STUDY REGARDING THE BUCKET-WHEEL EXCAVATORS USED IN HARD ROCK EXCAVATIONS

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Abstract: The machinery predominantly used for overburden removal as well as for lignite and inter-bedded waste layers extraction in open pit coal mining operations in Europe, is the bucket wheel excavator. The existence of hard rock structures –in form of continuous layers or spread boulders, characterized by a much higher cutting resistance as the normal rock- produces downtimes, increased equipment wear, or even severe damage of the bucket wheel excavator's structural components or operational subsystems, leading to increased energy consumption, lower production rate and, finally, increased mining costs.

Keywords: BWE, hard inclusions, rocks, tools, boom, structure

1. GENERAL REMARKS

The present paper, based on some preliminary results of research performed in the frame of BEWEXMIN - RFCS project aims at the development of solutions to reduce failure rates of bucket wheel excavators working in these conditions. This outcome can be achieved by developing methods for adaptation of already working excavators to those conditions and prescription of standard requirements for newly built ones, and on the other hand, a system of continuous surveillance of machinery superstructure's stresses, able to indicate in due time the emerging threats.

The above-mentioned project includes three main research tasks. The aim of the first task is to define requirements to be set during bucket wheel excavator construction in order to obtain as low as possible dynamic loads on the machine's load carrying structure in view to ensure a proper resistance. The present paper deals mainly with the first issue, presenting the main implications between BWE parameters and the adaptability to excavate hard inclusions.

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One of the frequent problems that need to be addressed when mining coal deposits is the presence in the working face of cohesive materials having high mechanical strength in relation to the average rock to be excavated. These are generally called “hard formations” or “hard inclusions” and are in the form of either continuous layers or boulders.

This problem is of particular importance in Europe where lignite deposits are exploited in large opencast mines utilizing Bucket Wheel Excavators (BWEs) as the main means of excavation.

Often it is difficult or impossible to excavate these hard inclusions with BWEs. If their location has been previously determined by exploration, they are usually blasted. But it is not uncommon to discover them when it is too late, that is when the BWE actually digs into them. The actually operating of BWEs are designed to excavate materials with an “earthy” texture with low mechanical strength. Dynamic and stochastic impact loads exerted on the machine during these encounters are the most common causes of major BWE component failures leading to downtime, production disruption, and high-cost repairs.

The complexity and difficulty to address this issue is synthetized in Fig. 1.

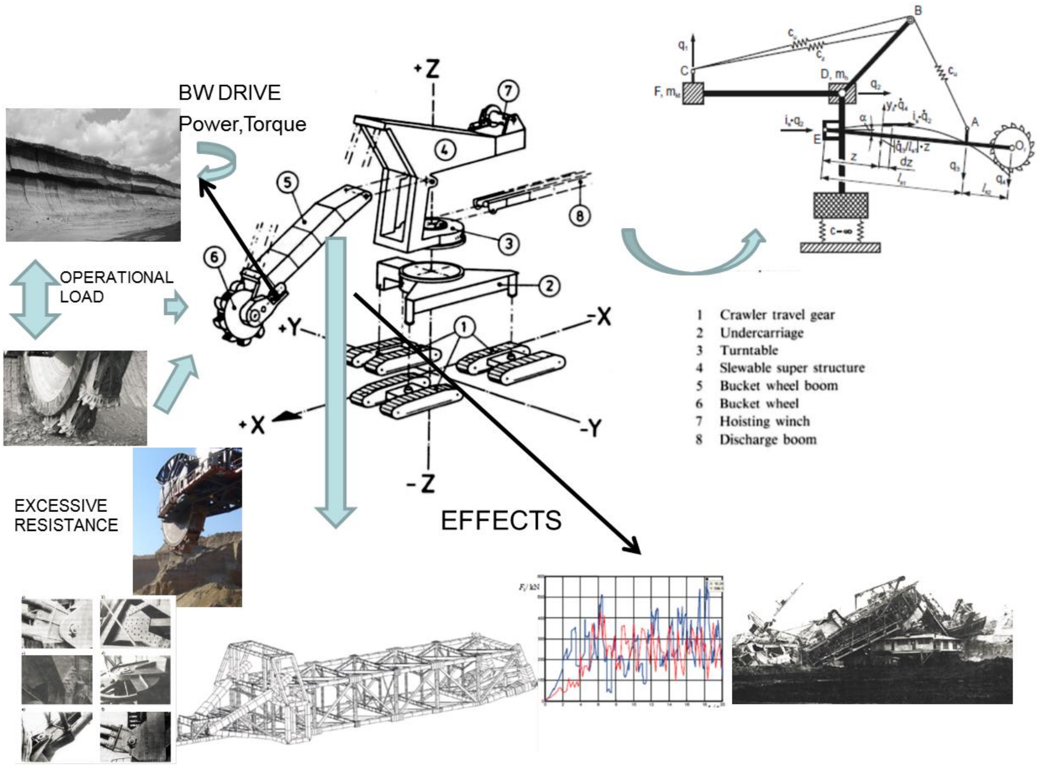
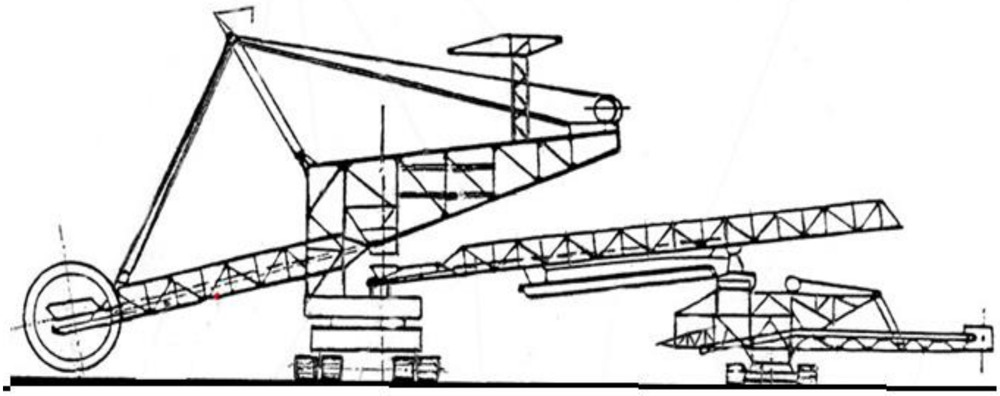


Fig. 1. Logic scheme of the complex problem of excavating hard formations/inclusions with BWE

The basic components of a BWE (Fig. 2, a,b) which are subject of unwanted effects produced while excavating these rock structures, belongs to the so called superstructure, mainly the boom. The source of excessive loads is the interaction between the working face and the bucket wheel's working elements, the so-called mining system. These components (teeth, buckets, BW, drive, boom, upper structure, discharge boom), appear in principle in all BWEs, though, according to the specific mine conditions, their individual design may diverge widely.

The geometric and dimensional features of the BWE have a large influence on the scale and severity of damages produced as results of these unwanted effects.

a)



b)

Fig. 2. Typical BWE construction on working face (a) and associated technical drawing (b)

The existing BWEs can weigh up to 12500 t and excavate material from a maximum bank height of about 50 m. The diameter of a bucket wheel (BW) varies from 2.4 to 22 m and the nominal cutting rate varies from 200 to 12500 m^3/h, in some cases it can be as high as 20000 m^3/h.

Even in the largest capacity BWEs the size of the buckets is relatively small, compared to the size of the equipment (usually less than 5 m^3), making them primarily appropriate for mining unconsolidated materials.

The excavation is achieved by the sideward slewing of the bucket wheel against the slope. This motion, which is essential for excavating over long distances, is achieved by a long slewable boom (Fig. 3).

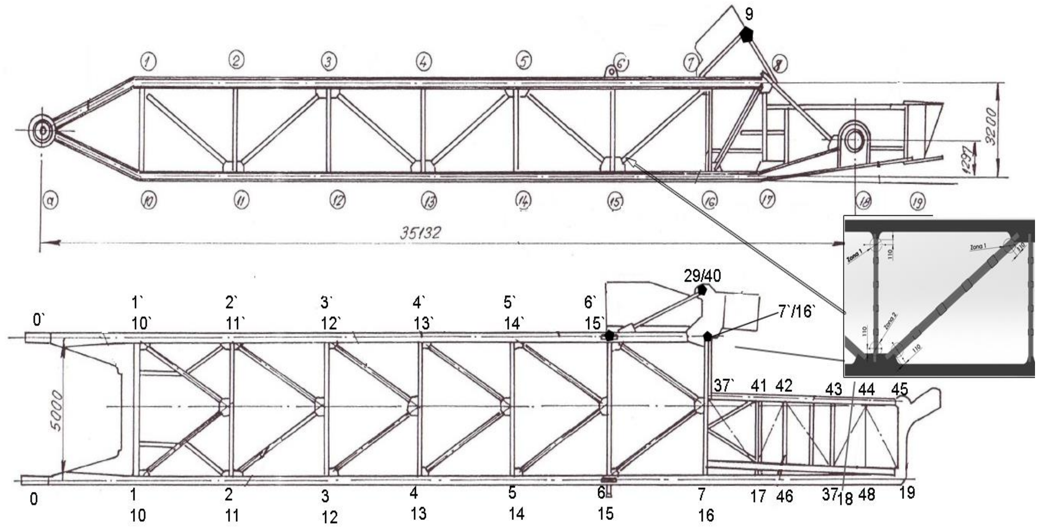


Fig. 3. Typical boom truss structure

The boom is fastened to a slewable superstructure by a pivot joint which is mounted on the undercarriage. The superstructure, which consists of a high rigidity platform and a tower which is seated on it, slews by means of a motor and gearbox. A flexible suspension, which rapidly cuts out dynamic and impact loads, and a safety clutch, which protects the motor from overloading caused by increased stresses exerted during the excavation, ensure high reliability and longevity, as well as fatigue durability.

In order to increase the cut range as high as possible above the track level, the BW can be raised and lowered by means of this main boom.

The bucket wheel Fig.5.a is considered the basic component of the BWE. By rotation it removes the material from the excavation face and discharges it onto the conveyor belt that is located inside the main and the discharge boom. The design of the BW is carried out having in mind the specific application as a whole, since the total output of the machine is over time entirely dependent on it. Hence, BWs are typically tailor-made according to the requirements of the mine in which they will be used.

The diameter of the BW affects the cutting speed, the bucket cutting force, the BWE operating weight, the construction cost, and the cut geometry. (Fig.4)

Through the years the size of the BW was constantly increasing. The need for larger-size BWs derives from the fact that the output of a BWE is proportional to the BW diameter. However, when designing a large-diameter BW, factors such as the operating weight and the cost of construction are of crucial importance.

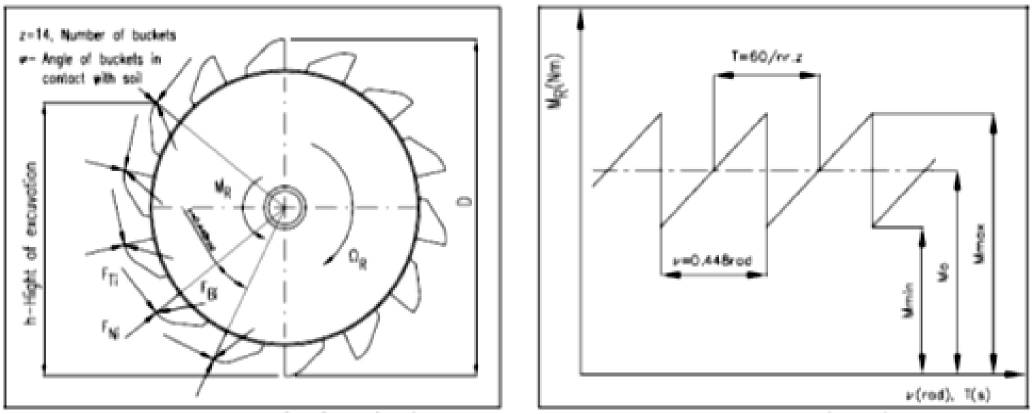
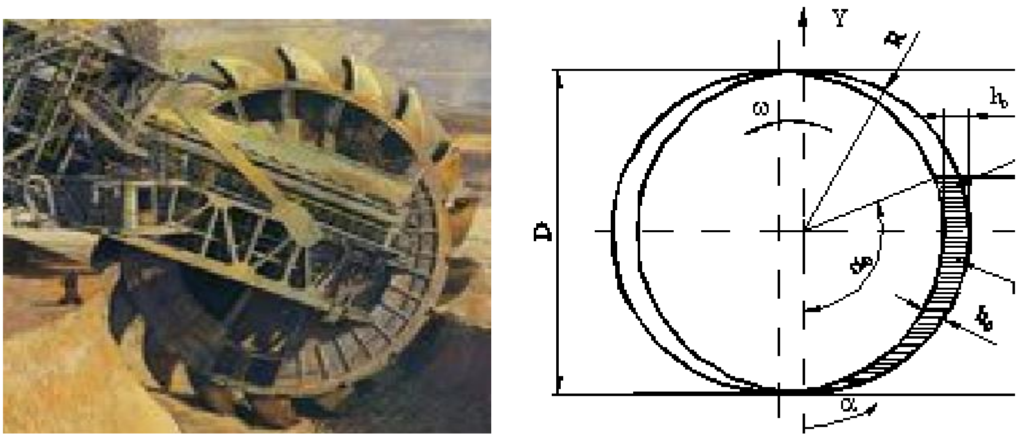


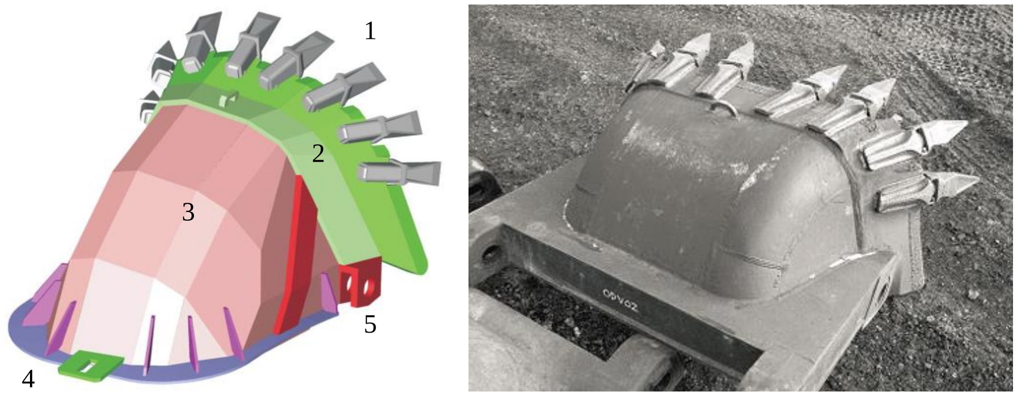
Fig. 4. Forces acting on bucket wheel and saw like load due to bucket spacing



a) *b).*

Fig. 5. Typical bucket wheel **(a)** cutting height relative to BW diameter **(b)**

The selected cutting height usually varies from 50 to 70% of the BW diameter, (fig. 5.b) which is allowed by both the cutting resistance of the material, the filling of buckets and the stability angle of the face slope. When selective mining has to be implemented for the excavation of thin layers of material or when the cutting resistance of the material is high, the cutting height can be less than 50% of the BW diameter, resulting in lower output. The bucket is a steel structure, either pressed or welded, which is mounted at the circumference of the BW. (fig. 6). The design of the bucket should ensure the efficient filling with and discharging of the excavated material. The shape of the bucket cutting edge can be rectangular, trapezoidal or circular. The bucket cutting edge and teeth are made of heavy duty steel plate that is additionally armoured with wear-resistant material on the cutting lip.



a) *b)*

Fig. 6. Typical bucket design 1 Tooth, 2 Lip, 3 shell, 4 attachments a) rounded b) rectangular

The part of the bucket that primarily comes in contact with the excavated material is the side lip, as well as a part of the front lip, and the teeth mounted on them. Most of the digging is carried out by the bucket corners, which in the cases of rectangular or trapezoidal buckets are extended and well armoured against wear. When the excavated material is highly abrasive, additional teeth are placed on the cutting lips, either by bolts or by wedges, in order to further protect the lips from wear.

The excavated material has a fluid-like behaviour, filling the bucket when the cutting edge reaches the horizontal position. If the terrace height is shorter than the radius of the BW, the optimum utilization of the bucket capacity cannot be achieved. Regarding the discharge of the excavated material, it should take place while the BW passes over the discharge area.

Fig. 7. a) Chain mat instead of shell of buckets b) bucket with corner cutters for soft material

In the case of very sticky materials, special consideration is required in order to ensure discharging from the bucket, as they tend to adhere to the walls. It is common to use chain mats, as those shown in Fig.6, which push the material out due to their deadweight. The effectiveness of the chain mats reduces as the rotational speed increases, resulting in increasing the centrifugal force

Additional cutters are installed when the size of the excavated material lumps has to be reduced. These pre-cutters are attached in the periphery of the BW body and between the actual buckets.

Preventing large lumps from entering the buckets and the conveyors can also be achieved by reducing the space between the back and the lip of adjacent buckets, either by lengthening the back of the buckets, or by increasing their number on the BW.

The maximum value of the cutting speed occurs at the outer region of the BW, reducing while moving towards the centre of it. Since the difference between the speed in the region of the cutting edge and the periphery of the BW is considered insignificant, the circumferential speed of the BW's outer edge can be assumed to be the cutting speed of the bucket.

The BW circumferential speed should ensure that the centrifugal force acting on the excavated material will be not more than one third of its gravitational force, so that the effect of gravity will be sufficient enough to allow for bucket discharge. There is a critical circumferential speed over which emptying of the bucket does not occur. A relationship between the critical circumferential speed at which the material is retained in the bucket wheel and the diameter of the BW has been demonstrated.

The key parameters affecting bucket discharge, and thus the circumferential cutting speed, are associated with the specifications of the BW and the buckets, as well as the properties of the excavated material (i.e. the size of the excavated material, the free flow angle, the internal friction angle, the coefficient of friction etc.). The selected circumferential speed should not exceed 55% of the critical circumferential speed ensuring that: (i) the centrifugal force will not reduce the effect of gravity on bucket discharge, and (ii) the duration of the BW passage over the discharge area will be sufficient to ensure the total discharge of the bucket.

As is known, the depth of the cut varies along the horizontal arc of the excavated face. To counterbalance this cutting depth variation, the slewing speed is adjusted accordingly. Current BWEs are capable of automatically changing the slewing speed of the boom as a function of the angle that is defined by the boom and the axis of face advancement, by the so-called cosine steering. The typical maximum slewing speed is approximately 1 m/s.

As a general rule, in order to keep the output of the BWE as high as possible, large slewing angles should be avoided. Additionally, in order to ensure good bucket filling, the slewing speed should be selected in regard to the circumferential speed and the cutting height.

The diversity of the mechanical properties of the excavated material, the volume and the cutting contour of the bucket, the shape and the condition of bucket teeth, and the bucket cutting speed, are only few of the numerous parameters determining the energy required for the excavation of a material. To date there is no reliable method to calculate the cutting resistance of a material, i.e. the force required to excavate it.

Laboratory tests can only be used as an initial indicative guideline for a specific material since there is a scale effect and the results significantly vary depending on the size and geometry of the test sample. Sufficient information about the cutting resistance of materials already excavated in an existing mine can be derived from machine operational data, but it is difficult to correlate measured power with other parameters, because the measured power available for excavation is directly correlated to the BW drive motors power. However, only part of this power is actually consumed for excavation. In order to calculate the power available for excavation, first, the power required for lifting the material to a height of about half the BW diameter should be deducted from the total installed motor power. The remaining power is consumed by the cutting resistance, the frictional, and the inertial forces. These last ones can be determined only by theory issued formulas, so the vicious circle is closed. The truth is somewhere at middle.

2. ADAPTATION OF BWE AND TECHNOLOGICAL PARAMETERS IN VIEW TO IMPROVE EXCAVATION OF HARD INCLUSIONS

The effect of the cutting resistance on the dynamic behaviour of the BWE is crucial. The occurrence of hard inclusions that are difficult to excavate has a substantial influence on the operation of a BWE. The dynamic and stochastic impact loads exerted on the machine, while performing heavy duty operations, are the most common causes of BWE failure.

In the definition of mining resistance of excavated rocks, known as Cutting resistance, a parameter at the boundary of intrinsic rock mechanical parameters are now a subject of debates among specialists. In our approach, for the project's purpose's, the issue is to select- find the best metric to be used applicable for –"normal "resistance, "excessive" resistance both in case of continuous layers (insertion) in excavated block and "accidental " excessive resistance occurred when unexpected intercalations or boulders appears in the excavated face responsible of impulsive loads. In the literature and BWE design and construction practice three kind of metrics are used:

A) specific cutting resistance k which is related to

1) length of cutting edge-K_L, in kN/m

2) cross section of chip- K_F, in kN/m2and

B) depth of cut (height of chip) K_h, in kN/m.

C) specific cutting energy w_s, which is expressed in energy/volume and SI units in MPa. It is confirmed that a good linear correlation exists between w_s and UCS.

A1 is used mainly in German literature; it has as historical origin in first use of Bucket Wheel machines in reclaiming/loading of bulk material purposes. On our opinion, this metric is suitable for actual BWEs only for soft rocks, and generally appropriate for loaders/ reclaimers, with buckets without teeth (with lips only) and very good for tools with large width, such as dredges and bulldozers.

A2 is preferred by majority of specialists, but, it is really an alternative of the specific cutting energy, hidden behind other unities of measure. So it is at least redundant, if not useless taking into account that it is relatively invariant on technological factors.

For BWEs the average values of K_L and K_F are utilized for calculating the cutting force acting on an entire bucket when K_h allow calculating the cutting force on individual tooth considering the geometry of chip as resulting from geometry and kinematic of bucket wheel, boom and bucket.

In past years, we determined on hundreds of samples of lignite and overburden rocks covering the entire coal field of Oltenia, the four parameters. Our opinion after analysing the great amount of results is that the pair K_h and w_s are the most appropriate for accurate estimation of cutting forces starting from individual teeth towards bucket and wheel (bottom to top or element to ensemble approach) because the number of teeth in contact with the rock and number of buckets involved in excavation is variable during a unitary cut and a block cut. This approach is more relevant to analyse and highlight the variability of load on wheel, which exists even in rock with "normal" resistance and increases dramatically in two cases of encountering "excessive" resistance.

If the extent of the hard inclusions is large, their occurrence is foreseen, blasting or other types of machines should be used for their excavation. In the case of small-size hard inclusions, the BWE can expose and push them down onto the crawler level. When the size of bucket is larger than the size of the inclusion, it is transferred with the flow of material on the conveying line, and produces damages on this segment. During the actions of handling these events, no actual production takes place, thus the average output of the BWE reduces.

In order to excavate hard inclusions, the operator of the BWE has to reduce the circumferential speed of the BW (which is technically possible only at last generation BWEs), the slewing speed of the boom, and the depth of the cut. All these if possible to be performed, lead to additional unproductive times.

The adaptation of the cutting parameters to the properties of the excavated material results in the variation of the BWE's performance.

Heavy design BWEs are reported to excavate boulders and layers of hard material with a thickness of up to 600 mm. However, the machines do not directly cut such hard material but rather break it into smaller pieces manageable by the material handling system. Material with a compressive strength of 70 to 140 MPa is reported to be excavated in this manner.

Natural tendency of permanently improving performances of BWE, especially in term of capacities, has not been adequately followed by calculation methods. A good proof of this is relatively frequent damaging of BWE. Non–allowed deformations and fractures of BWE subassemblies are primarily caused by lack of compliance while analysing real dynamic loads.

Oscillations of excavating structure (bucket wheel + boom + boom suspension (ropes) appears even during excavation process in “normal resistance” rocks. Because the rocks excavated in open pit lignite mines are non-homogenous, the excavating forces have a double kind of stochastic variability in time. A quasi-periodic variation due to successive entrance/exit in/from operation of buckets, progressive loading with excavated material of buckets and sudden unloading superimposed with a random fluctuation of cutting forces.

The increased tendency of bucket-wheel excavators to oscillations is found by [4] to be associated with the characteristics of the oscillatory system, mainly in terms of low dissipative (damping) capacity the permanent excitation from the bucket wheel – rock interaction. An interesting analysis regarding the positive feedback loop effect explained by increase of summary cutting force vertical component acting on bucket wheel, produced by the vertical oscillation of excavation system, which in some cases lead to increasing oscillation’s amplitude, a.s.o.

This analysis may provide solutions of effective suppression of different oscillations by dissipation of the energy of the oscillatory system directly in the cutting process, as requirements on both the design and the operational parameters of the cutting equipment.

Thus, it has been established that efficient suppression of bucket-wheel excavator tendencies to oscillations in a vertical plane and a decrease in the working unit oscillation amplitude to a safe level even in the regime of a power resonance can be achieved by damping the system with forces which, in case of a corresponding design of cutting equipment, are formed directly in the process of pit face cutting.

This solution is simple and “ideal” as the excavator operating system takes upon itself the function of a damper and, simultaneously, the ability of the main system to perform the task for which the excavator is intended improves. It is shown in [3] that cutting equipment with technically sharp self-sharpening teeth mounted on buckets at the angle $\psi = 0$ simultaneously ensures suppression of rotor oscillations in the pit face, a decrease in excavation power intensity and rotor drive loading by 40–45%, and a decrease in the side cutting force and rotation drive load by 2.5–3 times. As a result, the productivity of machines drastically increases and their reliability and operational effectiveness improve.)

3. CONCLUSIONS

The continuous layers of hard formations cannot be generally excavated by BWEs. For their excavation are required loosening operations by pre-excavation blasting works or the use of other types of machines, such as impact rippers, classic excavator and others.

Seldom occurrences of boulders or short veins generally are managed by auxiliary measures. A common finding is that small (dimension less than bucket volume are not excavated in proper sense, but they are removed from soft embedding rock. Even in this case, they produce unwanted effects on mining system of BWE.

In some cases, as reported in [7] when such a formation is encountered it causes lateral deflection of cutting system which can produce lateral (horizontal) excitations on the excavator's structure oscillation.

As a general remark, the aggressiveness against proper operation and structural safety of BWE of regular, well known continuous layers of hard formations is as important as the sudden encountering of small extent and much unknown hard boulders. The difference is as in risk theory frequency of occurrence vs. extent of damages produced.

The boulders are of different shape and sizes (from irregular to round and from 0.1 to 15 m) as well as of different mineralogical compositions. They are embedded in a matrix material consisting of claystones, sands, gravel and loam (the overburden of the lignite deposit).

Their density ranges from 2200 to 2700 kg/m^3, and their compressive strength from 10-143 MPa. These large variations, especially for the compressive strength, determines specific dynamic and stochastic impact loads acting on the BWEs for each mine that must be studied more thoroughly.

In most cases the BWEs can handle boulders ranging from 0.5 up to 1 m in size (depending on their mineralogical composition and strength). The larger ones usually require blasting works or mechanical disaggregation (using other machines).

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