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DETERMINATION AND ANALYSIS OF THE THEORETICAL PRODUCTION OF A BUCKET WHEEL EXCAVATOR

OKREŚLANIE I ANALIZA TEORETYCZNEJ WYDAJNOŚCI PRACY KOPARKI WIELONACZYNIOWEJ KOŁOWEJ

The theoretical capacity of a bucket wheel excavator is the basis of mining theory. The paper concludes that the use of "$1/\cos\varphi$" to adjust the speed of a bucket wheel excavator will result in rapid speeds, which may cause nonuniform flow from the distribution of material flow, and decreased capacity utilization. Consequently, this scenario may produce unreasonable structure parameters and performance parameters that are based on theoretical analysis and mathematical derivation. If the rotary speed of an excavator body is too fast, it will require excessive mechanical strength and will generate increased rotary drive power, power consumption and extractive costs. Thus, the rotary speed of an excavator body should be appropriately reduced.

Keywords: bucket wheel excavator, theoretical production, rotary speed, excavator body

Teoretyczna wydajność koparki wielonaczyniowej kołowej jest podstawą w teoretycznych obliczeniach wydajności wydobycia. Autorzy pracy wyciągnęli wniosek, że wykorzystanie zależności $1/\cos\varphi$ przy sterowaniu prędkością pracy koparki prowadzi do zbyt dużych prędkości, co powodować może nierównomierność strumienia urobku i ograniczone wykorzystanie mocy przerobowych koparki. W konsekwencji, mamy do czynienia z nieuzasadnionymi parametrami konstrukcyjnymi i eksploatacyjnymi opartymi na analizach teoretycznych i matematycznych wyprowadzeniach. Jeśli prędkość obrotowa w ruchu korpusu koparki jest zbyt duża, wymagane będzie dostarczenie nadmiernej siły by wygenerować odpowiednio dużą prędkość obrotową, prowadząc do wzrostu zużycia energii i kosztów wydobycia. Dlatego też konieczna jest odpowiednia kontrola prędkości obrotowej w ruchu koparki.

Słowa kluczowe: koparka kołowa wielonaczyniowa, teoretycznie obliczone wydobycie, prędkość obrotowa, korpus koparki

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1. Introduction

Considering the high investment and operation costs, reliability analysis of mining machineries is essential to achieve a lean operation and to prevent the unwanted stoppages (Rahimdel et al., 2013). The bucket wheel excavator, which is primarily utilized for digging soft-textured material, such as clay, mineral sand, gravel, marl, brown coal and hard coal, is one of the predominant mining equipment in a surface mine (Tanasijevic et al., 2011; Che, 1993; Bošnjak et al., 2009; Kun et al., 2013). A continuous mining system, which includes a bucket wheel excavator and belt conveyor, is the primary mining system in a surface mine (Bošnjak et al., 2011; Rusiński et al., 2010; Lu et al., 2011; Gottvald & Zdenek, 2011; Sharma et al., 2009). By adopting a bucket wheel excavator-belt conveyor continuous mining system, the Fortu surface mine and Bergheim surface mine of the Rhine Lignite Company in Germany have achieved production scales of 50 Mt/a and mining ergonomics above 120 t/d. Currently, the world's largest bucket wheel excavator reports a daily production of $24 \times 10^4 \mathrm{m}^3/\mathrm{d}$ (Johnson & King, 2010; Vrublová et al., 2012; Rusiński et al., 2010; Daniel & Orban, 2010). By our research experiences of the bucket wheel excavator system for many years, it is found that the current adjustment speed rule for the rotary speed of the bucket wheel excavator body is unreasonable. As a result, it may produce adverse effects in the determination of the production, structure and performance parameters, rotation drive power of the body and mechanical strength of a bucket wheel excavator.

2. The previous determination of the theoretical production for the bucket wheel excavator

Previous progress has been made in determining the theoretical production of a cell-type bucket wheel excavator with a non-extension dipper arm, under the condition of a vertical section.

The thickness of the vertical section t_φ is expressed as

$$t_\varphi = t_{\max} \cos\varphi, \quad \mathrm{m} \tag{1}$$

where t_φ is the thickness of the crescent vertical section, in which the angle between the dipper arm and the midline of the walking road is φ; $t_{\max}$ is the thickness perpendicular to the crescent section, in which the angle between the dipper arm and the midline of the walking road is 0°; and φ is the angle between the dipper arm and the midline of the walking road.

The theoretical production is Q_{th}, in which the angle between the dipper arm and the midline of the walking road, is expressed as φ:

$$Q_{th} = 60 f h v_s t_\varphi, \quad \mathrm{m}^3/\mathrm{h}\ (\text{loose}) \tag{2}$$

where Q_{th} is the theoretical production; f is the loose factor of the ore and rock in the bucket; h is the slice height of the bench; v_s is the rotary-cutting linear velocity of the centroid of the crescent vertical section, in which the angle between the dipper arm and the midline of the walking road is φ.

When Equation (1) is substituted into Equation (2), we obtain

$$Q_{th} = 60 f h v_s t_{\max} \cos\varphi, \quad \mathrm{m}^3/\mathrm{h} \tag{3}$$

When $\varphi = 0$ and $v_s = v_{s0}$, we obtain

$$Q_{th} = 60fht_{\max}v_{s0}, \quad \mathrm{m^3/h} \tag{4}$$

To maintain constant production for a bucket wheel excavator in different rotation positions, Equations (3) and (4) can be simultaneously solved as

$$v_s = \frac{v_{so}}{\cos\varphi}, \quad \mathrm{m/min} \tag{5}$$

where v_{s0} is the rotary-cutting linear velocity of the centroid of the crescent vertical section, in which $\varphi = 0°$. We can obtain the rule for adjusting the speed from this equation.

The rotary-cutting linear velocity of the centroid of the crescent vertical section of the midline of the walking road is expressed as

$$v_{s0} = \omega_{so}(R_s + 0.4D), \quad \mathrm{m} \tag{6}$$

where R_s is the rotary radius of the bucket wheel center and D is the diameter of the bucket wheel.

According to Equation (1), in which the angle between the dipper arm and the midline of the walking road is 90°, the thickness of the crescent vertical section is 0. The thickness of the crescent vertical section becomes 0 when the angle between the dipper arm and the midline of the walking road exceeds 90°. That can be attributed to an intersecting circle with an equivalent radius on the front and back edges of the vertical section of a bucket wheel excavator with a non-crowding dipper arm. The drop distance between the intersecting circles is $t_{\max}$ (Fig. 1).

According to Equation (6), the rotary-cutting linear velocity of the centroid of the crescent vertical section of the midline of the walking road is approximate. This value is approximate because the distance between the centroid of the crescent vertical section and body rotary center is a function of $t_{\max}$, which is the thickness of the crescent vertical section, R_s', which is the rotary radius of excavation, and h, which is the bench slice height. Equation (6) does not consider these factors.

This theoretical conclusion contains errors, which may produce adverse effects in the determination of the production, structure and performance parameters, rotation drive power of the body and mechanical strength of a bucket wheel excavator.

3. Analysis of the theoretical production of a bucket wheel excavator

As shown in Fig. 1, the theoretical production of a bucket wheel excavator can be represented as

$$Q_{th} = 60A'hf, \quad \mathrm{m^3/h}\ \text{(loose)} \tag{7}$$

where A' is the change rate of the horizontal section area of the centroid of the crescent vertical section, R_s' is the rotary radius of excavation and R_s is the rotary radius of the center of the bucket wheels. As a result, $R_s' = R_s + 0.5D$.

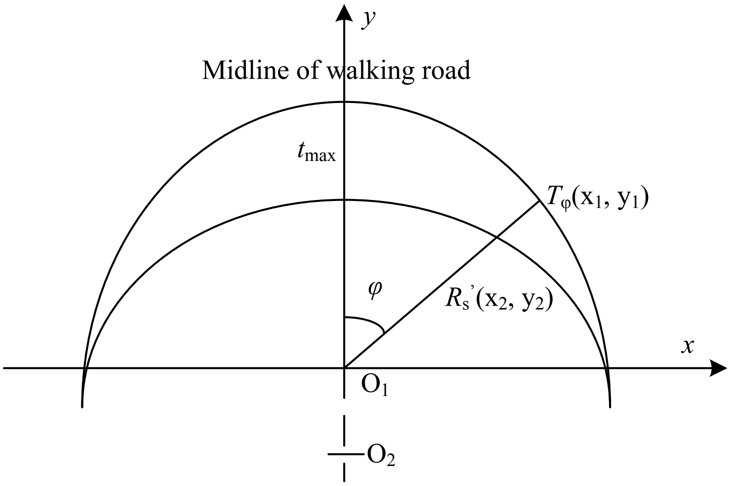

Fig. 1. Variation in thickness of the crescent vertical section

As shown in Fig. 1, the front and back edges of the horizontal section area of the centroid of the crescent vertical section and the dipper arm in the rectangular coordinate system can be represented as follows:

$$x_1^2 + y_1^2 = R_s'^2 \qquad \text{(circle 1)} \tag{8}$$

$$x_2^2 + (y_2 + t_{\max})^2 = R_s'^2 \qquad \text{(circle 2)} \tag{9}$$

$$y = x \cdot \operatorname{ctg}\varphi \qquad \text{(dipper arm)} \tag{10}$$

The intersection point (x_1, y_1) of the line of the dipper arm and the circle can be obtained with simultaneous Equations (8) and (10), where

$$\begin{cases} x_1 = R_s'^2 \sin\varphi \\ y_1 = R_s'^2 \cos\varphi \end{cases}$$

The intersection point (x_2, y_2) of the line of the dipper arm and the circle can be obtained with simultaneous formulas (9) and (10), where

$$\begin{cases} x_2 = \sin\left(\sqrt{R_s'^2 - t_{\max}{}^2 \sin^2\varphi} - t_{\max}\cos\varphi\right) \\ y_2 = \cos\left(\sqrt{R_s'^2 - t_{\max}{}^2 \sin^2\varphi} - \delta\cos\varphi\right) \end{cases}$$

In the circumstance in which the angle between the dipper arm and the midline of the walking road is φ, t_φ is the thickness of the crescent vertical section (that is, the distance between point (x_1, y_1) and point (x_2, y_2)) is expressed as follows:

$$t_\varphi^2 = (x_1 - x_2)^2 + (y_1 - y_2)^2$$

That is,

$$t_\varphi = R_s' + t_{\max}\cos\varphi - \sqrt{R_s'^2 - t_{\max}{}^2 \sin^2\varphi}\,, \quad \text{m} \tag{11}$$

where t_φ is the thickness of the crescent vertical section, R_s' is the rotary radius of excavation and φ is the rotary angle of the body, in which the angle between the dipper arm and the midline of the walking road is φ.

As shown in Fig. 1, if we assume ρ is the polar radius, φ is the polar angle in polar coordinates, and A is the horizontal section area of the centroid of the crescent vertical section, in which the angle between the dipper arm and the midline of the walking road φ, A can be represented as

$$A = \iint\limits_{\Omega} \rho d\rho d\varphi = \int_0^{\varphi} d\varphi \int_{R_S'-t_\varphi}^{R_S'} \rho d\varphi = \frac{1}{2}\int_0^{\varphi}\left(2R_s't_\varphi - t_\varphi{}^2\right)d\varphi$$

$$d\varphi = \omega(\varphi, R_s')\,dt \tag{12}$$

where $\omega(\varphi, R_s')$ is the rotary angular velocity, in which the angle between the dipper arm and the midline of the walking road is φ; the rotary radius of excavation is R_s'; and t is time.

The change rate of the crescent section area to time can be represented as follows:

$$A' = \frac{1}{2}\left(2R_s't_\varphi - t_\varphi{}^2\right)\omega\left(\varphi, R_s'\right) \tag{13}$$

When Equation (11) is substituted into Equation (13), we obtain

$$A' = \frac{1}{2}\left(2t_{\max}\cos\varphi\sqrt{R_s'^2 - t_{\max}{}^2\sin^2\varphi} - t_{\max}{}^2\cos 2\varphi\right)\omega\left(\varphi, R_s'\right), \quad \text{m}^2/\text{min} \tag{14}$$

When Equation (14) is substituted into Equation (7), we obtain

$$Q_{th} = 60\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}{}^2\sin^2\varphi} - 0.5t_{\max}\cos 2\varphi\right)\omega\left(\varphi, R_s'\right)t_{\max}hf\,, \quad \text{m}^3/\text{h (loose)} \tag{15}$$

When the angle between the dipper arm and the midline of the walking road is zero,

$$Q_{th} = 60(R_s' - 0.5t_{\max})\,t_{\max}\omega_{so}hf \tag{16}$$

where $\omega(\varphi, R_s')$ is the rotary angular velocity, in which the angle φ between the dipper arm and the midline of the walking road is zero, and the rotary radius of excavation is R_s'.

If we consider a uniform distributing of material flow and ensure the bucket is full, then

$$Q_{th} = 60SJ, \quad \text{m}^3/\text{h (loose)} \tag{17}$$

where J is the rated capacity of the bucket and S is the rate of the dumping hopper.

When Equation (17) is substituted into Equation (15), we obtain

$$\omega(\varphi, R_s') = \frac{JS}{\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}{}^2 \sin^2\varphi} - 0.5t_{\max}\cos 2\varphi\right)t_{\max}hf}, \quad \text{r/min} \tag{18}$$

$$\left(\omega(\varphi, R_s') \geq \omega_0^0\right)$$

where ω_0^0 is the minimum rotary angular velocity of the excavator body to ensure the rated theoretical production, $v_{0,\min}$ is the minimum rotary linear velocity of the bucket wheel center to ensure the rated theoretical production, L the length of the dipper arm, d is the distance between the hinge shaft of the upper and lower amplitude modulation of the dipper arm and the rotary center of the excavator body.

When the angle φ between the dipper arm and the midline of the walking road is zero (that is, the dipper arm is right in front of the midline of the walking road) and the rotary radius of excavation is R_s' (the rotary radius when excavating a slice), the rotary angular velocity of the excavator body can be expressed as follows:

$$\omega_{s0} = \frac{JS}{(R_s' - 0.5t_{\max})t_{\max}hf}, \quad \text{r/min} \tag{19}$$

Thus, when the rotary angular velocity of the excavator body conforms with Equation (18), its production is balanced.

As demonstrated by Equation (15), the position of the centroid of the crescent vertical section is a function of the thickness of the centroid of the crescent vertical section $t_{\max}$, the rotary radius of excavation R_s' and the slice height of the bench h.

Based on this analysis, we can conclude that the influence of the production of a bucket wheel excavator will increase with an increase in the rotary angle of the excavator body and the thickness of the centroid of the crescent vertical section, when the rule of "$1/\cos\varphi$" is employed to adjust the speed of the excavator.

If the rotary speed of the excavator body of a bucket wheel excavator varies with the rule of "$1/\cos\varphi$" and the angle φ between the dipper arm and the midline of the walking road, the rotary angular velocity of the excavator body should be represented as follows:

$$\omega(\varphi, R_s') = \frac{\omega_{s0}}{\cos\varphi}, \quad \text{r/min} \tag{20}$$

The theoretical production of a bucket wheel excavator should be represented as follows:

$$Q_{th} = 60\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}{}^2\sin^2\varphi} - 0.5t_{\max}\cos 2\varphi\right)\omega_{s0}t_{\max}hf / \cos\varphi, \quad \text{m}^3\text{/h (loose)} \tag{21}$$

The theoretical production of a bucket wheel excavator is represented by Equation (21), in which the rule of "$1/\cos\varphi$" is incorporated to adjust the speed of a bucket wheel excavator and the angle between the dipper arm and the midline of the walking road is φ.

4. Case study

The type of bucket wheel excavator in the Rhine lignite surface mine is $SchR_s\frac{4400}{14}41$, whose basic parameters are as follows: the bucket wheel diameter D is 17.0 m, the radius of the bucket wheel center R_s is 62.0 m, the rotary angular velocity of the excavator body ω_{s0} is 0.1542 r/min when $\varphi = 0$, the thickness of vertical section $t_{\max}$ is 1.55 m, the slice height of the bench h is 8.5 m, the loose factor of ore and rock in the bucket f is 1.45, the rated capacity of the bucket J is 4.4 m^3 and the rate of the dumping hopper S is 33 times per minute$^{(2)}$.

According to the influence on the theoretical production of a bucket wheel excavator, which is attributed to the centroid of the crescent vertical section, the corresponding equations are as follows by Equation (4):

$$Q_{th} = 60fht_{\max}v_{s0} = 60\times1.45\times8.5\times1.55\times11.0716 = 12690.54\ (\text{m}^3/\text{h})$$

$$v_{s0} = \omega_{so}(R_s + 0.4D) = 0.1542\times(65.0 + 0.4\times17.0) = 11.0716\ (\text{m/min})$$

By using the theory developed in this paper and based on the equations through Equation (15), it can be concluded that the theoretical production of a bucket wheel excavator is as follows:

$$\begin{aligned} Q_{th} &= 60(R_s' - 0.5t_{\max})t_{\max}\omega_{so}hf \\ &= 60\times(65.0+0.5\times17.0\text{-}0.5\times1.55)\times1.55\times0.1542\times8.5\times1.45 = 12853.99\ (\text{m}^3/\text{h}) \end{aligned}$$

The theoretical production of a bucket wheel excavator is 12853.99 (m^3/h), instead of 12690.54 (m^3/h), with a difference of 12690.54 (m^3/h) and an error rate of 1.27% for the $SchR_s\frac{4400}{14}41$ under certain parameters, such as the angle φ between the dipper arm and the midline of the walking road is zero. The actual loose loading volume in the bucket is 6.49 m^3 instead of 6.41 m^3. Thus, the theoretical production of a bucket wheel excavator, which is influenced by the centroid of the crescent vertical section, is relatively small.

The analysis of the theoretical production of a bucket wheel excavator with the rule of "1/cosφ" (with Equation (18) and Equation (21)).

The results of the comparison of the influence of the rule of "1/cosφ" on the theoretical production of a bucket wheel excavator under certain parameters are listed in table1.

TABLE 1

The influence of the rule of "1/cosφ" on the theoretical production of a bucket wheel excavator

Items		0°	10°	20°	30°	40°	50°	60°	70°	80°
1/cosφ	ω, (r/min)	0.1542	0.1566	0.1641	0.1781	0.2013	0.2399	0.3084	0.4509	0.8880
	Q_{th}, (m^3/h)	12854.0	12862.2	12877.6	12912.0	12950.5	13011.5	13100.3	13253.8	13643.7
ω (φ, R_s')	ω, (r/min)	0.1542	0.1565	0.1638	0.1773	0.1998	0.237	0.3026	0.4373	0.8366
	Q_{th}, (m^3/h)	12854.0	12854.0	12854.0	12854.0	12854.0	12854.0	12854.0	12854.0	12854.0
Difference (m^3/h)		0	8.2	23.6	58.1	96.5	157.5	246.3	399.8	789.7
Error rate (%)		0	0.06	0.18	0.45	0.75	1.23	1.92	3.11	6.14

As shown in Table 1, the material flow excavated by a bucket wheel excavator is balanced with the use of the theory of $\omega(\varphi, R_s')$, as developed in the paper. The material flow is non-uniform when the rule of "1/cosφ" is employed to adjust the speed of a bucket wheel excavator. A theoretical production of 13643.7 m^3/h is achieved when the angle φ between the dipper arm and the midline of the walking road is 80°, which is 789.7 m^3/h greater than the resulting theoretical production when φ is zero, with an increase of 6.14%. Thus, the volume of every bucket will increase 0.3988 m^3. If the bucket is full when the bucket wheel excavator is working on the midline of the walking road ($\varphi = 0°$), it will leak material while working on both sides of the working face (when φ is approximately 80°). If the bucket is full when the bucket wheel excavator is working on both sides of the working face (when φ is approximately 80°), the bucket will not be full when working on the midline of the walking road ($\varphi = 0°$), for which the error rate is 6%.

Thus, the rotary speed of the excavator body is excessive for the rule of "1/cosφ" that is employed to adjust its speed, which will cause increased rotary drive power and a decreased utilization rate of production.

5 Conclusions

Using "1/cosφ" to adjust its speed, the paper concludes that the speed of a bucket wheel excavator is too fast, which will lead to a nonuniform distribution of material flow and a decrease in capacity utilization, as well as an unreasonable determination of structure parameters and performance parameters. If the rotary speed of the excavator body is excessive, it will cause an increase in rotary drive power, power consumption, extractive cost, and required mechanical strength. Thus, the rotary speed of the excavator body should be appropriately reduced.

The results of the analysis of the theoretical production of a bucket wheel excavator provide the basis for determining the effective production and actual production, testing and inspection, and the structure parameters and performance parameters of a bucket wheel excavator.

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