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COMMENTS ON “DETERMINATION AND ANALYSIS OF THE THEORETICAL PRODUCTION
OF A BUCKET WHEEL EXCAVATOR”UWAGI I KOMENTARZE DO PRACY: ”OKREŚLANIE I ANALIZA TEORETYCZNEJ WYDAJNOŚCI
PRACY KOPARKI WIELONACZYNIOWEJ KOŁOWEJ”

This paper comments on the recently published work dealing with the problem in the determination of the theoretical output of the bucket wheel excavator. It also includes remarks on the inadequacy in the problem approach and highlights the mistakes in the mathematical model. This work emphasizes the demand for a much wider and deeper approach to the problem of determining the output of the bucket wheel excavator.

Keywords: bucket wheel excavator, cutting depth, slewing speed, theoretical output

Opublikowany niedawno artykuł autorstwa Che i Chena (2014) poświęcony jest ważnej kwestii jaką jest określenie teoretycznej wydajności koparki kołowej wielonaczyiniowej. W załączonym przeglądzie literatury Che i Chen (2014) nie umieścili pozycji odnoszących się do metod urabiania, parametrów pracy koparki oraz teoretycznej wydajności wydobycia i być może to właśnie jest przyczyną pewnych niedokładności powstałych w trakcie rozwiązywania problemu. Intencją autora obecnej publikacji było:

- Odniesienie się do krytycyzmu wyrażonego przez Che i Chena (2014) dotyczącego procedury obliczania prędkości w ruchu łukowym podanej w cytowanej literaturze przedmiotu (Pajer i in., 1971; Vetrov, 1971; Rasper, 1975; Durst i Vogt, 1988);
- Zbadanie różnic pomiędzy procedurą określania teoretycznej wydajności zaproponowaną w pracy Che i Chena (2014) a odpowiednimi rozwiązaniami podanymi w literaturze;
- Określenie prawidłowości i stosowalności teorii zaprezentowanej w pracy Che i Chena (2014) poprzez porównanie wyników uzyskanych z wykorzystaniem ich teorii oraz teorii podanych w wymienionych pozycjach literatury.

W rozdziale 2 pracy (Che i Chen 2014) zatytułowanym „Uprzednio stosowane metody określania teoretycznej wydajności pracy koparki kołowej wielonaczyiniowej” autorzy nie podali głównych odniesień literaturowych z których zaczerpnięte zostały równania (1)-(6)**. Ponadto, nie podali charakterystyki modelu działania koparki, na podstawie którego wyprowadzone zostały rzeczzone równania, co stanowi

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** W celu uniknięcia dwuznaczności, numeracja równań w pracy (Che i Chen, 2014) została zachowana, w tej publikacji równania oznaczone zostały literami.

poważne przeoczenie. Che i Chen (2014) kwestionują prawidłowość równania (6), lecz przedstawione w niniejszej pracy analizy i uwagi prowadzą do następujących wniosków:

- Stwierdzenie w pracy (Che i Chen 2014) że równanie (6) nie uwzględnia wpływu t_{\max} i h nie jest prawdziwe. Dowód: Równanie (6').
- Stwierdzenie że równanie (6) nie uwzględnia wpływu $R_{s^{\wedge}}$ – „...czyli obrotowego promienia działania...”, (Che i Chen 2014) jest prawdziwe, w przeciwnym razie równanie (6) byłoby nieprawdziwe. Równanie (6) uwzględnia odpowiedni promień zdefiniowany w równaniu (i), które jest prawdziwe. Dowód: Równanie (6').

W rozdziale 2 pracy (Che i Chen 2014) zatytułowanym: „Analiza teoretycznej wydajności koparki kołowej wielonaczyniowej” kierując się błędnymi wnioskami odnośnie niedokładności równania (6) autorzy podjęli próbę skorygowania powyższej niedokładności, by w ten sposób poprawić istniejącą teorię. W trakcie realizacji koncepcji wykorzystania równania (11) do zdefiniowania zasad rządzących zmianą prędkości kątowej wysięgnika Che i Chen (2014) popełnili błąd. Przyjęli oni mianowicie, że wyrażenie (14), otrzymane dla górnego przekroju wykopu e odnosić się będzie także do wszystkich przekrojów, dla całej wysokości wrębu. Pominęli w ten sposób fakt iż prędkość w ruchu łukowym wysięgnika nie jest wielkością stałą, patrz: równania (f) i (f'), i przyjęli jej wartość maksymalną, równanie (f'). Dlatego też równania (15), (16), (18) i (19) nie są prawidłowe.

Wszystkie wejściowe dane obliczeniowe a także sposób ich zapisu (Tabela 1) zostały zaczerpnięte z pracy (Che i Chen 2014). Ponadto, zaprezentowane dane o pracy koparki wielonaczyniowej SchRs $\frac{4400}{14}$ wykorzystywanej w kopalni „Zukunft” w Reńskim Zagłębiu Węglowym, zaczerpnięto z pracy (Durst i Vogt 1988). Osiągnięcia badań teoretycznych Che i Chen (2014, strona 289) przedstawione dla konkretnej koparki wielonaczyniowej kołowej eksploatowanej w kopalni odkrywkowej lignitu w Reńskim Zagłębiu Węglowym „...” (Che i Chen 2014).

Obliczenia głębokości wrębu i prędkości kątowej wysięgnika oraz teoretycznej wydajności pracy przeprowadzono na cztery sposoby, co obrazuje Tabela 2:

- Wariant 1 – z wykorzystaniem teorii rozwiniętej przez Che i Chena (2014, strona 289);
- Wariant 2 różni się od Wariantu 1 tylko zasadą określającą zmiany prędkości kątowej, i.e. określona jest ona wzorem: „...zasada $1/\cos\varphi$ (Che i Chen 2014, strona 289);
- Wariant 3 wykorzystuje znane równania podane w cytowanej literaturze przedmiotu (Durst i Vogt, 1988; Pajer i in., 1971; Rasper, 1975);
- Wariant 4 różni od Wariantu 3 wyłącznie wyrażenie określające głębokości wrębu, w Wariantcie 4 zastosowane zostało wyrażenie pozwalające na dokładne obliczenie głębokości wrębu.

Zaprezentowane wyniki prowadzą do następujących wniosków:

- Maksymalna teoretycznie obliczona wydajność dla wszystkich wariantów jest niższa od wartości maksymalnej otrzymanej przy wykorzystaniu równania (s), tak więc nie zachodzi niebezpieczeństwo nadmiernego przeciążenia łyżki, jak to zostało stwierdzone w pracy Che i Chena (2014);
- Maksymalne teoretycznie wyliczone wydajności dla wariantu 1 i 2 należy odrzucić z powodu błędów w definicji promienia odniesienia R_e , określonego równaniem (I), co zostało szczegółowo omówione w rozdziale 3 tej pracy;
- Gdy teoretyczna wydajność obliczana jest w oparciu o dokładny wzór na głębokość wrębu (Wariant 4), otrzymujemy nieco wyższe wartości niż w Wariantcie 3. Procentowo, różnica ta jest mniejsza niż 1% dla $0 \leq \varphi \leq 50.8^\circ$, poniżej 2% dla $0 \leq \varphi \leq 64.5^\circ$ i poniżej 3% dla $0 \leq \varphi \leq 75.6^\circ$ (rys. 11). Maksymalna wartość (5.9%) osiągana jest dla $\varphi = 80^\circ$. Z punktu widzenia zastosowań inżynierskich, taki poziom błędów jest dopuszczalny, zwłaszcza gdy uwzględnimy jego rozkład w zakresie $0 \leq \varphi \leq 80^\circ$, oraz fakt że błąd ten sprawia, że ryzyko zagrożenia maleje.
- Obniżenie teoretycznej wydajności po tym jak prędkość kątowa osiąga wartość maksymalną (rys. 9): „... jest akceptowalne ponieważ odnosi się do niewielkiej tylko części całkowitej objętości przenoszonego materiału” (Durst & Vogt, 1988, strona 46).

Publikacja autorstwa Che i Chena (2014) jest godną uwagi próbą ulepszenia istniejącej teorii opisującej działanie koparek kołowych wielonaczyniowych. Jednakże, uwzględniając przedstawione uwagi i komentarze, nasuwają się następujące spostrzeżenia:

- Badany problem jest nie jest problemem nowym i bogata literatura przedmiotu powinna być zostać uwzględniona;
- Matematyczne wzory zawierają błędy, które nieuchronnie prowadzą do nieprawidłowych wniosków.

Celem niniejszej pracy było zwrócenie uwagi na potrzebę zastosowania znacznie szerszego podejścia do problemu obliczania wydajności koparek kołowych wielonaczyniowych niż podejście zaproponowane w pracy Che i Chena (2014).

Słowa kluczowe: koparka kołowa wielonaczyniowa, głębokość wrębu, prędkość w ruchu łukowym, teoretyczna wydajność

1. Introduction

The recently published paper by Che & Chen (2014) is devoted to the very important problem of the determination of the theoretical output of the bucket wheel excavator (BWE). In their references, Che & Chen (2014) have omitted to cite related literature dealing with excavating technologies, BWE working parameters and theoretical output. And that is probably the reason of certain inadequacies arising during problem solving. The intention of the author of this contribution was:

- To determine the validity of the criticism exposed by Che & Chen (2014), dealing with the procedure of slewing velocity calculation given in the literature references (Pajer et al., 1971; Vetrov, 1971; Rasper, 1975; Durst & Vogt, 1988);
- To investigate the differences between the procedure of theoretical output determination developed by Che & Chen (2014) and the corresponding procedure given in the related literature;
- To determine the validity and applicability of the theory presented in Che & Chen (2014) by comparing the results obtained by using their theory and the theory given in the above cited literature.

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

In Section 2 (Che & Chen, 2014) titled “The previous determination of the theoretical production for the bucket wheel excavator” authors have omitted to quote the key references from which the Equations (1)-(6)¹ are taken over. Besides, they did not specify the characteristics of the BWE working device model on the basis of which the mentioned equations were obtained. That also presents a serious oversight.

A model of the BWE working device developed by Bošnjak (1991), Fig. 1, encompasses all relevant structural parameters as well as the duty cycle parameters that are essential for the analysis of the kinematics and the cutting geometry. Based on that model, the RADBAG software was in-house developed and successfully used in (Bošnjak et al., 2006a, 2006b, 2008, 2009, 2012a, 2012b; Arsić et al., 2011) for defining the BWE external load induced by resistance to excavation.

Equations (1)-(6) quoted in Section 2 (Che & Chen, 2014) deal with the BWE working device model, Fig. 1, for which $E = d = e = 0$ and $\alpha = \nu = \varepsilon = 0^\circ$. These equations can be found in the related literature (Vetrov, 1971; Pajer et al., 1971; Rasper, 1975; Durst & Vogt, 1988).

¹ To avoid any confusion, the numbering of equations in (Che & Chen, 2014) is retained, whilst in this paper the equations are marked by letters.

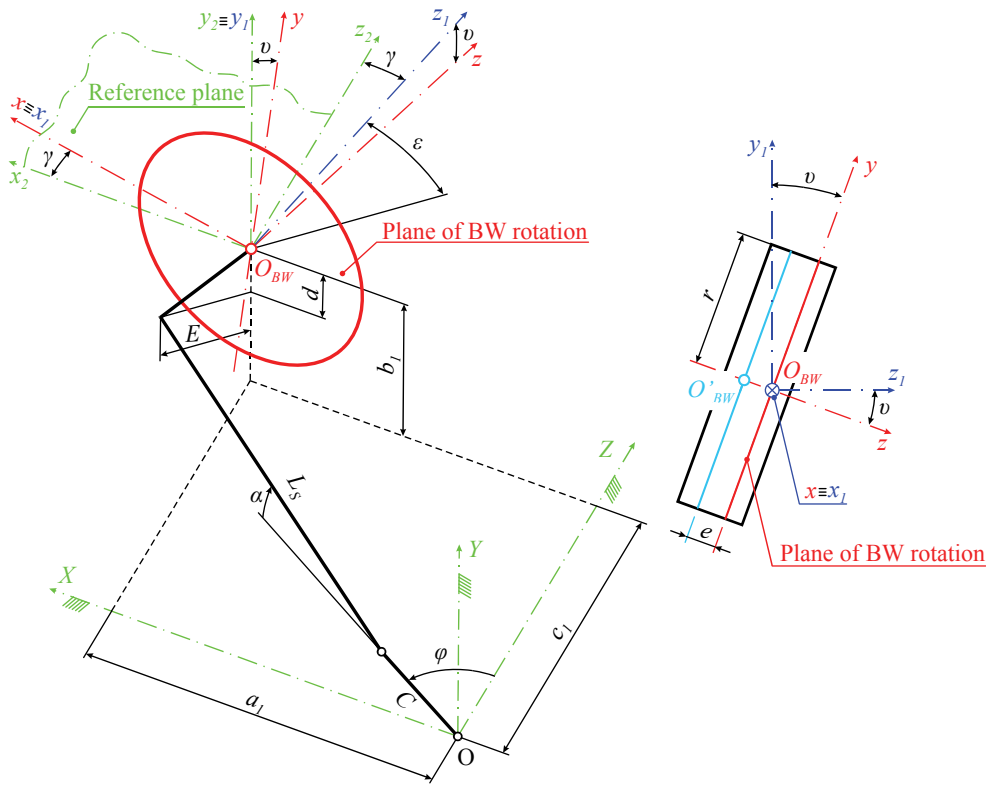


Fig. 1. Kinematic model of the BWE working device (Bošnjak, 1991; Bošnjak et al., 2006a; Arsić et al., 2011): C – distance between the bucket wheel boom’s hinge and slewing axis OY ; L_s – bucket wheel boom (BWB) length; E – bucket wheel (BW) eccentricity in the horizontal plane; d – BW eccentricity in the vertical plane; r – BW radius; e – distance between the plane of the BW rotation² and the plane in which the mean integral value of the cutting depth³ is realised; α – BWB inclination angle; φ – superstructure slewing angle; ϵ – BW inclination angle in the horizontal plane; ν – BW inclination angle in the vertical plane

Che & Chen (2014) call into question the validity of Equation (6),

$$v_{s0} = \omega_{s0} (R_s + 0.4D) \tag{6}$$

indicating “... 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 statement delivered by Che & Chen (2014) is not accurate, which will be made evident below. In the polar coordinate system O'_{BWP} , Fig. 2, the equation of the circle c_1 is of the form

² Generally, an arbitrary plane perpendicular to the axis of bucket wheel rotation.

³ When taking into account the shape and width of the buckets, the cutting depth is not uniquely defined and because of that the concept of the mean integral value of the cutting depth was proposed in (Bošnjak, 1991).

The lateral area of the cut is determined by the equation (Bošnjak, 1991)

$$A_{L\psi} = \int_{\pi-\psi}^{\pi} \int_{\rho_1}^{\rho_2} \rho d\rho d\xi = \frac{D}{2} t_\varphi (1 - \cos\xi) \tag{e}$$

The slice width is variable due to the slewing velocity changeability, Fig. 2,

$$v_{sA,\varphi} = v_{smin,\varphi} = R_s \omega_{s\varphi} \tag{f}$$

$$v_{sB,\varphi} = v_{smax,\varphi} = \left(R_s + \frac{D}{2} - \frac{1}{2} t_\varphi \right) \omega_{s\varphi} \tag{f'}$$

where $\omega_{s\varphi}$ is the angular velocity for the arbitrary superstructure angle φ .

According to Rasper (1975, page 42) the slewing velocity of the centroid of the sickle cut is relevant for determining the volume of the sickle cut, Fig. 2. The sickle cut centroid abscissa in relation to the coordinate system $O'_{B\psi}xyz$, Fig. 2, is determined by the next expression (Bošnjak, 1991)

$$x_{C_\psi} = \frac{1}{A_{L\psi}} \int_{\pi-\psi}^{\pi} \int_{\rho_1}^{\rho_2} \rho^2 \sin\xi d\rho d\xi = \frac{0.5D(0.5\psi - 0.25\sin 2\psi)}{1 - \cos\psi} \tag{g}$$

Thus, for the BWE working device model used in Che & Chen (2014) i.e. in case of $E = d = e = 0$ and $\alpha = \nu = \varepsilon = 0^\circ$, Fig. 1, the slewing velocity in the centroid of the cut lateral area is

$$v_{sC_\psi,\varphi} = \left(R_s + x_{C_\psi} \right) \omega_{s\varphi} \tag{h}$$

For $\psi = \pi/2$, a case which is considered in (Che & Chen, 2014), the height of the cut, Fig. 2, is $h_\psi \Big|_{\psi=\frac{\pi}{2}} = h = \frac{D}{2}$ and the Equations (e), (g) and (h) give

$$A_{L\psi} \Big|_{\psi=\frac{\pi}{2}} = \frac{D}{2} t_\varphi = ht_\varphi \tag{e'}$$

$$x_{C_\psi} \Big|_{\psi=\frac{\pi}{2}} = 0.5D \frac{\pi}{4} = h \frac{\pi}{4} \approx 0.393D \approx 0.4D = 0.8h \tag{g'}$$

$$\begin{aligned} v_{sC_\psi,\varphi} \Big|_{\psi=\frac{\pi}{2}} &= \left(R_s + x_{C_\psi} \Big|_{\psi=\frac{\pi}{2}} \right) \omega_{s\varphi} = \left(R_s + h \frac{\pi}{4} \right) \omega_{s\varphi} \approx \\ &\approx (R_s + 0.4D) \omega_{s\varphi} = (R_s + 0.8h) \omega_{s\varphi} = R_e \omega_{s\varphi} \end{aligned} \tag{h'}$$

Thus, the sickle cut centroid abscissa has a constant value which obviously, Equation (g'), depends on the cut height h . Because of that, the relevant radius, Equation (h'),

$$R_e = R_s + 0.8h = R_e(R_s, h) \tag{i}$$

which presents the distance between the centroid of the cut lateral area and the slewing axis OY , depends on the cut height. This conclusion is valid for any superstructure slewing angle, for $\varphi = 0$ accordingly, when Equation (h') has the form of Equation (6).

On the other hand, based on Equations (3), (5), (6) and (i) we obtained the expression for calculating the minimum angular slewing velocity at $\varphi = 0$,

$$\omega_{s0} = \frac{Q_{th}}{60R_e t_{max} hf} = \omega_{s0} (Q_{th}, R_e (R_s, h), t_{max}, h, f) \text{min}^{-1} \quad (j)$$

which enables the achievement of the required BWE theoretical output. Note that t_{max} in (Che & Chen, 2014) is $t_{\varphi} \Big|_{\varphi=0, \psi=\frac{\pi}{2}}$.

Having in mind Equations (i) and (j), Equation (6) could be written in the following form

$$\begin{aligned} v_{s0} &= \omega_{s0} (R_s + 0.4D) = \omega_{s0} (Q_{th}, R_e (R_s, h), t_{max}, h, f) R_e (R_s, h) = \\ &= v_{s0} (t_{max}, R_e, h, Q_{th}, f) \end{aligned} \quad (6')$$

Based on the presented analyses and comments it is conclusive as follows:

- The statement in (Che & Chen, 2014) that Equation (6) does not consider the influence of t_{max} and h is not true. Proof: Equation (6').
- The statement that Equation (6) does not consider the influence of R_s' "... which is the rotary radius of excavation ..." (Che & Chen, 2014) is fortunately true, otherwise Equation (6) would be false. Equation (6) includes the relevant radius defined by Equation (i) which is true. Proof: Equation (6').

Finally, we can conclude that Equation (6) does not include the errors stated by Che & Chen (2014).

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

In Section 3 (Che & Chen, 2014) titled "Analysis of the theoretical production of a bucket wheel excavator", led by the false conclusion about the inaccuracy of Equation (6), the authors have attempted to correct the mentioned inaccuracy and in that way improve the existing theory.

Introducing Equations (5) and (6) into Equation (3), for $\varphi = 0$ we obtain

$$Q_{th} = 60(R_s + 0.4D)\omega_{s0}t_{max}hf \quad (k)$$

By comparing the structure of Equation (k) and the structure of Equation (16) developed by Che&Chen (2014)

$$Q_{th} = 60(R_s' - 0.5t_{max})t_{max}\omega_{s0}hf \quad (16)$$

we can conclude that the only difference is in the choice of the relevant radius. Instead of R_e , Equation (i), Che & Chen (2014) adopted

$$R_s' = R_s' - 0.5t_{max} = R_s + 0.5D - 0.5t_{max} = R_e + 0.1D - 0.5t_{max} \quad (l)$$

which presents the distance between the center of the cut top cross-section and the slewing axis OY, Fig 2. Hence, Che & Chen (2014) have overlooked the already mentioned fact that the slew-

ing velocity is not of a constant value, Equations (f) and (f'). They have adopted its maximum value (Equation (f')) and in that way made a mistake.

The exact expression for the cutting depth,

$$t_{\varphi} = R_s' + t_{\max} \cos \varphi - \sqrt{R_s'^2 - t_{\max}^2 \sin^2 \varphi} \quad (11)$$

that Che & Chen(2014) reported as a result of their own investigations, has long been known in science (Vetrov, 1971, page 306). By using the approximate expression for the cutting depth (Dombrovskiy, 1972, page 63; Durst & Vogt, 1988, page 37; Pajer et al., 1971, page 163; Rasper, 1975, page 42; Vetrov, 1971, page 307)

$$t_{\varphi,a} = t_{\max} \cos \varphi \quad (1)$$

we make the relative percentage error

$$E_r = \frac{t_{\varphi} - t_{\varphi,a}}{t_{\varphi}} \times 100(\%) \quad (m)$$

whose value depends on the BWE's structural and technological parameters: R_s , D , t_{\max} and φ . When it comes to the calculation of the theoretical output, the considered error is on the side of safety because expression (1) gives a slightly lower value of the cutting depth than expression (11), except for $\varphi = 0$ when $t_{\varphi,a}|_{\varphi=0} = t_{\varphi}|_{\varphi=0} = t_{\max}$. For real structural and technological parameters of the machine, the level of the aforementioned error is acceptable from an engineering point of view, as will be shown in Section 4 of this paper. Therefore, and also in contemporary BWEs the "cosine φ control" is applied (for example, BWE Krupp SchRs 1600 in Mining basin "Kolubara" – Serbia, put into exploitation in 2010), which means that the superstructure angular velocity changes according to the law

$$\omega_{s\varphi} = \frac{\omega_{s0}}{\cos \varphi} \quad (n)$$

In the range of the superstructure angular velocity regulation, it allows the maintaining of the constant value of the product

$$\omega_{s\varphi} t_{\varphi,a} = \frac{\omega_{s0}}{\cos \varphi} t_{\max} \cos \varphi = \omega_{s0} t_{\max} = \text{const} \quad (o)$$

and in that way the constant value of the BWE theoretical output.

During the realization of the idea of using Equation (11) for defining the law of changing the superstructure angular velocity, Che & Chen (2014) have made a mistake. They adopted that the expression (14), derived for the top cut cross-section, is valid for all cut cross-sections i.e. for the entire height of the sickle cut. That way they have neglected the fact that the slewing velocity is not of a constant value, Equations (f) and (f'), and have adopted its maximum value, Equation (f'). Therefore, Equations (15), (16), (18) and (19) are not accurate.

4. Case study

All calculation input data, as well as their notations, Table 1, are taken over from (Che & Chen, 2014). In addition, the data for BWE SchRs $\frac{4400}{14}$ which is in exploitation in the “Zukunft” Mine of “Rheinische Braunkohlenwerke”, presented in (Durst & Vogt, 1988) were also used. Achievements of their theoretical considerations Che & Chen (2014, page 289) presented for that particular BWE „... in the Rhine lignite surface mine ...” (Che & Chen, 2014).

The calculation of the cutting depth, the superstructure angular velocity and the theoretical output was done in four ways, Table 2, as follows:

- Variant 1 is based on the theory developed in the paper by Che & Chen (2014, page 289);
- Variant 2 differs from Variant 1 only in the law of changing of the angular velocity i.e. it is based on the “... rule $1/\cos\varphi$...” (Che & Chen, 2014, page 289);
- Variant 3 is based on the well-known equations given in the referenced literature (Durst & Vogt, 1988; Pajer et al., 1971; Rasper, 1975);
- Variant 4 differs from Variant 3 only in the expression for the cutting depth i.e. in Variant 4 the exact expression for the cutting depth is applied.

TABLE 1

Input data (Che & Chen, 2014)

Nomenclature	Notation	Value
BW diameter	D	17 m
Slew radius at BW centre	R_s	65 m
Angular slewing speed of BWB at slewing angle $\varphi = 0$	ω_{s0}	0.1542 min^{-1}
Maximum angular slewing speed of BWB at $\varphi = 80^\circ$	ω_{smax}	0.8880 min^{-1}
Maximum cutting depth	t_{max}	1.55 m
Height of cut	h	8.5 m
Swell factor	f	1.45
Bucket capacity	J	4.4 m^3
Number of discharges per unit of time	S	33

TABLE 2

Formulae for calculation

Nomenclature and formula		Equation ¹⁾	Unit
1	2	3	4
Variant 1	Excavation radius $R'_s = R_s + 0.5D$	unnumbered (page 285)	m
	Cutting depth at BWB angle φ $t_\varphi = R'_s + t_{max} \cos \varphi - \sqrt{R'^2_s - t^2_{max} \sin^2 \varphi}$	11	m
	Angular slewing speed of BWB at slewing angle $\varphi = 0$ $\omega_{s0} = \frac{JS}{(R'_s - 0.5t_{max})t_{max}hf}$	19	min^{-1}

1	2	3	4
Variant 1, continued	Angular slewing speed of BWB at slewing angle φ $\omega(\varphi, R'_s) = \frac{JS}{\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}^2 \sin^2\varphi} - 0.5t_{\max} \cos 2\varphi\right)t_{\max} hf}$	18	min^{-1}
	Theoretical output at BWB slewing angle φ $Q_{th} = 60\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}^2 \sin^2\varphi} - 0.5t_{\max} \cos 2\varphi\right)\omega(\varphi, R'_s)t_{\max} hf$	15	m^3/h
	Theoretical output at BWB slewing angle $\varphi = 0$ $Q_{th} = 60\left(R'_s - 0.5t_{\max}\right)t_{\max}\omega_{s0} hf$	16	m^3/h
Variant 2	Excavation radius $R'_s = R_s + 0.5D$	unnumbered (page 285)	m
	Cutting depth at BWB angle φ	11	m
	Angular slewing speed of BWB at slewing angle $\varphi = 0$	19	min^{-1}
	Angular slewing speed of BWB at slewing angle φ $\omega(\varphi, R'_s) = \frac{\omega_{s0}}{\cos\varphi}$	20	min^{-1}
	Theoretical output at BWB slewing angle φ $Q_{th} = 60\left(\cos\varphi\sqrt{R_s'^2 - t_{\max}^2 \sin^2\varphi} - 0.5t_{\max} \cos 2\varphi\right)\omega_{s0}t_{\max} hf / \cos\varphi$	21	m^3/h
Variant 3	Cutting depth at BWB angle φ $t_\varphi = t_{\max} \cos\varphi$	1	m
	Slew speed at center of mass of the sickle cut for $\varphi = 0$ $v_{s0} = \omega_{s0}(R_s + 0.4D)$	6	m/min
	Slew speed at center of mass of the sickle cut for BWB slewing angle φ $v_s = v_{s0} / \cos\varphi$	5	m/min
	Theoretical output at BWB slewing angle φ $Q_{th} = 60fhv_s t_{\max} \cos\varphi$	3	m^3/h
Variant 4	Cutting depth at BWB angle φ $t_\varphi = R'_s + t_{\max} \cos\varphi - \sqrt{R_s'^2 - t_{\max}^2 \sin^2\varphi}$	11	m
	Slew speed at center of mass of the sickle cut for $\varphi = 0$	6	m/min
	Slew speed at center of mass of the sickle cut for BWB slewing angle φ	5	m/min
	Theoretical output at BWB slewing angle φ	3	m^3/h

¹⁾ Equation numbering according to (Che & Chen, 2014).

4.1. On angular slewing speed of BWB at slewing angle $\varphi = 0$

Based on the data presented in Table 1, by applying the equations given in Table 2 (unnumbered equation on page 285 in (Che & Chen, 2014) and Equation (19)), we obtain

$$R'_s = R_s + 0.5D = 65 + 0.5 \times 17 = 73.5\text{m} \tag{p}$$

$$\begin{aligned}\omega_{s0} &= \frac{JS}{\left(R'_s - 0.5t_{\max}\right)t_{\max}hf} = \\ &= \frac{4.4 \times 33}{(73.5 - 0.5 \times 1.55) \times 1.55 \times 8.5 \times 1.45} = 0.1045 \text{ min}^{-1}\end{aligned}\quad (q)$$

Calculated value of ω_{s0} is for $\approx 32.23\%$ lower than the corresponding value presented in Table 1 ($\omega_{s0} = 0.1542 \text{ min}^{-1}$). Besides that, it is lower than the minimum superstructure angular velocity for the considered BWE. Namely, in (Durst & Vogt, 1988, page 95) it is stated that the superstructure angular speed is adjustable between:

$$\begin{aligned}\omega_{s,\min} &= 2.05 \times 10^{-3} \text{ s}^{-1} = 0.123 \text{ min}^{-1}, \\ \omega_{s,\max} &= 1.03 \times 10^{-2} \text{ s}^{-1} = 0.618 \text{ min}^{-1}.\end{aligned}$$

The unrealistic low value $\omega_{s0} = 0.1045 \text{ min}^{-1}$ (lower than $\omega_{s,\min} = 0.123 \text{ min}^{-1}$) obtained by using Equation (19) in (Che & Chen, 2014) is the consequence of the error made during the determination of the BWE theoretical output. Equation (17) in (Che & Chen, 2014) yields

$$Q_{th} = 60SJ = 60 \times 33 \times 4.4 = 8712 \frac{\text{m}^3}{\text{h}} \quad (r)$$

which is also $\approx 32.23\%$ lower than the value of the theoretical output $Q_{th,a} = 12853.99 \text{ m}^3/\text{h}$ reported on page 289 in (Che & Chen, 2014) and adopted as a reference value for the case study in (Che & Chen, 2014). Fig. 3. shows the dependence of the angular velocity on the su-

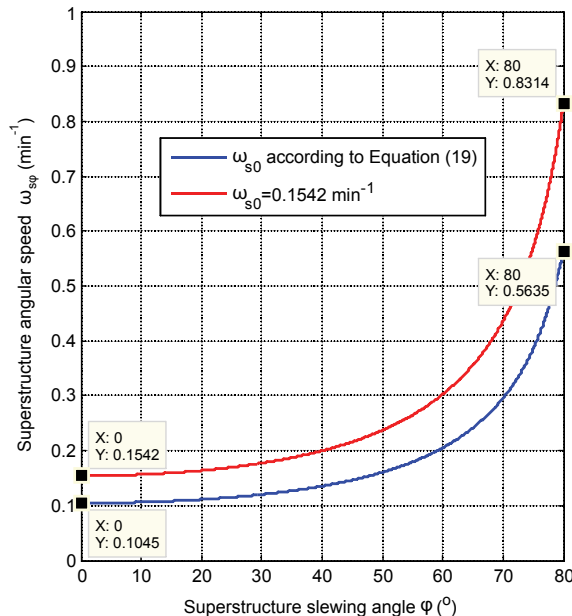


Fig. 3. Dependence of the angular velocity on the superstructure slewing angle

perstructure slewing angle according to Equation (18), for $JS = 4.4 \times 33 = 145.2 \text{ m}^3/\text{min}$ and $JS = Q_{th,a}/60 = 12853.99/60 = 214.23 \text{ m}^3/\text{min}$. Having in mind the structure of Equation (18) it is conclusive that on the entire calculation domain of the angle φ the angular velocity will be lower for $\approx 32.23\%$ if ω_{s0} is calculated based on the theoretical output defined by Equation (17).

Che & Chen (2014) have omitted the fact that the bucket wheel of the BWE SchRs $\frac{4400}{14}$ is of a half-cell type (Durst & Vogt, 1988, page 95). For that type of bucket wheel the filling volume is determined as $J_{nom} = 1.5J$ (Durst & Vogt, 1988, page 64), which gives

$$Q_{th,hcBW} = 60S(1.5J) = 60 \times 33 \times (1.5 \times 4.4) = 13068 \frac{\text{m}^3}{\text{h}} \quad (\text{s})$$

By introducing that value of the theoretical capacity into Equation (19) we obtain

$$\begin{aligned} \omega_{s0} &= \frac{1.5JS}{\left(R_s' - 0.5t_{\max}\right)t_{\max}hf} = \\ &= \frac{1.5 \times 4.4 \times 33}{(73.5 - 0.5 \times 1.55) \times 1.55 \times 8.5 \times 1.45} = 0.1568 \text{ min}^{-1} \end{aligned} \quad (\text{s}')$$

In this way calculated, the angular velocity value is for $\approx 1.69\%$ higher than the value adopted by Che & Chen (2014), Table 1. Besides, Che & Chen (2014) did not present the way of ω_{s0} calculation, but they certainly did not use their Equation (19). However, Durst & Vogt (1988, page 37) state that for normal operation, the depth of a cut in the travel direction of the machine at slewing angle $\varphi = 0$ should not exceed

$$t_0 = 0.9t_{\max} = 0.9 \times 1.55 = 1.40 \text{ m} \quad (\text{t})$$

Apart from that, according to Durst & Vogt (1988, pages 93 and 94) "... the effective output per unit time must, however, be at least 25% higher than the theoretical value to ensure that it is achieved as an average over a longer period of time." If we adopt the assumption of $T = 4000 h_n$ net operating hours per year, the required average theoretical BWE output (in m_{bank}^3) is given as

$$Q_{th,r,b} = 1.25 \frac{Q_{year,r,b}}{T} \left(\frac{\text{m}_b^3}{\text{h}} \right) \quad (\text{u})$$

i.e.

$$Q_{th,r} = 1.25f \frac{Q_{year,r,b}}{T} \left(\frac{\text{m}^3}{\text{h}} \right) \quad (\text{v})$$

When proving the theoretical output of the considered BWE, Durst & Vogt (1988, page 95) state that the required yearly output is $Q_{year,r,b} = 25 \times 10^6 \text{ m}_b^3$, which, according to Equation (v) gives

$$Q_{th,r} = 1.25f \frac{Q_{year,r,b}}{T} = 1.25 \times 1.45 \times \frac{25 \times 10^6}{4000} = 11328.13 \frac{\text{m}^3}{\text{h}} \quad (\text{v}')$$

If we adopt the thus calculated theoretical output as the reference value, then for $t_{\max} = 1.55$ m and $t_0 = 1.4$ m, Equation (j) gives $\omega_{s0,t_{\max}} = 0.1376 \text{ min}^{-1}$ and $\omega_{s0,t_0} = 0.1524 \text{ min}^{-1}$ respectively. For $JS = Q_{th,r}/60$ Equation (19) gives

$$\begin{aligned} \omega_{s0} &= \frac{Q_{th,r}}{60(R'_s - 0.5t_{\max})t_{\max}hf} = \\ &= \frac{11328.13}{60 \times (73.5 - 0.5 \times 1.55) \times 1.55 \times 8.5 \times 1.45} = 0.1359 \text{ min}^{-1} \end{aligned} \quad (q'')$$

Durst & Vogt (1988, page 95) adopted $\omega_{s0} = 0.1542 \text{ min}^{-1}$ which is slightly higher (for $\approx 1.18\%$) than $\omega_{s0,t_0} = 0.1524 \text{ min}^{-1}$ calculated for $t_0 = 1.4$ m. Che & Chen (2014) did not adopt the value $\omega_{s0} = 0.1045 \text{ min}^{-1}$ obtained by their Equation (19). They also adopted $\omega_{s0} = 0.1542 \text{ min}^{-1}$ which is for 47.56% higher than the value obtained by their Equation (19).

Finally, based on the facts:

- That Equation (19) gives the value of ω_{s0} which is considerably lower than the minimum value achievable by the considered machine;
- That in their Case study Che & Chen (2014) adopted the same value of ω_{s0} as the one Durst&Vogt (1988, page 95) obtained by the theory existing in the reference literature; it is conclusive that Equation (19) should be rejected, which Che & Chen (2014) have implicitly done by not using the mentioned equation in their Case study.

4.2. Numerical examples and discussions

Based on the equations given in Table 2, the appropriate software was in-house developed. It enables calculation of the cutting depth, the angular velocity and the theoretical output on the entire calculation domain of the superstructure slewing angle (φ).

First of all, despite the already presented objections, numerical experiment of Che & Chen (2014) was repeated. To make this possible, Fig. 4, value $JS = Q_{th,a}/60 = 12853.99/60 = 214.23 \text{ m}^3/\text{min}$ was used to substitute the actual value $JS = 4.4 \times 33 = 145.2 \text{ m}^3/\text{min}$ in Equations (18) and (19). The results of the repeated numerical experiment, Figs. 5 and 6, Table 3, indicate the existence of numerical errors in the paper of Che & Chen (2014, page 289, Table 1). It can be observed that the maximum percentage difference of the theoretical output (6.81%) corresponds to the maximum percentage difference between the angular velocity (6.81%), Figs. 5 and 6, as it was expected due to the form of Equations (15) and (21).

TABLE 3¹⁾

The influence of the rule “ $1/\cos \varphi$ ” on the BWE theoretical output: V1 vs V2

Items		0°	10°	20°	30°	40°	50°	60°	70°	80°
1/cos φ (V2)	ω (min^{-1})	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	12860.2	12879.0	12911.2	12958.7	13026.3	13125.8	13295.2	13729.4
$\omega(\varphi, R'_s)$ (V1)	ω (min^{-1})	0.1542	0.1565	0.1638	0.1773	0.1997	0.2367	0.3020	0.4359	0.8314
	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	6.2	25.0	57.2	104.7	172.3	271.8	441.2	875.4
Error rate (%)		0	0.05	0.19	0.45	0.82	1.34	2.12	3.43	6.81

¹⁾ The form of the table and all signs are taken from Che & Chen (2014, page 289, Table 1)

²⁾ Shaded cells indicate errors in Table 1 in Che & Chen (2014, page 289)

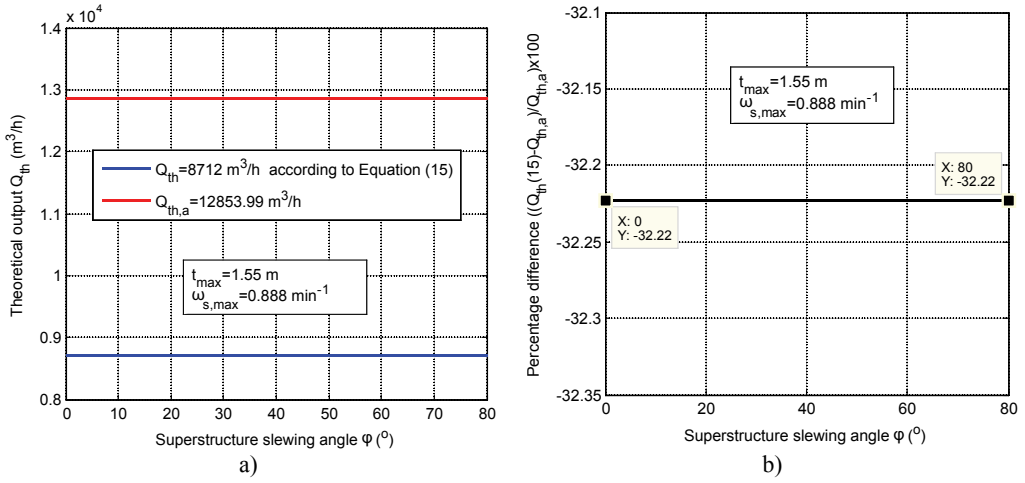


Fig. 4. (a) Theoretical output; (b) percentage difference

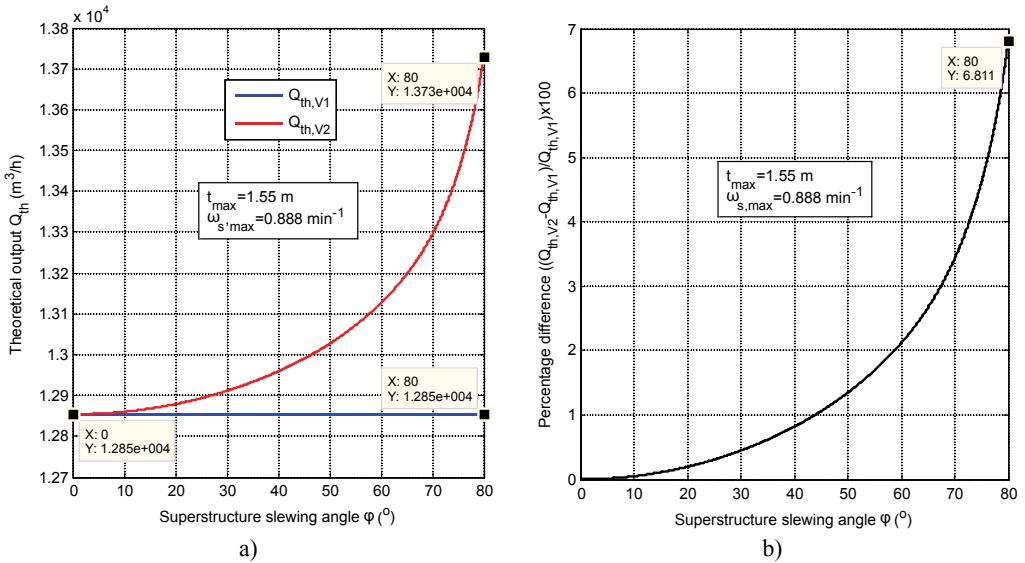


Fig. 5. V1 vs V2: (a) theoretical output; (b) percentage difference

Che & Chen (2014, page 289, Table 1) have adopted that the superstructure angular velocity can reach the value of $0.8880 min^{-1}$ which is higher than the maximum value of $0.618 min^{-1}$ attainable by the considered BWE (Durst & Vogt, 1988, page 95). After reaching the maximum value of $0.618 min^{-1}$ (at $\varphi = 76.26^\circ$ for Variant 1; at $\varphi = 75.56^\circ$ for Variant 2) the angular velocity remains constant, Fig. 7a, so that the maximum percentage difference is 4.78%, Fig. 7b, instead of 6.81% as it was in the previous case. The same conclusion also applies to the theoretical output, Figure 8. At

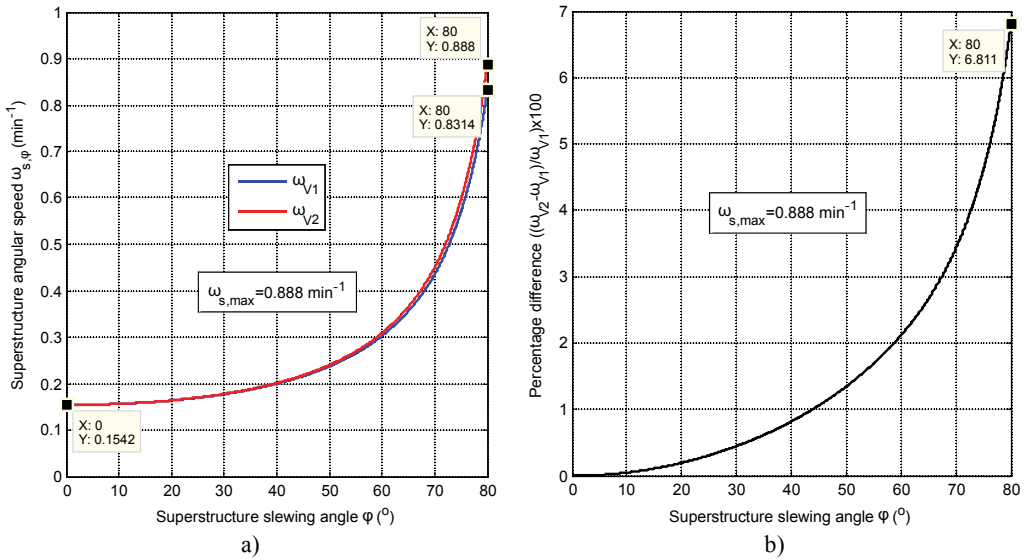


Fig. 6. V1 vs V2: (a) BWB angular velocity; (b) percentage difference

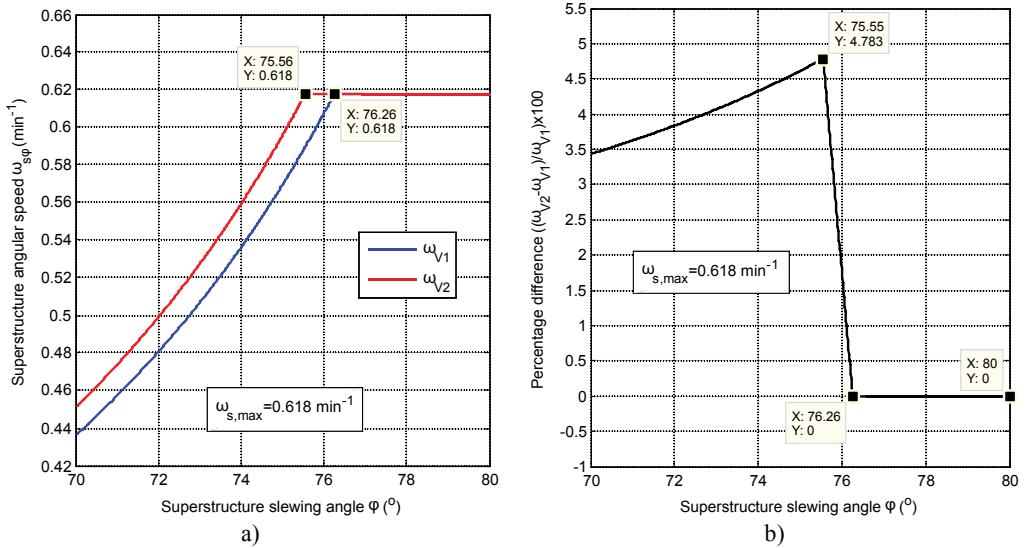


Fig. 7. V1 vs V2: (a) BWB angular velocity for $70^\circ \leq \phi \leq 80$; (b) percentage difference

maximum angular velocity, the theoretical output for Variant 2 reaches maximum value of 13468.8 m³/h. After reaching maximum angular velocity, the theoretical output decreases for both variants and at $\phi = 80^\circ$ has the same value of 9554.9 m³/h i.e. the percentage difference of the theoretical output is equal to zero. Thus, the considered BWE at $\phi = 80^\circ$ cannot achieve the theoretical output of 13729.4 m³/h, Table 3, as follows from the calculations presented in Che&Chen (2014).

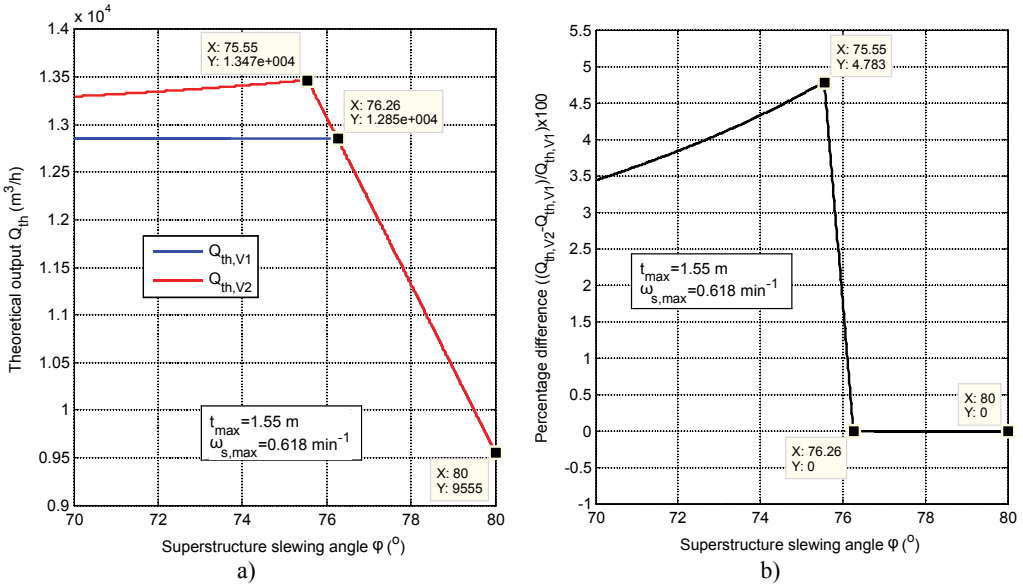


Fig. 8. V1 vs V2: (a) Theoretical output for $70^\circ \leq \varphi \leq 80^\circ$; (b) percentage difference

For real exploitation parameters of the considered machine presented in Durst & Vogt (1988, page 95) i.e. for useful cutting depth $t_0 = 1.4$ m (Equation (t)) and maximum BWB angular velocity $\omega_{s,max} = 0.618$ min⁻¹, we obtain lower values of the theoretical output for all calculation variants (listed in Table 2), Figs. 9 and 10, Table 4.

TABLE 4

Extreme values of the theoretical output for $t_0 = 1.4$ m

Variant	$Q_{th,max}$ (m ³ /h)	$Q_{th,min}$ (m ³ /h)
1	11610.1	8585.5
2	12123.9	8585.5
3	11462.4	7977.2
4	11872.7	8401.5

Based on the results presented, the following conclusions have been drawn:

- The maximum theoretical output for all of the considered variants is lower than the maximum value obtained by using Equation (s), so there is no danger of bucket overcharging as stated in Che & Chen (2014);
- Theoretical output values for both Variant 1 and Variant 2 should be rejected because of the error in defining the reference radius R'_e , Equation (1), as already stated in Section 3 of this paper;
- When the theoretical output is calculated based on the exact expression for the cutting depth (Variant 4), we obtain somewhat higher values compared to Variant 3. The percentage difference, Fig. 11, is lower than 1% for $0^\circ \leq \varphi \leq 50.8^\circ$, lower than 2% for $0^\circ \leq \varphi \leq 64.5^\circ$ and

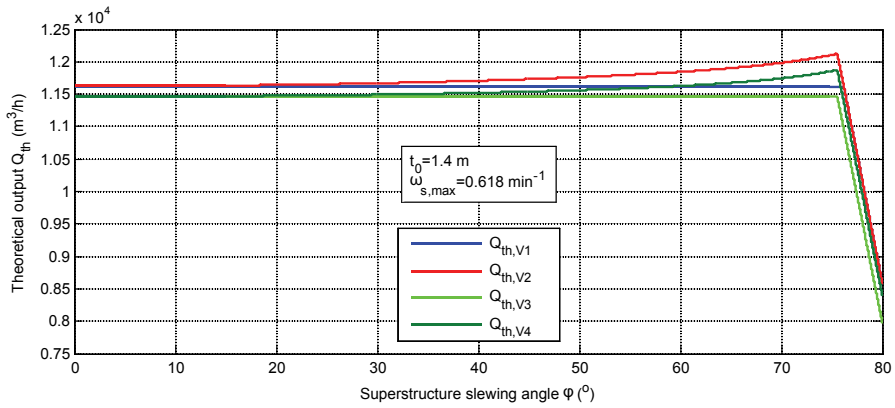
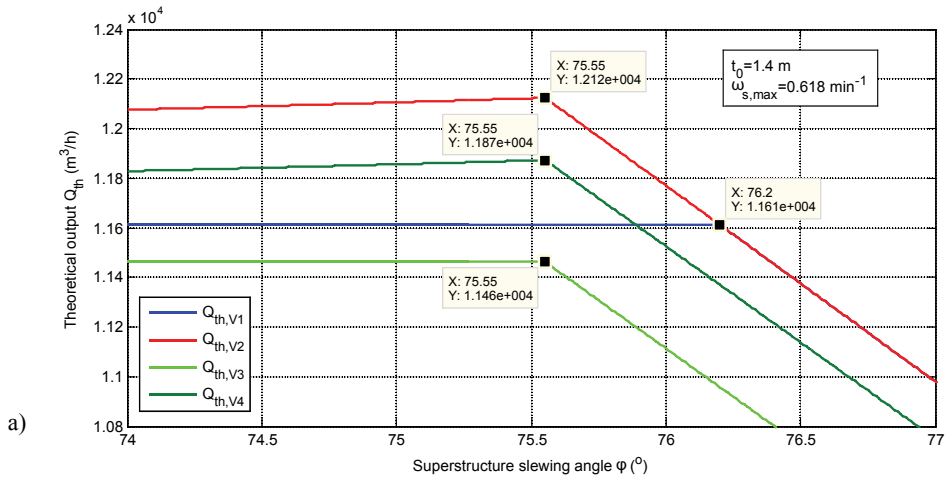
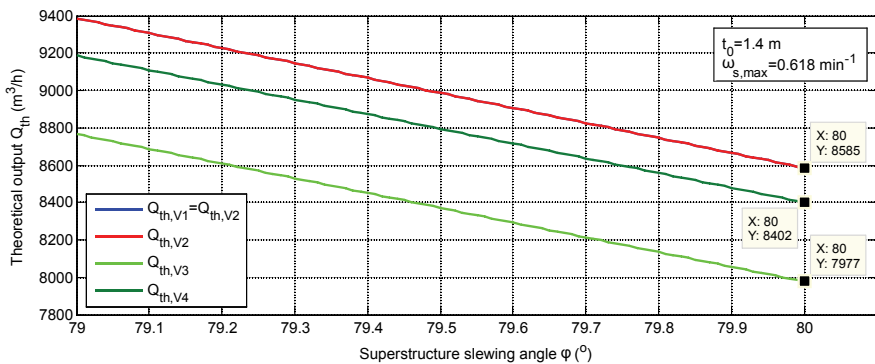


Fig. 9. Theoretical output for $t_0 = 1.4$ m and $\omega_{s,max} = 0.618 \text{ min}^{-1}$



a)



b)

Fig. 10. Details of theoretical output curves for $t_0 = 1.4$ m: (a) detail of maximum values ($74^\circ \leq \phi \leq 77^\circ$); (b) detail of minimum values ($79^\circ \leq \phi \leq 80^\circ$)

less than 3% for $0^\circ \leq \varphi \leq 75.6^\circ$. Maximum value (5.9%) is achieved at $\varphi = 80^\circ$. From the engineering point of view this level of error is acceptable, especially having in mind its distribution in the range $0^\circ \leq \varphi \leq 80^\circ$, and the fact that the error is on the side of safety;

- The decrease of the theoretical output after the angular velocity has reached maximum value, Fig. 9, "... could be accepted as it applies to a small percentage of the total volume to be excavated" (Durst & Vogt, 1988, page 46).

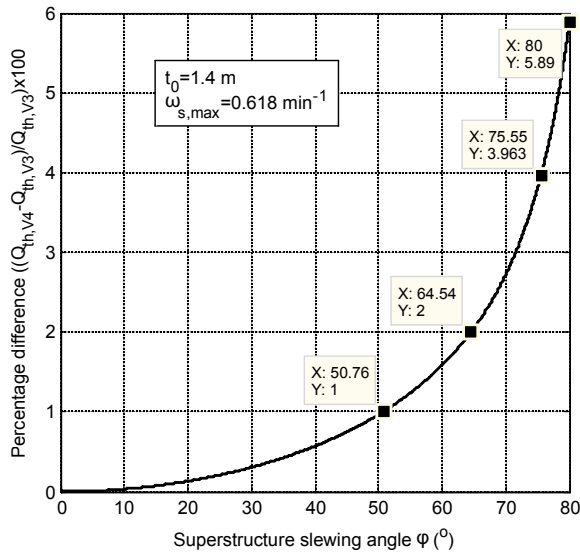


Fig. 11. Percentage difference of BWE theoretical input: V3 vs V4

5. Conclusion

The paper written by Che & Chen (2014) presents a praiseworthy attempt to improve the existing theory of excavating with bucket wheel excavators. Despite that, based on the presented comments and analyses, some observations should be made, as follows:

- The investigated problem is relatively old, and therefore related extensive literature should have been taken into consideration;
- The mathematical formulations presented include considerable mistakes, which inevitably led to wrong conclusions.

Finally, the purpose of this contribution was to point out the need for a much wider approach to the problem of determining the output of the bucket wheel excavator than that of Che & Chen (2014).

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