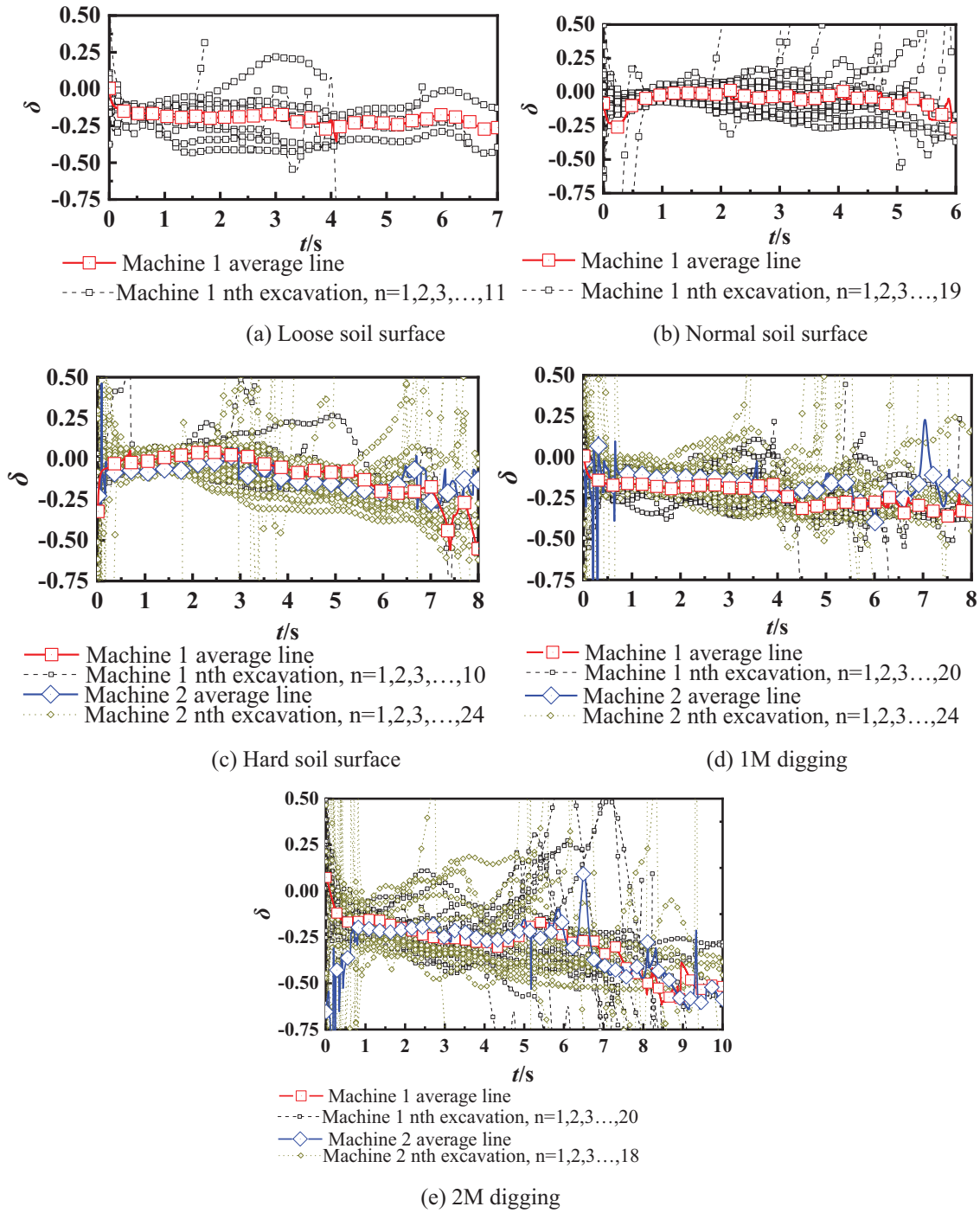


Fig. 2. Resistance moment coefficient δ curve with time.

can be found to cover most of the values. Accordingly, the determination of the main value interval satisfied two conditions, i.e., the interval length is as small as possible, and the concentration of the interval is as high as possible. However, the interval length and interval concentration are a pair of contradictory indicators. Therefore, the interval length was determined by subtracting the lower limit from the higher limit of the main value interval, and the distribution probability was the goal of optimization.

The left and right ends of the interval were the design variables, and their range was equation (1). The core composite experiment and orthogonal test sample too few design variables, reducing fitting accuracy and affecting optimization. Hence, 20 sets of experimental data were generated using the space filling Latin hypercube technique, and their interval lengths and distribution probabilities were calculated. After the DOE model was created, the data were fitted to the experimental data using kriging interpolation, and the fitted model was then optimized

Table 1. Force coefficient interval distribution.

Machine type	Test type	ε Main value interval	Distribution probability	δ Main value interval	Distribution probability
Machine 1	Loose soil surface	(−0.20, 0.54)	81.3%	(−0.35, 0.19)	79.8%
	Normal soil surface	(−0.17, 0.73)	79.6%	(−0.26, 0.12)	79.4%
	Hard soil surface	(−0.14, 0.68)	80.2%	(−0.25, 0.1)	80.5%
	1M digging	(−0.14, 0.69)	80.0%	(−0.37, −0.06)	85.5%
	2M digging	(−0.07, 0.62)	82.3%	(−0.49, 0.07)	80.3%
Machine 2	Hard soil surface	(−0.36, 0.50)	79.7%	(−0.34, 0.12)	80.8%
	1M digging	(−0.29, 0.37)	80.4%	(−0.36, 0.06)	80.6%
	2M digging	(−0.20, 0.32)	83.8%	(−0.60, 0.01)	80.4%

using a genetic algorithm to get the desired results.

$$\begin{cases} -1 \leq X_1 < 0 \\ 0 < X_2 \leq 1 \end{cases} \quad (1)$$

2.3 Analysis of optimization results of force characteristics

Table 1 present the force value coefficient main value interval optimization results. In terms of ε , the probability of interval distribution reached over 80% for the same machine, whereas there were differences in the range of the main value intervals for different excavation test types. Without taking into account excavation of the loose soil surface, machine 1 demonstrated a general trend of decreasing interval range for all types of main value intervals. The change was fully indicated in the data results of machine 2. On the other hand, for the same test type, the range of the main values of the coefficients of machine 2 was smaller than that of machine 1. Compared with ε , the range of the main values of δ was wider than that of the corresponding machine of ε . There was no obvious law in the range of the main value of δ , whereas the left end point of each main value range was increased significantly in the negative direction with the change of the test type, and the right end point tended to reach zero.

Different test types were subjected to different excavation resistance, such that the main value interval should be different for different test types, whereas the coefficient interval distribution changes generally. In addition, the resistance coefficient and the resistance moment coefficient refer to the ratio of normal resistance and moment to tangential resistance as a reference, such that the main value interval of the two in different excavation resistance range should be considered.

The average excavation resistance to be overcome for this experimental test machine weighing 20 t was 80 KN. As depicted in Figure 3, the comparison of the excavation resistance on the trajectory suggested that the digging points where the excavation resistance was greater than the average excavation resistance were almost all located in the middle section of the digging trajectory, and very few points were located at the initial or end of the digging stage.

Thus, the coefficient distribution on each section of the excavation trajectory was determined with the average excavation resistance as the boundary to ensure the statistical data that fully indicate the resistance characteristics of the excavation process.

Tables 2 and 3 list the distribution of coefficients under different excavation resistance ranges. As depicted in the table, the change in excavation resistance resulted in a change in the concentration of the main value interval. When $F > \bar{F}$, the probability of the resistance coefficient in the main value range was elevated by 1.3–20.6%, and that of the resistance moment coefficient in the main value range was risen by 1.1–16.4%. When $F < \bar{F}$, the probability of the resistance coefficient and the resistance moment coefficient in the main value range declined by at least 14.9% and at most 48.0%.

The results suggested that there were relatively optimal main value intervals for ε and δ , whereas different ranges of excavation resistance determined different digging speeds and digging methods, corresponding to different resistance coefficients and resistance moment coefficients. Moreover, the main value intervals for ε and δ varied at different stages. Besides, the higher excavation resistance was primarily indicated at the stage of stable execution of digging, and both the resistance coefficient and the resistance moment coefficient achieved more concentrated values at higher excavation resistance. As mentioned above, the same main value interval is difficult to maintain for the same model in different digging scenarios, and whether there are differences in the distribution of each resistance force coefficient for different machines should be explored.

Table 4 presents the distribution of resistance force coefficients of 36.5 t excavator and 20 t excavator under 2M digging. As depicted in the table, differences were identified in the distribution of resistance-associated coefficients of the same tonnage machine (as explained above), and different tonnage machine. Compared with the 20 t machine, the machine 3 exhibited a wider distribution of both resistance coefficients and resistance moment coefficients, and its main values fell into a wider range. Moreover, the midpoints of the main values of ε and δ reached 0.05 and −0.05 for machine 3, 0.275 and −0.21 for machine 1, 0.06 and 0.295 for machine 2, suggesting that the main value range of ε of machine 3 shifted to the left

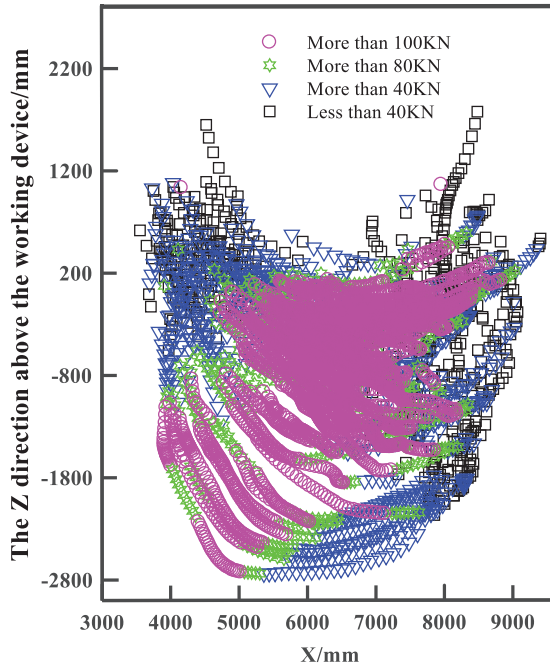


Fig. 3. Distribution of excavation resistance on the trajectory.

compared with that of 20 t machine, and the main value range of machine 3 shifted to the right compared with that of δ .

The distribution of resistance-associated coefficients still varied with the tonnage machine, considering that besides the different working resistance faced by their tonnage differences, and the inconsistency of experimental test scenarios may be one of the factors as well. On the other hand, numerous test scenarios were considered in this study, whereas the test pattern may be too fixed compared with the free operation test, and the experimental content can be optimized subsequently. Furthermore, whether there is a universally applicable main value interval should be explored in depth.

2.4 Comparative verification of force characteristics

The limit digging force model used the normal force and moment as a function of the tangential force according to the main value interval of the resistance coefficient and the resistance moment coefficient to calculate the limit digging force for a given digging attitude under the whole machine constraints.

In this work, we present a comprehensive set of main value intervals of force coefficients for the 20 t machine under a wide range of operating situations. The main value interval of the force coefficient was previously established artificially by researcher for a study involving a 36.5 t excavator (given in Tab. 4). As illustrated in Figure 4, the bucket limit digging force applied to the 36.5 t excavator, derived from the main value interval of a 20 t excavator, was notably higher than its application-specific interval, exceeding the resistance in all cases. Conversely, the arm limit digging force applied across different intervals showed resolved approximately consistent force values, but the

force was unable to overcome the resistance. Besides, the bucket limit digging force dropped up to 15.57 kN and at least 1.81 kN with an average dropped of 8.77 kN when applied to a specific interval, and the arm limit digging force dropped up to 10.36 kN and at least 0.84 kN with an average dropped of 1.81 kN.

As revealed by the results of the above analysis, the coefficients of resistance in different working conditions took different values, different machines of the same tonnage had different values of coefficients in the same working conditions, and the coefficients of different tonnage excavators conformed to significantly different laws, the specific interval changed the limit digging force significantly.

3 Excavation resistance direction characteristics

3.1 Directional angle analysis

The test pilot was asked to focus on the role of the excavator bucket hydraulic cylinder and arm hydraulic cylinder, while the boom hydraulic cylinder was primarily adopted to adjust the digging posture (in case of non-digging) or to lift the material. Figure 5 presents a graph of the change in angle and resistance in the respective direction over time during a particular excavation. In contrast, the arm and bucket inverse angle fluctuated with the change of resistance angle, especially the bucket inverse angle trend change became more significant. The above-described law is a common phenomenon indicated in the process of multiple excavation, besides observing multiple plots found that when the value of the excavation resistance force is at a higher level of resistance angle changes gently, and vice versa, the resistance angle changes steeply. In brief, 1) bucket inverse angle and resistance angle correlation were high. 2) Resistance to a certain extent can indicate the trend of the resistance angle. The same reason to the average excavation resistance as the boundary was followed to explore different excavation resistance under the resistance direction law characteristics.

3.2 Analysis of optimization results of directional characteristics

Given the correlation between the resistance angle θ and bucket inverse angle β_1 , the relationship between the θ and β_1 was further studied, difference angle was set as $\Delta\theta = \theta - \beta_1$, and the distribution of the $\Delta\theta$ during multiple digging was counted to obtain its optimal main value interval. Table 5 and Table 6 present the main value interval optimization results of the θ and $\Delta\theta$, it can be seen that the different types of digging tests and differences in the machine type have some influence on the range of the main value interval. The concentration and distribution trend of the main value interval varied due to a change in excavation resistance. When $F > \bar{F}$ the probability of θ falling into the main value interval was maintained at about 90%, when $F < \bar{F}$, the probability of θ falling into the main value interval declined significantly.

Table 2. When $F < \bar{F}$, force coefficient interval distribution.

Machine type	Test type	ε Distribution probability	Probability increase	δ Distribution probability	Probability increase
Machine 1	Loose soil surface	92.8%	11.5%	84.8%	5.0%
	Normal soil surface	92.7%	13.1%	92.1%	12.7%
	Hard soil surface	91.1%	10.9%	88.5%	8.0%
	1M digging	91.9%	11.9%	95.0%	9.5%
	2M digging	83.4%	1.1%	91.5%	11.2%
Machine 2	Hard soil surface	96.1%	16.4%	94.1%	13.3%
	1M digging	93.7%	13.3%	90.5%	9.9%
	2M digging	86.8%	3.0%	92.5%	12.1%

Table 3. When $F > \bar{F}$, force coefficient interval distribution.

Machine type	Test type	ε Distribution probability	Probability decline	δ Distribution probability	Probability decline
Machine 1	Loose soil surface	47.1%	-34.2%	64.9%	-14.9%
	Normal soil surface	36.3%	-43.3%	37.4%	-42.0%
	Hard soil surface	41.5%	-38.7%	52.5%	-28.0%
	1M digging	39.6%	-40.4%	54.0%	-31.5%
	2M digging	56.7%	-25.6%	55.6%	-24.7%
Machine 2	Hard soil surface	31.7%	-48.0%	41.9%	-38.9%
	1M digging	33.1%	-47.3%	45.4%	-35.2%
	2M digging	36.0%	-47.8%	49.6%	-30.8%

On the other hand, the difference angle had a wider range of values than the resistance angle. The main value interval of $\Delta\theta$ varied for different test types under the same machine, as well as for different machines. Moreover, the main value range of the difference angle of 2M digging significantly shifted to the right compared with other test types. When $F > \bar{F}$, the concentration of the main value interval was increased, all about 90%, and the highest even reached 98%. When $F < \bar{F}$, the distribution probability declined significantly. The above results suggested that the change in excavation resistance significantly changed the trend and concentration of the distribution of resistance angle and difference angle. Furthermore, the overall excavation resistance faced by the 2M digging exceeded the other test types, such that the θ and $\Delta\theta$ were less affected by the change in excavation resistance for the 2M digging of both machines. The above phenomenon again verified the finding that the greater the excavation resistance, the more stable the change in the direction of resistance.

Table 7 presents the comparison table of θ (resistance angle) and $\Delta\theta$ (difference angle) between the two types of machine of 20 t and the machine of 36.5 t at 2M digging. As depicted in the table, significant differences were identified in the distribution of θ and $\Delta\theta$ between different tonnage machines, especially the distribution position of the main value interval was different, and the distribution position

of the correlation coefficient of machine 3 resistance direction was significantly to the left.

3.3 Comparative verification of directional characteristics

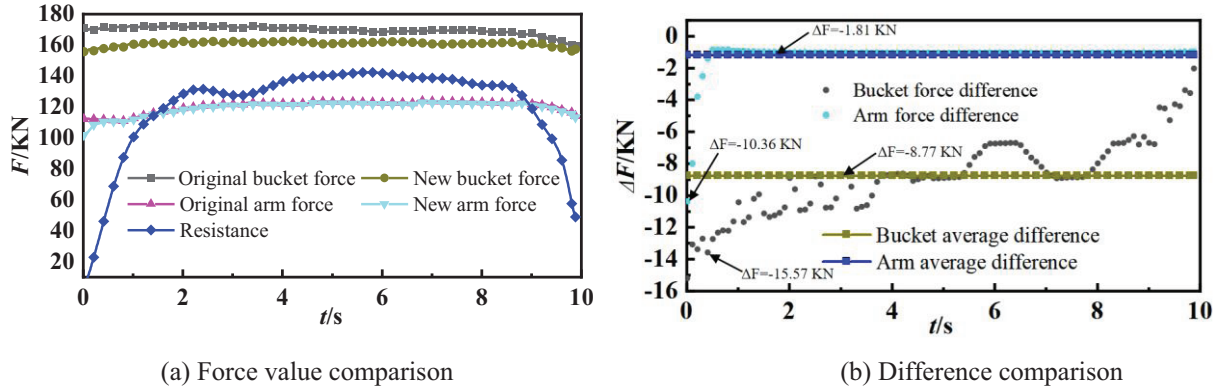
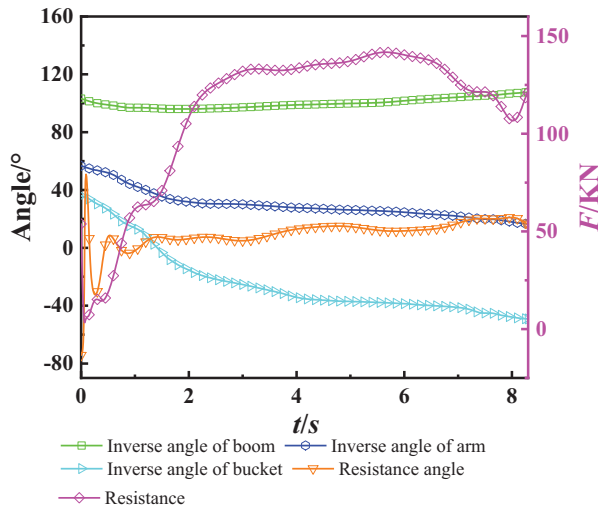
The arm hydraulic cylinder and bucket hydraulic cylinder were used as the active hydraulic cylinders in the composite digging force model. The directional angle range was defined using the main value interval of the resistance angle and the difference angle, and the composite digging force was calculated for a specific attitude while taking into account the limitations of the entire machine.

As shown in Figure 6, the composite digging force solved by applying a specific interval (given in Tab. 5) was less than the original interval (36.5 t machine, given in Tab. 7), with a dropped of up to 16.63 kN and an average dropped of 6.53 kN. The force value was similar to the excavation resistance, continuous stance adjustments were needed during the actual excavation process in order to utilize the bucket limit digging force.

In brief, the main values of θ and $\Delta\theta$ varied in different working conditions under the same machine type. Compared with the difference of working conditions, the

Table 4. Comparison different tonnage machines.

Coefficient	Machine type	Main value interval	Distribution probability
ε	Machine 1 (20 t)	(−0.07, 0.62)	83.4%
	Machine 2 (20 t)	(−0.2, 0.32)	86.8%
	Machine 3(36.5 t)	(−0.4, 0.5)	80.6%
δ	Machine 1 (20 t)	(−0.49, 0.07)	91.5%
	Machine 2 (20 t)	(−0.60, 0.01)	92.5%
	Machine 3(36.5 t)	(−0.4, 0.3)	95.6%

**Fig. 4.** Limit digging force comparison.**Fig. 5.** Directional angle comparison.

change in machine type more notably affected the distribution of θ and $\Delta\theta$. The different tonnage of excavator also led to different main values of θ and $\Delta\theta$.

4 Dynamic characteristics of the excavation resistance

4.1 Rotation angular velocity analysis

Figure 7 presents the relative angular velocity of the respective component of the front-end work device of the

excavator and the curves of the change of excavation resistance with time during an excavation process. The increasing and decreasing trends of the resistance law curve were nearly consistent with the angular velocity law curve of the respective member, where the bucket angular velocity law curve changed significantly. On the other hand, the relative angular velocity of the respective member fluctuated less when the resistance tended to be larger and stabilize.

Despite the relatively slow working speed of the excavator, given the motion inertia brought by its large dead weight, its motion speed inevitably affected the excavation process with the boom, arm, and bucket as the front-end working devices of the excavator. The bucket as the end-effector directly contacted the soil, and the change of the bucket angular speed directly indicated the dynamic excavation of the excavator.

4.2 Analysis of optimization results of dynamic characteristics

The statistics of the bucket's rotary angular velocity ω_1 in multiple excavations was analyzed to obtain its distribution at different stages. Likewise, its main value interval was determined in accordance with response surface optimization.

The distribution of bucket's rotary angular velocity ω_1 when $F > \bar{F}$ arouses the major attention. As depicted in Table 8, the main value of ω_1 changed between different test scenarios and different machines, whereas the

Table 5. When $F > \bar{F}$, direction coefficient distribution.

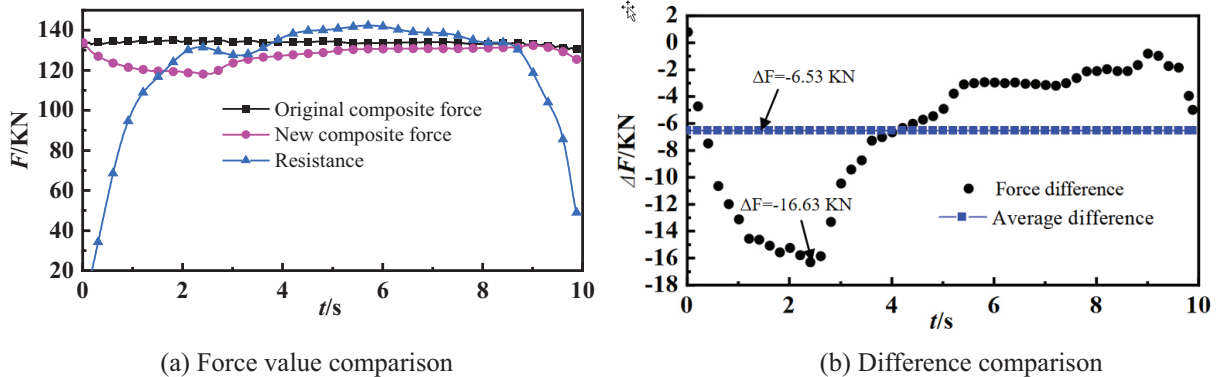
Machine type	Test type	θ Main value interval	Distribution probability	$\Delta\theta$ Main value interval	Distribution probability
Machine 1	Loose soil surface	(-11, 28)	93%	(-20, 68)	95%
	Normal soil surface	(-10, 42)	95%	(-20, 69)	96%
	Hard soil surface	(-5, 35)	90%	(-10, 70)	91%
	1M digging	(-12, 29)	93%	(-26, 74)	94%
	2M digging	(-5, 36)	88%	(20, 109)	88%
Machine 2	Hard soil surface	(-17, 29)	95%	(-40, 65)	97%
	1M digging	(-16, 20)	93%	(-21, 71)	94%
	2M digging	(-10, 19)	94%	(29, 78)	98%

Table 6. When $F < \bar{F}$, direction coefficient distribution.

Machine type	Test type	θ Main value interval	Distribution probability	$\Delta\theta$ Main value interval	Distribution probability
Machine 1	Loose soil surface	(-11, 28)	58%	(-20, 68)	52%
	Normal soil surface	(-10, 42)	54%	(-20, 69)	49%
	Hard soil surface	(-5, 35)	60%	(-10, 70)	58%
	1M digging	(-12, 29)	54%	(-26, 74)	53%
	2M digging	(-5, 36)	77%	(20, 109)	65%
Machine 2	Hard soil surface	(-17, 29)	31%	(-40, 65)	31%
	1M digging	(-16, 20)	31%	(-21, 71)	31%
	2M digging	(-10, 19)	53%	(29, 78)	49%

Table 7. Comparison different tonnage machines.

Coefficient	Machine type	Main value interval	Distribution probability
θ	Machine 1 (20 t)	(-5, 36)	88%
	Machine 2 (20 t)	(-10, 19)	94%
	Machine 3(36.5 t)	(-40, 15)	96.4%
$\Delta\theta$	Machine 1 (20 t)	(20, 109)	88%
	Machine 2 (20 t)	(29, 78)	98%
	Machine 3(36.5 t)	(-20, 15)	94.5%

**Fig. 6.** Composite digging force comparison.

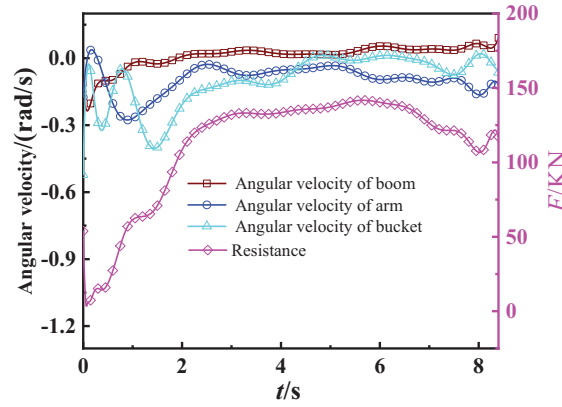


Fig. 7. Angular velocity versus time curve.

Table 8. When $F > \bar{F}$, ω_1 distribution.

Machine type	Test type	ω_1 Main value interval	Distribution probability
Machine 1	Loose soil surface	(−0.39, 0.02)	94.3%
	Normal soil surface	(−0.36, 0.04)	93.5%
	Hard soil surface	(−0.32, 0.10)	91.2%
	1M digging	(−0.31, 0.02)	88.5%
	2M digging	(−0.32, 0.03)	87.9%
Machine 2	Hard soil surface	(−0.36, 0.05)	94.6%
	1M digging	(−0.35, 0.04)	94.5%
	2M digging	(−0.37, 0.04)	97.5%

Table 9. When $F > \bar{F}$, ω_2 , ω_3 distribution.

Machine type	Test type	ω_2 Main value interval	Distribution probability	ω_3 Main value interval	Distribution probability
Machine 1	Loose soil surface	(−0.17, 0.02)	96.7%	(−0.01, 0.03)	90.3%
	Normal soil surface	(−0.17, 0.03)	93.6%	(−0.01, 0.02)	90.5%
	Hard soil surface	(−0.16, 0.06)	90.6%	(−0.02, 0.02)	84.8%
	1M digging	(−0.16, 0.03)	93.5%	(−0.01, 0.04)	92.0%
	2M digging	(−0.19, 0.02)	95.6%	(−0.03, 0.06)	95.5%
Machine 2	Hard soil surface	(−0.19, 0.03)	94.9%	(−0.01, 0.04)	91.5%
	1M digging	(−0.17, 0.02)	94.6%	(−0.01, 0.04)	90.6%
	2M digging	(−0.18, 0.04)	93.7%	(−0.02, 0.08)	94.2%

difference was small, and the difference between the left and right endpoints of each main value range was at most 0.08. Besides, the degree of concentration was high, with the probability of interval distribution of at least 88.5%. The boom, arm, and bucket were interconnected and did not come into contact with the excavated object, whereas they played direct roles in the excavation process. On that basis, their rotary angular velocities should be analyzed.

Table 9 list the interval distribution of ω_2 (arm rotary angular velocity) and ω_3 (boom rotary angular velocity) when $F > \bar{F}$. As depicted in these tables, compared with ω_1 , the distribution of the main value interval of arm and

boom rotary angular velocity was smaller. Notably, the ω_3 was primarily concentrated in an interval length of no more than 0.1. Moreover, the distributions of ω_2 almost maintained a high degree of concentration in the same main value interval, and the probability of interval distribution exceeded 90%.

As indicated by the results, the bucket, arm, and boom had definite and slightly different main value intervals. The bucket and arm, i.e., the main actuators of the excavation task, achieved a wider range of main values due to the complexity of the task and the unpredictability of the motion. In contrast, the boom was primarily employed for

attitude adjustment as an auxiliary actuating member, and it makes sense that its rotary speed fluctuated less. Moreover, the range of rotary angular velocity of the boom was increased steeply during 2 M digging, such that the boom should be rotated more significantly to retract the hydraulic cylinder for digging and to extend the hydraulic cylinder to lift the bucket. Besides, under the greater operating range, the boom should perform more of its stance adjustment functions. With the increase in travel and the more important role it played in the digging task, the angular speed of the boom rotation during 2 M digging changed significantly.

When $F > \bar{F}$, the probability of the distribution of the main value interval of the rotary angular velocity of the respective component was significantly high, suggesting that the operating angular velocity of the excavator was more stable at this stage. On that basis, the data foundation was laid for the calculation of the dynamic theoretical digging force and trajectory planning. Besides, the main value interval serves as an excellent solution to the problem of unknown value of the speed variable. Furthermore, the corresponding main value interval may vary with the tonnage model, and more experiments should be performed to collect more comprehensive data for more reasonable analysis to discover a more general and accurate dynamic law.

5 Conclusion

The study of resistance characteristics underpins the establishment and refinement of the theoretical digging force model. In this study, the differences of resistance characteristics under different scenarios were investigated from the perspective of experimental design, and the main value interval was optimized in accordance with the response surface optimization theory. Next, the data results under different machine types and tonnages were compared and analyzed. Finally, the effect of interval variation on the theoretical digging force model was analyzed.

When the two types of 20 t backhoe hydraulic excavator were subjected to different working conditions, the performance of the excavation resistance in terms of force characteristics and direction characteristics became inconsistent, as indicated by a certain difference in the corresponding coefficients. Type differences led to more significant differences in the main value interval of the corresponding coefficients. The degree of difference in the performance of the excavation resistance law in a wide variety of aspects was more significant under different tonnage excavators in similar working conditions, and there were significant differences in the corresponding of the main value interval. The law of resistance characteristics influenced the assessment index of excavator performance, as demonstrated in this study by the decline in theoretical digging force resulting from interval variation. Most of the values of the rotary angular velocity of the front-end work unit of the two types of 20 t backhoe hydraulic excavators fall into a distinct but slightly different main value interval in a wide range of

working conditions, whereas the above-described difference tends to be reduced with the order of the bucket, arm, and boom.

The data collected in this paper were derived from two different types of 20 t backhoe hydraulic excavators, encompassing a sufficient variety of excavation conditions. However, the distinction between the conditions and the machine types was not sufficiently pronounced. Future research should incorporate more excavation experiments conducted under significantly different conditions. Additionally, to enhance the understanding of the universality or variability of the resistance characteristics, it is essential to demonstrate these findings with a larger dataset.

Funding

This work was supported by Key R&D Program Project of Shaanxi Provincial Department of Science and Technology (2024NC-YBXM-203).

Conflicts of interest

The contact author has declared that neither of the authors has any competing interests.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contribution statement

TL conceptualized the study, wrote the original draft of the paper, and reviewed and edited the paper. ZR and XP provided precious comments for the paper. SC and JL was responsible for data curation and validation.

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Cite this article as: T. Li, Z. Ren, X. Pang, S. Cao, J. Li, Comparative analysis study of resistance characteristics of backhoe hydraulic excavators, *Mechanics & Industry* **25**, 36 (2024)