Estimating the Remaining Operating Time of Mining Headframe with Consideration of Its Current Technical Condition

Eugeniusz Rusiński\textsuperscript{a}, Przemysław Moczko\textsuperscript{b}, Piotr Odyjas\textsuperscript{c, *}

\textsuperscript{a,b,c}Institute of Machine Design and Operation, Faculty of Mechanical Engineering, Wroclaw University of Technology, Łukasiewicz st. 7/9, 50-371 Wroclaw, Poland

Abstract

The condition of headframes in underground mines has a substantial effect on the proper operation and safety of hoisting equipment. One of the potential problems that might occur during operation is the tilting of these structures, which can lead to difficulties in operation and, in extreme cases, to failures. The paper presents an original method of evaluating the technical condition of headframes, estimating the remaining operating time and finding the causes of irregularities in the operation of this kind of structures. To show this, a series of experimental studies and structural analyses were conducted on a model headframe. Based on experimental tests and numerical calculations, the operational safety of the structure was established along with limit values of operational parameters and possible preventative measures were proposed.

© 2013 The Authors. Published by Elsevier Ltd.
Selection and peer-review under responsibility of the Vilnius Gediminas Technical University.

Keywords: mining headframe; estimating the operating time; finite element method.

1. Introduction

Headframes play an important role in the mining industry. Headframes for permanent duty are most frequently used for [1]:
- operating service shafts;
- operating lift shafts;
- operating production and service shafts;
- operating shafts for material handling.

For each of the above functions it is essential that the headframe be operational for as long as possible, which mainly depends on the method of operation, mining damages or quality of the ground on which the headframe is constructed. The main decisive factors influencing the technical condition and degradation rate of the headframes are:
- corrosion (especially in the supporting area);
- loads resulting from operation of mine hoists in normal mode and failure mode;
- irregular ground settlement under the foundation.

Due to the above factors the load capacity may decrease, local deformations might occur, or the headframe might start tilting, which is especially frequent in the case of A-frame headframes, in which the hoisting machine is located in the vicinity of the headframe tower.

The technical condition of headframes is regularly inspected. These inspections consist of visual and nondestructive tests and geodesic surveys of the headframe foundation, which allow one to determine the possible tilt of the headframe.
The conditions and requirements related to construction and operation of headframes are established in the Polish law [2] (ROZPORZĄDZENIE MINISTRA GOSPODARKI z dnia 28 czerwca 2002 r. w sprawie bezpieczeństwa i hygienny pracy, prowadzenia ruchu oraz specjalistycznego zabezpieczenia przeciwpożarowego w podziemnych zakładach górniczych). According to this document the maximum tilt of headframe during operation may not exceed 1/500 of the height of the headframe defined as the vertical distance from the supporting beams to the center-line of the highest head sheave. If this value is exceeded, it is necessary to establish the cause of such state and its influence on the safety of the headframe and the mine hoist. Based on such studies one can undertake actions aimed at decreasing the tilt or approving the condition of the headframe if the results of studies allow for it. To this end, it is required to perform a detailed analysis of the causes of headframe tilt and to establish the limit state of the tilt, which, if exceeded, could lead to failure. The limit state in this case may constitute such tilt which increases the risk of loss of stability and/or which causes the maximum stresses in the headframe structure to reach their limit values [3].

As mentioned above the tilting of headframes depends on many factors, such as irregular ground and foundation settlement or overload of the structure resulting in cracks, plastic deformations or buckling.

Using as an example a headframe which exhibited excessive tilt, a comprehensive method was proposed aimed at establishing the causes of such tilt, evaluating its effects on the structure and defining corrective measures to alleviate the problem. The study analyzed a 17.5-meter-tall steel welded A-frame headframe, which is located in one of the Polish mines (Fig. 1). Since early 1990s the tilt of the headframe has been gradually increasing until its value recently exceeded the limit allowed by law [2]. As a result tests and analyses had to be performed aimed at establishing the causes of the tilt and the limit values which guarantee operating safety of the headframe. The results of such actions may also serve as the basis for obtaining a design exception approval concerning the maximum tilt of the headframe, which would allow its further safe operation. To this end, the authors proposed an original method based on experimental tests and numerical studies, which allows one to estimate the operating period of the headframe, establish the causes of its tilt and devise possible measures to prevent further tilt.

The use of numerical methods and tests on a real object is widely popular in evaluating the technical condition of structures [4-5], [6], [7-8], [9] and the causes of failures of technical structures [4-5], [7-8], [10], [11-12].

2. Tests on real structure

The purpose of tests on a real structure was to measure the conformity of the real structure with the specifications and to evaluate the technical condition of the headframe through visual studies, NDT and thickness measurements, especially in
corroded areas. This made it possible to calculate how potential defects or the wear of the structure influence the tilt of the headframe and its tension level. Additionally the results of these analyses were used to build a numerical model, which is analogous to the real structure.

As a result of visual inspection some minor discrepancies were found between the real structure and the specifications. These differences pertained to secondary elements (mainly the distribution of braces), which do not have significant influence on the strength of the structure.

An analysis of the technical condition demonstrated substantial corrosion of the headframe’s supporting beams (Fig. 2a). Corrosion was removed during tests (Fig. 2b) in order to enable thickness loss tests of corroded areas in the supporting structure. Supporting beams determine the safety of headframe foundation and therefore they should be subject to detailed visual inspection during experimental tests (Fig. 2).

The results of experimental studies were used in the subsequent stage of numerical calculations by establishing the influence of the aforementioned effects of wear on the structure’s load capacity. The details of these analyses are presented in the following section.

![Fig. 2. Corroded flanges of supporting beams (a) supporting beams after sand blasting (b)](image)

3. Numerical calculations

Numerical calculations for the headframe were performed using the finite element method [13], [14], [15]. These included static calculations and a linear stability analysis of the structure. The calculations were performed in accordance with the current [3] norm on headframe loads and [16] norm on wind actions on structures, for several dimensioning cases of loads, both for the current state and the predicted state. The purpose of this was to establish the maximum allowable tilt of the headframe as well as the factors which caused the previous tilting of the headframe. Additionally the values of stress were tested for individual load cases in order to establish the tension level of the structure and to identify the most tensioned elements during headframe operation.

In the first stage, the geometric model of the studied structure was created in accordance with the technical documentation and the specification conformity analysis of the real object. Based on the geometric model, a discreet model of the headframe was built (Fig. 3 and 4) followed by a calculation model which used appropriate limit conditions (Fig. 5). This model included the current tilt of the headframe, the settlement of the A-frame support and the decreased sections of support beams due to corrosion. Based on the analysis of directions of headframe displacements, the settlement of the A-frame support was initially identified as the cause of headframe tilt.

Table 1 presents the results of MES calculations for the dimensioning cases of current loads (denoted as A) and estimated loads (denoted as P). The stress contours for selected load cases are presented in figures 6-8, whereas the displacement vectors in the direction of the headframe tilt are depicted in Fig. 9.

The headframe structure was built of general purpose St3SX steel (new notation S235JRG1 [17]). Based on this fact it was established that the plasticity limit of the material from which the headframe was built was 235 MPa. However, because the value of 215 MPa was assumed for calculations in the stage of headframe design, this value was chosen as the limit value for the studied structure.
Based on the performed analyses, presented in table 1, one can see that for the current load states, i.e. loads during normal headframe operation, the stress values are significantly lower than the limit value related to the plasticity limit of steel used in the headframe structure. The areas of maximum stress values are presented in figures under the table. The predicted cases are characterized by higher stress values because in these cases it is this single parameter that determines the maximum allowable values of headframe tilt in the context of its operation. An analysis of predicted cases was performed in order to establish the limit load capacity in terms of stress and buckling.

The purpose of the buckling analysis was to assess the stability of the headframe in the state of maximum predicted tilt and was performed for the worst case scenarios of load P2 and P5. The results of the buckling analysis are presented in table 2 and in figures 10 and 11. These results indicate that the projected loss of stability will occur as a result of the material exceeding its plasticity limit and not as a result of buckling of the structure.
Table 1. Results of headframe calculations – equivalent stress according to Huber-Mises hypothesis

| Load case | Loads according to norm: PN-G-03002:1997 | H-M-H equivalent stress [MPa] |
|-----------|------------------------------------------|-------------------------------|
| Current state A1 | base | 102 (Fig. 6) |
| A2 | additional | 180 |
| A3 | additional | 168 |
| Predicted state P1 | additional | 162 |
| P2 | additional | 215 (Fig. 8) |
| P3 | additional | 190 |
| P4 | additional | 197 |
| P5 | exceptional | 210 (Fig. 7) |
| P6 | exceptional | 126 |
| P7 | exceptional | 119 |
| P8 | exceptional | 118 |

Table 2. Results of stability analysis for the headframe structure – buckling coefficients for the most dangerous load cases in the estimated state of headframe tilt

| Load case | Buckling coefficient |
|-----------|----------------------|
| P2        | First buckling mode shape | 1,623 | Second buckling mode shape | 1,786 | Third buckling mode shape | 1,831 |
| P5        | First buckling mode shape | 1,347 | Second buckling mode shape | 1,465 | Third buckling mode shape | 1,875 |
Fig. 6. Contours of H-M-H equivalent stress – A1 load case

Fig. 7. Contours of H-M-H equivalent stress – P5 load case

Fig. 8. Contours of H-M-H equivalent stress – P2 load case
4. Estimating the remaining operating time of headframe

By analyzing the settlement test results of characteristic points of the headframe over several years and by applying numerical analysis it is possible to estimate remaining time of operation and define the limit tilt value. Table 3 compares the values of headframe tilt based on numerical calculations. A simple analysis shows that the maximum tilt of the headframe can be approx. 58.8mm, which corresponds to the settlement of foundation by 5.5mm. Considering the current tilt of the headframe the limit value could be reached in approximately 6 years.
5. Summary and conclusions

The assessment of the current technical state and the prediction of the technical state in the case of complex technical structures is a difficult task which often requires an interdisciplinary approach. This is because there are a number of different phenomena related to operating conditions, external factors or random phenomena, all of which can influence the degradation of such structures. The combination of such phenomena determines the safety of operation of such structures. If the technical condition deviates from the specifications it is necessary to establish the causes of such phenomenon, its impact on the safety of operation and possibly to devise corrective measures, which could restore appropriate operating safety margins. The article presents an original approach to solving such problems, based on tests on an A-frame headframe, whose tilt during operation exceeded the allowable value [2]. In order to evaluate the safety of operation of the structure and estimate its further operating time the authors implemented their own original experimental and numerical method. The article presents numerical calculations which use the finite element method. Numerical calculations made it possible to establish the current tension level of the headframe for the current tilt. The results also included the parameters of limit conditions for headframe operation. It is important to note that the calculations took into consideration the current state of the headframe with advanced corrosion as well as its structural form, which in some areas does not comply with the design specifications.

The studies demonstrated that the root cause of headframe tilt is the settlement of the foundation under one of the A-frame supports caused by poor ground quality, which was verified by a geodesic survey. This settling is mainly caused by self-weight loads of the structure, though it is possible that structural vibrations during operation could influence the thickening of ground under the support, thus causing its settlement.

A numerical analysis of the headframe in the predicted states showed that the headframe could still tilt by approximately 14 mm, which, given its current tilting rate, would occur over several years of operation. If the headframe tilts by this value, the material in one of the headframe posts might reach its plasticity limit (case depicted in Fig. 9). The structure may then sustain damages caused by the structure reaching its limit load-carrying capacity in this area [18].

As corrective measures which could stop the headframe tilt and therefore prevent the possibility of reaching the limit state, method of stabilizing the ground under the settling foundation of the A-frame support was proposed.

References
[1] Ledwoń, J., 1954. Wieże wyciągowe: obliczenia i konstrukcja. Budownictwo i Architektura, Warszawa (in Polish).
[2] Rozporządzenie Ministra Gospodarki z dnia 28 czerwca 2002 r. w sprawie bezpieczeństwa i higieny pracy, prowadzenia ruchu oraz specjalistycznego zabezpieczenia przeciwpożarowego w podziemnych zakładach górniczych [ORDER of 28 June 2002 of the Minister of Economy concerning occupational safety and health, traffic regulation and specialised fire-fighting protective equipment in underground mining facilities] (in Polish).
[3] PN-G-03002:1997. Górnictwo – Wieże szybowe – Obciążenia (in Polish).
[4] Bošnjak, S., Arsić, M., Zrnić, N., Rakin, M., Pantelić, M., 2011. Bucket wheel excavator: Integrity assessment of the bucket wheel boom tie-rod welded joint, Engineering Failure Analysis 18(1), pp. 212-222.
[5] Bošnjak, S., Pantelić, M., Zrnić, N., Gnjatović N., Đorđević, M., 2011. Failure analysis and reconstruction design of the slewing platform mantle of the bucket wheel excavator O&K SchRs 630, Engineering Failure Analysis, article in press.
[6] Harnatkiewicz, P., Rusiński, E., Moczko, P., 2010. The lifetime prediction of a rotary screw compressor of a liquid cooler subjected to high pressure and high frequency loads, Engineering Failure Analysis 17(6), pp. 1290-1299.
[7] Rusiński, E., Czmochowski, J., Iłuk, A., Kowalczyk, M., 2010. An analysis of the causes of a BWE counterweight boom support fracture, Engineering Failure Analysis 17(4), pp. 179-191.
[8] Rusiński, E., Moczko, P., Przybyłek, G., 2010. Numeryczno-doświadczalna metoda oceny stanu technicznego stalowych ustrojów nośnych, Górnictwo Odkrywkowe 4, pp. 302-305 (in Polish).
[9] Smolnicki, T., Stanco, M., 2009. Prognozowanie zużycia odkładowiowego wielkopowłokowych טלży tocznych o bieżniach miękkiach, Acta Mechanica et Automatica 3(1), pp. 98-100 (in Polish).
[10] Dmochowski, G., Berkowski, P., Schabowicz, K., Wójcicki, Z., Grosel, J., Dłucik, Ł., 2010. “Failure analysis of RC floor slab in indusrail hall”, The 10th International Conference “Modern Building Materials, Structures and Techniques”, 2010, Vilnius, Lithuania, pp. 587-592.
[11] Rusiński E., Moczko P., Czmochowski J. 2008. Numerical and experimental analysis of a mine's loader boom crack, Automation in Construction. Vol. 17, no. 3, 271-277.
[12] Rusiński, E., Czmochowski, J., Moczko, P., 2007. Failure reasons investigations of dumping conveyor breakdown, Journal of Achievements in Materials and Manufacturing Engineering 23(1), pp. 75-78.
[13] Rusiński E., Czochowski J., Smolnicki T. 2000. Zaawansowana metoda elementów skończonych w konstrukcjach nośnych. Oficyna Wydawnicza Politechniki Wrocławskiej, Wrocław 2000 (in Polish).

[14] Rusiński, E., 1994. Metoda elementów skończonych-system COSMOS/M, Wydawnictwo Komunikacji i Łączności, Warszawa (in Polish).

[15] Zienkiewicz, O. C., Taylor, R. L., Zhu, J. Z., 2005. The Finite Element Method. 5th Edition, Vol. 1, 2. Elsevier.

[16] Eurokod 1: Oddziaływania na konstrukcje - Część 1-4: Oddziaływania ogólne - Oddziaływania wiatru, PN-EN 1991-1-4:2008.[Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions, PN-EN 1991-1-4:2008].

[17] PN-EN 10025-1 Wyroby walcowane na gorąco ze stali konstrukcyjnych - Część 1: Ogólne warunki techniczne dostawy (in Polish).

[18] Olszak W., Perzyna P., Sawczuk A. 1965. Teoria plastyczności. Państwowe Wydawnictwo Naukowe, Warszawa 1965 (in Polish).