GUIDELINES FOR THE DESIGN OF OPENCAST MINING MACHINES AND MATERIAL HANDLING EQUIPMENT

WYTYCZNE DO PROJEKTOWANIA MASZYN GÓRNICTWA ODKRYWKOWEGO ORAZ MASZYN I URZĄDZEŃ PRZEŁADUNKOWYCH

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Opencast mining machines and material handling machines perform an important role in many branches of industry (e.g. mining and rock processing, power) all over the world. This fact caused that different standards were developed containing guidelines for the design of such facilities. The most important of them, which will be discussed in details in the presented article, are: the Australian Standard (AS), German Standard (DIN) and ISO Standard. The advantages and disadvantages of each of them will be discussed, and with all the consequences of using the chosen standard. The authors also present self-developed solutions and recommendations that go beyond the scope of the mentioned standards.

Keywords: mining, mining machines, material handling machines, carrying structures, design standards

Maszyny podstawowe górnictwa odkrywkowego oraz maszyny przeładunkowe pełnią istotne role w wielu gałęziach przemysłu (górnictwo i przetwórstwo skalne, przemysł energetyczny, inne) na całym świecie. Fakt ten spowodował, iż powstały różne opracowania zawierające wytyczne do projektowania tego rodzaju obiektów. Najważniejsze z nich, które zostaną omówione szerzej w prezentowanym artykule, to norma australijska (AS), niemiecka (DIN) oraz norma ISO. Przedstawione zostaną wady i zalety poszczególnych z nich, a przede wszystkim to jakie konsekwencje pociąga za sobą stosowanie wybranej normy. Autorzy przedstawiają również samodzielnie opracowane rozwiązania i zalecenia wykraczające poza zakres wskazany w wymienionych normach.

Słowa kluczowe: górnictwo, maszyny górnicze, maszyny przeładunkowe, ustroje nośne, normy

INTRODUCTION

In heavy industry such as mining, power, rock and mineral processing, and in the accompanying material handling industry, a group of machines with relatively large overall dimensions and often the complexity of the structure are used. The design form of this type of objects is mainly due to the efficiency required in a given industry and the tasks that they perform. In the area of application mentioned, the characteristic machines are bucket wheel excavators, spreaders, stacker-reclaimers, various types of loaders and auxiliary equipment. High investment costs related to design and erection are very characteristic for this type of objects, and therefore the expected operational life is calculated in decades [1][2]. Examples of these objects are shown in Fig. 1

Maintenance costs during operation are also important - the lowest failure rate is expected, which corresponds with maximum availability. These machines are very often planned to work 24 hours a day, 7 days a week. Downtimes generate significant costs in the system. It is estimated that in the case of the Tamnava East (Serbia) mine system the downtime generates losses exceeding 9,000 €/h [3].

Guidelines on the design and maintenance of the technical condition of machines discussed in this article are presented in many standards. Although they refer to the same group of objects, the requirements they contain often differ, which is largely due to the regulations in which the given standard was developed, as well as the geographical area on which the machine was designed. Therefore, the ability to use the listed positions, the awareness of the consequences of their use, but also the ability to combine the proposed solutions to obtain the best object, becomes crucial. The article will present a comparison to facilitate the use of the discussed standards and the selection of the most appropriate one for the implementation of the project.

GENERAL RECOMMENDATIONS

Designing machines and devices in purpose of using in the mining industry, material handling industry, rock processing industry, and more is based on a few selected standards that were created on the basis of data collected by explorers and scientists over the years. Following documents had the greatest impact on current standards:

- BG 1986 [4] – Calculation and dimensioning of large-scale opencast mining machines. German standard. This standard is no longer valid, but it was the basis for developing the standard currently in use.

Fig. 1. a) Bucket wheel excavator SchRs4000, b) stacker 33000TPH
Rys. 1. a) Koparka kołowa SchRs4000, b) zwałowarka składowiskowa 33000TPH

- DIN 22261 [5] – Excavators, stackers and auxiliary equipment in brown coal opencast mining. The standard DIN 22261 came into force in June 1997 and replaced the standard BG 1986. The standard consists of six parts. Directly with the design of load-bearing structures are related parts 1-3: (1) Construction, Commissioning and Tests, (2) Calculation Guidelines, (3) Welded connections. The Polish equivalent of the DIN standard is PN-G--47000, which is a faithful translation and division into parts [6].
- FEM 2.131/2.132 – Guidelines for the design of mobile devices for the transport of bulk materials. The norm was published in 1978. The second edition was developed in 1992 and became the basis for creating the ISO 5049 standard.
- ISO 5049 [7] – Mobile devices for continuous transport of bulk materials. The standard was published in 1994 and is used to design all machines and devices for dumping and re-loading powdery materials. This standard, however, does not apply to the design of basic opencast mining machines, in which the standard DIN 22261 is most commonly used.
- AS 4324.1 [8] – Mobile devices for continuous transport of bulk materials – Basic requirements when designing steel structures. This norm was published in 1995, however, the first works on its creation are dated to 1978 [9]. This standard is based, unlike other standards, on two previously unrelated documents, i.e. BG 1986 and ISO 5049. As a result of this combination, the guidance presented in the AS 4224.1 standard includes both basic opencast mining machines as well as material handling machines and mobile devices for continuous transport of bulk materials.

Currently, there are other standard guidelines that could also be the basis for calculating the objects in question. Here, for example standards like: Eurocode, AA, TGL (not applicable standard). But due to the lack of their practical widespread use when designing the discussed structures, they were not included in this article.

Of all the items listed above, the most recognizable and commonly used standards are DIN 22261, ISO 5049 and AS 4324.1. The article will discuss the design guidelines presented in these standards. First of all, issues related to design in terms of static loads, dynamic loads, fatigue strength and stability of machines will be discussed.

Calculations of carrying structures under static load

Calculation issues in the field of static loads relate mainly to yield strength and problems related to buckling elements of the object. Because static loads are key loads due to the safety of the object, it is extremely important to determine them correctly.

These standards usually use calculations in accordance with the principle of permissible stresses. However, it is also possible to perform calculations in accordance with the principle of limit states (AS 4324). In an approach consistent with the permissible stress method, the specific load cases are assigned to appropriate safety factors. The modern approach in standards is the grouping of loads, taking into account their probability. According to DIN 22261, the following four load groups can be distinguished: H – main loads (including the variable loads of the fatigue case), HZ – main and additional loads, HZS – main, additional and special loads, HZG – main, additional and extraordinary loads. According to ISO 5049 can be distinguished three load groups: Group I – main loads, Group II – additional loads, Group III – extraordinary loads. In AS 4324 the load groups are defined similarly to ISO 5049 with the difference that the fatigue case is an additional, separate combination (F/I) in accordance with the fatigue case formulated in DIN 22261 (H1B). As already mentioned, the corresponding safety factors are assigned to each load group as shown in Table 1.

As shown, the ISO 5049 standard presents the most user--friendly load combinations. It contains only three groups and three corresponding safety factors. The DIN and AS standards define four and five different values of safety factors, respectively. More significant differences can be noticed by analyzing individual groups of load combinations. While the first group contains the same loads, regardless of the standard, the groups of main and additional loads differ from each other. In the DIN standard, this group consists of two subgroups: HZ2 (normal operation with wind load) and HZ3 (machine excluded from work taking into account wind extraordinary/stormy). For the case of HZ2, this standard provides for the effect of normal loads with mining forces (U, S), which is a fundamental difference compared to the other two standards, taking into account in this case the extraordinary values of both these forces. The ISO standard does not divide the group of main and additional loads (II) into any subgroups. The case of normal operation in the ISO standard simultaneously takes into account: the load of excavated material, wind load, steel occurring, temporary dynamic loads and unique, peripheral and lateral, digging resistance, which is the heaviest

Tab 1. List of factor of safety
Tabela 1. Zestawienie współczynników bezpieczeństwa

Standard	Load cases			
	H1a/I	HZ/II	HZS/III	HZG/III
DIN 22261	1.5	1.33	1.2	1.1
ISO 5049	1.5	1.33	1.2	
AS 4324	1.5	1.33	1.2/1.1/1.0	

impact load. In the AS standard, group II is divided into four subgroups: II/1 (normal operation, a case similar to ISO, with the difference that the inclination during operation was replaced by an extraordinary inclination), II/2 (normal operation, load combination corresponding to the DIN HZ2 case), II/3 and II/4 (machine off from work, combination similar to the DIN HZ3 case, takes into account the load of the excavated material and its lack, it takes into account the inclination).

The third group of loads in the DIN standard consists of 13 combinations, in the ISO standard of 9 combinations, and in the AS standard of 16 combinations. As for the main loads in this group, they are similar in each of the standards. The essential things should be distinguished that in the AS standard in one case (III/6) the extraordinary load of the conveyors with the material and clogging of the overflows are taken into account. DIN and ISO standards do not provide for the simultaneous occurrence of both loads. In the case of machines with long boom and a chute located at the end of the boom, the summation of these loads is the main factor affecting the dimensioning of the carrying structure as well as the stability of the entire machine. Another case that does not exist in DIN and ISO standards, but has been introduced in the AS standard, is a combination of III/14 loads, in which the bucket wheel and drive are to be lost. If you additionally take into account that for all machines with an open ball races bearing it is necessary (in accordance with the AS) to design appropriate hooks to prevent overturning, designing such a machine becomes a challenge.

The information presented above shows that despite describing in the three mentioned standards regarding the same machines, the determination of their operational conditions, in the form of loads combinations and load cases, is in many cases different.

Another factors that should be taken into account are the differences resulting directly from the definition of loads included in the calculation cases. For example, the AS standard requires the use of safety factor 1.1 already when determining the digging force and lateral force. Another difference is defining the forces resulting from grounding (A, AA, A1, A2). The AS standard, like DIN, requires the definition of two levels forces of partial grounding. Additionally, in certain situations the AS standard requires consideration of the case of full grounding. This requirement applies not only to the bucket wheel boom, but also to all other booms. The DIN standard, however, provides grounding only for the bucket wheel boom, which in the most disadvantageous situation is limited by the stability on the bearing or by the load capacity of the catching hook. The AS and ISO standards require an additional 20 % inclination when for travel of the crawler mounted machines. The DIN standard on this point does not suggest the inclination increase.

To sum up the part related to the static load, it can be concluded that the AS 4324 standard puts the highest demands on the constructed objects. DIN 22261 standard is a detailed work out on the basis of which safe objects are created, although its requirements are not as high as in the case of the AS 4324 standard. The ISO 5049 standard leaves considerable freedom in defining many parameters, therefore, the authors recommend using it only to experienced users. In addition to technical requirements, standard AS 4324 also recommends additional auditing the developed project by an independent expert. From the experience of the authors, based on carrying out many design and calculation works, in accordance with all the above-mentioned standards and conducting, as an Independent Expert, audit of projects of more than 50 machines, it can be concluded that the application of the AS 4324 standard increases the operational safety and reliability of opencast mining machines and material handling machines. On the other hand, the requirements set out in this standard contribute to the increase of the dead weight, and thus the costs of the designed machines. It can be estimated that machines designed based on the AS 4324 standard have approximately 20 % more weight compared to machines with the same parameters, but designed in accordance with DIN 22261 standard or ISO 5049 standard.

Calculations of carrying structures loaded dynamically

One of the main factors determining the shaping of a supporting structure characterized by vibrations, and often impact loads, are equivalent dynamic coefficients used for calculations. Although the concept of dynamic coefficient is common to most standards, their defined and recommended values may vary depending on the adopted calculation guidelines. This also applies to the discussed standards for the design of opencast mining machines and machinery and equipment for the transport of bulk materials discussed in this article, hence the standards: DIN 22261, AS 4324 and ISO 5049.

For Australian (AS) and German (DIN) standards, the general assumptions regarding the use of dynamic load factors are the same. However, there is one very important difference, namely the adopted values of these coefficients. As it results from subsection 2.1, the AS 4324 standard places higher demands on designing due to static loads. A similar situation occurs also in the case of dynamic loads, which values in the AS standard are much higher than in the DIN standard. An important gap in both standards is the lack of guidelines for conducting experimental verification tests of actual values of coefficients. The ISO standard is the norm containing the least information related to dynamic loads. It does not contain a definition of the coefficient and computational application that would be comparable to the two already mentioned standards.

The definition of the dynamic coefficient [10] presented in the DIN standard is based on the difference between the highest and lowest recorded acceleration values. A big disadvantage of using the dynamic coefficient is the total omission of phenomena actually related to dynamics. The dynamic coefficient is in fact the multiplication factor that is taken into account in the static / fatigue calculations. DIN and ISO standards do not require an analysis of the dynamic response of the system. The AS standard is once again proving to be more demanding in this respect, because it recommends analyzing the resonance capability resulting from the excitation frequency corresponding to the bucket discharge frequency. The authors of this article have already proved that because of such formulated requirements regarding the dynamics of objects, they does not rarely work in resonance [11]. Lack of requirements for conducting experimental verification tests in this area may lead to the operation of machines with a higher load than expected, which in turn leads to accelerated degradation.

Calculation of carrying structures in terms of fatigue strength

This chapter will cover issues related to fatigue strength assessment. Firstly the load definition will be described. Secondly will be presented a short comparison of fatigue calculation methods.

According to the standard [5], which is the most commonly used standard for opencast mining machines, the fatigue load case (H1b) consists of individual variable loads: excavated material (F), inclination (N), digging force (U), lateral digging force (S), dynamic effects (D). Loads that change direction during operation, through their alternate operation, result in a twofold increase in amplitude. Loads changing direction are: lateral digging forces, inclination and dynamic effects. Therefore, the fatigue load case is defined as follows:

H1b: F, 2NQ, 2NL, U, 2S, 2DQ, 2DV, 2DL,

where the inclination and dynamic loads are defined by the appropriate directional component. From the presented H1b load definition, it appears that 3 out of 8 components are associated with a dynamic load factor. This fact emphasizes the need for a proper definition of dynamic loads due to its significant impact on the assessment fatigue life. In the latest version of the standard (2016) [13] the name of fatigue load case on HD has been changed. The related of loads remained unchanged, but the reader should be aware of the change of the name H1b to HD, because over the years the H1b designation became representative as a case of fatigue life assessment.

The Australian standard [8] in this aspect is similar to the DIN standard and defines the case of fatigue load in the same way. However, it should be noticed that the values of load factors of dynamic differ significantly in both standards, which will have a significant impact on the results obtained.

The ISO standard can also be taken into account when defining the fatigue load case [7]. Unfortunately, separate combination of fatigue load cases has been not defined. However, it is recommended to use the loads defined for the main load, which may occur in more than 2x104 cycles. In this way, the identified loads should be implemented in the calculations in a way that generates maximum tensile stresses. The ISO standard, compared with the other two, gives greater independence in the combination of fatigue loads, but if you perform this task correctly, it should produce a combination similar to the combination defined in DIN. In practice, many designers use the DIN combination directly instead of using it according to the ISO recommendations.

The second issue is the assessment of the durability of the structure, while the loads are already identified. Referring to the most frequently used DIN standard, the criterion of unlimited fatigue strength is met if the obtained range of stresses does not exceed the limit of fatigue determined for a given type of structural node (connection type). This approach ignore the effect of the number of cycles associated with a single load.

The ISO standard presents a similar approach. It also refers to permissible levels of fatigue stress determined separately for a given type of connection. The correct reading of fatigue curves, however, requires more detailed information on the connector itself and information on the cycle characteristics.

In the latest edition of DIN (2016) the fatigue calculation method was changed and standardized with fatigue recommendations according to Eurocode 3. This method is based on the stress damage hypothesis according to the Palmgren-Miner theory. The same method has already been recommended in the AS standard.

Because the finite element method has become one of the major engineering tools in recent years, it is also used to assess the fatigue of carrying structures. In this case, the major defect is the high sensitivity to the parameters of the model, which can largely affect the results. During the FEM analysis, in fatigue calculations recommend using the „hot-spot" method [14]. This requires preparing the model and stress readings in a specific way [15][16].

STABILITY

In all of presented standards (DIN 22262, ISO 5049, AS 4324) there is a similar approach to stability calculations based on the stability coefficient v0 calculated on the basis of the following equation:

$$\nu_o = \frac{M_s}{M_o} \qquad (1)$$

where:

M_s – the minimum stabilizing moment calculated with reference to the overturning axis

M_o – the maximum overturning moment calculated with reference to the same overturning axis

The above ratio is calculated for the most unfavorable load combinations and cannot be less than the safety coefficients assigned to the load combination groups. However, there are some differences in the results of stability calculations carried out in accordance with the recommendations in individual standards. In DIN 22261 standard, there is an additional requirement for multiplication by 1.05 ratio of all constant loads, which reduces the stability of the machine. This is due to the fact that permanent loads cannot be fully confirmed at the design stage. Another difference concerns machines whose body rotational motion takes place using ball bearings (both with catching hooks and without them). In the case of such a solution, it is assumed that overturning axis is on the diameter, which should be calculated as 95% of the radius of the bearing. According to the AS standard, it is necessary to install the safety hooks at overturning always when using the solution to rotate the body through a bearing with open raceway.

As mentioned in Section 2.1, there are also significant differences in load combinations and calculations of elementary loads in DIN, ISO and AS standards. The most restrictive AS standard imposes many stability requirements on designers. For example, a load combination III/6 (blocked chute and unusual material on the conveyor) is usually decisive in machines with long booms, where the chutes are placed at the ends of the booms. Similarly, support requirements are for all booms (the DIN standard provides support only for wheeled and chain excavators) it also makes it difficult to meet the stability requirements.

Because the stability of opencast mining machines and material handling machines is of great importance for the safety of their operation, the safety factors cannot be exceeded, as in the case of strength calculations, where an excess of 5% is permissible. As a consequence, it is necessary for the designer to pay particular attention to the initial design of the machines in which the carrying part, dimensions and position of the overturning axis have been defined.

KEY ISSUES NOT COVERED BY THE STANDARDS

Since all the mentioned standards relate to the design of new machines, it is important to evaluate the technical condition of the machines and determine the remaining life of the machines after many years of operation. The estimated time of exploitation of a new opencast mining machines or bulk material handling machines is define at around 30 years. However, there are many objects that have already exceeded this age. Due to the long delivery time of new machines and their very high unit cost, users must make difficult decisions regarding the moment when machines worth millions, should be taken out of service. The answer to the question of whether the assumed durability has been exhausted is crucial. Many years of exploitation, in various conditions, makes it difficult to make this decision. In addition, old machines must provide adequate operational safety so that accidents involving humans and do not occur and do not generate excessive maintenance costs. The main problem in this case is the steel carrying structure of the machine, which is essentially not renewed, unlike the mechanical or electrical elements of the machine.

In recent years, many publications have been published regarding the above-mentioned issues [17]. The authors of this article have developed a comprehensive guide and recommendations for the assessment of technical condition, monitoring methods and strategies aimed at extending the time of safe exploitation use of specialized mining and material handling machines [2]. The main emphasis in the proposed solutions lies in the following activities:

•numerical identification of the effort of carrying structures with the use of three-dimensional calculation models based on MES, which are then used for fatigue calculations,

• identification of operation loads, mainly performed by means of experimental tests on tested machines, assessment of the durability limit based on the identified effort and the actual load acting on the analyzed objects,

• implementation of an appropriate technical condition monitoring approach to detect or predict structural failure at the earliest possible stage allowing corrective action to be taken,

• development and implementation of modernization of machines and devices, both locally and globally, including the above information on the technical condition.

These tests complement knowledge about the degree of structural degradation, prediction of residual durability and in most cases allow to extend service life at a reasonable cost and the expected level of safety

Another important issue is that the standards and available literature, in comparison with the operational experience, indicate a large discrepancy in the rate of dynamic effects. Observations have shown that the actual values of the dynamic coefficient do not correspond to the values adopted at the design stage [17]. This problem was noticed and „solved" (increased values of the dynamic effects coefficient, which leads to an increase in the structure weight) in the AS standard. An important disadvantage of all standards, however, is the lack of recommendations regarding the validation of the factor value at the design stage.

Recent research [18] and the developed method (Fig. 2)[12] fills the gap in the methods for calculating the dynamics of large-size machines. It is also based on the real rate of dynamics effects, which according to standards is the basis for these calculations. Thanks to this, the proposed method is compatible with all current requirements of designers of large-size machines. Includes calculations, experimental verification and evaluation. The method has already been tested and its effectiveness has been proven [17]. In addition, the method takes into account the impact of body dynamics on the structure of the chassis [19]. Until now, this dependence has been neglected in most calculations.

SUMMARY AND CONCLUSIONS

Designing and testing of opencast mining machines and specialized material handling machines requires extensive knowledge and experience in applying the available standards. The article discusses three of them: DIN 22261, ISO 5049 and AS 4324. The main differences regarding the assumptions for the definition of loads, load combinations and calculation methods are presented. The AS 4324 standard is the most demanding, due to the many failures that occurred in the Australian industry before its introduction. These requirements increase the safety and reliability of machines, but they also have a significant im-

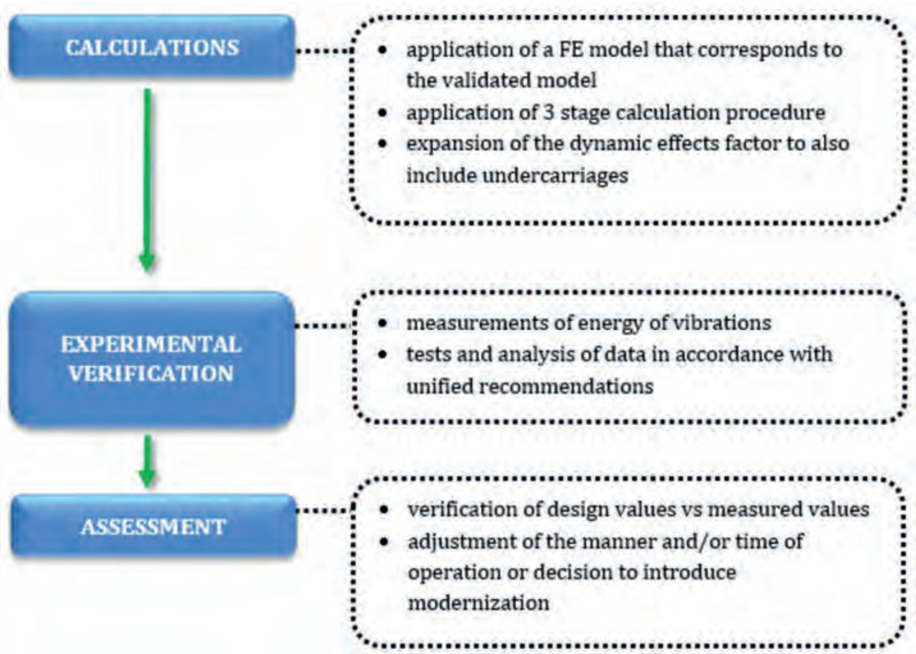

Fig. 2. The method of evaluation of large-size carrying structures with use of the dynamic load factor [12]
Rys. 2. Metoda oceny wielkogabarytowych ustrojów nośnych z zastosowaniem współczynnika obciążeń zastępczych [12]

pact on the weight of machines, which is about 20% greater than machines designed based on ISO or DIN standards. It is worth to mention that there has been a change in the approach to fatigue calculations that scientists have recommended for a long time in their publications [20][21]. The damage cummulation method (Palmgren-Miner) is increasingly used in design standards.

Nevertheless, there are still gaps in the standards to be filled in order to improve the quality and safety of the designed facilities. The commonly used method of designing large-size machines basically neglects or underestimates the dynamic loads of designed structures. None of the standards constitutes an validated method of experimental research that could be used to verify the actual values of the adopted dynamic coefficients. The DIN standard excludes the effect of fatigue dynamic loads and other variable loads on the chassis of the machines discussed.

In addition, it is necessary to conduct an assessment of the technical condition of existing machines in order to obtain information on the remaining time of safe operation. There are no standards that could help managers make decisions about the time when machines worth millions should be out of service or when, how and what to do to extend their ability to continue working with the appropriate level of safety [22]. The above-mentioned gaps in the field of design and operation cause in effect numerous failures of opencast mining machines and material handling machines, which practically always generate excessive costs related to repair and downtime, and unfortunately sometimes lead to fatal accidents.

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