International Journal of Mining Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Evaluating performance of lignite pillars with 2D approximation techniques and 3D numerical analyses

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ARTICLE INFO

Article history:
Received 22 December 2016
Received in revised form 18 February 2017
Accepted 16 March 2017
Available online xxxx

Keywords:
Geomechanics
Room and pillar
Underground lignite mine
Finite element method
3D numerical analysis
Average pillar stress

ABSTRACT

This paper attempts to investigate the use of approximate 2D numerical simulation techniques for the evaluation of lignite pillar geomechanical response, formed via the room and pillar mining method. Performance and applicability of the developing methodology are assessed through benchmarking with a more direct and accurate 3D numerical model. This analysis utilizes an underground lignite mine which is being developed in soft rock environment. Through the decisions made for the optimum room and pillar layout, the design process highlights the strong points and the weaknesses of 2D finite element analysis, and provides useful recommendations for future reference. The interpretations of results demonstrate that 2D approximation techniques come near quite well to the actual 3D problem. However, external load approximation technique seems to fit even better with the respective outcomes from the 3D analyses.

1. Introduction

Pillar design in everyday practice is still greatly influenced by the utilization of empirical formulas that calculate the safety factor of the pillar, based on the assessment of both the pillar strength and the average stress imposed on it. The latter is estimated using the tributary area method, which despite its limitations, is widely accepted by the engineering community. However, the issue of assessing the strength of the pillar structure, despite the several proposed empirical equations, is something that is still under research [1–4]. Knowledge of pillar strength, and the determination of required safety factors for a given loading condition are the most important aspects of pillar design [5]. Many researchers, over the years, have proposed equations either of broad use or utilized formulas and assumptions to model specific geological structures and conditions.

The efficiency of the above can be thought as satisfactory on a first level of design detail, as numerous mines were designed and exploited following the recommendations of this empirical approach [6,7]. However, the empirical formulas have several weaknesses. Either the general design guidelines produced, required the setting up of an optimization process for the selection of the most appropriate room and pillar dimensions, or the large calibration of the models was subjected to rigorous constraints and assumptions concerning primarily both the encountered geological formations and the stress field conditions. Furthermore, the empirical design process may be used for assessing the structural integrity of pillar but has provided limited or no insight relating to the anticipated excavation deformations or estimates of the required support characteristics.

The introduction of new methods of analysis, as the utilization of numerical codes, has brought about a new level of detail that is now available to the engineer. Numerical modeling in mine design may reveal and investigate many critical aspects that improve and deepen the insight of it [8–10]. Applied in conjunction with a conceptual model of the mine and appropriate rock mass properties and failure criteria, they allow the evaluation of alternative mining strategies with respect to the rock mass response to different layouts of openings and pillars [11]. Numerical analyses have the ability to further test the structural integrity of the pillar under several loading states and assess the selected design features under various scenarios. Thus, they allow for a more thorough understanding regarding the behavior of the excavation. The estimation of pillar strength is possible using numerical modeling and it may provide a viable and perhaps better alternative to earlier conventional pillar strength approaches [12]. Even so, room and pillar mining method is quite difficult to be satisfactorily simulated with 2D plane strain numerical models, since the transverse excavations simulation to the initial parallel drifts violates the plane strain

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http://dx.doi.org/10.1016/j.ijmst.2017.06.014
2095-2686/

Please cite this article in press as: Deliveris AV, Benardos A. Evaluating performance of lignite pillars with 2D approximation techniques and 3D numerical analyses. Int J Min Sci Technol (2017), http://dx.doi.org/10.1016/j.ijmst.2017.06.014

assumption, as the formers are found ahead of 2D analysis plane. Room and pillar principle has a 3-Dimensional aspect as a number of cross cut excavations are located in the out of plane direction [13]. This of course is almost the case for every mining or tunneling problem that has a complex geometry to model which cannot satisfactorily approximated using a two dimensional plane strain analysis [14]. The simulation of these excavations and the actual formation of the rock pillar require the use of further approximation techniques in order to reflect in a satisfactory level the existing 3-Dimensional conditions. Some approximations in 2D models do exist in an attempt to model the 3-Dimensional geometry and loading states developed, though they are not yet universally acceptable nor broadly used [15,16].

The introduction of 3D numerical codes and software and the progress in computing power can allow for a valuable insight to the expected conditions, and therefore is the optimal way of conducting a precise assessment regarding the abovementioned subject. The transverse excavations sequence, the loading process and the potential failure mechanisms in the pillar may be simulated directly by means of the 3D numerical model. However, the intensive utilization of 3D numerical models is not yet universally available and preferable in routine analyses in this kind of engineering problems. The primary reason about this is the fact that 3D numerical models demand great computational resources since they are very time consuming numerical procedures. Improvements in parallel processing coding of software and computer power will be essential to model more detailed large scale three dimensional examples [17]. The use of 3D numerical models, even nowadays, is greatly computationally expensive and time consuming, and inhibits their implementation in the routine mining design [18]. Based on the above issues, it is of major importance to test the validity of approximations developed in 2D plane strain models, so as to assess their performance and to propose improvements or methods of practical use to refine their accuracy.

In this context, this paper compares and assesses the behavior modeled by the use of 2D numerical techniques that approximate the geomechanical response of the pillar, versus the use of direct 3D numerical analyses. This is made for the case of an underground lignite exploitation model that is designed using the room and pillar mining method, in relatively low overburden. The design process is given, and the results regarding the selected pillar geometry and the anticipated response of the rock mass (lignite seam and measure rocks) is presented in detail to allow for a direct benchmarking of the design methods and analyses used.

2. Modeling 3D geometry with 2D simulation approximations

As mentioned before, transverse excavations have a major influence in a 2D model and violate the plane strain conditions. Sometimes, the problem of obtaining technically sound mine pillar design analyses at reasonable cost is of great importance. Hence, in this paper an attempt to investigate mine pillar performance by 2D finite element plane strain models and approximation techniques compared to direct 3D analysis results is made. Previous research efforts in the subject were confined mainly in the numerical simulation of the one quarter of pillar magnitude. Nowadays, with the developments in computer science, larger areas of underground openings may be modeled. Thus, issues and questions are arisen, related to the way where previous simulation attempts were accurate and whether they require some refinement.

An approximation technique that is used in the simulation of the transverse excavations and the formation of a rock pillar, suggests the use of an augmented unit weight material in the overburden of the excavations [19]. The value of the overweight material γ' may be calculated from Eq. (1):

$$\gamma' = \gamma\left(1 + \frac{W_R}{W_P}\right) \tag{1}$$

where γ is the actual unit weight of the overburden rock material, kN/m^3; and W_R and W_P are the width of the room and the width of the pillar respectively, m. The authors of this paper suggest that the material with the augmented unit weight has to be applied only in the vertical extent just above the pillar and not in the whole overburden rocks domain of the model. The latter option is considered to be very conservative that does not simulate the transverse excavations properly.

An alternative approximation technique is suggested by the authors, and its effectiveness will be examined through the results both of the 2D numerical analysis and the correlation of them with the corresponding outcomes from the 3D numerical models. The suggested technique is based on the following statement: prior to the execution and simulation of the transverse excavations the average normal stress σ_P in the longitudinal pillar can be found with relative accuracy from the results of the 2D numerical stress analyses.

The average normal stress σ_P is approximately equal to the average value taken from the distribution of the major principal stress σ_1 as measured within the pillar. As soon as the transverse excavations have been completed and the rock pillar is finally formed, the average normal effective stress σ'_P in the pillar may be approximately calculated from Eq. (2):

$$\sigma'_P = \sigma_v\left(1 + \frac{W_R}{W_P}\right)^2 \tag{2}$$

where σ_v is the geostatic vertical in-situ stress, MPa.

The transverse excavations simulation may be actualized via the application of an external uniform surface load in the area projected just above the pillar at a subsequent stage of the modeling procedure. The magnitude of this external load q may be considered to be simply the difference between these two calculated average normal stresses, the one prior and the other after the completion of the excavations denoted by Eq. (3):

$$q = \sigma'_P - \sigma_P \tag{3}$$

3. Case example of an underground lignite exploitation

In order to satisfy the principal target of this paper that is to estimate the correlation of 2D plane strain approaching techniques with the more direct and realistic 3D analysis results, the investigation of an underground lignite mine exploitation case example excavated by the room and pillar mining method is deemed as an essential issue. Based upon a private shallow underground lignite mine in Northern Greece, firstly, representative geometries regarding the excavation spans, and secondly, geotechnical parameters about the encountered geological formations are directly taken into account and utilized in the numerical models.

The initial lignite productive drift is shown in Fig. 1, and it is noted that the first field monitoring data regarding stress and deformations of underground works are expected soon for the purposes of comparison and calibration of the numerical modeling results cited in the paper. The engineering parameters for both the openings surrounding materials and for the lignite seam are displayed in Table 1. All the following engineering parameters are important in the subsequent numerical procedures. It is argued that the stiffness and uniaxial strength of the pillar controls the initial pillar behavior, against applied loading and defines the onset of failure [20]. Once failure has commenced, the geometry of the pillar plays a role in pillar deformational behavior and controls the rest of the failure process. With increase in width to height ratio,