Influence of deep coal mines on the stability of shallow cavities

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ABSTRACT: Wallonia and Hauts-de-France regions encounter complex developments of multi-level mining cavities that may affect the stability of shallower ones. This work focusses on an abandoned room-and-pillar quarry that extracted phosphatic chalk. On the same site, coal was mined out at depths from 200 to 750 m. To evaluate the influence of deep coal mines on the stability of shallow cavities, the geometry of created voids was modelled, integrating the mining sequence. In addition, detailed topographic and structural surveys of the chalk quarry were completed by rock mass quality assessment. Then a finite element geomechanical model combining the room-and-pillar quarry and the longwall mining was created. Specific vertical cross sections were investigated. The model revealed the progressive influence of coal mining on the room-and-pillar quarry as the surface mined out increased. These large models finally provide boundary conditions for local models in which the influence of specific parameters can be investigated.

Keywords: post mining, stability analysis, finite element model, room-and-pillar, longwall mining.

1 INTRODUCTION

Numerous underground cavities, either man-made or natural, occur in Wallonia (Belgium) and Hauts-de-France regions. Both territories exhibit a comparable geological context and, hence, similarities in the typology of underground cavities. In particular, chalk, limestone, sand and clay were extracted by underground quarries. About 900 abandoned underground quarries are identified in each region. Their size varies from a couple of galleries around an access shaft to a well-structured network of rooms and pillars on areas covering several dozens of hectares. Beside the quarries, other cavities are also known. Some of them are particular to a region: karsts are mainly a concern in Wallonia, whereas military works are specific to Hauts-de-France. This variety of shallow depth cavities represent an issue for the authorities and the communities in terms of land management and planning and economic development of the territories.

Also in relation with a common geology, both regions have a similar industrial history, closely related to coal mining. The coal fields extend from the Nord-Pas-de-Calais basin towards Liège area, and even further northwards. They are characterized by numerous thin coal seams with a limited thickness (0.5 to 1 m in Wallonia, 0.8 to 2.9 m in Nord-Pas-de-Calais), separated by quite thick sandstone-claystone interburden. Most seams cover large areas, up to several dozen km², and are influenced by complex geological processes (folding, faulting, underthrust). Mining generally started at shallow depth but reached 1000 m or more in some areas. During the 19th-20th centuries, coal was mined out quite intensively by the longwall technique. Cumulated production reached about 2 billion tons in each region.

In some places, shallow cavities come above deep coal mines. This is particularly the case in Mons area (Wallonia), which is the subject of this study. The influence of coal mining on the ground surface is well documented, with a subsidence reaching several meters. The aim of this work is to use geomechanical numerical simulations to reproduce the mining sequence at various depths and then understand the potential influence of deep mining on shallow cavities.

2 STUDIED SITE AND GEOLOGICAL CONTEXT

The studied site is located close to the town of Mons (Wallonia) very close to major infrastructure in the region. Phosphatic chalk from the Malogne underground quarry was mined out between 1877 and 1925, by the room-and-pillar method, on an area of 67 ha. Chalk extraction occurred mainly on one level, at a depth between 13 and 25 m. Rooms are typically 4 to 5 m wide and 5 to 9 m high. They are separated by 3.5 to 4.5 m wide pillars. Nowadays, the northern part of the site is under water. It is a typical example of underground cavities where stability problems have risen.

Figure 1 depicts a typical N-S cross section with the main lithologies and underground water level. Phosphatic chalk is part of the so-called Mons Basin which is generally known as an extension of the Paris Basin. It is described as an accumulation of sediments, mainly Cretaceous, in a subsidence zone (Vandycke et al. 1991). Phosphatic chalk is a calcarenite occurring on top of the chalk group, on the southern edge of the basin, forming a lens dipping to the North. It is overlain by a hardground level with an average thickness of about 60 cm (Robaszynski et al. 2001). Structurally, the area exhibits a horst and graben system due to extension tectonics at the Late Cretaceous (NW-SE and NE-SW) and during the Tertiary (N-S and E-W). In terms of hydrogeological conditions, due to the seasonal underground water level fluctuations, three zones can be identified, namely dry, transitional, and saturated zone.

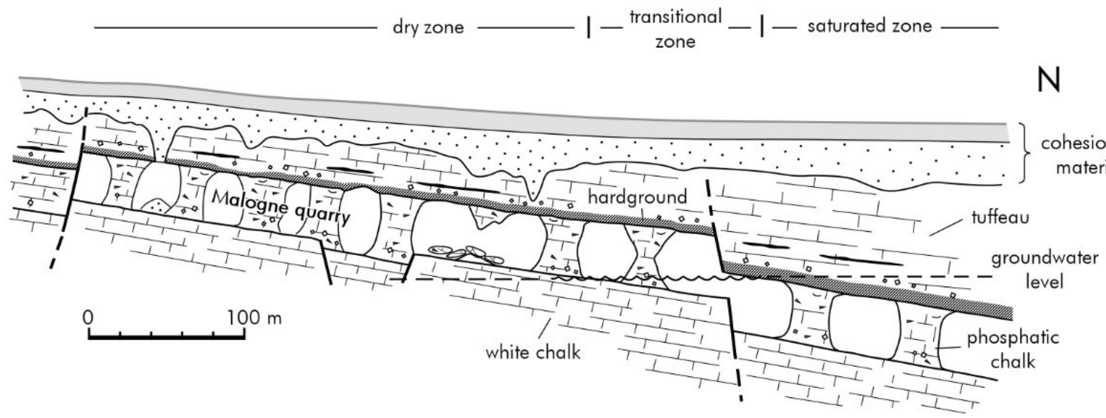

Figure 1. Vertical N-S cross section showing the Meso-Cenozoic formations in the phosphatic chalk quarry.

Coal mining in this particular area began industrially in 1860 and continued until 1963, at depths ranging from 200 m to 840 m (Figure 2). The Paleozoic basement is mainly composed of Upper Carboniferous rocks. Locally, the coal seams form a monocline to the North of the site and tend to become steeper to the South. A set of 24 seams were identified from mining archives, cumulating in a total thickness of 4 to 8 m. The interburden is mainly composed of sandstones, siltstones, shales, and thin unmined coal seams.

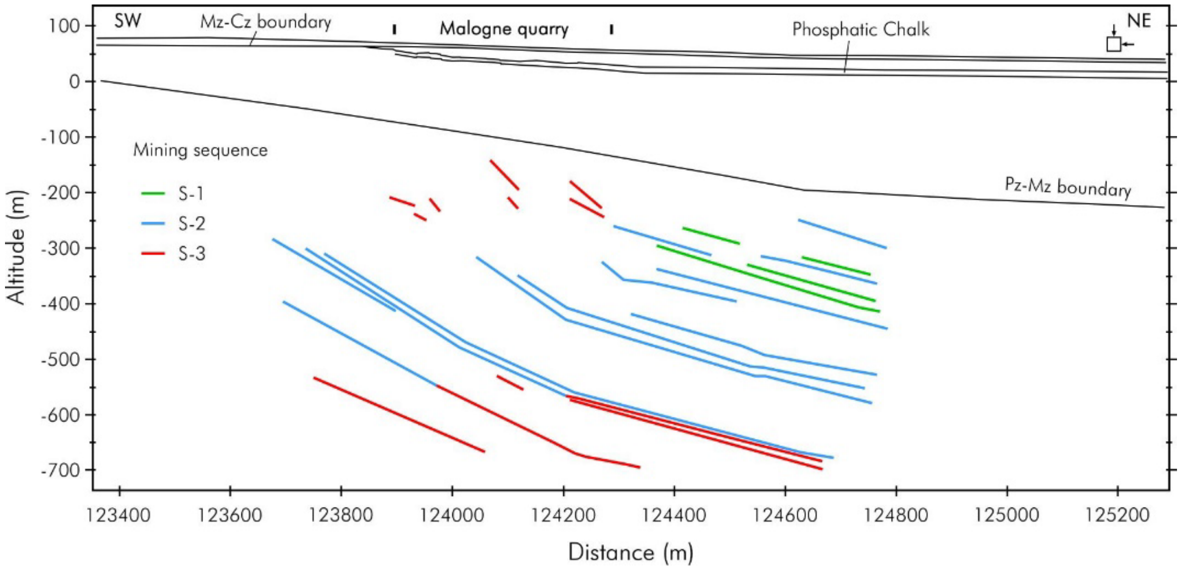

Figure 2. FEM geometry along the SW-NE profile with details of underground works. Coloured lines - coal seams according to their mining sequence (S1 to S3).

3 METHODOLOGY

The influence of deep coal mines on shallower cavities is investigated using 2D finite element modelling in typical vertical cross sections. This implies building large models that extend from the surface to several hundreds of meters deep, and wide enough to account for the lateral influence of longwall coal mines. A first step consists in modelling the geology and geometry of the underground works, both for the phosphatic chalk and the coal seams. Geomechanical data were also collected, in laboratory, in situ and from the literature, to address the constitutive behaviour of the geomaterials. A third step is the FEM analysis itself, with special consideration for the mining sequence.

3.1 Modelling of the underground works

Modelling underground excavations both at shallow and great depth involves the collection of numerous data, including geological and geometrical data. A large part of the chalk quarry is still accessible. It is modelled from a detailed survey of the rooms and pillars combined with systematic measurements of the rooms heights. In addition, a structural survey was performed to include the main discontinuities in the model and assess the quality of the rock mass. Geomechanical zonation based on RMR highlighted a rock mass quality ranging from good to fair in the dry zone, and from good to poor in the transitional zone. Three typical cross sections were investigated to account for various geomechanical and hydrological conditions. In this paper, results are presented along a SW-NE profile (Figure 2) i.e. with the maximum dipping direction of the coal seams and crossing various geomechanical zones in the phosphatic chalk.

In longwall mining, the draw angle determines the model extension to assess the effects on surface (Brady & Brown 2005). A typical value of 30° is considered, based on research on Belgian and French collieries (Al Heib et al. 2005, Vervoort & Declercq 2017). This led to investigate all coal mining works in a 500 m radius around the chalk quarry. Mining archives provide the boundaries of the mined-out coal seams, as well as their thickness, at a scale of 1:1 000, allowing for an accurate modelling. Several preliminary computations were performed to determine the model width, such that a vertical displacement less than 20 mm (common cut-off value for ‘zero’ subsidence; Brady & Brown 2005) is found for the ground surface at the boundary of the model. For the SW-NE profile, a model width of 3700 m is used.

3.2 Geomechanical data

The geomechanical properties assigned to the various domains of the model were obtained through laboratory experiments and archives data (Table 1). Laboratory tests were performed mainly on Meso-Cenozoic rocks, both in dry and saturated conditions (Georgieva et al. 2020 a, b). An elastic perfectly plastic constitutive model is assumed for all materials, with a Mohr-Coulomb yield criterion. Data in Table 1 account for rock mass quality.

One challenge was to assess geomechanical properties of Carboniferous rocks, i.e. coal seams and interburden, but also to estimate the properties of compacted goafs long time after mine closure. In the latter case, laboratory archives were used to produce an initial dataset. Then, a calibration procedure was developed to adapt the mechanical properties (Georgieva et al. 2022). In this procedure, the ground surface evolution before and long time after (2013) mining is used as a reference for estimating the subsidence. Model properties were adapted until the vertical displacements of the ground surface matched with the measured subsidence.

Table 1. Geomechanical properties used in the model. γ, unit weight. E, Young's modulus. ν, Poisson's ratio. Rt, tensile strength. C, cohesion. φ, internal friction angle. Data from Georgieva et al. (2020 a, b, 2022).

Material	γ (MN/m³)	E (MPa)	ν	Rt (MPa)	C (MPa)	φ (°)
Cohesionless materials	0.03*	20	0.33	0	0	30
Ciply Tuffeau	0.03*	160	0.2	0.01	0.1	30.4
Hardground - dry	0.055*	16 600	0.11	0.7	5.4	30.4
- saturated	0.058*	11 900	0.17	0.4	3.2	
Phosphatic chalk - dry	0.017	1 140	0.23	0.06	0.4	30.4
- saturated	0.021	600		0.03	0.22	
White chalk - dry	0.015	1 400	0.25	0.07	0.54	30.4
- saturated	0.019	730		0.03	0.26	
Coal host rock	0.024	17 000	0.15	4.8	5.2	41
Coal	0.015	3 000	0.3	1.5	1.9	48
Compacted goaf	0.012	7 750	0.1	1.5	1.7	21

* Increased unit weight (see Section 3.3)

3.3 2D FEM modelling

The modelling of room-and-pillar excavations is a three-dimensional problem that can be treated as a 2D case. However, the 2D plane strain analysis underestimates the load on pillars. Therefore, an extra ground load is simulated by increasing the unit weight of the overlying layers (Descamps et al. 2019). When comparing the pillar stress in 2D and 3D, a ratio of 2.3 is found and applied.

When building the FEM model, particular care was taken in defining the excavation sequence to obtain realistic results. Three coal mining stages were defined: before (S1), at the same time (S2) and after (S3) the chalk extraction (Figure 2). In addition, a two-step process is implemented: first, the coal is excavated to create a cavity, and then compacted goaf properties are assigned to the corresponding domain. Of course, this approximation does not account for the rock volume that really caved. Each step is followed by a computation run in order to obtain the new state of the model.

4 RESULTS AND DISCUSSION

A reconstruction of the initial stress state was first performed by considering the real topographical surface on which the gravity forces act. Afterwards, the mining progress was simulated and the new state of stress and corresponding displacements were calculated. The first active mining stage (S1) corresponds to the excavation of about 10 % of all coal seams included in the model and resulted in an increase of the vertical stress mainly in the interburden (Figure 3a). This stage does not affect the shallow cavities. The vertical displacements reached up to 0.5 m in the rock mass above the mined out area.

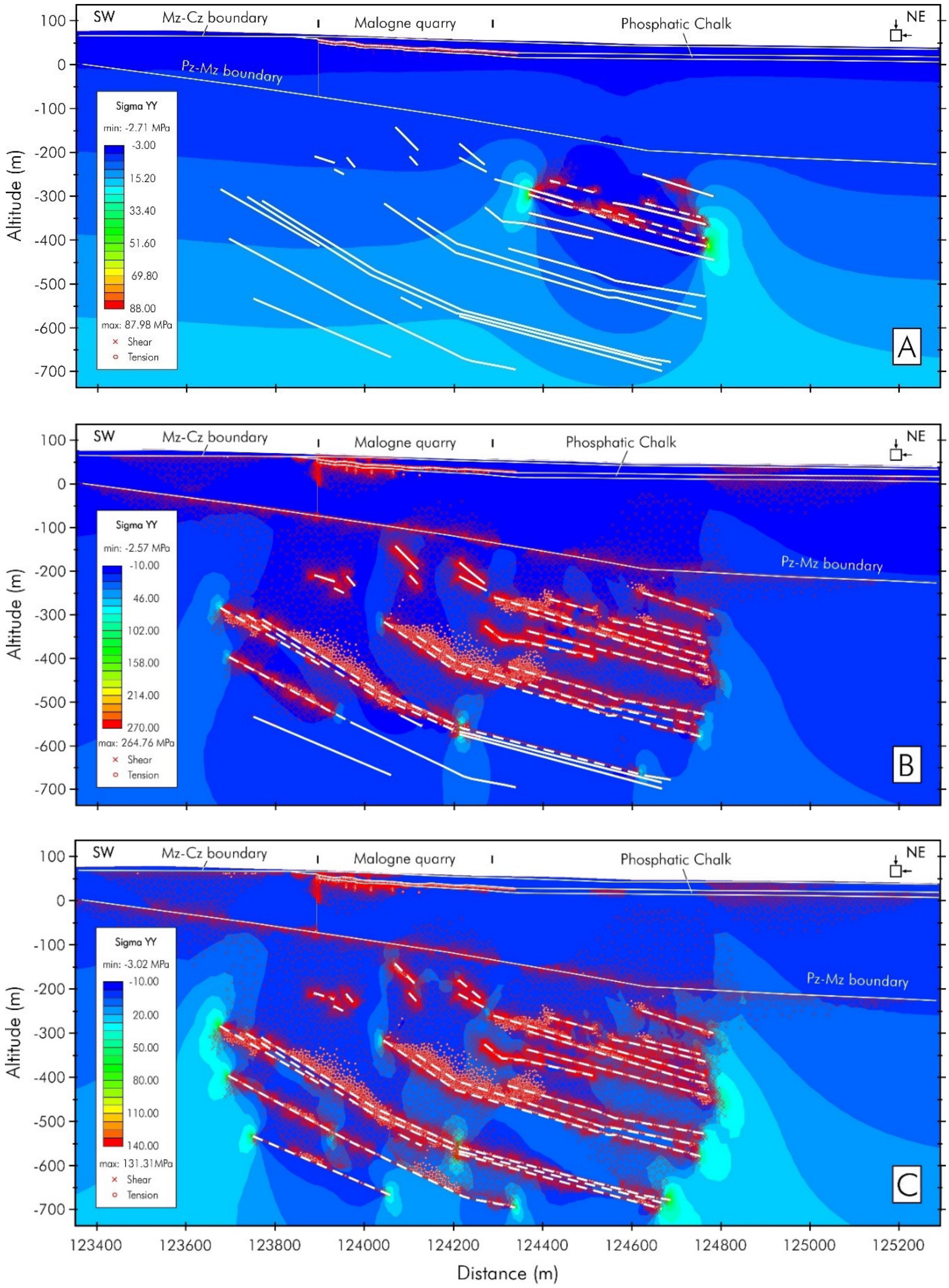

Figure 3. Vertical stress distribution and damaged zones (a) at the end of S1 (coal mining before chalk quarrying), (b) during S2 (simultaneous mining of coal and chalk), and (c) S3 (coal mining after abandonment of chalk quarry).

During the simultaneous mining of chalk and coal (S2), coal extraction continues upwards and, at the same time, intensive mining of deeper seams also begins (Figure 3b). This results in stress increase and development of a damaged zone, mainly in the interburden between neighbouring seams. Initially this is more pronounced in the deeper levels where the excavation works are more intensive.

However, at the end of S2, the lateral development of the colliery is such that a significant part of the interburden is mobilized in a large goaf zone. When evolving upwards, this goaf zone approaches the ground surface. This could have a direct impact on the stability of the shallow phosphatic chalk cavities. In addition, a shear zone is observed below the chalk quarry. In terms of vertical displacements, at the end of this stage, a maximum of 3.4 m is found where the cumulated thickness of mined out coal is the highest. In the vicinity of the chalk quarry the vertical displacement varies between 1.2 and 3m. At the end of this stage, all rooms in the chalk quarry are excavated and most of the coal seams (more than 75 %) are mined out.

The last stage (S3) consists of the coal mining after abandonment of the room-and-pillars quarry (Figure 3c). Zones of higher stress concentration form at the boundaries of the excavated coal seams. The goaf zone propagates gradually and further indications for affecting the shallow cavities are found. The mining induced deformations also increased: at the end of mining, the vertical displacement at the ground surface just above the chalk quarry reaches about 4.6 m.

5 CONCLUSIONS

Coal mining in Wallonia and Hauts-de-France has significantly affected the ground surface in these regions, and hence shallow-seated underground cavities, as shown in this case study. To investigate the rock mass response to such excavations and to assess the interaction between deep and shallow cavities, a methodology has been proposed using FEM. The simulations indicate that coal mining generated large goaf zones that propagate through the interburden and can trigger instabilities in the shallow cavities. In the studied case, vertical displacements reach several meters in the vicinity of the shallow openings; they form an asymmetric profile controlled by the geometry of mined out coal seams. Such results provide the boundary conditions for further investigation of instabilities at the scale of the chalk quarry.

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REFERENCES

Al Heib, M., Nicolas, M., Noirel, J.F. & Wojtkowiak, F. 2005. Residual subsidence analysis after the end of coalmine work. Example from Lorraine colliery, France. - In: *Symp. Post Mining,* Nancy, France: pp. 1-9.

Brady, B. & Brown, E. 2005. Rock mechanics for underground mining. - Springer, 3rd edit.: 647 pp.

Descamps, F., D. Danis, J.-P. Tshibangu, K. Meessen. 2019. Influence of an open-pit quarry on the stability of an underground cavity. - In: *ISRM Cong., Proc. Int. Symp. Rock Mech.*, pp. 290-298.

Georgieva, T., Descamps, F., Gonze, N., Vandycke, S., Ajdanlijsky, G. & Tshibangu, J.P. 2020a. Stability assessment of a shallow abandoned chalk mine of Malogne (Belgium). *Europ. J. Environ and Civil Eng.*, DOI.org/10.1080/19648189.2020.1762752.

Georgieva, T., Descamps, F., Vandycke, S., Ajdanlijsky, G. & Tshibangu, J.P. 2020b. Caracterisation geomecanique d’une carriere souterraine abandonnee par des mesures in-situ. In: *JNGG2020*, France, 8 p.

Georgieva, T., Descamps, F., Vandycke, S., Ajdanlijsky, G. & Tshibangu, J.P. 2022. Influence des exploitations de charbon profondes sur la stabilité de cavités souterraines. - In: *JNGG2022*, France, 8 p.

Robaszynski, F., Dhondt, A. & Jagt, J. 2001. Cretaceous lithostratigraphic units (Belgium). - In: *Geol. Belgica*. 4, pp. 121-134.

Vandycke, S., Bergerat, F. & Dupuis, Ch. 1991. Meso-Cenozoic faulting and inferred paleostresses in the Mons Basin. *Tectonophysics*, 192, pp. 261-271.

Vervoort, A. & Declercq, P-Y. 2017. Surface movement above old coal longwalls after mine closure. *Journal of Mining Science*, 27, pp. 481-490.