AGH Journal of Mining and Geoengineering • Vol. 36 • No. 2 • 2012

Danuta Domańska *

INITIAL ASSESSMENT OF SAFETY OF CONCRETE LINING OF SHAFT INLETS USING NUMERICAL CALCULATIONS

1. Introduction

Shaft inlets make the connections between shafts and most frequently horizontal workings at given mining and ventilation levels of mines or they are made at the point of contact of the shaft tube with other auxiliary workings (such as e.g. tube channels, channels supplying fresh air or chambers of different type). The considered structures are often made as [9]: one-sided horizontal or inclined structures, two-sided horizontal, inclined or mixed structures and two-sided symmetrical or asymmetrical structures. The size of inlets is mainly associated with the number and size of hoisting machines, the type of horizontal transportation system, the number of loading levels, the levels for people getting in and out, the type of transported materials, shaft equipment and ventilation aspects.

In the case of cage shafts there are basements below inlets for near-shaft equipment, while around the shaft there is often a by-pass for people (passway). Assuming that long materials will be transported in a shaft, it is impossible to increase the height of inlet to a height enabling components to enter the horizontal workings considered [6, 7, 15]. Inclined inlet roof in the area of connection of shaft with horizontal workings, usually at the angle of 30°–45°, is also advantageous due to a decrease of airflow resistance.

The selection of inlet supports is mainly due to obeying the special safety rules which exist due to the long period of usage and large sizes. Taking into account a tendency in the Polish hard coal mining industry to mine deeper and deeper seams it will be necessary to design new shaft inlets operating in conditions of increased action of rock mass on their supports.

A problem in the designing of shaft inlets with the use of numerical calculations made by the Robot Structural Analysis Professional computer programme is mentioned in the

---

* Institute of Mining Technology KOMAG, Gliwice

project [2, 3]. The assessment of safety in considered designs, which were modelled in a spatial way, was made including the selected strength hypothesis [3].

2. Modelling of shaft inlets with use of Robot Structural Analysis Professional computer programme

Computer programmes, which enable numerical calculations of designs, are at present the standard designer's tools in the proper selection of the support of underground mining objects. To use these programmes effectively their capabilities should be carefully considered in regards to a given design problem. Thus, an attempt to analyze the operation of shaft inlets using the Robot Structural Analysis Professional computer programme based on the Finite Elements Method (FEM) was undertaken in the project [13]. Calculations for the underground structures considered with the use of the above mentioned programme can be realized after the projection of these structures used on a plane or in a spatial system. The significant limitations of the Robot Structural Analysis Professional programme are the difficulties encountered in the precise recreation of some structures of shaft inlets at the stage of their spatial modelling. In the case of the location of inlets at shallow depths, supports made of bricks or betonite can be considered as typical. For workings on lower levels supports of higher load-bearing capacity such as e.g. concrete or reinforced concrete supports, which are often built with use of a temporary support such as a support made of steel or a bolt support are used. Shaft inlets, which at present are often designed for depths exceeding 1000 m, require additional reinforcement of standard structures, e.g. with the use of steel frames and sprags, or the implementation of individual solutions. The biggest problem at the stage of the modelling inlets with the use of the Robot Structural Analysis Professional programme can be found in the case of supports made of many components, e.g. bolt-concrete-steel support or brick support. Due to the demonstrative character of the project, the spatial modelling of inlets in a concrete support has been undertaken. Two computational modules of the Robot Structural Analysis Professional programme [13], i.e. shell structure and volume structure are considered to be the most useful for the modelling of operation of the discussed structures. It was found that the first of them, which refers to a typical shell thickness not exceeding about 0.1 m [8], could be used to model a shell-type inlet support for horizontal workings. However, during the creation of the spatial model apart from the horizontal working made e.g. with shell-type support, a part of the shaft tube, due to its non standard thickness was also included. Due to the fact that the Robot Structural Analysis Professional programme does not allow for the creation of a model consisting of solids and shells penetrating each other, the inlet area was treated as a solid structure and modelled by the isoparametric volume of finite elements with an approximation of the displacement field by shape functions of the first order [13].

A series of simplified models of the inlets of cage shafts (excluding shaft basements), which are made of concrete of C16/20 class [10], was used during analyses [3]. From a geometric point of view, the horizontal inlets, inlets inclined from 20° up to 55°, symmetrical and asymmetrical inlets as well as two-sided and one-sided inlets were considered [3]. Parts of the horizontal workings with a support thickness of 0.5 m or locally thickened up to 1.0 m were modelled together with sections of the shaft of diameter 8.0 m and support thickness 0.5 m [3].

Loads to shaft supports were determined on the basis of the standard [11] and loads to horizontal workings were estimated according to rules specified in the standard [12] for exemplary models of deformation pressure and Cymbarewicz models, assuming the installation of structure in rocks of the following characteristic geotechnical parameters:

— compression strength: $R_{cs}^{(n)} = 40$ MPa,
— angle of internal friction: $\phi_s^{(n)} = 34°$,
— cohesion: $c_s^{(n)} = 7$ MPa,
— coefficient of elasticity: $E_s^{(n)} = 10000$ MPa,
— Poisson's ratio: $v_s^{(n)} = 0.23$,
— bulk density: $\gamma_s^{(n)} = 0.025$ MN/m^3,

and of divisibility into plates and soaking according to GIG: $r > 0.8$.

For the underground structures considered different methods of resting on the rock mass, including among others elastic foundation, which is treated as a basic variant, were implemented [2, 3]. Conditions of elastic support of objects located at an assumed depth of 300 m to 800 m [3] were characterized with the use of the Winkler-Zimmermann one-parameter model [1, 14, 16].

A view of exemplary model of inlet is presented in figure 1.

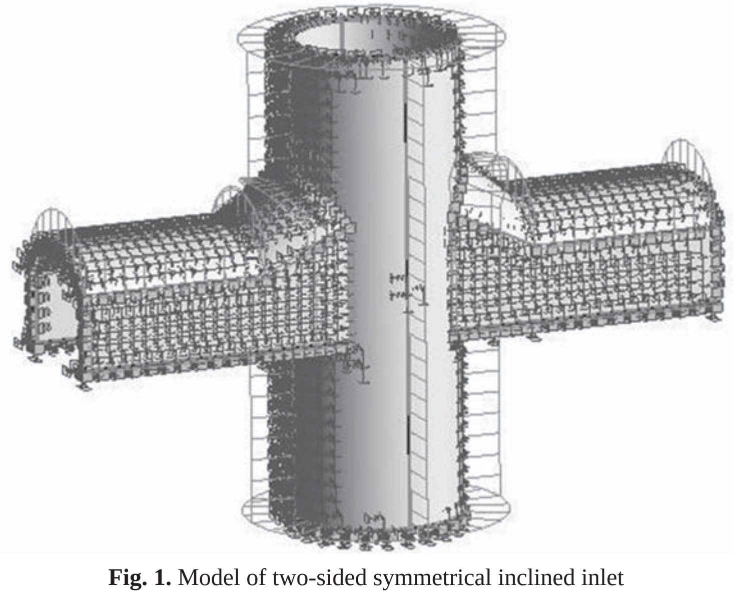

Fig. 1. Model of two-sided symmetrical inclined inlet
— method of load and support

3. Assessment of safety of shaft inlet supports on the basis of the results of numerical calculations and selected strength hypothesis

The results of the calculations for the discussed structures, which were obtained by using the Robot Structural Analysis Professional programme, can be presented in a form of tables and maps (isolines) of stresses and deformations in a global or local coordinate system. The reduced stresses determined according to the Huber-Mises-Hencky hypothesis, the first invariant of stress state, displacement in the local and global system as well as deformations of the model are also presented in a graphical and numerical form. Tensile stresses are treated as positive ones [13].

A specified strength hypothesis should be taken into account to make an assessment of safety of the structure on the basis of the results of computational analysis. The Huber-Mises-Hencky hypothesis entered by the Robot Structural Analysis Professional programme, which is commonly used for ductile materials, e.g. metals (besides states of all-around tensile stress), can't be applied to brittle materials such as e.g. concrete [5]. It should be emphasized that the versatile rules for the assessment of the safety of concrete structures, which operate in a complex state of stress, have not been developed yet, mainly due to a lack of a sufficient number of tests, while existing strength hypothesis refer to specific ranges and configurations of stresses, which arise in a given object, directly connected with the conditions of their verification.

To make an assessment of stability of considered mining workings the following three strength hypothesis were finally assumed [3]:

- Coulomb-Mohr hypothesis,
- Botkin hypothesis,
- K. & J. Hruban hypothesis.

On the basis of the first of the above mentioned hypothesis, commonly used in strength calculations of grounds and rocks, the safety condition of the structure was determined by determining the following coefficient [3]:

$$n_1 = \frac{2 \cdot f_{cd} \cdot f_{ctd} - (\sigma_1 + \sigma_3) \cdot (f_{cd} - f_{ctd})}{(f_{cd} + f_{ctd}) \cdot (\sigma_1 - \sigma_3)} \tag{1}$$

where:

σ_1, σ_3 — maximal and minimal main stress, MPa,

f_{cd} — computational compressive strength of concrete acc. to standard [10], MPa,

f_{ctd} — computational tensile strength of concrete acc. to standard [10], MPa.

It can be assumed that the structure will not be destroyed if the following condition is met at all the structure points:

$$n_1 \geq 1 \tag{2}$$

When in a structure there are no points beyond that range in which the considered criterion is in force, this is confirmed the following relationship:

$$\frac{\sigma_1 + \sigma_3}{2} \leq f_{ctd} \tag{3}$$

According to Botkin criterion [5], coefficient estimated on the basis of the following equation can be used to assess the structure safety:

$$n_2 = \frac{2\sqrt{2} \cdot f_{cd} \cdot f_{ctd} - \sqrt{2} \cdot (f_{cd} - f_{ctd}) \cdot (\sigma_1 + \sigma_2 + \sigma_3)}{(f_{cd} + f_{ctd}) \cdot \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}} \tag{4}$$

This coefficient is determined at the points for which:

$$\sigma_1 + \sigma_2 + \sigma_3 \leq \frac{2 \cdot f_{cd} \cdot f_{ctd}}{f_{cd} - f_{ctd}} \tag{5}$$

where:

σ_1, σ_2, σ_3 — main stresses at a given point of the structure, which meet the following condition: $\sigma_1 \geq \sigma_2 \geq \sigma_3$, MPa,
other — as in formula (1).

As for the Coulomb-Mohr hypothesis, the above mentioned strength criterion is considered to be met when the value of n2 coefficient at all points of the structure is not lower than 1 and when there are no points, which do not meet the condition (5).

In turn, according to strength hypothesis given by K. & J. Hruban [5], the assessment of structure safety can be made by calculating the following coefficient:

$$n_3 = \frac{f_{cd}}{\sqrt{\hat{\sigma}_1^2 + \hat{\sigma}_2^2 + \hat{\sigma}_3^2 - 2 \cdot \nu_c \cdot (\hat{\sigma}_1 \cdot \hat{\sigma}_2 + \hat{\sigma}_2 \cdot \hat{\sigma}_3 + \hat{\sigma}_3 \cdot \hat{\sigma}_1)}} \tag{6}$$

where:

$\hat{\sigma}_j$ — stress, which in the case of compressing is equal to:
$\hat{\sigma}_j = \sigma_j$ while for tensioning it is equal to:

$$\hat{\sigma}_j = \frac{f_{cd}}{f_{ctd}} \cdot \sigma_j$$

$j = 1, 2, 3$ — number of main stress,
ν_c — Poisson's ratio of concrete according to the standard [10],
other — as in formula (1).

As it was in the case of the previous strength hypothesis, the value of n_3 coefficient should not be lower than 1 to keep safety of the structure.

The above approach to an assessment of structure safety, when talking about the chance of its destruction on the basis exceeding the assumed strength condition, it can be considered to be too rigorous, especially when the material can be exposed to local destruction in a form of e.g. scratch [4]. Therefore the best method for the assessment of structure safety on the basis of distribution and the amount of material strain should be the subject of further considerations.

4. Basic observations as regards the operation of shaft inlets gained in the analyses of results

Considering maps of main stresses σ_1 obtained from numerical calculations of shaft inlets, some concentration of tensile stresses can be observed in the area, where the shaft has contact with shaft bottom, i.e. within the direct inlet, which is especially noticeable for inclined inlets (Fig. 2). In the case of horizontal inlets higher tensile stresses σ_1 appear within shaft tube than in the vertical sections (Fig. 2).

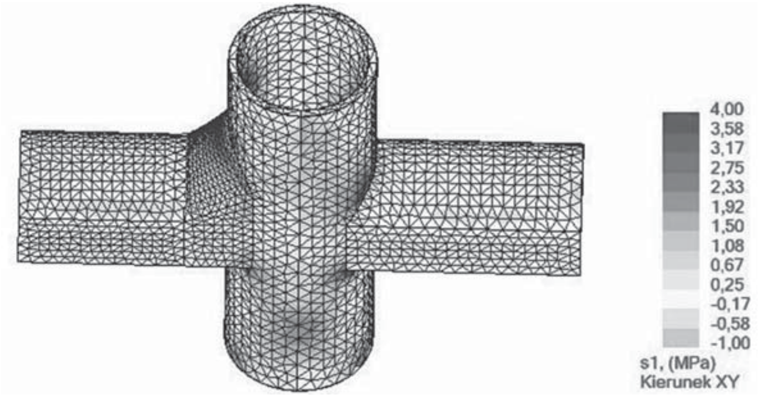

Fig. 2. Two-sided asymmetrical inlet – map of main stress σ_1

Significant tensile stresses σ_1 also appear in the roof of the inlet support (Fig. 3a) and in the middle areas of straight walls (Fig. 3b).

In turn, the extreme compressing stresses σ_1 appear mainly along the connection point of the side walls with the roof.

The indirect main stresses σ_2 represent both compressing and tensioning of the structure, but tensile stresses first of all arise in a key point of roof workings (Fig. 4) and in the lower part of straight walls.

In turn, σ_3 the stresses are mainly a compressions of the extreme values, which appear in the area in contact with roof the inlets with shaft and in the area in connection which the straight walls and with the roof of the support (Fig. 5).

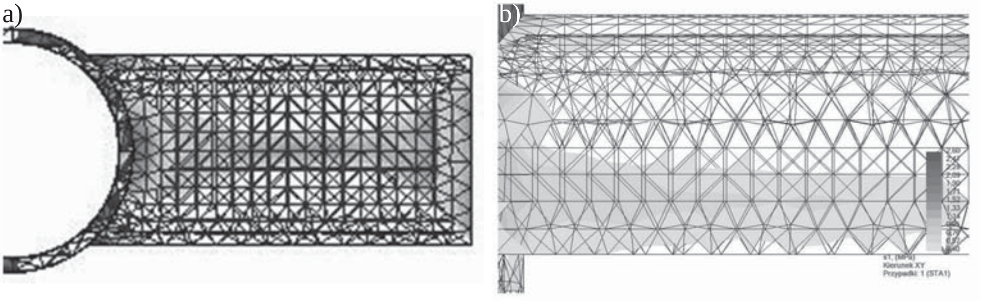

Fig. 3. One-sided horizontal inlet — map of maximal main stress σ_1:
a — in the area of inlet roof, b — on the wall of inlet working

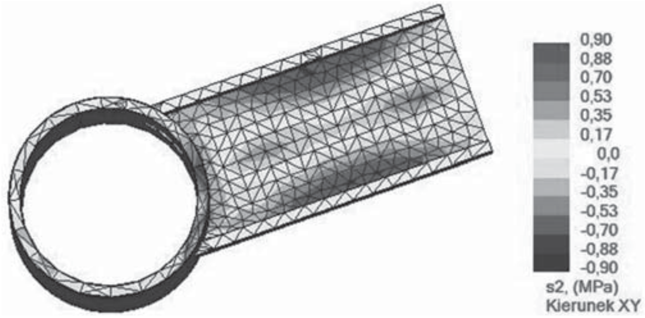

Fig. 4. One-sided horizontal inlet — a map of main stress σ_2
within horizontal working is shown

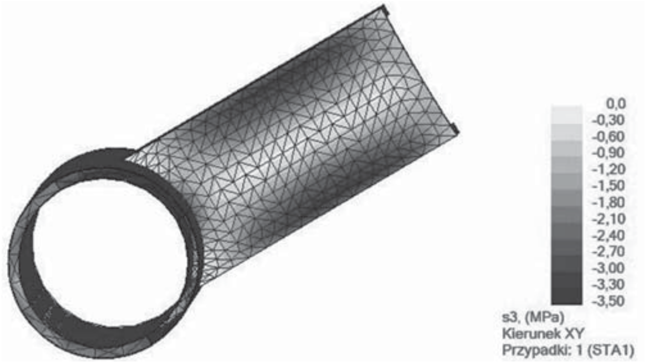

Fig. 5. One-sided horizontal inlet – map of main stress σ_3
within horizontal working

The thickening of the support of the direct inlet causes a drop in strain on the material used in its construction while an increase of the inclination of inlet workings, which means an increase of their height, results in an increase in the values of stresses σ_1 and a strain in the support material. In the case of the modelling of the support of horizontal workings, made of higher class concrete, the strain in the material decreases. The significant decrease of strain in the material of the support of shaft bottom working occurs also in the situation of load drop in the shaft, especially when the rocks surrounding the shaft are above critical depth, i.e. according to the standard [11], these rocks do not exert a load to the shaft support.

All inlets have a similar character of deformations under the applied load, i.e. the convergence of a shaft tube in a perpendicular direction to longitudinal axis of horizontal workings (Fig. 6a) (except models without load of shaft tube) and deformation of horizontal workings both in their roof part and at the height of straight walls (Fig. 6b) are noticeable.

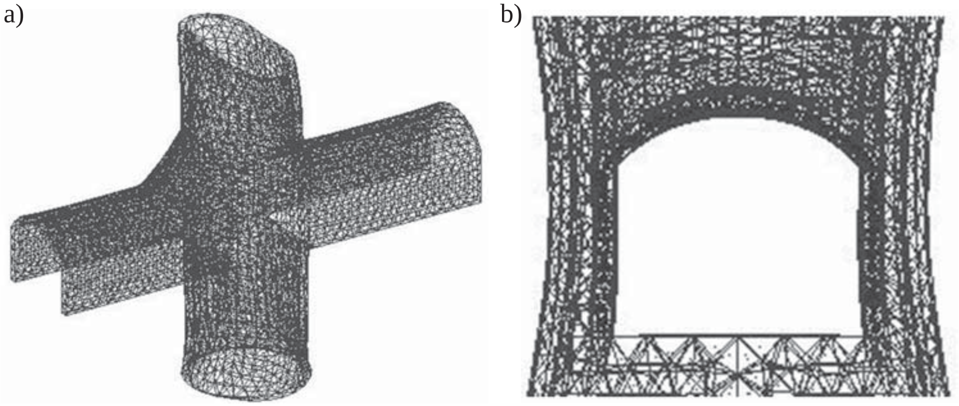

Fig. 6. Two-sided asymmetrical inlet — deformation of structure:
a — in the area of shaft and horizontal workings, b — in the area of horizontal workings

Points from beyond the ranges of the Mohr and K. & J. Hruban hypothesis are present in the structures, among others, when the highest of the main stresses have values exceeding the concrete strength to tensile stress. The appearance of significant tensile stresses in some points of the structure justifies the necessity in reinforcement of the structure, especially in the area in connection with a shaft with inlets, where strain on the material is the highest.

In a case when after numerical calculations for the model of the inlet of a determined geometry, which operates in specific mining-and-geological conditions strength conditions are not met, a structure should be modified in such way that the accepted strength hypothesis would not signal any danger to its safety.

5. Summary

The modelling of shaft inlets as spatial structures is one possible method which can be used for the recreation of shaft inlets. The Robot Structural Analysis Professional computer programme based on the Finite Elements Method was used for numerical calculations in a series of simplified models of shaft inlets in concrete support to realize the above-mentioned work [3].

Among others, the determination of stresses in volumetric components and assumption of linear-and-elastic and isotropic model of material as well as the lack of the possibility to create a model consisting of solids and shells penetrating each other should be considered as a limitation of the mentioned programme as regards to the modelling of shaft inlets.

Strength conditions resulting from a selected strength hypothesis of Coulomb-Mohr, Botkin and K. & J. Hruban were assumed to assess the safety of a structure, which operates in a complex stress state. It was assumed that the considered structure meets a given strength criterion when a determined safety condition is not exceeded at any of its points (item 3). However, it should be emphasized that one, comprehensive hypothesis, which would be fully proved by the tests and which would represent the strength properties of any considered material at all possible configurations of stresses, can't be found for concrete material. Also, as it results from the observations [2, 3], the values of considered coefficients n_1–n_3 obtained for the given models can significantly alter what indicates discrepancies in the method for the assessment of structure safety implemented by each hypothesis.

The analyses [2, 3], which signal the problem of spatial modelling of shaft inlets, are mainly of a qualitative character. However, in many cases they can be useful at the design stage of considered underground structures.

REFERENCES

[1] Biernatowski K.: *Fundamentowanie*. Warszawa, Państwowe Wydawnictwo Naukowe 1984.
[2] Domańska D.: *Projektowanie wlotów szybowych z wykorzystaniem techniki komputerowej*. Gliwice, Instytut Techniki Górniczej KOMAG (praca niepublikowana), 2009.
[3] Domańska D.: *Uwagi o projektowaniu wlotów szybowych z wykorzystaniem techniki komputerowej*. Gliwice, Instytut Techniki Górniczej KOMAG. Monografia — nr 8, 2010.
[4] Gawędzki A.: *Mechanika materiałów i konstrukcji prętowych*. Politechnika Poznańska, Alma Mater 2003.
[5] Godycki-Ćwirko T.: *Mechanika betonu*. Warszawa, Arkady 1982.
[6] Kawecki Z., Wąsik J.: *Zasady projektowania kopalń. Część VI. Projektowanie podszybi, komór i wyrobisk głównego odwadniania*. Katowice, Śląskie Wydawnictwo Techniczne 1993.
[7] Kostrz J.: *Górnictwo tom VI. Wykonywanie wyrobisk cześć 3. Pogłębianie szybów i roboty szybowe*. Katowice, Wydawnictwo „Śląsk”, 1972.
[8] Menyhard I.: *Konstrukcje powłokowe. Obliczenia statyczne i kształtowanie*. Warszawa, Arkady 1971.
[9] Pękacki W.: *Budownictwo górnicze podziemne. Część I. Wykonywanie wyrobisk korytarzowych i komorowych*. Katowice, Wydawnictwo „Śląsk” 1971.
[10] PN-EN 1992-1-1:2008: *Eurocod 2. Projektowanie konstrukcji z betonu. Część 1-1: Reguły ogólne i reguły dla budynków*.
[11] PN-G-05016:1997: *Szyby górnicze. Obudowa. Obciążenia*.
[12] PN-G-05020:1997: *Podziemne wyrobiska korytarzowe i komorowe. Obudowa sklepiona. Zasady projektowania i obliczeń statycznych*.
[13] Robot Millennium: *Podręcznik użytkownika tom 1 i 2*. Kraków, Firma Informatyczna Robobat Sp. z o.o.
[14] Rossiński B.: *Fundamentowanie*. Warszawa, Arkady 1978.
[15] Walewski J.: *Zasady projektowania kopalń. Część V. Projektowanie szybów i szybików*. Katowice, Wydawnictwo „Śląsk” 1965.
[16] Wiłun Z.: *Zarys geotechniki*. Warszawa, Wydawnictwa Komunikacji i Łączności 2008.