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Bucket wheel excavators: Dynamic response as a criterion for validation of the total number of buckets

Nebojša B. Gjnatović*, Srđan M. Bošnjak, Ivan Lj. Milenović, Aleksandar Z. Stefanović

University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade, Serbia

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ABSTRACT

An original method for validation of the number of buckets on the working device of a bucket wheel excavator based on the dynamic response of its slewing superstructure (SS) is presented. A set of 16 seemingly acceptable solutions which satisfied the rigid design restrictions, based on the preservation of the existing (a) bucket wheel drivetrain, (b) theoretical capacity, (c) characteristics of the excavated soil and (d) position of the superstructure centre of gravity (CoG), was analysed. Already on the basis of the limiting vertical and lateral accelerations of the bucket wheel centre, which represents a well-grounded indicator of its dynamic behaviour prescribed by the code DIN 22261-2, 14 out of 16 analysed design variants have been discarded, reducing the set of possible solutions to only two – the originally-designed variant (with 17 buckets), and the variant with 20 buckets. Conclusions on the validity of these two design variants were derived on the basis of the dynamic response analysis of the referent points of the SS. The analysis of the impact of soiling on the dynamic response of the SS has shown that negative dynamic effects, observed in the preceding analysis of the originally-designed solution, increase with the amount of the adhered material. Although the redesigned variant with 20 buckets has proven as the only suitable solution from the standpoint of dynamic behaviour of the SS, the results have to be assessed carefully due to the fact that the reduction of the mass of the bucket wheel steel structure by more than 14% leads to the appearance of unfavourable dynamic effects, even though the SS CoG position is preserved.

1. Introduction

Due to the perennial exploitation in extremely harsh working conditions, failures and breakdowns of the bearing structures and mechanical subsystems of bucket wheel excavators (BWE) [1–6] occur relatively frequently. The most important consequence of such failures, besides the risk to the safety and life of the workers [7–9], is the downtime of the machine, which accumulates extremely high financial losses [10,11]. Modernization of the BWE fleet is conducted in two equally represented directions. In addition to the acquisition of new units, redesign, followed by modernization [12] of the dated and obsolete machines (for example, the average age of the BWEs in the biggest mining basin in Serbia, Kolubara, is 29 years [10]), is also executed in order to reduce power consumption, reduce maintenance costs by decreasing the number of scheduled repairs and, most importantly, increase productivity by reducing the number of accidental stops. Apart from the age of excavating units, relatively frequent failures and accidental stops are also the consequence of an everlasting tendency towards improving the performances of BWEs, which has not been adequately supported by the calculation methods and technical regulations. This points to a conclusion that it was practically impossible to carry out a detailed stress-strain analysis and the dynamic behaviour analysis during the stage of their design, as stated in [13]. Redesign, conducted in order to achieve modernization of the machine, is a procedure inevitably followed by the alternation of operating (constructional) parameters which strongly influence the structural behaviour of the BWEs.

The excavating subsystem, consisting of a bucket wheel (BW) with its belonging drivetrain, is the most important part of a BWE, since its construction determines the output and total behaviour of the machine. Although the literature relevant to the field of BWEs clearly states that the redesign of an excavating system with the goal of correcting the design errors would be difficult and expensive, if at all possible, after the machine has been constructed [14], in modern engineering practice there is a rising number of scientific institutions and research and development centres dealing with this extremely complex engineering challenge [15–26]. As a part of the overall modernization of the excavating units operating on the open-cast mines in the Oltenia coal basin

* Corresponding author.
E-mail address: ngnjatovic@mas.bg.ac.rs (N.B. Gnjatović).

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(Romania), 17 out of 33 BWEs of the same design conception (SchRs 1400) were subjected to revitalization and modernization [15], based on the replacement of the existing BW drivetrain (essentially replacing the gearbox of the classical design with a planetary type) and changing the number of buckets (replacing 9 filling +9 cutting with 20 filling-cutting buckets) [16]. Apart from the analysis of the impact of change in the number of buckets on the modal characteristics of the BW steel structure [17], additional information on the consequences of such changes on the dynamic behaviour of the redesigned BWEs was not available to the authors of this paper. A similar project, on a smaller scale, was conducted in the Kolubara open-pit mine in Serbia, when the 55-year old BWE SchRs 350 was subjected to redesign and modernization of the excavating subsystem [18], which included substituting the planetary gearbox in place of the existing, spur-geared, as well as the installation of two additional buckets on the BW (increasing the total number from 8 to 10). In paper [19], the analysis of excitation due to the resistance to excavation and conclusions on the, potentially, more favourable influence of the said excitation on the dynamic behaviour of the system, have been presented.

Negative dynamic effects, which have been diagnosed experimentally, gave rise to the need to replace the existing bucket wheels on two conceptually-different BWEs (SchRs 4600.50 and SchRs 4600.30), operating in the Bełchatów surface mine in Poland [20]. On the basis of the experimental and numerical modal analyses of the entire structures, conclusions were drawn on the design of a unique BW steel structure and the corresponding number of buckets which would satisfy the requirements for safe operation of both BWEs without changes to the existing drivetrains.

Since the deployment of the BWEs SRs 2000 (1970), one of its most widespread models (a total of 55 units [24] are in exploitation in various European and Asian surface mines), the manufacturer (Takraf) has dedicated special attention to raising the levels of effectiveness and reliability of the excavating device. The bucket wheel structure has been significantly improved (a single-walled in place of the double-walled design conception), and an array of modern designs of the bucket wheel drivetrain of different conceptions and power have been installed [21–24]. Research has been carried out with respect to the impact of dynamics of the SS [27] on the loading of the undercarriage, the influence of the redesigned BW boom head on its modal characteristics [26], and the impact of the input shaft on the dynamic response of the bucket wheel drive [25].

To the authors' best knowledge, none of the aforementioned cases provide any information on the impact of the number of buckets on the dynamic response of the slewing superstructure (SS). On the other hand, the number of buckets is a key parameter because of its influence on the overall dynamic behaviour of the SS and, as such, is decisive in the process of selection and validation of the appropriate design solutions. For this reason, an original method for performing research on the influence and validation of the number of buckets based on the dynamic behaviour of the SS, using the BWE SchRs 1600, Fig. 1, as the base model, is presented in this paper.

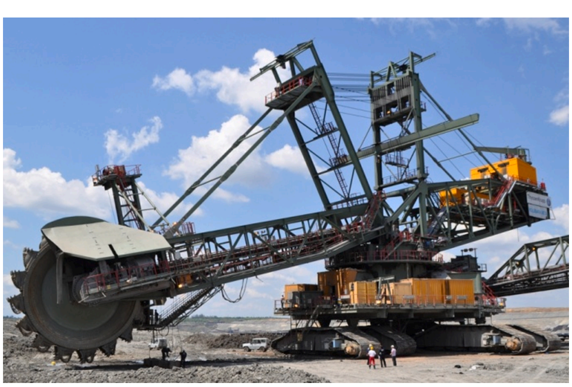

Fig. 1. BWE SchRs 1600 (Serbian mining basin Kolubara): mass (with the mobile conveyor) 3345 t, declared theoretical capacity 6600 m^3/h.

2. Dynamic model of the slewing superstructure

A numerical analysis of the dynamic responses of large scale machines such as BWEs can often prove difficult to perform due to several obstacles, such as the extreme complexity of the corresponding dynamic system and limitation of the finite element analysis, which is reflected on the discrete nature of the method.

Dynamic behaviour of the BWE SchRs 1600 SS was investigated using a reduced spatial dynamic model with 64 DOF, Fig. 2, developed and validated according to the procedures presented in [28–30]. Validation of this procedure, which supplements the finite element method in its application for the dynamic behaviour analysis of the spatial truss structures of BWEs, was conducted on the basis of the relevant measurements and used to develop the models and conduct dynamic response analyses of the SSs with different design conceptions [31,32]. The model, presented in Fig. 2, allows modal analysis, as well as the analysis of the dynamic response in a continuous domain of variation of both the constructional parameters and the parameters of excitation. The development procedure for this model is presented in detail in [33].

Although BWEs are constructions with changeable configuration, which makes the analysis of their dynamic behaviour extremely complex [29,34,35], according to the findings presented in [30], the influence of the BW boom inclination angle on the modal characteristics of the analysed excavator SS is not significant, Fig. 3. A change in the geometric configuration of the SS of the analyzed BWE does not have an impact on the values of the 6th, 7th, 8th, 10th, 12th and 14th natural frequencies, Fig. 3(a). Relative changes in the values of the 2nd, 3rd, 9th, 11th and 13th natural frequencies are lower than 1%. The inclination angle of the BW boom has some impact on the 1st, 4th and 5th natural frequencies, whose maximum absolute values of percentage deviations equal to 2.5%, 1.6% and 3.3%, respectively, Fig. 3(b), (c) and (d). Being that the said value changes are acceptable from the standpoint of engineering accuracy, a conclusion can be drawn that changes in the geometric configuration do not have a significant impact on the modal characteristics of the system. Therefore, the horizontal position of the BW boom was adopted as referent for further analysis, Table 1.

3. Selection and validation of the total number of buckets on the bucket wheel

The newly-developed method of selection and validation of the total number of buckets on the basis of dynamic response of the superstructure is conducted in three stages, which are:

- determining the boundaries of the interval of change of the total number of buckets;
- validation of the total number of buckets based on the criterion of resonant states;
- validation of the total number of buckets based on the criterion of limiting accelerations, including the analysis of the impact of soiling and mass of the BW steel structure.

Later in this paper, the application of the proposed method is demonstrated on the example of BWE SchRs 1600, adhering to the following design restrictions (DRs):

- DR1-Preservation of the declared theoretical capacity ($Q_{0,D}$ = 6600 m^3/h = const.);
- DR2-Use of the same BW drivetrain (P_{BW} = 1150 kW = const., n_{BW} = 990 rpm = const.);
- DR3-Preservation of the BW diameter (D_{BW} = 12.25 m);

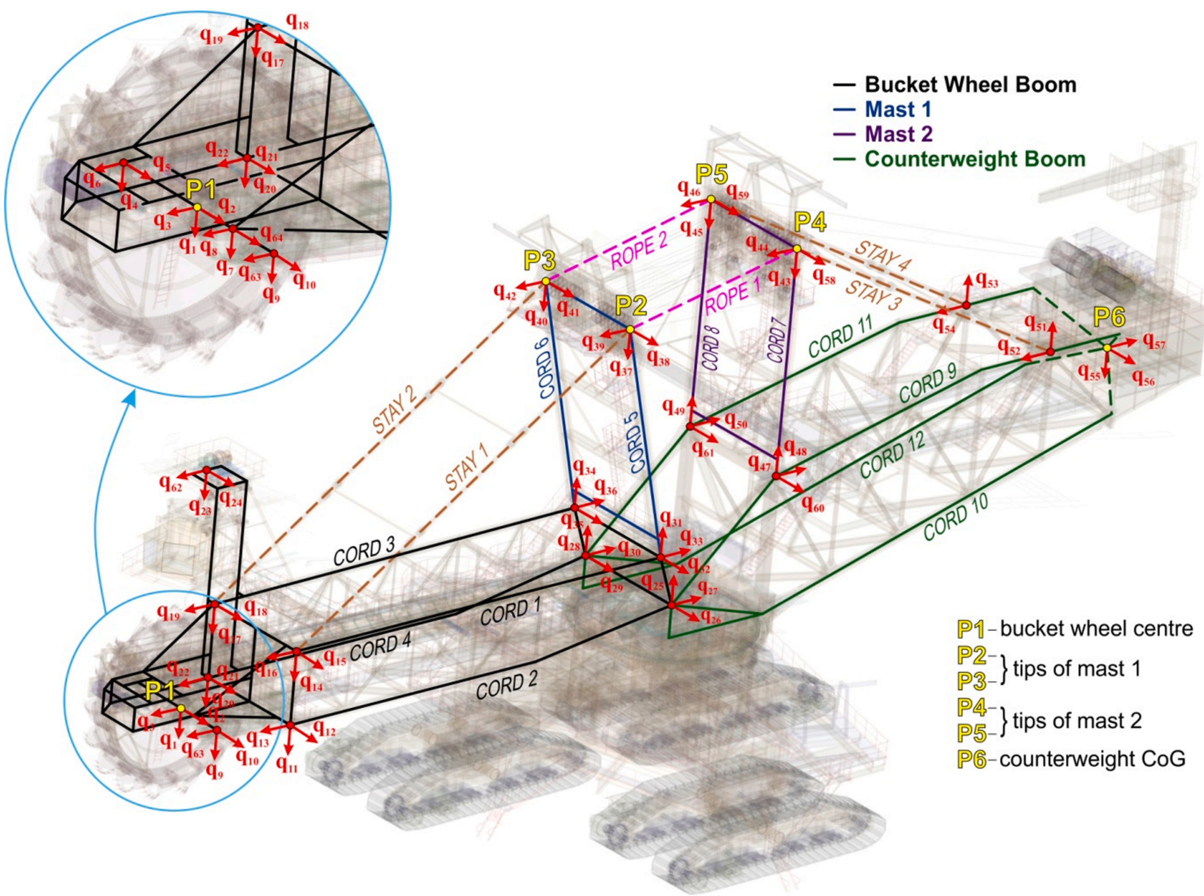

Fig. 2. Reduced spatial dynamic model of the BWE SchRs 1600 superstructure.

- DR4-The ability to excavate the soil dominantly present in the "Kolubara" open pit mine (specific cutting resistance k_A = 5 daN/cm^2, swell factor $f = 1.3$, [37]);
- DR5-Preservation of the position of the SS centre of gravity (CoG), determined and presented in [36, Subsection 7, Table 7, Variant 4 (V4)].

It is important to note that the use of the proposed method on a distinct model of the BWE in this paper is for demonstration purposes only, a fact which should not diminish the generality of its application.

3.1. Determining the boundaries of the interval of change of the total number of buckets

In the general case, changeability of the number of buckets in interaction with the soil is one of the fundamental characteristics of the excavation process of a BWE. The maximum and minimum number of buckets in interaction with the soil is determined by the ratio between the angle of excavation (ψ_E) and the angular step of the buckets, $\theta_B = 2\pi/n_B$, where n_B is the total number of buckets on the BW. The mean ($n_{B,E,a}$), minimum ($n_{B,E,min}$) and maximum ($n_{B,E,max}$) number of buckets in interaction with the soil are determined according to the expression [38]: $n_{B,E,a} = \psi_E/\theta_B$, $n_{B,E,min} = \mathrm{int}(n_{B,E,a})$, $n_{B,E,max} = n_{B,E,min} + 1$. The lower boundary of the set of the total number of buckets on the BW ($n_{B,min}$) is determined under the condition that, for the referent angle of excavation $\psi_E = \pi/2$, the mean number of buckets in interaction with the soil has to be higher than 2, i.e. $n_{B,E,a}$=$(\pi/2)/(2\pi/n_{B,min}) = n_{B,min}/4$ greater than 2=>$n_{B,min} = 9$. The upper boundary of the set of the total number of buckets on the BW is determined by the conditions of their discharge. For the remainder of the analysis, $n_{B,max} = 24$ is established. The influence of the total number of buckets on the number of buckets in interaction with the soil is shown in Fig. 4.

The number of discharges of the buckets is equal to the product of the number of buckets (n_B) and the frequency of the BW revolution (n_{BW}) [38], $n_D = n_B n_{BW}$. Starting from the fact that the theoretical capacity of the excavating device is proportional to the number of discharges and the volume of the buckets (q_B), $Q_0 = n_D q_B = n_B n_{BW} q_B$ [39], in order to meet the DR1 and DR2, any change in the number of buckets requires an appropriate change in their volume, $q_B = Q_{0,D}/(n_B n_{BW})$, Fig. 5.

A change in the total number of buckets, while adhering to the DR1-DR3, leads to the change of the referent chip cross-section dimensions: cutting width, $b_0 = [2Q_{0,D}/(n_B n_{BW} \psi_E D_{BW} f)]^{1/2}$, and cutting depth, $s_0 = b_0\pi/2$ [39], Fig. 6.

Based on the experimental-analytical research [37], characteristics of the soil found in the open pit mines of Serbia mostly befall under the IV category. According to [37], the specific resistance to excavation, reduced to the chip cross-section (k_A) befalls in the range between 3.1 and 6.4 daN/cm^2. Papers [40,41], which simulate the loads on three different design conceptions of the bucket wheel excavators, each operating, just like BWE SchRs 1600, in the open pit mine "Kolubara", adopt the average specific resistance to excavation of $k_A = 5.0$ daN/cm^2. With the attention to the facts that: (1) the number of buckets in interaction with the soil and the referent dimensions of the chip depend on the total number of buckets; (2) at the adopted value of $\psi_E = \pi/2$, the cutting depth of the observed bucket varies in the range of $s = 0 \ldots s_0$; (3) the specific resistance rises with the cutting depths that are lower than the critical value [42], the calculation of the available specific resistance to excavation has been performed, Fig. 7, where the available moment of excavation is determined adhering to the DR1-DR3. It is observed, Fig. 7, that for all the considered numbers of the buckets, the condition $k_{A,av} \geq k_A = 5.0$ daN/cm^2 (DR4) is satisfied, i.e. that the boundaries of the interval of change of the total number of buckets on the BW, $n_{B,min} = 9$ and

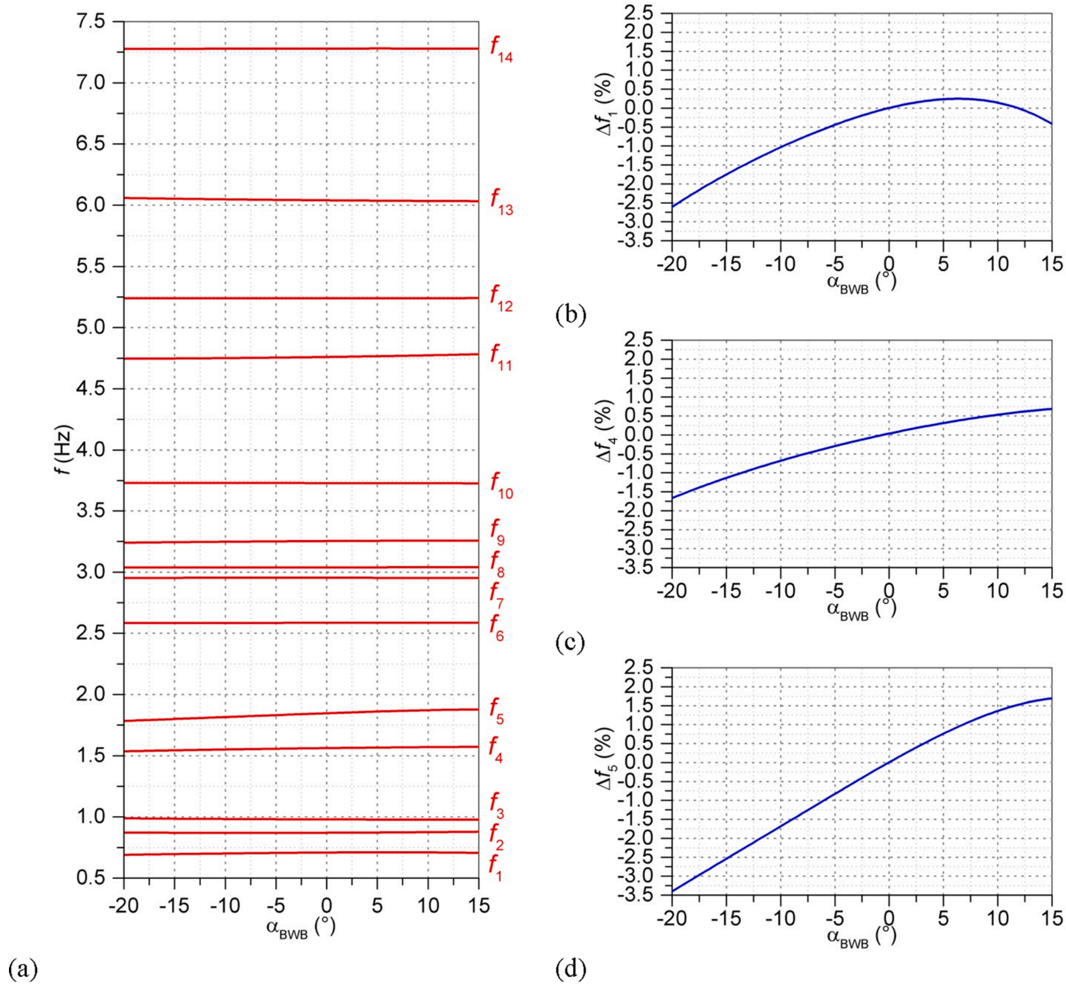

Fig. 3. The influence of the SS geometric configuration on the spectrum of natural frequencies: (a) the first 14 natural frequencies dependent on the BW boom inclination angle ($-19.52^\circ \le \alpha_{BWB} \le 14.1^\circ$, [36]); percentage deviations of the values of the 1st (b), 4th (c) and 5th (d) natural frequencies from values obtained for the horizontal position of the BW boom ($\alpha_{BWB} = 0^\circ$) ($\Delta f_i = \left(\left(f_i(\alpha_{BWB}) - f_i(\alpha_{BWB} = 0^\circ)\right)/f_i(\alpha_{BWB} = 0^\circ)\right) \times 100$ for i $= 1, 4, 5$).

Table 1
Natural frequencies of the reduced spatial dynamic model of the SS ($\alpha_{BWB} = 0^\circ$).

Mode	1	2	3	4	5	6	7	8	9	10	11	12	13	14
f (Hz)	0.71	0.87	0.98	1.56	1.85	2.59	2.95	3.04	3.25	3.73	4.76	5.24	6.04	7.28

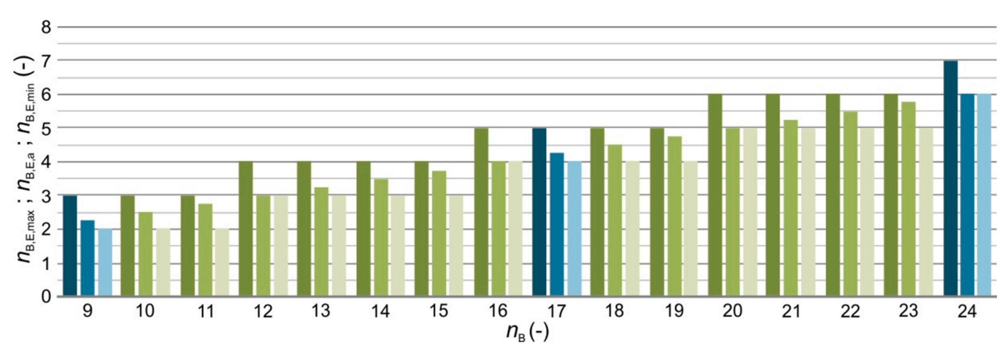

Fig. 4. Maximum, mean and minimum number of buckets in interaction with the soil for $\psi_E = \pi/2$.

$n_{B,max} = 24$, satisfy the DR1-DR4.

3.2. Validation of the total number of buckets based on the criterion of resonant states

In the second phase, from the set N_B={$n_{B,min} = 9,10,\ldots,n_{B,DES} = 17,$

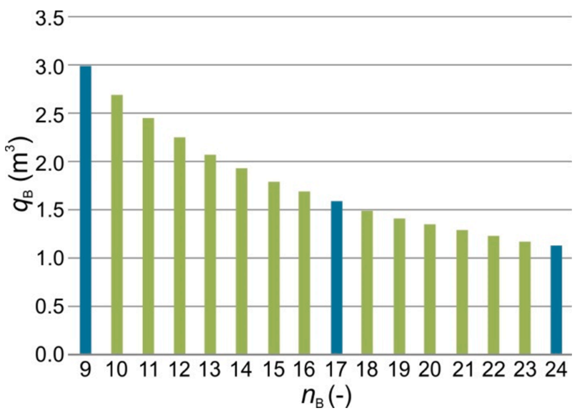

Fig. 5. Volume of buckets for $Q_{0,D} = 6600$ m^3/h and $n_{BW} = 4.08$ rpm.

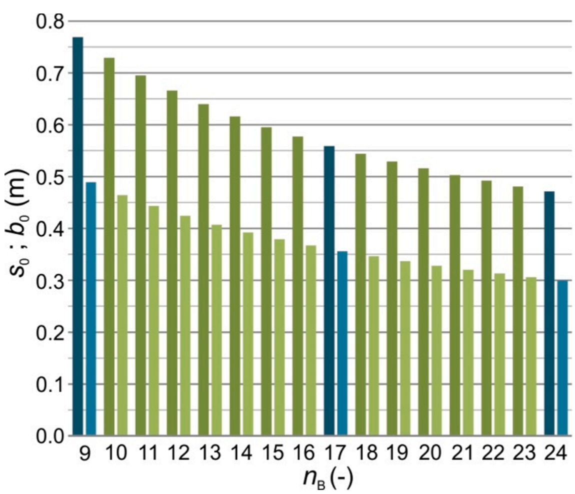

Fig. 6. Referent chip cross-section dimensions for $Q_{0,D} = 6600$ m^3/h, $n_{BW} = 4.08$ rpm, $D_{BW} = 12.25$ m and $f = 1.3$.

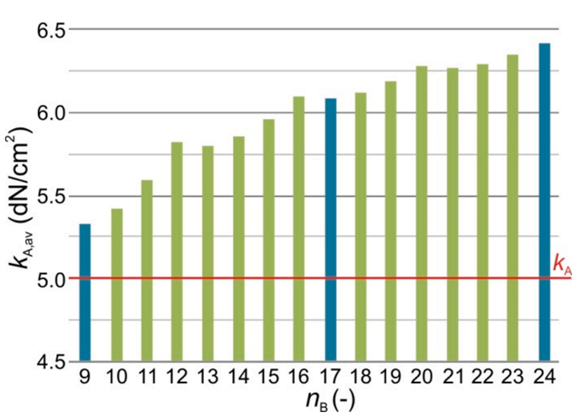

Fig. 7. Available specific resistance to excavation for $Q_{0,D} = 6600$ m^3/h, $n_{BW} = 4.08$ rpm, $D_{BW} = 12.25$ m, $f = 1.3$ and $\psi_E = \pi/2$.

…,$n_{B,max} = 24$}, the numbers of buckets which would lead to the appearance of resonances are eliminated. In order to apply the criterion of resonant states, apart from the natural frequencies of the dynamic model of the superstructure, Table 1, it is also important to identify the referent spectrum of frequencies of the external loads caused by the resistance to excavation.

3.2.1. Dynamic characteristics of the loads caused by the resistance to excavation

The loads caused by the resistance to excavation were calculated according to the procedures presented in [42–46] and then approximated with Fourier trigonometric polynomials with five harmonics, Fig. 8, with respect to the results and conclusions made in [32]. Even though the number of buckets (n_B) is a parameter of a discrete nature, the analyses were conducted in a continuous domain (parameter $n_{B,CON}$, $n_{B,CON,min} = n_{B,min}$, $n_{B,CON,max} = n_{B,max}$) in order to perceive the influence of the proximity of certain resonant states on the dynamic response of the construction. Change in the number of buckets leads to a change in the fundamental frequency of excitation $f_{E1} = n_B n_{BW}$ and, therefore, all of the higher excitation frequencies, mean values, $M_{T,m}=(M_{T,max} + M_{T,min})/2$, as well as amplitude values $M_{T,a}=(M_{T,max}–M_{T,min})/2$ of the considered loads, while their maximum values, according to the DR2, remain constant, Fig. 8, Table 2. It is observed that the frequencies and mean values of excitations monotonously rise with the increase of the number of buckets, while the values of amplitudes have a monotonously decreasing character. If the designed state ($n_{B,DES} = 17$) is taken as the basis for the analysis of the results presented in Table 2, it can be concluded that, Table 3: (1) the values of excitation frequencies are in the range between –47.1% and + 41.2%; (2) for $n_{B,min} = 9$, the mean values of loads caused by the resistance to excavation are 12.5% lower, while the load amplitudes are 65.5% higher; (3) for $n_{B,max} = 24$, the mean values of loads are 4.7% higher and load amplitudes are 25.5% lower. A change in the mean and amplitude values, along with the unchanged maximum value of the considered load (DR2), leads to the change in the values of the load unsteadiness indicators [38,44]: the non-uniformity coefficient, $\kappa_{nu}=(1–2M_{T,a}/M_{T,max})^{-1}$, and the coefficient of dynamism, $\kappa_d = M_{T,max}/M_{T,m}$, Figs. 9 and 10. Both of the indicators of load unsteadiness have a monotonously decreasing character, Figs. 9 and 10, which is the consequence of the already-described characters of the mean and amplitude load values. In relation to the designed state, the values of the coefficients κ_{nu} and κ_d for $n_{B,min} = 9$ are 42.1% and 13.7% higher, respectively, while, for $n_{B,max} = 24$, they are 10.3% and 4.6% lower, respectively.

3.2.2. Cut-off scanning of the frequency spectrums

By scanning the spectrums of the SS dynamic model natural frequencies (the first 14) and the frequencies of the excitation caused by the excavation process (the first 5), on the continuous domain of change of the total number of buckets (parameter $n_{B,CON}$), a total of 31 resonant states have been observed, Fig. 11, Table 4. On the discrete subdomain (parameter n_B), only one case which leads to the appearance of a

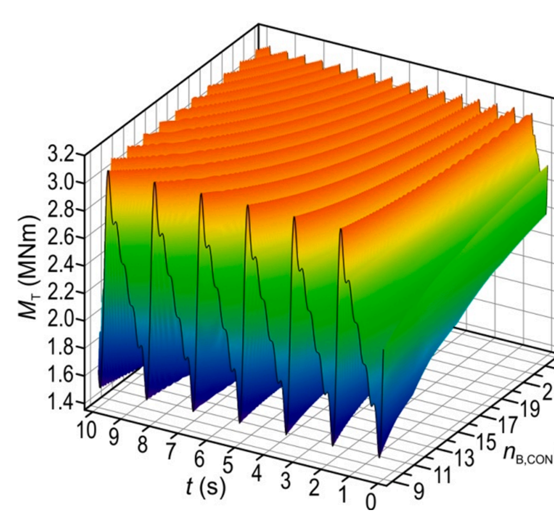

Fig. 8. Moment of excavation as a typical representative of the excavation loads.

Table 2
The first frequency of excitation (f_{E1}), mean ($M_{T,m}$) and amplitude values ($M_{T,a}$) of the moment of excavation.

n_B	$M_{T,m}$ (kNm)	$M_{T,a}$ (kNm)	f_{E1} (Hz)
9	2296.1	797.4	0.612
10	2363.2	730.3	0.68
11	2408.1	685.4	0.748
12	2439.8	653.7	0.816
13	2492.6	600.9	0.885
14	2530.4	563.1	0.953
15	2558.6	534.9	1.021
16	2580.3	513.2	1.089
17	2611.6	481.9	1.157
18	2635.8	457.7	1.225
19	2655.0	438.5	1.293
20	2670.5	423.0	1.361
21	2691.3	402.2	1.429
22	2708.1	385.4	1.497
23	2722.0	371.5	1.565
24	2733.6	359.9	1.633

resonance has been observed. Resonant state R28, Fig. 11, occurs for $n_B = 14$, Table 4, which can be discarded on the basis of the results of a modal analysis on its own.

However, based on the presented data, comments on the effects of the proximity to certain resonant states on the response of the system cannot be made, nor can any conclusion on the quality of the adopted design be derived. This is because modal analysis, on its own, cannot provide any insight on the ranges of resonant areas. Thus, in combination with the lack of proper recommendations by the known literature, it is necessary to perform the analysis of the dynamic system response.

3.3. Validation of the total number of buckets based on the criterion of limiting accelerations

The limiting accelerations of the referent points are used as a criterion for the diagnosis of negative dynamic effects during the experimental and analytical analysis of the dynamic response of BWEs [12,31,47,48]. In the third stage of the proposed method, the values of limiting accelerations prescribed by the standard [49], were adopted as the cut-off criterion for the assessment of the dynamic response of the SS model. The process of determining the dynamic response in the referent points of the model, Fig. 2, to the excitation caused by the resistance to excavation is described in detail in [33].

3.3.1. Cut-off scanning of accelerations of the bucket wheel centre

The response in the bucket wheel centre (BWC, referent point P1 in Fig. 2) is, undoubtedly, the most important indicator of the slewing superstructure's dynamic behaviour. Excessive displacements increase the influence of rheolinearity [44], while excessive accelerations lead to the appearance of high dynamic loads. The existing literature and technical regulations provide no limitations for the displacement of the BWC, only accelerations. According to the code [49], the maximum permissible values of the vertical and lateral accelerations of the BW centre are $a_{V,per} = 1$ m/s^2 and $a_{L,per} = 0.167$ m/s^2, respectively. In this stage of the process of validation of the number of buckets, the maximum values of vertical and lateral accelerations of the BWC ($a_{V,P1,max}=\ddot{q}_{1,max}$, $a_{L,P1,max}=\ddot{q}_{2,max}$, Fig. 2), Figs. 12 and 13, Tables 5 and 6, have been used to determine the number of buckets which would satisfy the

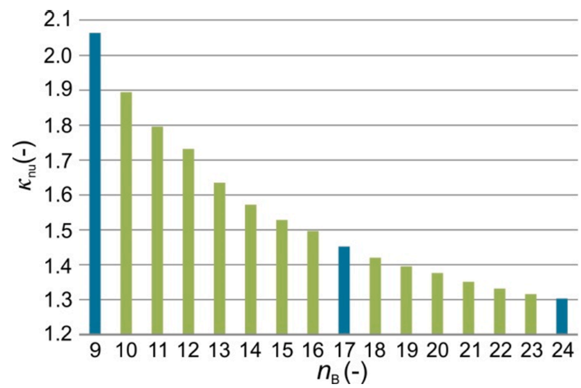

Fig. 9. Coefficient of non-uniformity.

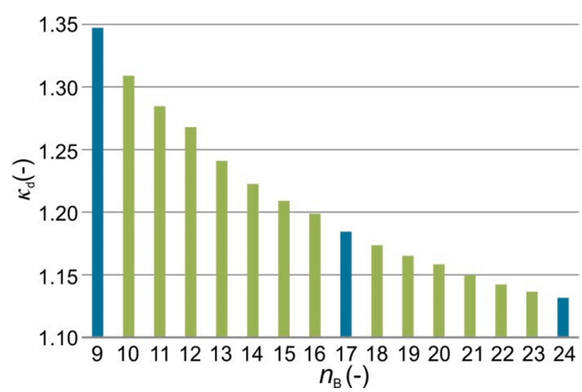

Fig. 10. Coefficient of dynamism.

Table 3
Percentage difference of the excitation frequencies (f_E), mean ($M_{T,m}$) and amplitude values ($M_{T,a}$) of the moment of excavation in relation to the designed state (base model).

n_B	$\frac{f_{E,n_B} - f_{E,n_{B,DES}}}{f_{E,n_{B,DES}}}100(\%)$	$\frac{M_{T,m,n_B} - M_{T,m,n_{B,DES}}}{M_{T,m,n_{B,DES}}}100(\%)$	$\frac{M_{T,a,n_B} - M_{T,a,n_{B,DES}}}{M_{T,a,n_{B,DES}}}100(\%)$
9	−47.1	−12.1	65.5
10	−41.2	−9.5	51.5
11	−35.3	−7.8	42.2
12	−29.4	−6.6	35.6
13	−23.5	−4.6	24.7
14	−17.6	−3.1	16.8
15	−11.8	−2.0	11.0
16	−5.9	−1.2	6.5
17	0.0	0.0	0.0
18	5.9	0.9	−5.0
19	11.8	1.7	−9.0
20	17.6	2.3	−12.2
21	23.5	3.1	−16.5
22	29.4	3.7	−20.0
23	35.3	4.2	−22.9
24	41.2	4.7	−25.3

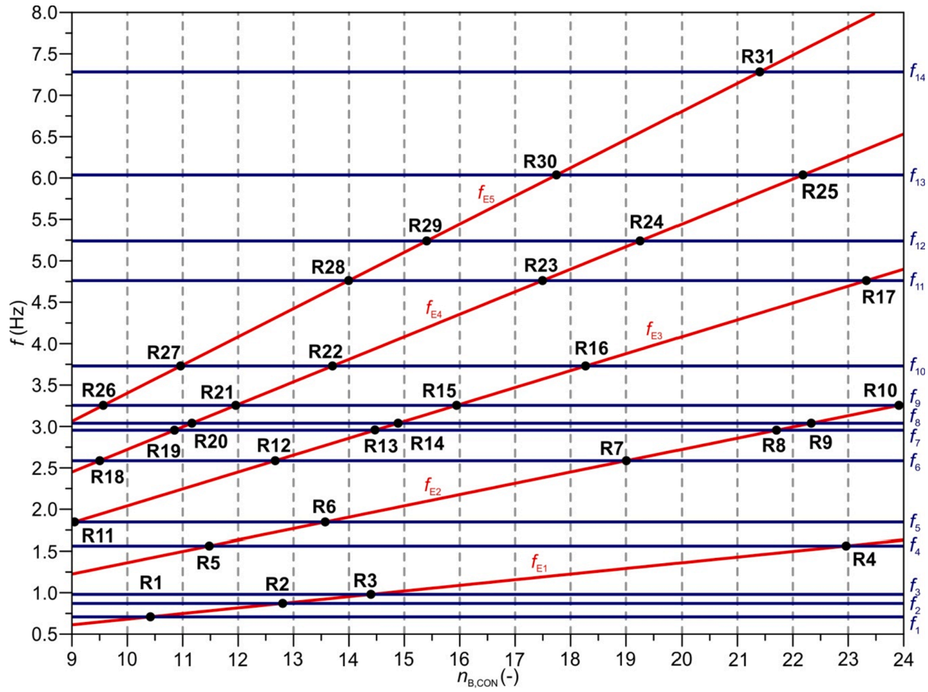

Fig. 11. The first 14 natural frequencies of the slewing superstructure model vs. the frequencies of the first five harmonics of the excitation caused by the resistance to excavation (resonances are marked with black dots and the label Ri, i = 1,2,…,31).

Table 4
The order of resonance and values of the analysed parameter.

$n_{B,CON}$	10.42	12.8	14.4	22.96	11.48	13.57	19.01	21.71
Label	R1	R2	R3	R4	R5	R6	R7	R8
Order	I				II			
$n_{B,CON}$	22.33	23.92	9.05	12.67	14.47	14.89	15.94	18.27
Label	R9	R10	R11	R12	R13	R14	R15	R16
Order	II		III					
$n_{B,CON}$	23.33	9.50	10.85	11.17	11.96	13.70	17.50	19.26
Label	R17	R18	R19	R20	R21	R22	R23	R24
Order	III	IV						
$n_{B,CON}$	22.18	9.57	10.96	14.00	15.40	17.75	21.40	
Label	R25	R26	R27	R28	R29	R30	R31	
Order	IV	V						

adopted criteria.

Based on the data presented in Fig. 12 and Table 5, it can be concluded that 6 out of 16 possible design variants do not satisfy the criterion of limiting vertical acceleration of the BWC. That includes the variant with 14 buckets on the BW, which has already been discarded by the modal analysis. The lateral acceleration of the BWC, Fig. 13 and Table 6, has a significantly higher sensitivity to the proximity to the resonant states, thus resulting in only 3 out of 16 considered variants satisfying the cut-off criterion of the limiting lateral acceleration. Worthy of a mention is the fact that the design variant with 10 buckets satisfies the lateral acceleration criterion but, at the same time, this cut-off parameter has insufficient sensitivity to the appearance of the first-order resonance (R1), whose modal deflection shape (see Fig. 7(b) in [33]), singles out vibrations of the system in the vertical plane as the dominant form of the system oscillations. With that in mind, this variant has been discarded, reducing the set of possible solutions to just two – the originally-designed one ($n_{B,DES} = 17$) and the variant with $n_B = 20$ buckets on the BW. Conclusions on the validity of these two design solutions can be derived only after taking into consideration the dynamic response analysis of the remaining referent points (P2, …, P6) of the reduced dynamic model of the SS, Fig. 2.

3.3.2. *Cut-off scanning of accelerations of the referent points of the slewing superstructure*

In addition to the BW boom (referent point P1: BWC), the standard [49] also limits the acceleration of the central structure and the masts (tips of the mast 1: referent points P2 and P3; tips of the mast 2: referent points P4 and P5), as well as the acceleration of the counterweight boom (referent point P6: counterweight CoG).

The originally designed solution ($n_{B,DES} = 17$) satisfies the criterion of limiting vertical accelerations in all referent points. This is also true for the criterion of limiting lateral accelerations, except for the referent points P2 and P3 (tips of the mast 1). In these points, the values of the maximum lateral accelerations are higher than those prescribed by the standard, Table 7, which is explained by the fact that the system is oscillating in the region dominantly influenced by the resonant states R15 and R16, Fig. 14. In these states, the 9th and 10th modes, whose deflection shapes are strongly influenced by the lateral motion of the mast 1 (see Fig. 7(r) and 7(t) in [33]) are entering a 3rd order resonance (Table 4). Equal values of the maximum lateral accelerations of the referent points P2 and P3, Table 7, are explained by the fact that, in the lateral direction, mast 1 behaves as a symmetrical, symmetrically-constrained and symmetrically-loaded substructure. For the variant

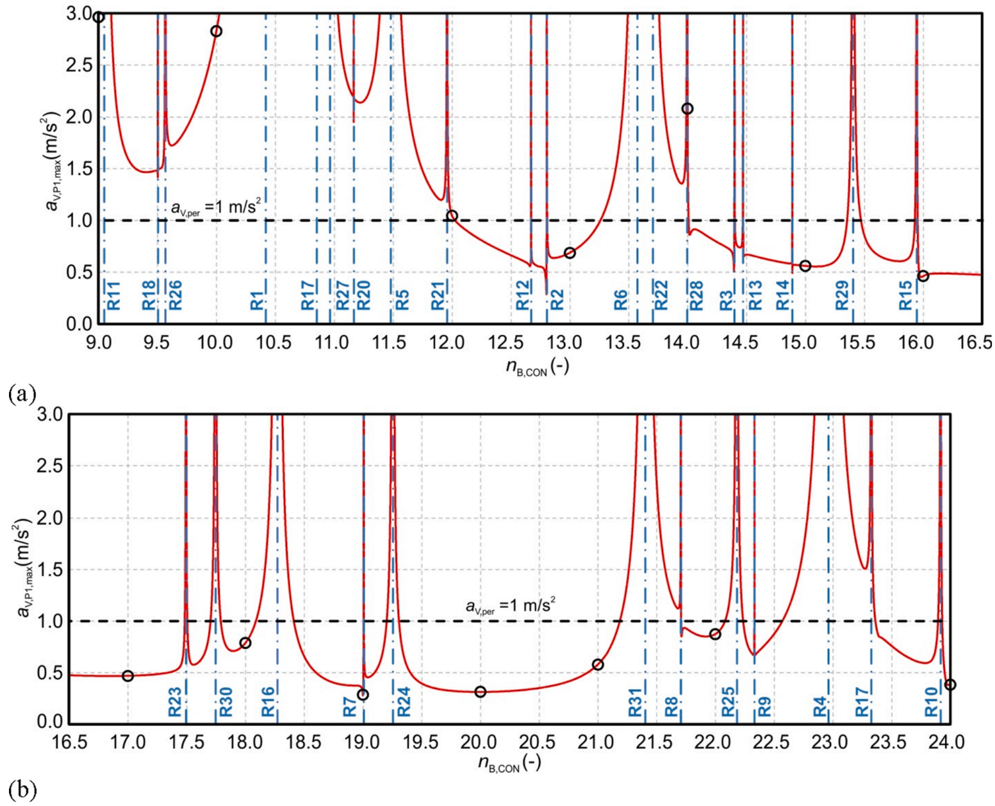

Fig. 12. Maximum vertical accelerations of the BWC: (a) $n_{B,CON} = 9\ldots16.5$; (b) $n_{B,CON} = 16.5\ldots24$.

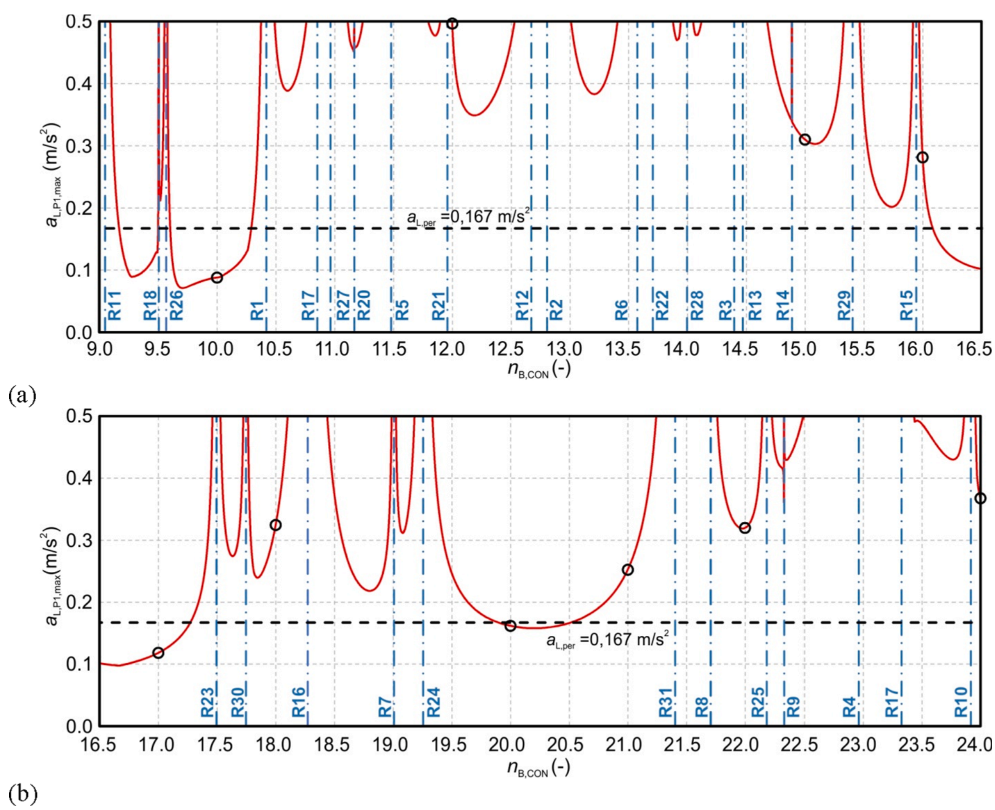

Fig. 13. Maximum lateral accelerations of the BWC: (a) $n_{B,CON} = 9\ldots16.5$; (b) $n_{B,CON} = 16.5\ldots24$.

Table 5
Maximum vertical accelerations of the BWC.

n_B	9	10	11	12	13	14	15	16
$a_{V,P1,max}$ (m/s^2)	2.964	2.826	3.979	1.045	0.687	2.078	0.560	0.462
n_B	17	18	19	20	21	22	23	24
$a_{V,P1,max}$ (m/s^2)	0.469	0.787	0.287	0.313	0.579	0.874	9.487	0.383

Table 6
Maximum lateral accelerations of the BWC.

n_B	9	10	11	12	13	14	15	16
$a_{L,P1,max}$ (m/s^2)	0.617	0.088	1.461	0.496	0.516	2.652	0.310	0.281
n_B	17	18	19	20	21	22	23	24
$a_{L,P1,max}$ (m/s^2)	0.118	0.324	1.098	0.162	0.252	0.32	5.972	0.367

Table 7
Maximum vertical (a_V) and lateral (a_L) accelerations of the referent points.

Referent point	a_{max} (m/s^2)	$n_{B,DES} = 17$	$n_B = 20$	a_{per}** (m/s^2)
P1	$a_{V,P1,max}=\ddot{q}_{1,max}$*	0.469	0.313	1.000
	$a_{L,P1,max}=\ddot{q}_{2,max}$	0.118	0.162	0.167
P2	$a_{V,P2,max}=\ddot{q}_{37,max}$	0.115	0.147	0.400
	$a_{L,P2,max}=\ddot{q}_{38,max}$	0.608	0.185	0.333
P3	$a_{V,P3,max}=\ddot{q}_{40,max}$	0.105	0.076	0.400
	$a_{L,P3,max}=\ddot{q}_{41,max}$	0.608	0.185	0.333
P4	$a_{V,P4,max}=\ddot{q}_{43,max}$	0.029	0.032	0.400
	$a_{L,P4,max}=\ddot{q}_{58,max}$	0.030	0.019	0.333
P5	$a_{V,P5,max}=\ddot{q}_{45,max}$	0.030	0.026	0.400
	$a_{L,P5,max}=\ddot{q}_{59,max}$	0.030	0.019	0.333
P6	$a_{V,P6,max}=\ddot{q}_{55,max}$	0.272	0.335	0.400
	$a_{L,P6,max}=\ddot{q}_{56,max}$	0.009	0.003	0.333

* $\ddot{q}_{i,max}$, i = 1,2,37,38,40,41,43,45,55,56,58,59-generalized accelerations of the dynamic model (Fig. 2).
** limiting accelerations prescribed by the code [49].

solution with $n_B = 20$ buckets, the criterion of limiting accelerations is satisfied in each of the referent points.

Even though the cut-off criterion of limiting accelerations in all of the referent points is satisfied only by the variant solution with $n_B = 20$ buckets, the analysis of the impact of soiling as well as the mass of the BW steel structure was also conducted for the originally-designed solution ($n_{B,DES} = 17$).

3.3.3. The impact of soiling

Up to this stage of the research, the impact of soiling (incrustation on the BW and the BW chute blockage), which inevitably occurs during the excavation, has not been considered. The maximum weight of the material in the BW chute is dictated by the preset maximum intensity of the force in the ropes of the BW boom hoisting mechanism. Once this intensity is reached the protection system is activated and the excavation process is halted. It is worth mentioning that, in practice, the mass of the material in the BW chute leading to a halt in the excavation process is always somewhat lower than the maximum calculation mass of the material inside the volume of the BW chute [49]. However, certain load cases in the current standards and regulations (for example load case HZS4.4 prescribed by the code [49]) call for the inclusion of the maximum calculation mass [50]. Therefore, in order to fully assess the impact of the material in the BW chute on the natural frequencies and the dynamic response of the SS while remaining compliant with the mentioned load case, its mass in the model (κm_{BWC}) has been varied over the range from $m_{BWC,min} = 0$ (empty BW chute, $\kappa = 0$) to $m_{BWC,max} = m_{BWC} = 61$ t, corresponding to the case of a completely blocked BW chute (completely filled BW chute, $\kappa = 1$). Masses of the material incrusted on the BW ($m_{BWI} \approx 20$ t) and the material in the completely blocked BW chute ($m_{BWCB} \approx 61$ t) are now taken into account, allowing for the inclusion of the operating conditions with sufficient accuracy, as presented in [50]. However, unlike strength calculations, negative dynamic effects may occur for any of the considered masses of the system, not just the maximum mass. Therefore the impact of soiling has been analysed in a continuous domain.

Results of the modal analysis conducted for the continuously-varying parameter κ of the adhered material (κ = 0-no soiling; κ = 1–100% soiling) [50] show that the values of all of the 14 analysed SS dynamic model's natural frequencies decrease as the mass of the adhered material increases, Fig. 15 and Table 8. However, the impact of the adhered material on the decrease of the values of the 9th and 10th natural frequencies is negligible. Therefore, comments on the quality of the design solution with 20 buckets can already be made on the basis of shifting of

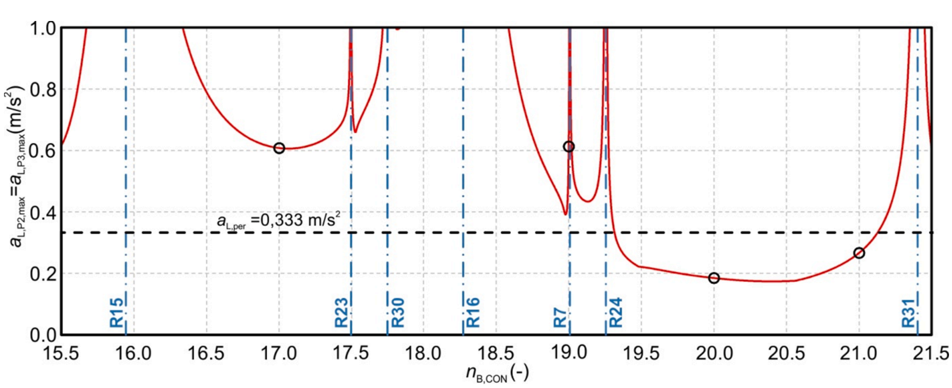

Fig. 14. Maximum lateral accelerations of the tips of the mast 1 (referent points P1 and P2).

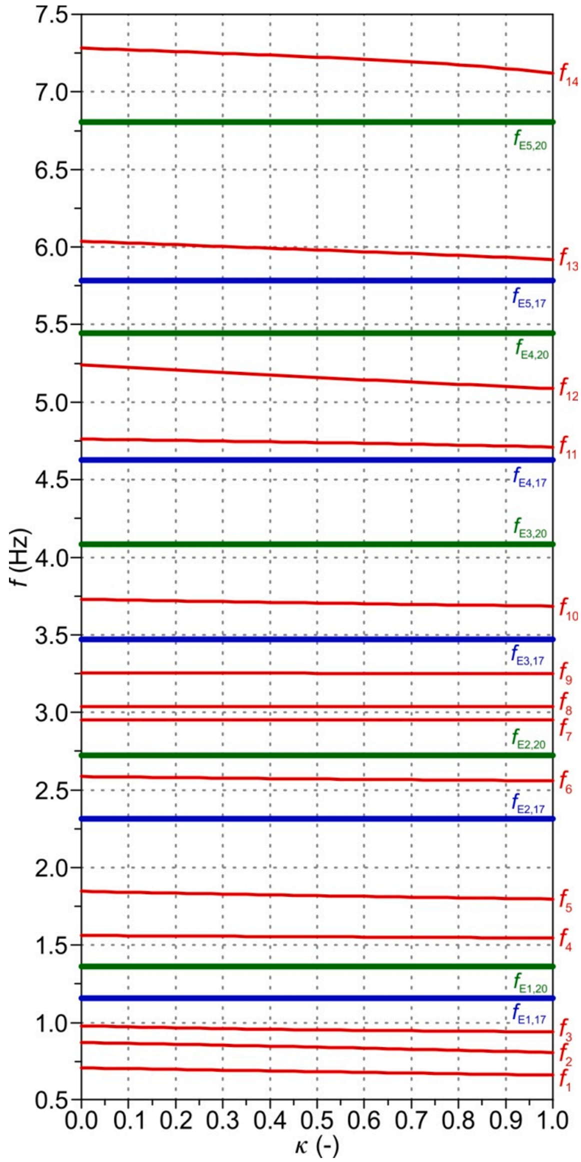

Fig. 15. The first 14 natural frequencies (red coloured lines), dependent on the mass of the adhered material, and the first 5 excitation frequencies for the originally designed solution ($n_B = 17$, blue coloured lines) and the variant with $n_B = 20$ (green coloured lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the 3rd frequency of excitation to the higher frequency ranges, thus moving the vibrations of the system to a domain without the negative dynamic effects, Fig. 15.

It is worth noting that, as it was concluded in [50], for the cases where no resonant states appear within the range of the analysed parameter, Fig. 15, no negative dynamic effects will appear if the values of maximum vertical and lateral acceleration of the referent points, obtained for the lower and upper boundaries of the parameter range, are below the limits prescribed by the code.

Since the values of vertical and lateral accelerations of the referent points (P1,P2,…,P6) for the case of no soiling ($\kappa = 0$) have already been presented in Table 7, the values of accelerations for the case of 100% soiling ($\kappa = 1$) are provided in Table 9.

By analysing the results presented in Tables 7 and 9, it is noticeable that the values of $a_{V,P1,max}$, $a_{L,P1,max}$, $a_{L,P2,max} = a_{L,P3,max}$ and $a_{V,P6,max}$ are closest to or even greater than the critical values for $\kappa = 0$ or $\kappa = 1$. In order to fully describe the character of change in their values, it is necessary to assess these accelerations in a whole domain of variation of the parameter κ, Fig. 16.

Table 8
Impact of the adhered material on the natural frequencies.

Mode	Natural frequencies (Hz)		Percentage difference
	$f_i^{\kappa=0}$	$f_i^{\kappa=1}$	$100\frac{f_i^{\kappa=1} - f_i^{\kappa=0}}{f_i^{\kappa=0}}$
1	0.709	0.662	−6.612
2	0.871	0.808	−7.255
3	0.980	0.941	−3.923
4	1.562	1.546	−1.046
5	1.847	1.797	−2.717
6	2.586	2.559	−1.056
7	2.954	2.953	−0.036
8	3.039	3.039	−0.001
9	3.254	3.250	−0.133
10	3.730	3.685	−1.199
11	4.761	4.711	−1.065
12	5.240	5.087	−2.921
13	6.037	5.920	−1.934
14	7.282	7.119	−2.238

Table 9
Maximum vertical (a_V) and lateral (a_L) accelerations of the referent points in the case of 100% soiling.

Referent point	a_{max} (m/s^2)	$n_{B,DES} = 17$	$n_B = 20$	a_{per} ** (m/s^2)
P1	$a_{V,P1,max} = \ddot{q}_{1,max}$ *	0.434	0.274	1.000
	$a_{L,P1,max} = \ddot{q}_{2,max}$	0.132	0.099	0.167
P2	$a_{V,P2,max} = \ddot{q}_{37,max}$	0.159	0.182	0.400
	$a_{L,P2,max} = \ddot{q}_{38,max}$	0.769	0.191	0.333
P3	$a_{V,P3,max} = \ddot{q}_{40,max}$	0.130	0.090	0.400
	$a_{L,P3,max} = \ddot{q}_{41,max}$	0.769	0.191	0.333
P4	$a_{V,P4,max} = \ddot{q}_{43,max}$	0.046	0.040	0.400
	$a_{L,P4,max} = \ddot{q}_{58,max}$	0.042	0.020	0.333
P5	$a_{V,P5,max} = \ddot{q}_{45,max}$	0.048	0.037	0.400
	$a_{L,P5,max} = \ddot{q}_{59,max}$	0.043	0.020	0.333
P6	$a_{V,P6,max} = \ddot{q}_{55,max}$	0.282	0.334	0.400
	$a_{L,P6,max} = \ddot{q}_{56,max}$	0.007	0.002	0.333

* $\ddot{q}_{i,max}$, i = 1,2,37,38,40,41,43,45,55,56,58,59-generalized accelerations of the dynamic model (Fig. 2).
** limiting accelerations prescribed by the code [49].

3.3.4. *The impact of the mass of the bucket wheel steel structure*

Any change to the number of buckets is inevitably reflected on the mass of the whole BW steel structure. This leads to the shifting of the position of the SS CoG [51,52], which may potentially jeopardize the static stability of the SS structure, as well as its radiaxial slew bearing [53,54]. As such, from the aspect of preservation of the static stability of the BWE, it is of utmost importance to adjust the distribution of the masses of the structure in order to keep the position of the structure's CoG in accordance with the designed solution. This is achieved by adjusting the mass of the CW. Simultaneously, apart from these adjustments, it is also important to carefully assess the effects of soiling on the dynamic behaviour in order to provide secure working conditions for the excavator.

In the analysis to follow, only the design solution of $n_B = 20$ buckets is considered because it has emerged as the only redesign option which fully satisfies the criteria of the prior analyses. With that in mind, the analysis has been conducted for the BW steel structure mass variations of ± 20%, while making the appropriate adjustments to the CW mass in order to keep the position of the superstructure CoG intact. The condition for the assessment of quality of the considered design solution was whether any amount of the adhered material would lead to the appearance of unfavourable dynamic effects. Based on the results of the previously-presented analyses, only the accelerations of the referent

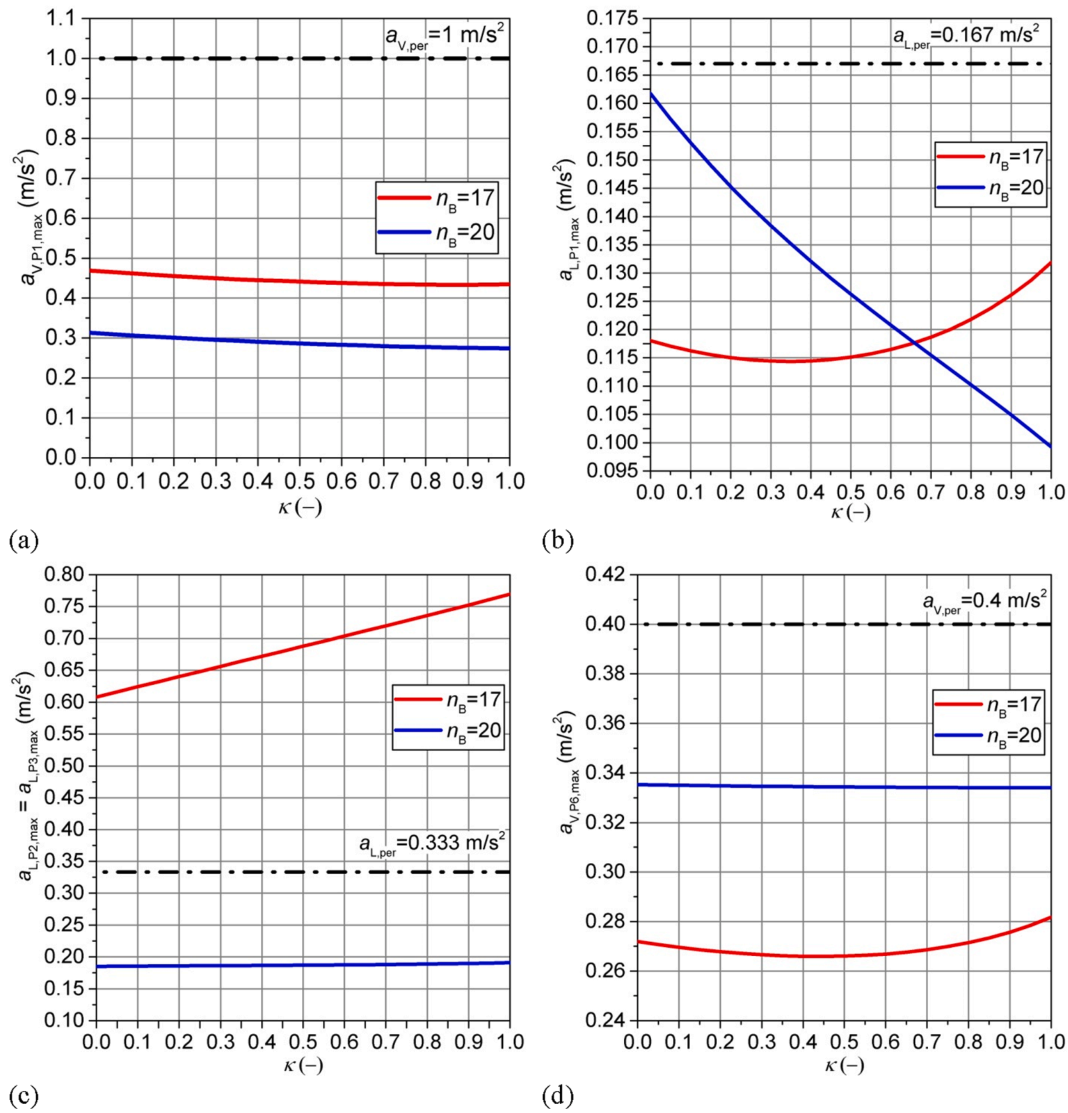

Fig. 16. Maximum accelerations for $n_B = 17$ and $n_B = 20$: (a) vertical, and (b) lateral in P1 (BWC); (c) lateral in P2 and P3 (tips of the mast 1); (d) vertical in P6 (CW CoG).

points whose values are in close proximity to the limits prescribed by the standard have been taken into consideration. Dynamic responses in the referent points of the SS were determined under the conditions of the simultaneous variations of the masses of both the BW steel structure ($\lambda m_{BWS,DES}$, $\lambda = 0.8\ldots1.2$, $m_{BWS,DES}$-mass of the originally-designed BW for $n_B = 17$) and the adhered material ($\kappa = 0\ldots1$), Fig. 17.

The results of the analysis show that maximum vertical accelerations in P1 (BWC) and P6 (CW CoG), Fig. 17(a) and 17(d), as well as maximum lateral accelerations in P2 and P3 (tips of the mast 1), Fig. 17(c), are lower than the limiting values for all of the considered masses of the BW steel structure, except for $\lambda = 0.8\ldots0.86$, because these solutions are discarded by the criterion of the limiting lateral acceleration in P1 (BWC), Figs. 17(b) and 18.

4. Discussion

In the first phase of the proposed method of validation of the total number of buckets on the basis of the dynamic response of the SS (Section 3.1), for the base model (BWE SchRs 1600) with $n_{B,DES} = 17$ buckets, the limits of the interval of change of the total number of buckets were determined respecting the condition that the average number of buckets in interaction with the soil, for the referent angle of excavation $\psi_E = \pi/2$, has to be higher than 2. Boundaries of the interval ($n_{B,min} = 9$ and $n_{B,max} = 24$) were established while accounting for and satisfying the strict limitations regarding the preservation of the technical–technological characteristics of the base model (DR1-DR3). Additionally, $\forall n_B \in \{n_{B,min} = 9, 10, \ldots, n_{B,DES} = 17, \ldots, n_{B,max} = 24\}$ the condition $k_{A,av} \geq k_A = 5.0$ daN/cm^2 is also met, Fig. 7, which deals with the capability to excavate a desired soil category, i.e. DR4 is also fulfilled. In comparison to $n_{B,DES} = 17$, $n_{B,min} = 9$ yields a 12.4% lower, while $n_{B,max} = 24$ yields a 5.4% higher value of the available specific resistance to excavation, Fig. 7.

In the second phase of the proposed method, a cut-off scanning was performed for the spectrums of the SS dynamic model's natural frequencies and the frequencies of excitation caused by the excavation process, for the frequency ranging up to 8 Hz. This has established that the 11th mode for $n_B = 14$ enters a 5th order resonance, Fig. 11. For this reason, the solution with $n_B = 14$ buckets on the BW was discarded.

A modal analysis proved to be insufficient for any further conclusions due to its inability to provide any insight on neither the ranges of the resonant areas nor the effects of the proximity of any set of solutions to the resonant states, which created a need for the analysis of the dynamic system response. For this reason, the first step in the third phase was a cut-off analysis of the BWC's acceleration, since it is the most important

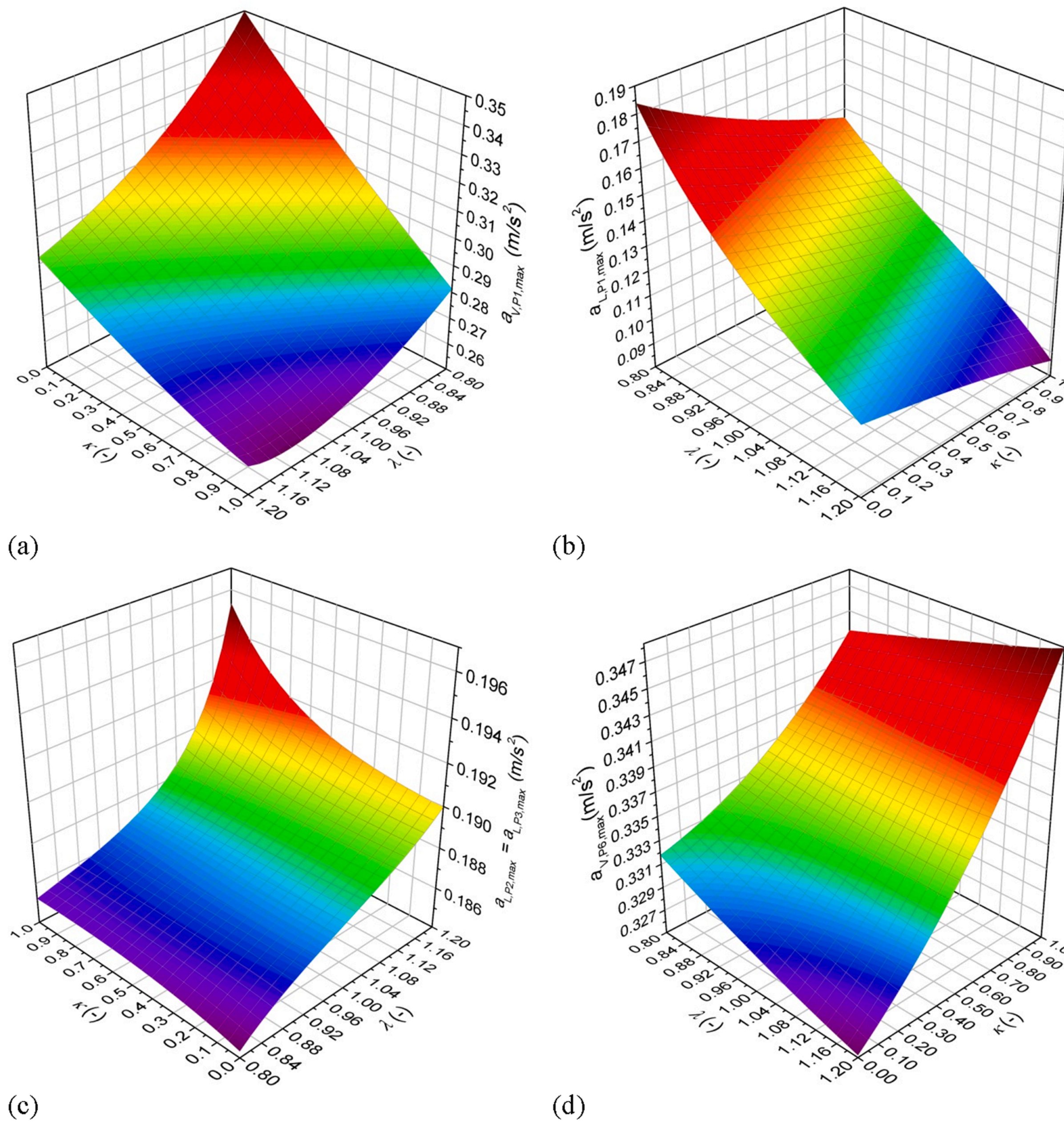

Fig. 17. Maximum accelerations for $n_B = 20$: (a) vertical, and (b) lateral in P1 (BWC); (c) lateral in P2 and P3 (tips of the mast 1); (d) vertical in P6 (CW CoG).

indicator of the dynamic behaviour of the SS. On the foundation of the results of the analysis, based on the limiting vertical and lateral accelerations prescribed by the code [49], 13 variant solutions have been eliminated. This means that, out of the initial 16, only two design variants remained – the original design ($n_{B,DES} = 17$) and the design variant with $n_B = 20$ buckets. The fact that the originally designed variant, which is in exploitation for nine years, belongs to the two-member set of the remaining solutions presents the validation of the proposed method. In order to assess the validity of these two design solutions, analyses of the dynamic response for the remaining referent points were performed. The results have shown that the variant solution with $n_B = 20$ buckets satisfies the criterion of limiting accelerations in the referent points of the SS, Table 7. For the original design of $n_{B,DES} = 17$ buckets on the BW, the values of lateral accelerations of the tips of the mast 1 are higher than those prescribed by the standard, due to the fact that the system is oscillating in the region heavily influenced by the resonant states R15 and R16, Fig. 14 and Table 7.

In the next step of the research, design solutions of 17 and 20 buckets were subjected to a dynamic behaviour analysis once again, this time accounting for the influence of soiling. The results of the modal analysis have shown a decline in values of all natural frequencies as the amount of the adhered material increases, Fig. 15 and Table 8. The effects of the adhered material are most noticeable in the cases of the first, second and third natural frequencies, which decrease by 6.6%, 7.2% and 3.9%, respectively. However, the declines in the values of the 9th and 10th natural frequencies, deemed the most interesting for observation during the stage of determination of the sets of the possible solutions, equal to 0.1% and 1.2%, Table 8, which may be declared negligible from the engineering point of accuracy. From the aspect of the maximum accelerations of the key referent points, the following observations have been made:

- the values of maximum vertical accelerations of the BWC decrease for both the originally-designed solution and the solution with 20

buckets with the increase of mass of the adhered material; at the start of the interval (no soiling), the maximum vertical acceleration of the bucket wheel centre is 50% lower for the variant with 20 buckets compared to that of the originally-designed solution, while at the end of the interval (100% soiling), this value is 58% lower, Fig. 16(a) and Tables 7 and 9,
- although the value of the maximum lateral acceleration of the BWC for the 20-bucket variant is in the close proximity to the limiting value at the start of the interval, its value declines almost linearly towards the end of the interval, Fig. 16(b) and Tables 7 and 9; at the start of the interval, the maximum lateral acceleration of the variant with 20 buckets is 37% higher than the acceleration of the original design; however, at the end of the interval, it is 25% lower,
- from the standpoint of the maximum lateral accelerations of the peaks of the mast 1, the values for the design solution with 20 buckets remain almost constant and 1.7 times lower than the limiting value, while the values in the original design variant monotonously grow as the mass of the adhered material increases, and are 1.8 times higher than the limiting value prescribed by the standard and 3.3 times higher than those on the design solution with 20 buckets at the start of the interval; at the end of the interval, the values for the original design are 2.3 times higher than the limiting value and 4.0 times higher than those of the 20-bucket variant, Fig. 16(c) and Tables 7 and 9,
- even as the mass of the adhered material increases, the maximum vertical accelerations of the counterweight CoG remain almost constant for the 20-bucket design solution, Fig. 16(d) and Tables 7 and 9. These values are 23% higher at the start and 18% higher at the end of the interval than the values on the original design; the maximum vertical accelerations of the counterweight CoG for the 20-bucket variant are almost insensitive to the increase in mass of the adhered material, and, since these values are lower than the limiting values, a conclusion can be drawn that they will not lead to any negative dynamic effects.

Any variation to the number of buckets on the BW inevitably results in changes to the mass of the BW steel structure. In order to assess the influence of the said mass on the dynamic response of the entire BWE, the mass of the BW has been varied in a ±20% domain in the subsequent analysis. However, modifications to the mass of the BW steel structure cause shifting of the position of the BWE superstructure CoG, which may result in a risk to the static stability of the machine and therefore has to be prevented. The only way to achieve this is to adjust the mass of the CW appropriately, keeping the superstructure CoG position the same as in the original design. As such, in addition to the mass of the BW steel structure, the mass of the CW has also been varied in the analysis, on a ±6.7% domain, ensuring the constant position of the superstructure CoG regardless of the number of buckets on the BW. The impact of soiling has been accounted for in the analysis and used as a criterion in assessing the quality of the results, depending on whether or not it would lead to the unfavourable dynamic effects. This analysis was conducted only for the accelerations of the referent points which have been classified as critical based on the results of prior analyses, meaning those in close proximity to the limits prescribed by the standard. The design solution with 20 buckets was the only variant to be considered for the analysis at this step of the research, as it was the only redesign option to fully satisfy the criteria of the prior analyses.

Based on the results of the analysis, the following conclusions can be made:

- The value of vertical acceleration of the BWC is the lowest in the case of 100% material adherence and the mass of the BW steel structure 12% higher than the original design, and equals to 0.257 m/s^2; the maximum vertical acceleration occurs for the lowest considered mass of the BW (20% lower than the original design) and 0% material adherence, and equals to 0.35 m/s^2; each of the maximum vertical accelerations is below the limit prescribed by the code, Fig. 17(a);
- The lowest value of the lateral acceleration of the BWC occurs for the maximum adherence of the material (100%) and maximum considered mass of the BW (+20%), and equals to 0.087 m/s^2; lateral acceleration of the BWC reaches its maximum value in the case of no adhered material (0%) and the lowest considered mass of the BW steel structure (−20%), and equals to 0.184 m/s^2; this value is 10.2% higher than the limit prescribed by the standard, Fig. 17(b);
- Lateral accelerations of the peaks of the mast 1 are the lowest for no material adherence and the lowest considered mass of the BW (−20%), and equal to 0.184 m/s^2; on the other hand, these accelerations reach their maximum for the maximum material adherence combined with the highest considered mass of the BW steel structure, equalling 0.195 m/s^2, Fig. 17(c); all of the maximum lateral accelerations are below the limit prescribed by the code;
- Vertical acceleration of the CW CoG is the lowest for no adherence of the material and the highest considered mass of the BW structure (+20%), and equals to 0.325 m/s^2; the highest value of the vertical acceleration of the CW CoG is observed for 100% of the adhered material and the highest considered mass of the BW (+20%), and equals to 0.348 m/s^2, Fig. 17(d); these values are below the limit prescribed by the code.

Although it is observed that certain parameter combinations lead to the unfavourable working conditions for the BWE, namely, the values of the lateral accelerations of the BWC that are above the limit prescribed by the standard, this issue can be avoided by adjusting the range of the analysed parameters. As adjustments to the domain limits for the variation of material adherence would make no sense from the practical standpoint, the appropriate solution is to modify the spectrum for the variation of the BW steel structure mass. Further analysis of the results shows that any reduction of the mass of the BW steel structure by more than 14%, Fig. 18, leads to unfavourable values of lateral accelerations of the BWC, causing the excavator superstructure to oscillate in the area where negative dynamic effects may occur.

5. Conclusion

The number and the volume of the buckets and the frequency of revolution of the bucket wheel are key technical-technological parameters of a bucket wheel excavator. A product of these parameters determines the theoretical capacity, which is a foundation for the calculation of the achievable output of a machine. On the other hand, the number of buckets and the frequency of the bucket wheel revolution, along with the installed drivetrain power of the excavating device, determine the available cutting force and moment of excavation. All of

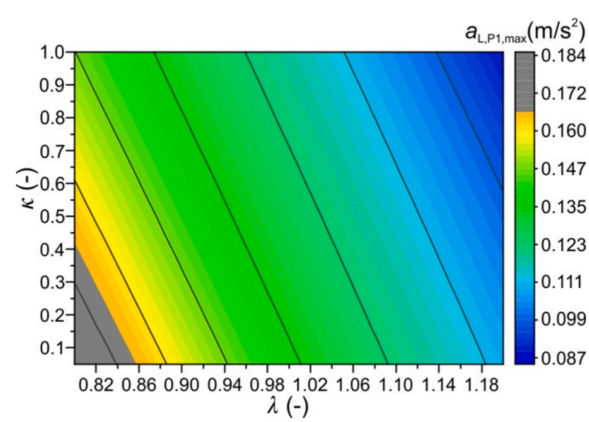

Fig. 18. Contour plot of maximum lateral accelerations in P1 (BWC) (grey area represents the values higher than the limiting one, i.e. 0.167 m/s^2).

these parameters determine the mean and amplitude values of the calculation load, caused by the resistance to excavation, and therefore also the indicators of unsteadiness of the mentioned loads – the coefficients of non-uniformity and dynamism. Regardless, no existing literature and technical regulations consider the dynamic response of a structure as the criterion for the selection of the number of buckets on the bucket wheel, which is, as indicated, a crucial parameter of the excavating device. This was exactly the motive behind the development of an original method of selection and validation of the total number of buckets, which can be summarized in three stages:

(i) determining the boundaries of the interval of change of the total number of buckets;
(ii) validation of the total number of buckets based on the criterion of resonant states;
(iii) validation of the total number of buckets based on the criterion of limiting accelerations, including the analysis of the impact of soiling and the mass of the BW steel structure.

The method offers valuable insight when an existing working device is being redesigned, something which is inevitable to occur considering: (a) that the BWEs are intended for multidecadal exploitation under harsh working conditions; (b) the everlasting tendency towards improving the reliability and efficiency, as well as modernizing the design conceptions for drivetrains and control methods. Additionally, the method supplements the set of useful tools for the design of new working devices. The application of this method is presented on the example of the BWE SchRs 1600, with harsh design restrictions – the preservation of the declared theoretical capacity, drivetrain parameters, bucket wheel diameter, the ability to excavate the soil of the desired category and the position of the CoG. Based on the results of the presented analyses, multiple observations have been made, all verifying the advantages of a 20-bucket design variant over the original design with 17 buckets:

- The first and, therefore, all of the other frequencies of excitation for the 20-bucket variant are 17.6% higher than those of the original solution;
- The coefficients of dynamism and non-uniformity are 2.2% and 5.2% lower for the 20-bucket variant, respectively;
- The 20-bucket redesign variant is able to overcome 3.3% higher resistance to excavation;
- The values of the maximum lateral accelerations of the tips of the mast 1 are 1.7 times lower than the limiting value (prescribed by the code DIN 22261-2) for the 20-bucket variant, unlike the original, 17-bucket, design where these values are 1.8 times higher than the limit;
- Taking the impact of soiling into account, the maximum accelerations of all referent points of the system for the entire domain of the analysed parameter are below the limiting values in case of the 20-bucket variant. In contrast, in case of the original design, the negative dynamic effects increase as the amount of the adhered material rises (up to 2.3 times higher than the limit, at the end of the analysed interval).

Although the design with 20 buckets was proven to be the only appropriate variant from the aspect of the dynamic behaviour of the system, the results have to be assessed carefully due to the fact that the reduction of the mass of the BW steel structure by more than 14% leads to the appearance of unfavourable dynamic effects, even though the position of the superstructure CoG is preserved.

By using the spatial reduced dynamic model of the BWE slewing superstructure developed on the basis of the finite element model and introducing the limiting accelerations of the referent points of the system, it is possible to avoid the appearance of the negative dynamic effects already at the design stage. This ensures the needed reliability and extends the lifespan of the structure and, simultaneously, reduces the risk of failures and breakdowns. The presented method represents a contribution to the field of the dynamic behaviour of the BWEs, even more so bearing in mind the fact that, in engineering practice and the effective technical regulations, the insufficient familiarity with the dynamic processes is compensated with the use of the quasi-static approach. For this reason, the method represents a step forward in defining the fundamental constructional parameters of these machines.

CRediT authorship contribution statement

Nebojša B. Gnjatović: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft, Writing - review & editing. **Srđan M. Bošnjak:** Methodology, Validation, Formal analysis, Writing - review & editing, Supervision. **Ivan Lj. Milenović:** Validation, Visualization. **Aleksandar Z. Stefanović:** Software, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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