Modernization and Unification of the Excavating Devices of Bucket Wheel Excavators SRs 2000 Deployed in Serbian Open Pit Mines

Srđan Bošnjak
Professor
University of Belgrade
Faculty of Mechanical Engineering

Nebojša Gnjatović
Assistant Professor
University of Belgrade
Faculty of Mechanical Engineering

Ivan Milenović
Research Assistant
University of Belgrade
Faculty of Mechanical Engineering

Aleksandar Stefanović
Research Assistant
University of Belgrade
Faculty of Mechanical Engineering

Marko Urošević
Research Assistant
University of Belgrade
Faculty of Mechanical Engineering

A bucket wheel with drive represents a vital subsystem of any bucket wheel excavator. A multidecadal experience in the exploitation and maintenance of bucket wheel excavators SRs 2000 has imposed a need for modernization and unification of the excavating devices of four of such machines, used for the excavation of overburden in Serbian open pit mines. This paper presents a portion of the research dedicated to the problems of strength and dynamic properties of the bucket wheel boom, static stability of the superstructure as well as installation of the unified design solution for the bucket wheel drive of the bucket wheel excavator SRs 2000. By installing a modernized design solution of the bucket wheel with drive, i.e. by the means of partial revitalization of the bucket wheel excavator, its exploitational life span is prolonged and, additionally, the level of reliability and availability of the overburden systems is increased, and a significant reduction in maintenance expenses is achieved.

Keywords: *bucket wheel excavator, excavating device, bucket wheel boom, strength, modal analysis, static stability, mounting and installation.*

1. INTRODUCTION

A widespread application and multidecadal exploitation of the bucket wheel excavator (BWE) TAKRAF SRs 2000 in working environments of varying properties (coal and overburden) has imposed a need for a permanent upgrade of its subsystems. A relatively large number of studies, dealing with the vibration problems and structural strength [1,2], bucket wheel with drive [3-9], as well as problems of efficiency [10] and effectiveness [11] of this type of a BWE has been performed and published.

Since the deployment of the BWEs SRs 2000 (1970), the manufacturer (TAKRAF) has dedicated special attention to the increase of the reliability levels of the bucket wheel drive, developing a plethora of improved design solutions for the bucket wheel (a single-walled bucket wheel in place of a double-walled design solution) with drive, with various conceptions and engine power outputs [9,12-14].

Figure 1. The BWE SRs 2000x32/5+VR92 in the OP "Tamnava West Field"

Correspondence to: Dr Nebojša Gnjatović, Ass. Professor
Faculty of Mechanical Engineering,
Kraljice Marije 16, 11120 Belgrade 35, Serbia
E-mail: ngnjatovic@mas.bg.ac.rs

Four SRs 2000-type excavators are deployed in Serbian open pit mines (OP) with the purpose of overburden excavation, three of which are being used in OP "Drmno", and one in OP "Tamnava West Field" [3], Figure 1. During 2016, TAKRAF has performed an extensive reconstruction of the excavating device on one of the BWEs in OP "Drmno": (1) a double-walled bucket wheel has been replaced with a single-walled variant; (2) a gearbox with a single 1250 kW electric motor has been introduced in place of an existing gearbox, powered by two, 670 kW, electric motors.

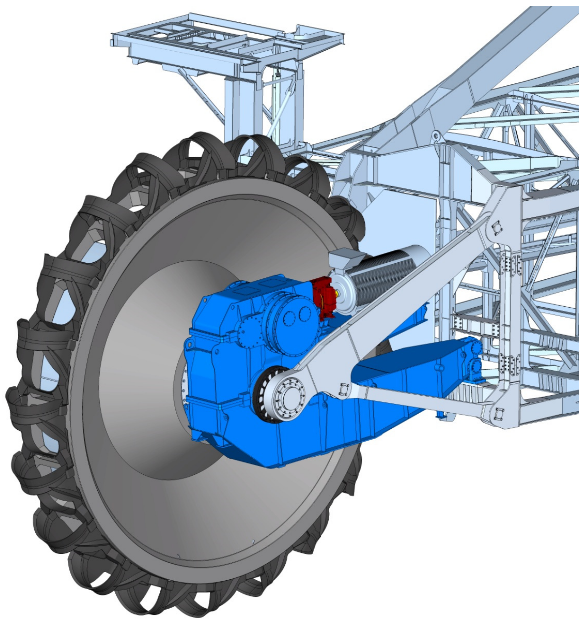

Figure 2 [15]. The single-walled bucket wheel with a single 1250 kW orbiting gearbox (manufactured by TAKRAF)

Redesigning a bucket wheel with drive poses a very challenging and complex engineering task [15-17]. On the basis of a positive impression of the performance of the BWE SRs 2000 with the redesigned bucket wheel boom head, as well as a thorough study by the research team the authors of this paper are a part of [15], a unified technical solution for the bucket wheel drive for the SRs 2000 type of excavators, consisting of a single 1250 kW electric motor, fully synchronized with the single-walled bucket wheel, has been proposed as the optimal for the needs of Serbian coal mines, Figure 2. In order to make the installation of the unified bucket wheel drive possible, the first frame of the bucket wheel boom also had to be reconstructed, Figure 3, as well as locally reinforced. This paper then proceeds to present a portion of the research [15] dedicated to the problems of strength and dynamic properties of the bucket wheel boom, static stability of the superstructure and, finally, the installation of the unified bucket wheel drive solution for the BWE SRs 2000.

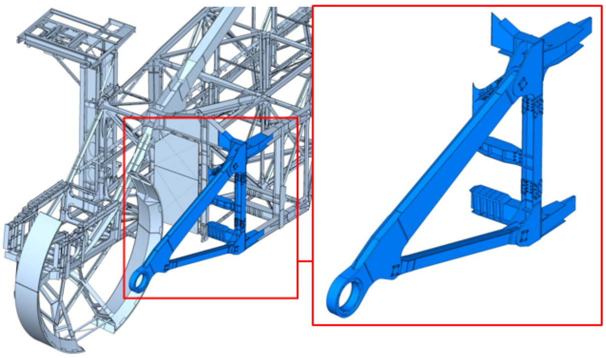

Figure 3 [15]. The redesigned first frame of the bucket wheel boom

2. STRENGTH OF THE BUCKET WHEEL BOOM SUBSTRUCTURE

BWE SRs 2000 was designed in accordance with the standard TGL 13472 [18], which was in effect at the time of its development. The differences between this standard and DIN 22261-2 [19], which is the current standard in effect, include:

the method for the calculation of the intensity of certain partial loads/influences;

the number of relevant load cases, as well as the method for forming the sets of partial loads which define them.

Validation of the redesigned structure of the bucket wheel boom has been achieved by applying a comparative analysis [16, 20, 21] of its response. For all the relevant load cases (LCs), the identification of the stress states has been performed for three representative positions of the bucket wheel boom: horizontal position - position 1; inclined position - position 2; declined position - position 3. The results of the finite element analyses of the original bucket wheel boom with the redesigned head (variant 1: V1), subjected to loads determined by the standard [19], have revealed the existence of five zones (labelled as "critical zones") in which the equivalent calculation stresses (von Mises) are higher than allowed, Figure 4. It is important to notice, Figure 5, that the critical zones appear in those subdomains of the original bucket wheel boom substructure where there was no need for reconstruction due to the installation of the redesigned bucket wheel. With the introduction of favorably-shaped reinforcements in the critical zones (variant 2: V2), the effects of the stress concentrators have been reduced significantly, bringing the stress values within the limits prescribed by the standard [17], Figure 6, for all load cases.

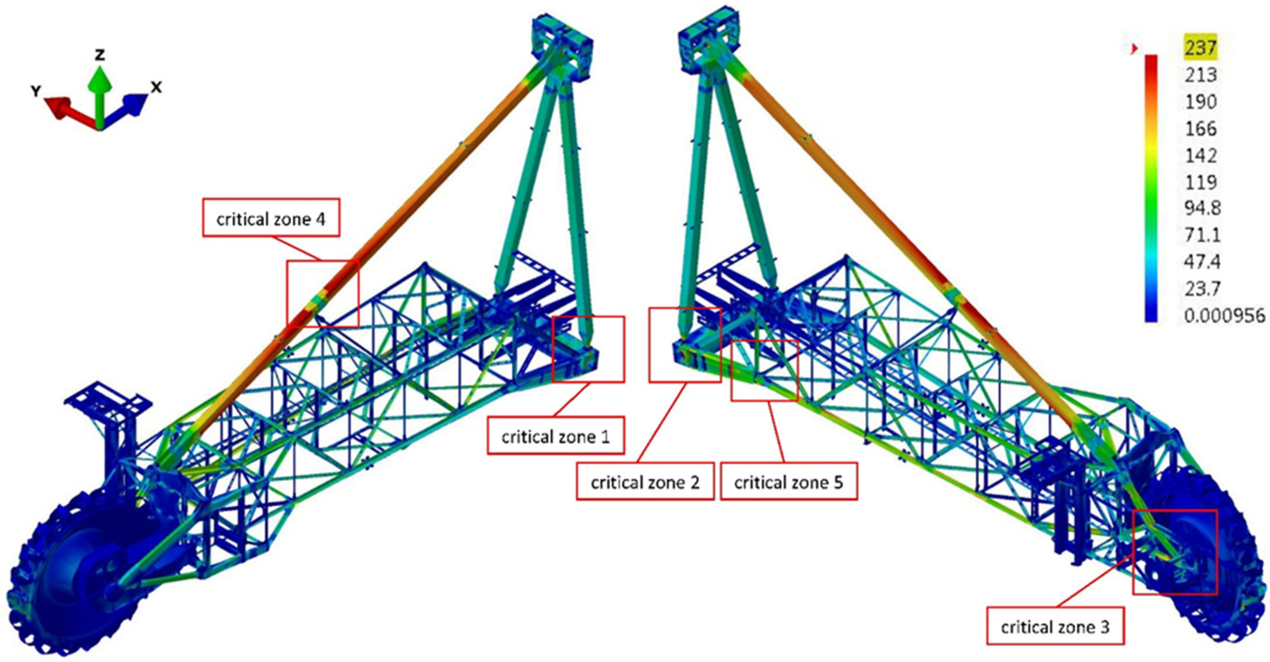

Figure 4 [15]. Critical zones of the bucket wheel boom substructure

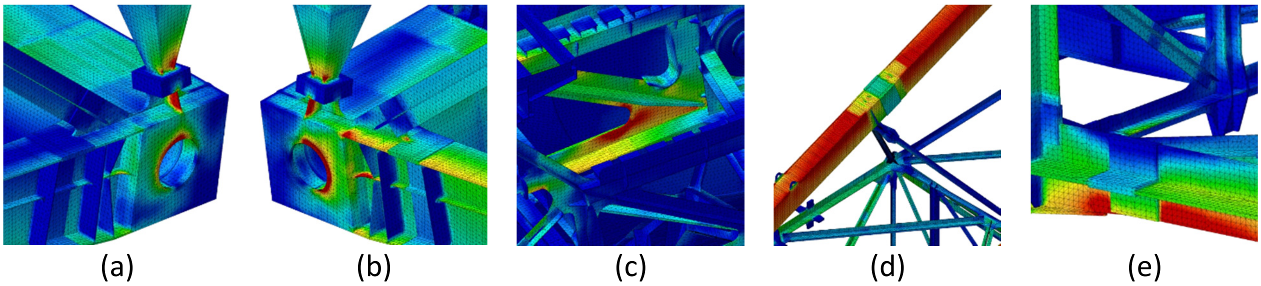

Figure 5 [15]. Von Mises stresses in BWB critical zones (LC H1.2, permissible stress value σ_{per}=237 MPa; BWB position 1; direction of the lateral loads: +y): (a) zone 1, σ_{vM}=303 MPa; (b) zone 2, σ_{vM}=280 MPa; (c) zone 3, σ_{vM}=304 MPa; (d) zone 4, σ_{vM}=245 MPa; (e) zone 5, σ_{vM}=272 MPa

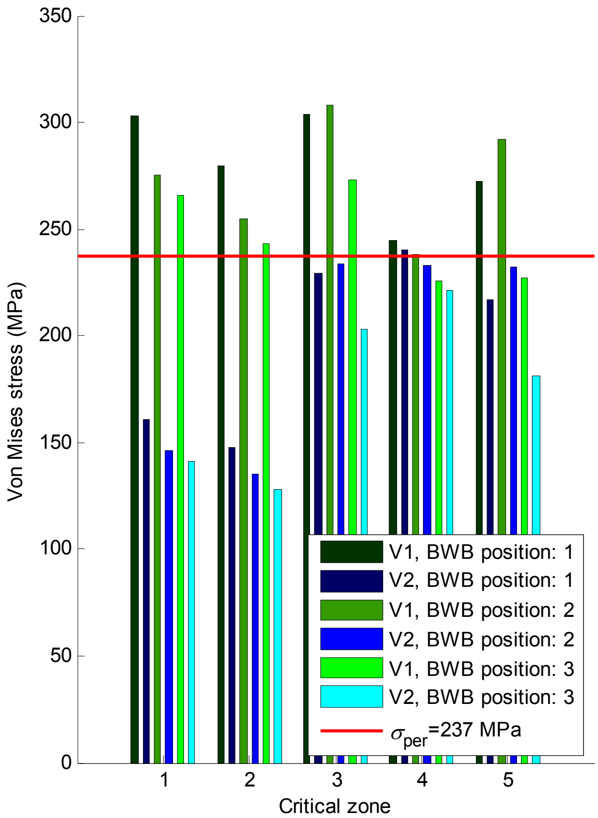

Figure 6 [15]. Von Mises stresses: V1 vs V2 in LC H1.2

3. MODAL ANALYSIS OF THE BUCKET WHEEL BOOM SUBSTRUCTURE

In order to avoid undesired dynamic effects [4,22,23], a modal analysis of the bucket wheel boom substructure has been performed for the variants V0 (state before the reconstruction) and V2 (state after the reconstruction), Figure 7, Table 1. The biggest percent differences between the natural frequencies occur in the second and third mode, when the bucket wheel boom is in position 3. In these instances, the natural frequencies of the redesigned bucket wheel boom (V2) are 12.6% and 20.0% higher, respectively. In each of the remaining cases the percent difference is less than 10%.

Numerical values of the critical excitation frequencies of the bucket wheel boom where resonant states may occur have been determined with a modal analysis of the entire superstructure. The final ranges of the electric motor frequencies that should be avoided are to be defined after the adjustments to the ballast and the control weighing of the superstructure.

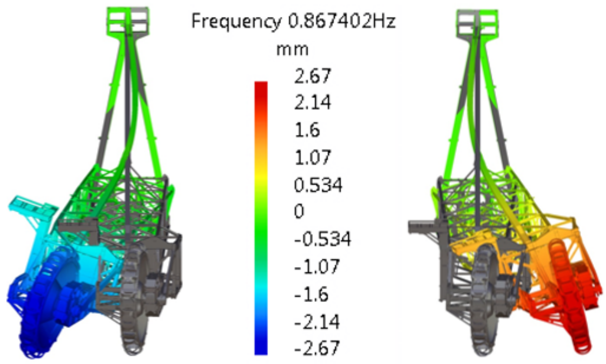

Figure 7 [15]. The fundamental mode of the redesigned bucket wheel boom substructure (V2)

Table 1 [15]. Frequencies of the first ten modes: V0 vs V2

Mode	BWB position					
	1		2		3	
	V0	V2	V0	V2	V0	V2
	Frequency (Hz)					
1	0.888	0.867	0.880	0.867	0.896	0.867
2	1.344	1.466	1.386	1.512	1.197	1.348
3	2.028	2.061	1.836	2.072	1.701	2.041
4	2.355	2.353	2.352	2.353	2.352	2.353
5	3.786	3.789	3.755	3.790	3.481	3.788
6	3.957	3.968	3.696	3.982	3.711	3.941
7	4.468	4.484	4.518	4.485	4.489	4.484
8	4.582	4.602	4.583	4.600	4.567	4.600
9	4.651	4.659	4.665	4.659	4.668	4.658
10	5.361	5.419	5.346	5.431	5.594	5.393

4. STATIC STABILITY OF THE SUPERSTRUCTURE

The superstructure of the BWE SRs 2000x32/5, Figure 8, consists of three fundamental substructures:

- substructure 1 (SuS1) - the bucket wheel boom;
- substructure 2 (SuS2) - the counterweight boom;
- substructure 3 (SuS3) - the slewing platform.

The bucket wheel boom substructure has a cylindrical joint connection to the counterweight boom substructure, and its inclination angle is adjustable via a rope wire mechanism. The counterweight boom is loosely rested on the slewing platform substructure, meaning that the connection is lost if the counterweight boom is tilted backwards. Meanwhile, on the side of the counterweight, it is connected to the slewing platform by cylindrical joints. The numerical model for the 'a posteriori' examination of the static stability of the superstructure [24] was formed by applying the concept of corrective mass [25].

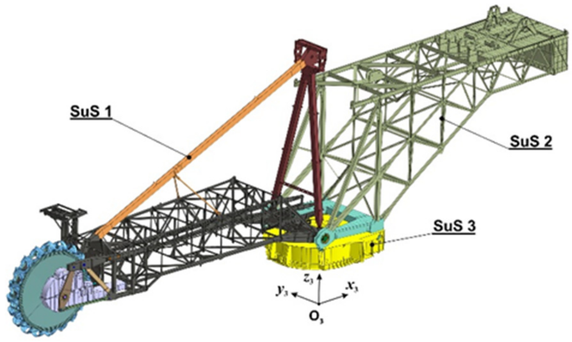

Figure 8 [15]. 3D model of the BWE SRs 2000x32/5 superstructure

According to DIN 22261-2 standard [19], the safety factor against the loss of static stability, i.e. against overturning, is determined by the ratio between the moment of stability (M_S) and the moment of overturning (M_P),

$$\nu = \frac{M_S}{M_P} \geq \nu_{DIN,min}, \quad (1)$$

under the condition that its value has to be higher than the minimum prescribed value for the relevant load case.

The standard TGL 13472 [18] offers two procedures for the proof of static stability. The first fully matches the procedure prescribed by the standard DIN 22261-2 [18], expression (1), with the condition

$$\nu_1 = \frac{M_S}{M_P} \geq \nu_{1TGL,min} = 1.25. \quad (2)$$

Therefore, unlike the standard DIN 22261-2, the standard TGL 13472 treats every load case with the minimum value of the safety factor: 1.25, expression (2). The other procedure is based on factorization of the moments of stability and overturning,

$$\nu_2 = \frac{\varepsilon M_S}{\sum_i \alpha_i M_{P,i}} \geq \nu_{2TGL,min} = 1.0, \quad (3)$$

where the reduction factor for the moment of stability equals to ε=0.97, while the value of the increase factor for the moment of overturning $\alpha_i > 1$ depends on the character of the partial load. Finally, according to the standard TGL 13472, the condition for the static stability is satisfied if at least one of the criteria defined by the expressions (2) and (3) is met.

The differences in the intensities of calculated partial loads and the criteria for the proof of static stability are especially pronounced in LC H1.2. Namely, the calculation procedure prescribed by the standard DIN 22261-2 yields twice the weight of the incrustation on the bucket wheel to that obtained in accordance with the standard TGL 13472. At the same time, for the same LC, the standard DIN 22261-2 prescribes a higher minimum value of the safety factor against overturning (1.5) than one precribed by the standard TGL 13472 (1.25). The minimum value of the safety factor against overturning on the BW side (BWS), obtained in accordance with the standard DIN 22261-2 is 6.5% lower than the minimum value prescribed by the said standard, Figure 9. However, if the procedure for proving the static stability prescribed by the standard TGL 13472 is applied, Figure 10, then the conclusion is that the superstructure meets both criteria of static stability prescribed by this standard.

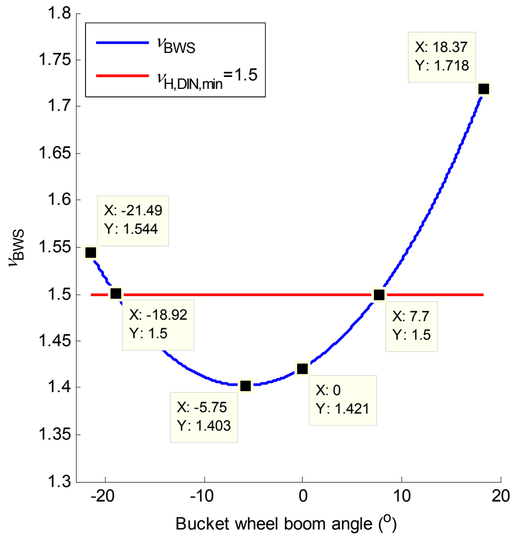

Figure 9 [15]. LC H1.2: safety factor against overturning on the BW side according to the standard DIN 22261-2

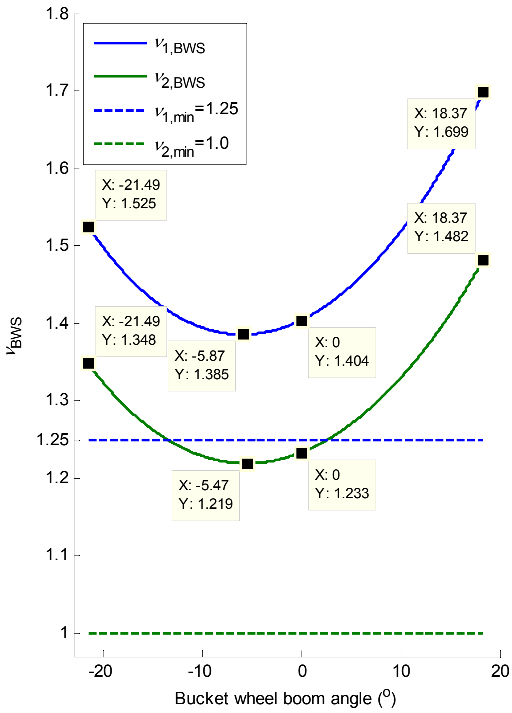

Figure 10 [15]. LC H1.2: safety factor against overturning on the BW side according to the standard TGL 13472

5. INSTALLATION OF THE UNIFIED BUCKET WHEEL WITH DRIVE

Installation of the unified bucket wheel with drive is conducted in five phases, namely:

- phase 1 – preparation of the worksite and the excavator for the reconstruction, Figures 11a,b,c;
- phase 2 – dismantling of the existing excavating device, Figures 11d,e,f;
- phase 3 – reconstruction and reinforcing of the bucket wheel boom, Figures 11g,h,i,j;
- phase 4 – installation of the unified bucket wheel with drive, Figures 11k,l;
- phase 5 – final steps before the bucket wheel excavator undergoes a test run.

In accordance with the schedule, Figure 12, the total time for the installation of the unified bucket wheel with drive, including functionality tests, amounts to 35 12-hour workdays.

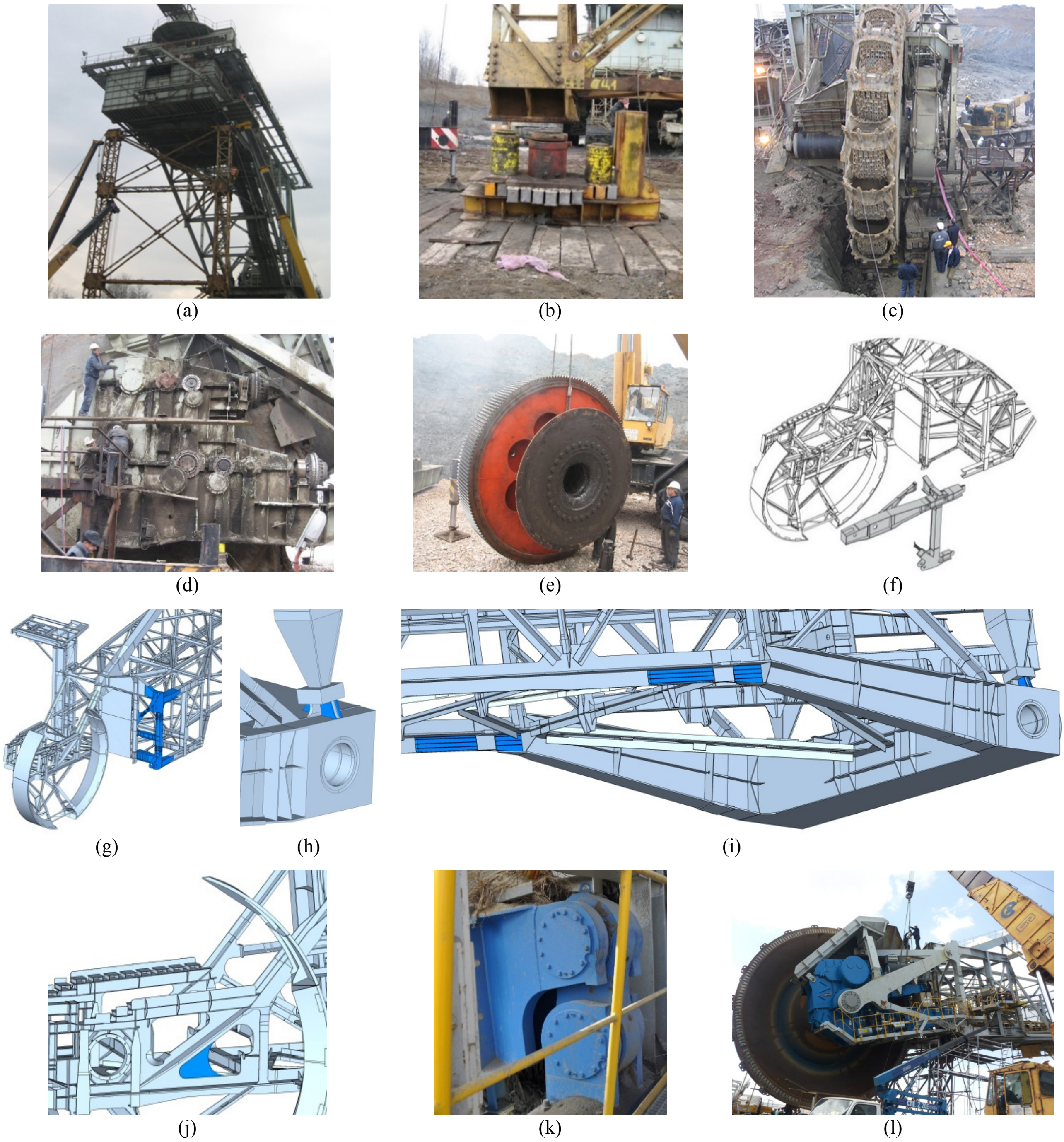

Figure 11 [15]. Phases of installation of the unified bucket wheel with drive: (a) mounting of the temporary support for the counterweight boom; (b) hydraulic cylinders for the supporting of the temporary support of the counterweight boom; (c) bucket wheel being prepared for dismantling; (d) dismantling of the subassemblies of the bucket wheel drive gearbox; (e) dismantling of the output shaft of the bucket wheel drive gearbox; (f) cutting and dismantling of a segment of the first frame of the bucket wheel boom; (g) installation of the redesigned segment of the first frame of the bucket wheel boom; (h) installation of the ribs in the zone of support of the A frame; (i) reinforcing of the vertical plates on the lower girders of the bucket wheel boom; (j) reinforcing of the gusset plate in the zone of axially-constrained bearing of the bucket wheel shaft; (k) installation of the torque arm support; (l) installation of the unified bucket wheel with drive

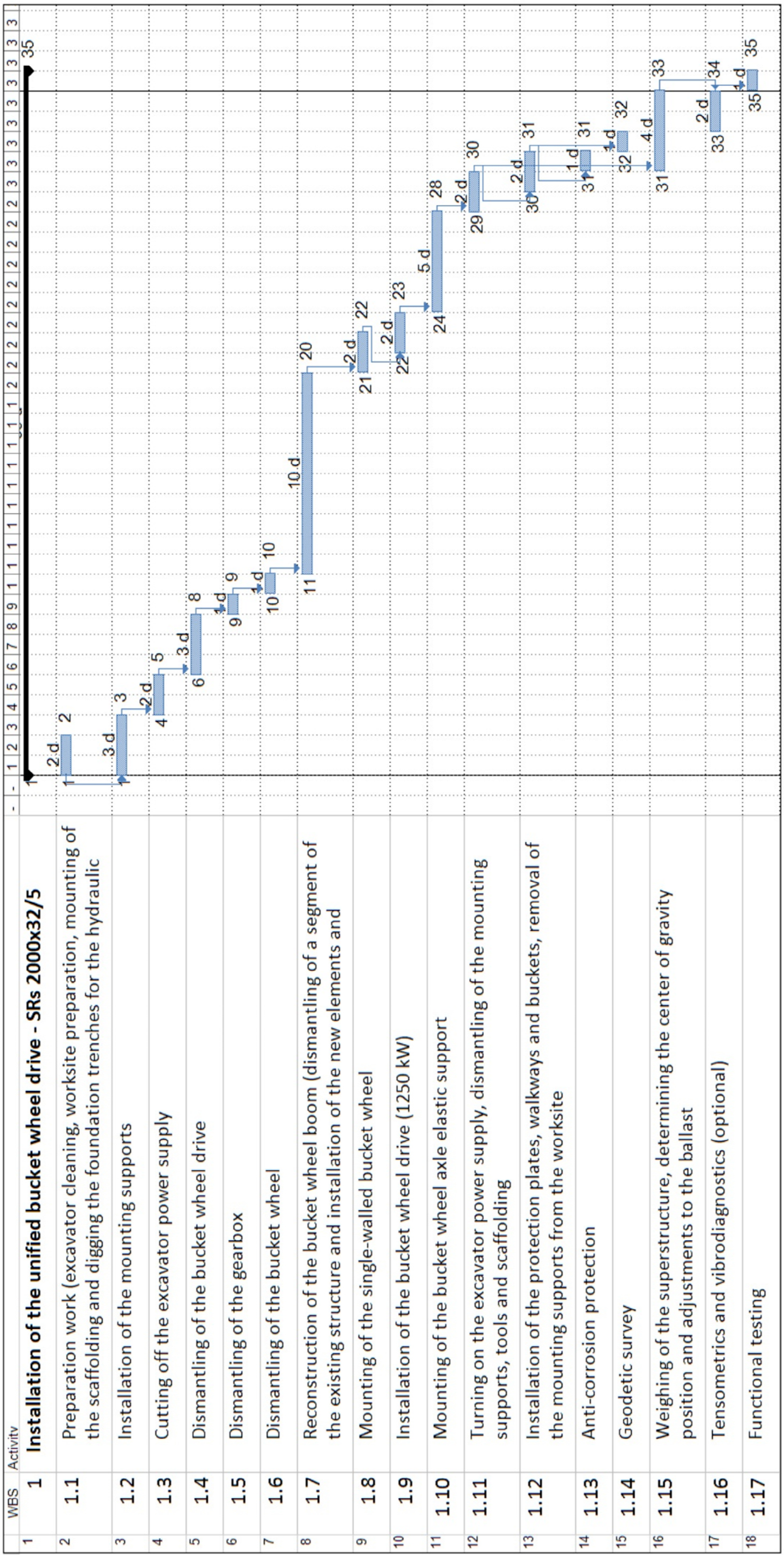

Figure 12 [15]. Schedule for the installation of the unified bucket wheel with drive

6. CONCLUSION

By modernizing the excavating devices of the bucket wheel excavators SRs 2000, the observed drawbacks of the double-walled bucket wheel (accumulation of the material on the bucket wheel body, above anything else) as well as the originally-designed support of the bucket wheel drive gearbox are eliminated. Replacement of the existing excavating device requires a detailed analysis of the influence of the newly developed solution on strength, dynamic response and static stability of the machine. Based on the results of the appropriate analyses [15], portions of which are presented in this paper, the following outcomes have been achieved:

- the local redesign of the bucket wheel boom has been fully defined, and its carrying capacity has been proven after its reconstruction;
- it is proven that the risk of occurrence of unwanted dynamic effects, i.e. resonance is eliminated after the reconstruction;
- the necessary correction of the ballast has been defined and the static stability of the superstructure after the reconstruction has been proven;
- the procedure for the installation of the newly designed excavating device has been described, along with the detailed specification of the required workforce, machinery, equipment and tools.

The installation of the newly designed bucket wheel with drive represents a partial revitalization of the bucket wheel excavator which extends its lifespan, along with increasing the reliability and availability of the overburden systems on the Serbian surface mines. Additionally, the unification of the excavating devices of the bucket wheel excavators BWEs SRs 2000 leads to a significant reduction of maintenance costs.

ACKNOWLEDGMENTS

This work is a contribution to the Ministry of Education and Science of Serbia funded project TR 35006.

The authors would like to express their gratitude to The Joint Japan-Serbia Center for the Promotion of Science and Technology for providing the resources to conduct simulations.

REFERENCES

[1] Pietrusiak, D., Moczko, P., Rusiński, E.: Recent achievements in investigations of dynamics of surface mining heavy machines, 24th World Mining Congress Proceedings, Instituto Brasileiro de Mineração, Rio de Janeiro, pp. 295–308, 2016.

[2] Rusiński, E., Czmochowski, J., Moczko, P., Pietrusiak, D.: Surface Mining Machines - Problems of Maintenance and Modernization, Springer International Publishing AG, Cham, 2017.

[3] Jovančić, P., Ignjatović, D., Maneski, T., Novaković, D., Slavković, Č.: Diagnostic procedure of bucket wheel and boom computer modeling – A case study: Revitalization bucket wheel and drive of BWE SRs 2000, Proceedings of the 14th International Scientific Conference: Computer Aided Engineering, Springer International Publishing AG, Cham, pp. 310-318, 2019.

[4] Jovančić, P., Ćelović, Š., Ignjatović, D., Maneski, T.: Redesigning components of power transmission according to numerical model and vibration diagnostics, Journal of Vibroengineering, Vol. 15, No. 3, pp. 1322-1329, 2013.

[5] Jovančić, P., Ignjatović, D., Gnjatović, N., Bošnjak, S.: Analysis of bucket wheel drive system at SRs 2000 excavators, for the unification purpose [in Serbian], Proceedings of the 13th International Conference "OMC 2018", Yugoslav opencast mining comittee, Belgrade, pp. 63-71, 2018.

[6] Karišić, D.: UT-Excavator Working Wheel Axle Side Search Tehnique [in Serbian], Proceedings of the International Congress on Process Engineering – Processing, Vol. 23, No. 1, pp. 1-7, 2017.

[7] Novaković, D., Jovančić, P.: Analysis and troubleshooting of the bucket wheel drive on bucket wheel excavators SRs 2000 – The road to modernization [in Serbian], Proceedings of the 8th International conference "COAL 2017", Yugoslav opencast mining comittee, Belgrade, pp. 247-256, 2017.

[8] Savković, M., Gašić, M., Arsić, M., Petrović R.: Analysis of the axle fracture of the bucket wheel excavator, Eng. Fail. Anal., Vol. 18, No. 1, pp. 433-441, 2011.

[9] Savković, M., Gašić, M., Zdravković, N., Novaković, D.: Analysis of the SRs bucket wheel excavator excavation drive solutions, IMK – 14 Research&Development, Vol. 32-33, No. 3-4, pp. 69-74, 2009.

[10] Jakovljević, I., Stepanović, S., Šubaranović, T.: Logistics approach to investigation of slice thickness-height ratio effects on excavation resistance of bucket wheel excavator, The International Journal Transport&Logistics, Vol. 10, No. 19, pp. 69-79, 2010.

[11] Živković, L., Lazić, M., Polovina, D.: Comparative analysis of the effectiveness work of the bucket wheel excavator SRs 2000 in opencast mines EPS and MIBRAG [in Serbian], Proceedings of the 11th International Opencast Mining Conference "OMC 14", Yugoslav opencast mining comittee, Belgrade, pp. 463-471, 2014.

[12] Gnilke, M.: Intelligent retrofit solutions for bucket wheel excavators, WISSENSPORTAL baumaschine.de 1(2006), pp. 1-7, 2006.

[13] Gnilke, M.: Aktueller Entwicklungsstand bei Schaufelradgetrieben mitt-lerer und großer Leistung, WISSENSPORTAL baumaschine.de 1(2006), pp. 1-8, 2006.

[14] Mizerski, Z., Gnilke, M.: New bucket wheel drive for BWE SRs 2000 in Bełchatów opencast mine [in Polish], Górnictwo i Geoinżynieria, Vol. 35, No. 3/1, 189-198, 2011.

[15] Bošnjak, S., Jovančić, P., Gnjatović, N., Ignjatović, D., Milenović, I. et al.: The Analysis of the Bucket Wheel Drivetrains on Bucket Wheel Excavators SRs 2000 with the Purpose of Unification, realized for JP „Elektroprivreda Srbije Beograd" - Beograd, Faculty of Mechanical Engineering and Faculty of Mining and Geology, Belgrade, 2019.

[16] Bošnjak, S., Petković, Đorđević, M., Gnjatović, N.: Redesign of the Bucket Wheel Excavating Device, Proceedings of the 19th International Conference on Material Handling, Constructions and Logistics - MHCL'09, University of Belgrade - Faculty of Mechanical Engineering, Belgrade, pp. 123-128, 2009.

[17] Durst, W., Vogt, W.: Bucket Wheel Excavator, Trans Tech Publications, Clausthal-Zellerfeld, 1989.

[18] TGL 13472: Steel supporting structures of heavy aggregates for open mining – Calculation, structural design, VVB Tagebauausrüstungen, Krane und Förderallagen, Amt für Standardisierung, Meßwesen und Warenprüfung, 1974.

[19] DIN 22261-2:2016-10: Bagger, Absetzer und Zuzatsgeräte in Braunkohlentagebauen - Teil 2: Berechnungsgrundlagen, Deutsches Instituts für Normung, Berlin, 2016.

[20] Bosnjak, S., Petkovic, Z., Dunjic, M., Gnjatovic, N., Djordjevic, M.: Redesign of the vital subsystems as a way of extending the bucket wheel excavators life, Technics Technologies Education Management, Vol. 7, No. 4, pp. 1620-1629, 2012.

[21] Bošnjak, S., Petković, Z., Zrnić, N., Dunjić, M., Dragović, B.: Redesign of the Bucket Wheel Excavators Substructures Based on the Comparative Stress – Strain Analysis, Advanced Materials Research, Vol. 402, pp. 660-665, 2012.

[22] Bošnjak, S., Oguamanam, D., Zrnić, N.: The influence of constructive parameters on response of bucket wheel excavator superstructure in the out-of-resonance region, Archives of Civil and Mechanical Engineering, Vol. 15, No. 4, pp. 977-985, 2015.

[23] Gnjatović, N., Bošnjak, S., Stefanović, A.: The dependency of the dynamic response of a two mast bucket wheel excavator superstructure on the counterweight mass and the degree of Fourier approximation of the digging resistance, Archives of Mining Sciences, Vol. 63, No. 2, pp. 491-509, 2018.

[24] Bošnjak, S., Gnjatović N., Milenović I.: From 'a priori' to 'a posteriori' static stability of the slewing superstructure of a bucket wheel excavator, Eksploatacja i Niezawodnosc – Maintenance and Reliability, Vol. 20, No. 2, pp. 190-206, 2018.

[25] Bošnjak, S., Gnjatović N., Savićević S., Pantelić M., Milenović I.: Basic parameters of the static stability, loads and strengthof the vital parts of a bucket wheel excavator's slewing superstructure, Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) Vol. 17, No. 5, pp. 353-365, 2016.