Numerical modelling and empirical tool for subsidence prediction by the use of backfill

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NUMERICAL MODELLING AND EMPIRICAL TOOL FOR SUBSIDENCE PREDICTION BY THE USE OF BACKFILL

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ABSTRACT

Geomechanical-numerical methods are an established tool for planning of underground excavations worldwide. By describing the interaction between rock mass and backfill it is possible to determine the suitability of backfill methods regarding subsidence and a potential increase of the extraction ratio.

DMT and INERIS, both have longterm experience in investigating and applying geotechnical parameters for designing and refining numerical models for planning and evaluating almost any underground excavation-project by geomechanical-numerical tools combined with empirical planning methods.

The presentation describes the planning approach for numerical models in mining and illustrates the advantages of this planning tool by means of several planning cases from the mining industry worldwide. The paper also describes the development of an empirical approach visualizing the backfilling effect on the prediction of subsidence of deep mines. The estimation of the effect of backfilling may be obtained by in-situ measurements and by the numerical modeling. A basic 2D numerical model was used to estimate the factor of subsidence reduction due to the backfilling exemplary for a room and pillar mine.

INTRODUCTION

Movement types relating to underground mines

The type of surface movement, the amplitude, and the extension of the movements depend on several factors: geometry and localization of the underground mine panels, depth, the nature of the overburden, the presence of water and, the mining methods: total and partial extraction methods. The prediction of the subsidence of room-and-pillar mining (partial extraction) is more complex than for e.g. longwall mining (full extraction). During the extraction the subsidence is very limited and afterwards it is difficult to determine when the mined cavities will collapse due to the degradation of pillars when mining activities have ceased.

One main function of backfilling is the generation of a counter bearing for the side and/or the roof pillars. A common method is the design of stable pillars between the rooms to guarantee the safety and to avoid rock mass fracturing and displacements (e.g. subsidence).

While implementing backfill this support effect could even be achieved with smaller pillars. The stabilization of the pillars is a result of the triaxial restraint of the pillar due to backfilling. The requirements on the material will most be little, even a loose rock in a filled case could be able to work as a counter bearing. For the stabilization of the side walls a partial backfill might be sufficient (Figure 1, middle). For a stabilization of a roof pillar a complete backfilling of the room is required (Figure 1, right).

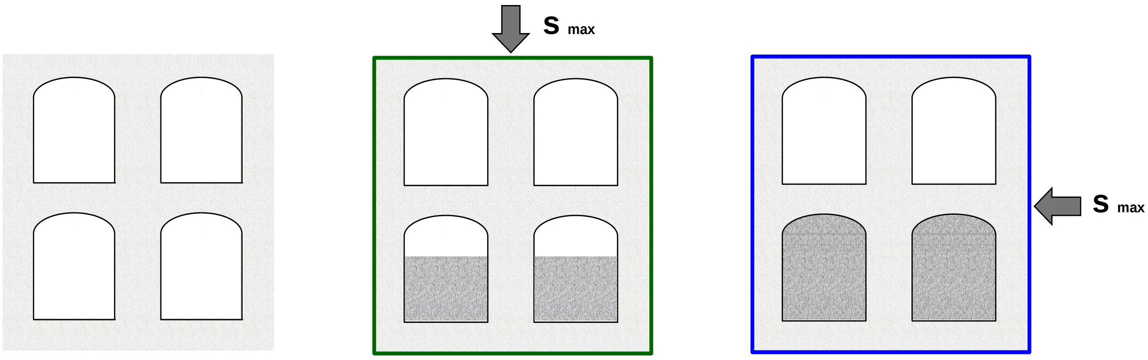


Figure 1: Room-and-Pillar with backfill

A modification of the classical Room/Stope-and-Pillar method is the Room/Stope-and-Pillar method with pillar recovery. Figure 2 shows a possible layout for mining an ore body.

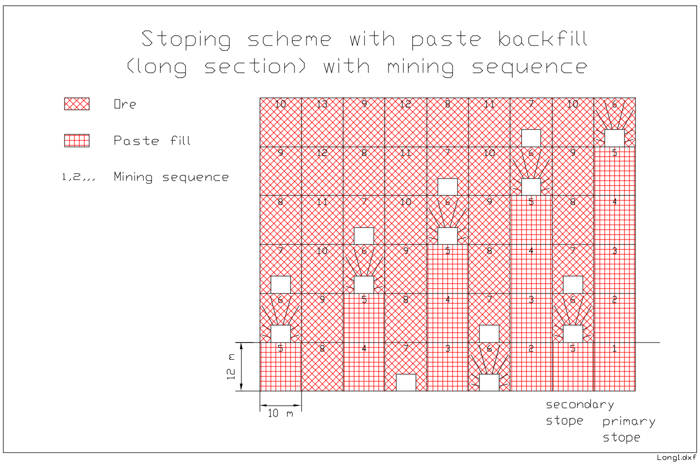


Figure 2: Room-and-Pillar with pillar recovery and backfill

The task of the backfill in this case is the refilling of the mined stopes to enable the pillar recovery. The requirements of the backfill depend on the dimensions of stopes and the mining sequence. Generally a cementitious backfill must be used. A low strength could be sufficient because the backfill ribs have to remain stable mainly for the period of pillar recovery.. After that a backfilling of the mined pillar area could be done with a low strength backfill.

For mining in slices (Figure 2) a stable floor or roof is required as well. In case of mining from the bottom to the top a stable floor is necessary for bearing the load of the used equipment (e.g. loader). For mining from top to bottom a stable roof is required to guarantee the safety of the mining process and the mining staff.

General backfill requirements

The backfill requirements are strongly related to the purpose of backfilling and the mining method and operation. The following parameters are essential for the characteristics of backfill:

- Compressibility
- Strength
- Degree of shrinkage
- Hardening time
- Viscosity and slump
- Percentage of stowed cavity volume
- Starting time for the stowing process

For the stability investigation the following mechanical backfill parameters are required:

- Young Modulus, Poisson Ratio (cement-based backfill)
- Bulk Modulus, Poisson Ratio (uncemented backfill)
- Consolidation behavior (load-yield characteristic) - (non-cement backfill)
- Hardening time (cementitous backfill)
- Compressive Strength
- Cohesion, Friction angle
- Density

For the investigation of the influence of backfill to the mining process different planning tool are available. Basically different approaches e.g. empirical or numerical can be used. The highest accuracy can be achieved by combination of both methods.

EMPIRICAL SUBSIDENCE PREDICTION

The basic aim of all subsidence prediction methods is to produce an acceptable accurate assessment of mining subsidence (Kratzsch, 1983, Whittaker and Reddish, 1989). Three different approaches can be applied: the empirical methods (NCB, 1975), semi-empirical (Bahuguna et al. 1993) and numerical methods (Al Heib, 1993). Empirical methods require feedback-data of case studies in order to predict the future subsidence for new extraction areas. This is the method of extrapolating available data to derive the future trend. Deck (Deck, 2002) listed more than 30 empirical relations to predict the subsidence and the different associated parameters (strain, tilt, etc.). Empirical methods can be used to predict the maximum subsidence for different mining methods and configurations thanks to improvement, and feedback and numerical modeling, the following relationship is one of those empirical relations (Proust, 1964):

$$Sm = O * f1 * f2 * G$$

With O: the thickness of the cavity or the worked seam. For room and pillar mining the thickness of the extraction layer is replaced by an equivalent thickness equal to $O' = \tau * O$. τ is the extraction ratio, the increasing of the extraction ratio leads to an increase of subsidence.

f1: factor which depends on the control mode of the mining area and voids, f1 varies between 0.25 (pneumatic filling) to 0.9 (total extraction and goaf). The backfilling can reduce the magnitude of subsidence.

f2: factor of depth varies from one basin to another. The value decreases with an increase of depth due to the consolidation of the caving grounds under the weight, growing with the depth of mine. Beyond the threshold, this phenomenon is counterbalanced by vault phenomena and by the fact that the conditions of appearance of sub-critical situations become increasingly frequent with great depths;

G: factor of dimensions of the exploitation, G varies according to the width and the length of the cavity compared to the depth.

As stated before in room and pillar deep underground mines, backfilling can have different functions, first to fill the void, to reduce the convergence of the strata and to increase the strength of the pillars and reduce the deformations and the subsidence. Concerning the first point, f1 factor allows the consideration of this effect. Whatever, the confining effect on pillars must be considered. The empirical equation can be modified considering the confining effect and the reducing of the convergence.

$$Sm = O * f1 * f2 * f3 * G$$

Parameter f3 depends on the quality of the backfilling, the depth and the behavior of the roof. A numerical modeling was carried out to quantify the role of the confining pressure and to estimate the value of the factor f3.

Figure 3 shows a basic regular mining area with square pillars with high extraction ratio equal to 88 %. The 2D section corresponds to a deep mine at 500 m depth; the pillar section is (5 * 5 m). Instant backfilling after the extraction was supposed in the calculation. Considering elasto-plastic behavior with Mohr-Coulomb criterion of the backfilling material, a parametric study was carried out concerning the Young modulus (50 to 500 MPa), the cohesion (0 to 1.5 MPa) and the friction angle as constant and equal to 30°. The Young modulus of the extraction layer is equal to 5000 MPa. The parameters of the backfilling can be increasing due to the increasing of the cement quantity and to the consolidation effect.

The results analyzed herein concern stress and displacement. Figure 4-a, presents the increasing of the confining pressure in the pillar and the decreasing of the convergence (on the surface) function of the increasing of Young modulus. The evaluation becomes negligible when the value of Young modulus is equal to 300 MPa: the horizontal confining stress equal to 0.6 MPa, the variation of vertical displacement (Δv) follows same tendency. Figure 4-b presents the increasing of the confining pressure and the decreasing of the convergence due to the effect of the increasing of the cohesion; the maximum effect can be obtained when the cohesion is less than 0.75 MPa. The maximum confining pressure can be reached at 1 MPa. Remember that the initial horizontal stress before the excavation is equal to 3 MPa, at the depth of the mine (500 m). The backfilling effect can be considered very important.

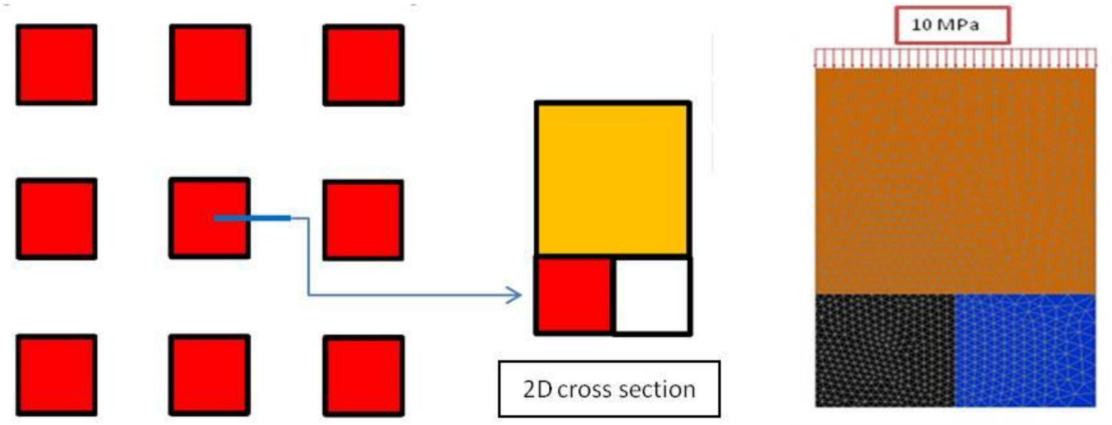
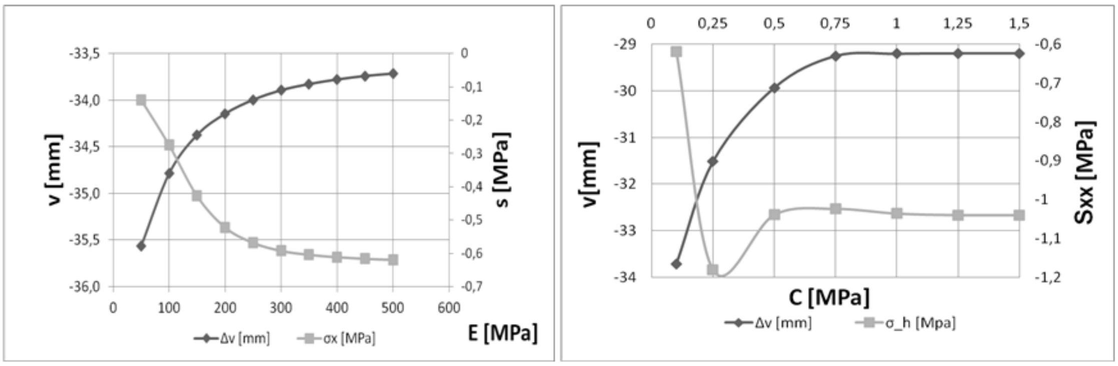


Figure 3. Numerical modeling to study the effect of the backfilling on the underground and surface behavior of room and pillar underground mine



a - Young modulus b - Cohesion

Figure 4. Effect of backfilling

The prediction of subsidence can be done by using empirical formula. The effect of backfilling on the stability of the pillar and the increasing confinement pressure and decreasing of surface displacement were studied using elementary numerical models. The parametric study shown with backfilling parameters of (E= 300 MPa, cohesion= 0.75 MPa, friction angle= 30°) can increase the confining pressure and decrease the convergence.

NUMERICAL MODELLING FOR DETAILED GEOTECHNICAL ANALYSIS OF BACKFILL BEHAVIOUR

Numerical basics

Numerical methods are widely used for solving a wide variety of technical problems. They are mainly employed in applications where analytical and empirical processes cannot provide the required degree of accuracy because of the existence of complex boundary conditions.

As a result of this, the mining industry employs geomechanical-numerical models extensively as operational planning tools. Analytical and empirical methods have so far proved to lack the required degree of precision for describing the interaction that takes place between heterogeneous strata and various types of support elements (rockbolts, standing supports, yielding arches and backfilling) in highly deformed systems. Compared with conventional calculation methods, numerical modeling can, for example, provide a detailed analysis of the fracture and deformation status of the rock strata surrounding a mining excavation. This produces a picture of the extent of the strata fracture zone and helps dimensioning the support measures required. In order to be able to understand the complex mechanical phenomena within the rock mass, with all its inhomogeneity and separation planes, it is necessary to develop and implement various constructive models in the way of mechanical equations that can reproduce the stress-deformation behavior of the rock mass with sufficient accuracy.

DMT has used several numerical programs for the solution of different geomechanical questions for several decades. For large scaled stress redistributions the program GEDRU, developed by DMT, is used. For the most planning cases the program FLAC – 2 and 3 dimensional – is applied, and in special cases other programs like PFC, UDEC or Ansys are used. The main focal point in the following is the application of the program FLAC for the solution of several geotechnical questions.

The German coal industry uses numerical models for a wide range of planning assignments, including:

- Backfilling of the goaf during longwall mining.
- Investigation of mining impact (surface subsidence, damage).
- Warranty of long term stability for underground openings like shafts, pit bottoms or main roadways.
- Investigation of the deformation behavior of temporary used underground openings like longwalls or gate roads.
- Support dimensioning.

The numerical modeling process essentially operates by reproducing all fundamental support elements (backfill, rockbolts, standing supports, roadside packs, injection material etc.) along with a wide range of boundary conditions that apply to the working of coal seams in geological deposits (geology, depth, single seam and multiple seam mining and so on).

Preparation of numerical models

The preparation of geomechanical-numerical models for control of underground openings requires a multitude of information as initial parameters. This includes information such as:

- Strata
  - Geology
  - Geotechnics
- Type and shape of an underground opening
  - 2 dimensional simulation (e.g. roadways)
  - 3 dimensional simulation (e.g. junctions)
- Rock stress
  - Primary rock stress
  - Secondary rock stress
- Rock support / backfill
  - Type of backfill
  - Backfill behavior (e.g. backfill strength)
  - Support elements
  - Support pattern

- Support behavior

To create models that are as realistic as possible, initial information with a high accuracy as well as extensive model calibration are required. To receive this information a lot of investigations have to be carried out (Figure 5):

- Backfill mechanical lab tests
- Geologic and geotechnical core logs
- Rock mechanical lab tests
- Stress measurements and calculations
- Underground support tests
- Laboratory support tests for the support material as well as for the installed support elements (grouted rock bolts including the rock mass)

The challenge is the modification of the lab parameters for the usage in the continuum-mechanical program FLAC. Due to a limitation of implementing each geotechnical element (e.g. joint) in a model a limitation of these test results (e.g. rock strength) is required. Therefore different empirical approaches as well as experiences are used. An additional point is a mostly limited amount of initial parameters or their poor quality. Due to these reasons a calibration of the model is required. DMT uses 2 different ways for model calibration:

- Physical modeling of underground roadways and backfill in a scale of 1:15
- Underground measurements and observation

The benefit of this extensive calibration process is the output of a comprehensive picture of the complex deformation and fracture structure around underground openings. The physical modeling technique especially permits a detailed view into the rock surrounding an opening. Thus it is possible to detect fractures in the rock and the backfilled area as well as support failure (e.g. bolt failure).

Based on these considerable initial parameters and calibration capabilities DMT has successfully developed numerical modeling as a reliable planning tool which can be used worldwide. In the following examples the application of numerical models four different planning cases will be described.

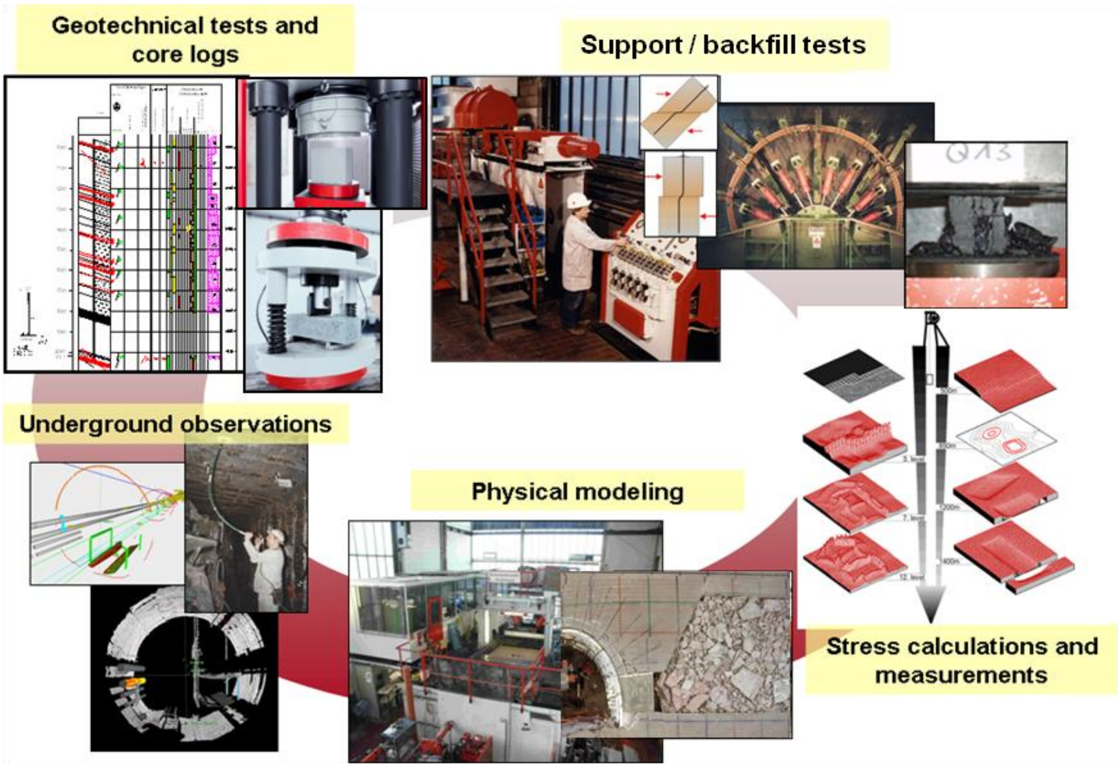
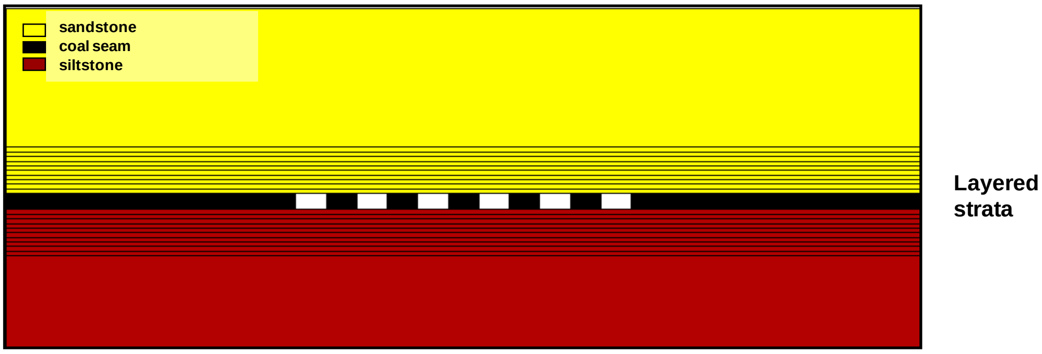


Figure 5: Required information for calibration of a numerical model

Application Case

This analysis was done for a cut-and-fill operation for a coal seam deposit. Figure 6 shows the model with the boundary conditions.



depth:	1000 m	Rock mass parameters	
→ vertical stress:	25 MPa	Sandstone:	44 MPa
ratio hor./vert. stress:	1	Coal:	5 MPa
		Siltstone:	23 MPa
room width:	6 m		
pillar width:	6 m	Seam thickness:	3.5 m
model width:	180 m	→ Calculation until equilibrium	
model heigth:	75 m		

Figure 6: Numerical base model with boundary conditions

The rooms were headed successively. In the base model a calculation without backfill was carried out. After development of several rooms the pillars collapse completely (Figure 7).

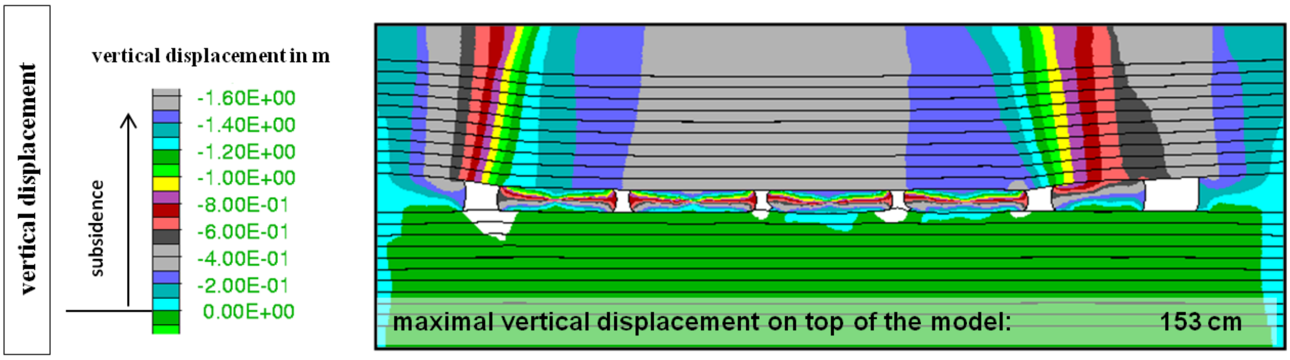


Figure 7: Model displacement after development of 5 rooms for base model without backfill

For this model several variations with different backfill rate and backfill strength were carried out. In the first variations of this basic model every room was backfilled 33% partial and 66% partial after heading parallel to heading of the next room (Figure 8 and 9). Figure 10 shows the same situation as in figures 7 to 9 but with completely filled rooms. The chosen backfill compressive strength was 5 MPa for these models.

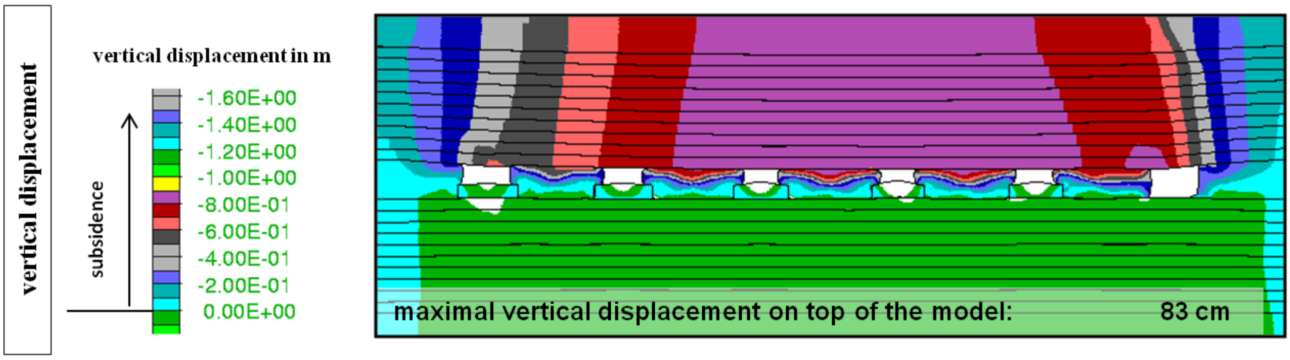


Figure 8: Model displacement after development of 5 rooms for base model with 33% backfill

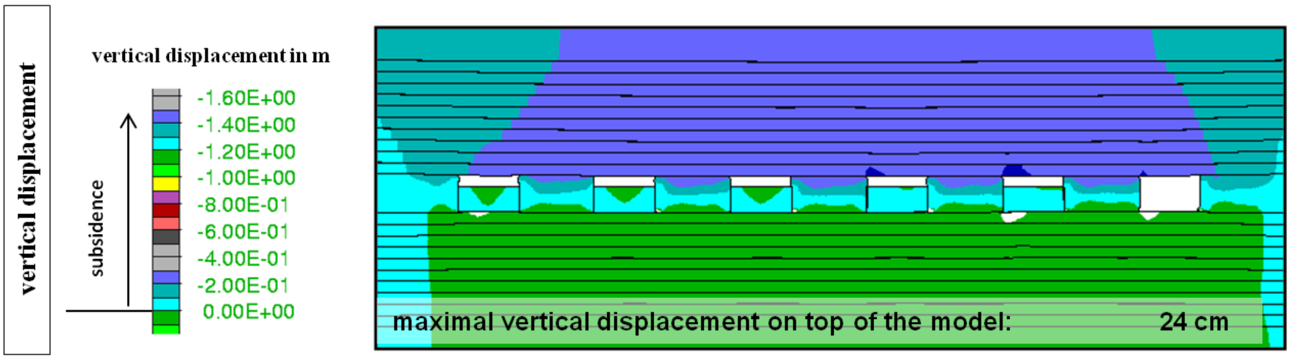


Figure 9: Model displacement after development of 5 rooms for base model with 66% backfill

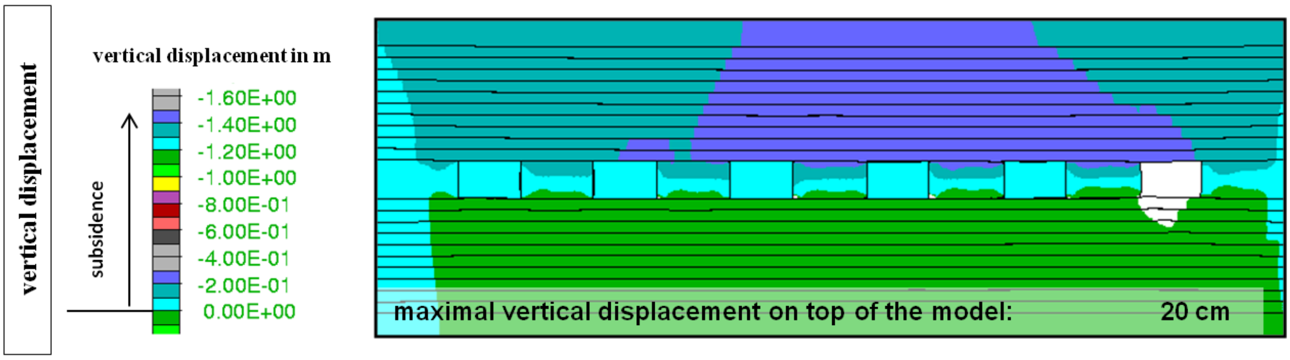


Figure 10: Model displacement after development of 5 rooms for base model with backfill

The same calculations were carried out with a backfill compressive strength of 1 MPa.

The vertical displacements are an indicator for the success of the backfill regarding the avoiding the subsidence. Figure 11 shows the results of the different models.

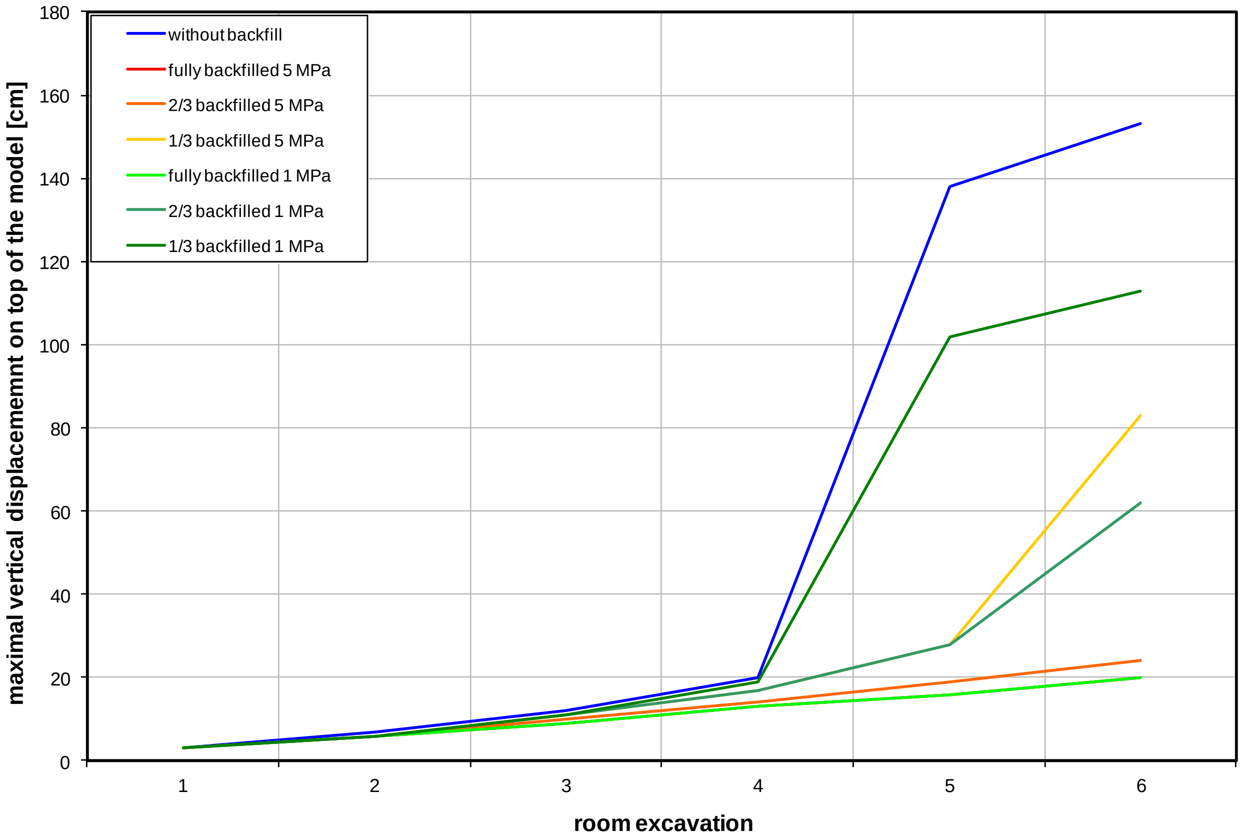


Figure 9: Vertical displacement (y-axis) related to backfilling degree and number of excavated rooms (x-axis)

The dark blue line is the model without backfill. End of this line is the extraction of the 6th room. The green lines are the calculations with backfill strength of 1 MPa, the red/yellow lines with backfill strength of 5 MPa. Up to the excavation of the fourth room no significant vertical displacements occur due to low span width of the excavated area. No pillar collapse is indicated. In the model without backfill the pillar collapse begins after heading the next room and results in high vertical displacement. The effect of backfilling can be assessed considering the other lines. A high degree of stabilization can be achieved with full backfilled rooms as well as partial backfill with high strength. But also with a partial backfill of only 1/3 of the room and a low compressive strength of 1 MPa the vertical displacement could be reduced by 20 % compared to the unfilled room. These were the first investigations within the research project and will be amended by a multitude of variation calculations with different backfill behavior and rock mass conditions.

CONCLUSION

Based on extensive experiences over long years in underground mining and physical modeling, DMT and INERIS has accumulated a comprehensive understanding of geomechanical processes, especially regarding the interaction of rock stress, rock mass structure and support technology like backfill. This knowledge was implemented in empirical investigations and the geomechanical-numerical models. By dint of continuous calibration and optimization, a high standard of modeling is assured.

As proven by various projects this advanced modeling technique is suitable for the solution for predicting mining induced impacts such as subsidence.This confirms that numerical modeling is a versatile tool in current mine planning with increasing importance for a safe, economic and trouble-free mining operation in the future.

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