

Backfill Design Under Challenging Conditions

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ABSTRACT

Salt mining in Austria commences today for more than 5000 years. Past mining activities have left remnant stopes which could pose a risk for mine stability. A research project was initiated to develop a backfill design methodology for the special conditions encountered in the salt mines. Special focus was laid on the determination of suitable rock mass parameters since the host rock exhibits a time-dependent behaviour. It was possible to establish parameters for the rock mass and the backfill using a large 3D-model comprising the complex mine geometry, high precision levelling measurement data and stress measurement data.

The filling of these remnant stopes was completed without incidents based on the findings of the presented study.

INTRODUCTION

Salt Mining in Austria

The mining of rock salt in Austria has a long history, which can be traced back to until ~ 3,000 B.C. according to recent archeological findings near Hallstatt, Upper Austria. All mining activities are bound to an evaporitic rock mass designated "Haselgebirge" which is part of the Northern Calcareous Alps (NCA). The deposit consists of layers of Halite, Anhydrite, Clay and various other evaporates. Caused by the alpine orogeny, the deposit was strongly sheared and folded resulting in very heterogeneous and scattered rock mass consisting of sheared layers with a thickness ranging from 0.1 to 10 m.

Early mining method used open stoping techniques on a very small scale. The introduction of solution mining as bulk mining method was documented for the first time in the year 1,147 (Medwenitsch 1957). This development enabled the miners to overcome the disadvantage of being forced to manually mine a low grade deposit. From this point on, fresh water was the main tool for mineral extraction of the halite.

The first solution mining methods incorporated a discontinuous operation, where in a first step an initial void was filled with water. In a second step, the then fully saturated brine was removed from the cavern, and the cycle was repeated. This procedure led to a solution process which was acting mainly on the sidewalls of the caverns resulting in very large lateral dimensions. Documented unsupported roof cross-sections of medieval caverns approached nearly 9,500 m² with a height of only a few m (Hofer, Klade 2010b).

Improvements in solution mining techniques led to cavern shapes with a more favorable diameter/height ratio, resulting in higher recovery of the deposit. Figure 1 gives an overview of various solution mining methods applied in Austrian salt mines.

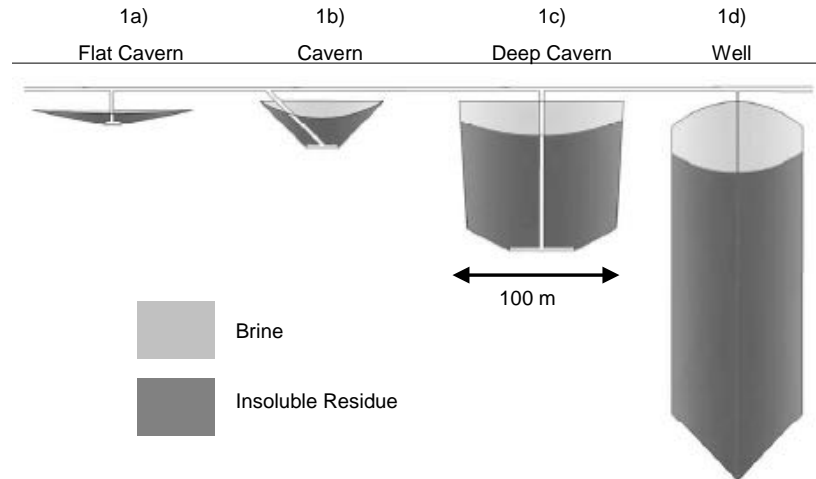


Figure 1. Past and present solution mining methods (after Hofer, Klade 2010b)

The most recent and currently applied method (Figure 1d), uses a drilled well with a co-axial pipe string to dissolve the halite in-situ. This method, in contrast to previous methods, has the advantage that an access for mine workers to the actual mining void is not necessary.

Currently, deep caverns and wells are in operation at three mining sites, namely Hallstatt, Altaussee (both underground) and Bad Ischl (surface well field). The brine produced at these sites is treated in a processing plant in Ebensee.

Problem Statement

Past mining activities have left a large number of caverns which were not backfilled during their operational phase. Nevertheless, what can be addressed as a sort of natural backfill, are the insoluble remnants of the dissolved rock mass. The composition of this backfill varies strongly depending on the mineral content of the rock mass, containing mostly Clay and Anhydrite. Additionally, the fill-factor of the caverns is depending on the salt content of the rock mass, leaving a large fraction of the cavern volume unfilled (see Figure 1).

Several incidents demonstrated, that open voids in caverns could pose a potential risk for local and regional mine stability (Hofer, Klade 2010a). To address this risk, a research project in cooperation with the Chair of Mining Engineering, University of Leoben, was initiated to develop a suitable backfill methodology for the challenging conditions in the salt mines. It was not the intention of this project to develop a general purpose backfill-product. Instead, a comprehensive procedure was developed to assure that the backfill properties meet the specific requirement of the planned backfill site. Especially the strength and deformational properties and the transportability as major design parameters were of concern.

DESCRIPTION OF TESTING AREA

Selection Parameters for Testing Area

To verify the developed methodology an underground testing area for full scale testing had to be selected. The suitability of this testing area was determined according to the following boundary conditions:

- To determine the time-dependent behavior of the rock mass, the influence of recent mining activities on surveying measurements had to be minimized. The absence of mining activities for at least three years was considered appropriate to fulfill this condition.
- Availability of surveying data, preferably precision leveling measurements in high spatial and temporal resolution.
- Safe access to the relevant caverns for mine workers and research staff.

A region of the salt mine Altaussee with the dimensions 510 m x 580 m x 400 m was considered as suitable to function as testing area. This region contains multiple caverns and access drifts mined in the 19th and 20th century. After the end of regular mining, only minor backfill and maintenance activities have been performed in this area.

Geological Description

The testing area is situated near the deposit boundary in a salt-bearing rock mass with salt contents ranging from 10%-90%. Insoluble remnants in this region contain large fractions of clay, anhydrite and polyhalite. Due to the heterogeneity of the deposits rock mass, the classification of the rock mass into regions with distinct properties was not possible. Nevertheless, three formations with separate parameter sets for the numerical simulation had to be distinguished:

- Deposit (Halite and insoluble remnants)
- Protective Layer to overburden strata
- Overburden Rock (Limestone)

The protective layer, which is situated between the deposit and the water-bearing overburden rock, consists of insoluble remnants of former deposit parts which were naturally solved. This layer forms a water barrier whose structural integrity must not be compromised. Any major water path penetrating this layer poses a potential risk for mine safety.

Due to the position of the test site under a high mountain slope, the overburden height is varying between 50 m to 500 m. Figure 2 gives an overview of the test site

Relevant Caverns

Eight caverns are situated across the test site on three different levels. Three of these caverns situated on the highest level were merged into one for modeling purposes due to certain caving events which occurred during the last 50 years. The remaining void in this cavern, which is situated in close proximity to the deposit limit, was selected for backfilling. This selection was based on the potential risk of caving into the protective layer resulting in a water inflow into the mine.

Accessibility to this region was limited due to the cross-section of the access drifts which were limited with four square meters.

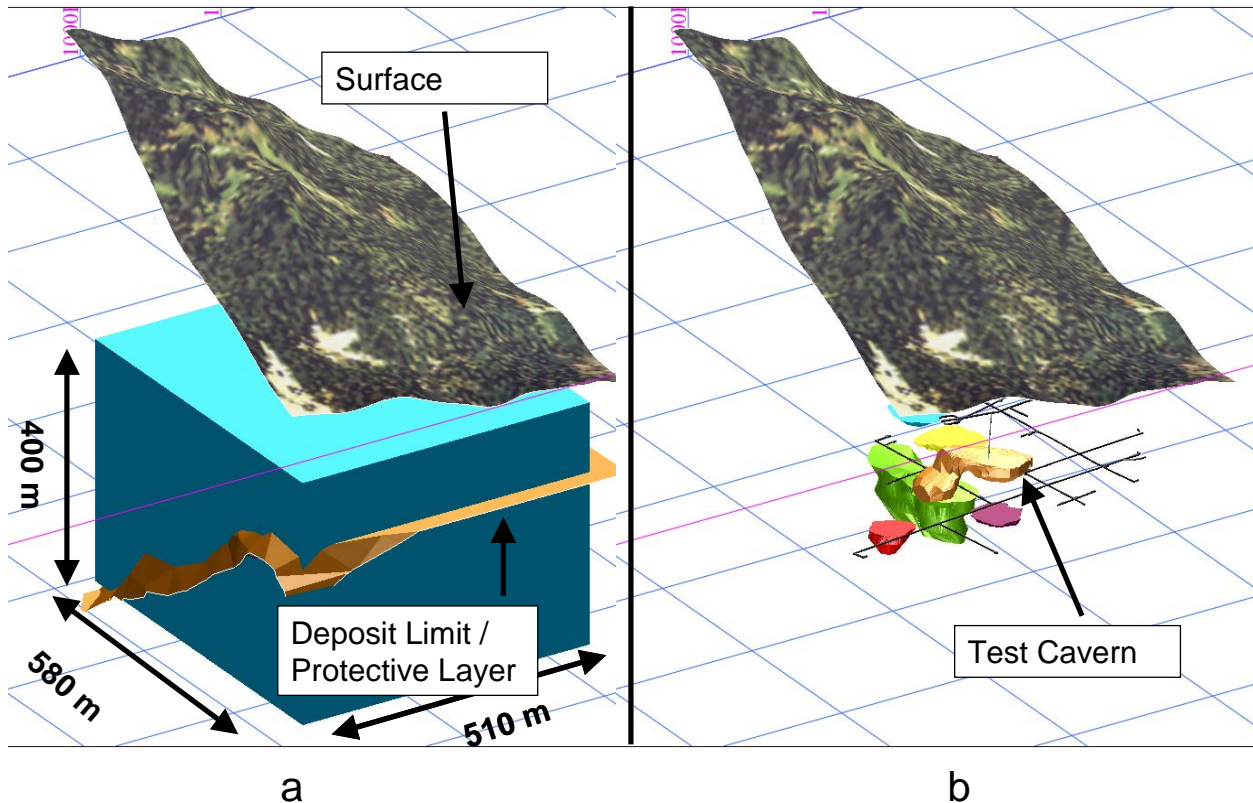


Figure 2. Overview of testing area

DETERMINATION OF ROCK MASS AND BACKFILL PARAMETERS

The determinations of realistic rock mass properties for all formations as well as the determination of the required properties for the backfill represent the major part of the research activities. These activities can be distinguished into three stages. As a first step, the test site was discretized into a 3D-Mesh which was used for numerical simulations. The second step comprised the back-calculation by numerical simulations calibrating them by using all available measurement data. The last step was another series of numerical simulations to determine the response of the system on various backfill products with the aim of determining the best suitable backfill properties.

Model Generation

Scope of the model generation process was the creation of a 3D-mesh which reflects the real geometry of the caverns and the geology as close as possible, but satisfies the following prerequisites:

- Number of elements. Due to limited computing resources, the number of elements comprising the 3D-mesh was set to ~ five million.
- Element quality. The rock mass exhibits a highly non-linear and time-dependent behavior. Based on these boundary conditions, the element quality as far as orthogonality and aspect-ratio was of major interest.

Mesh generation

A commercial pre-processor was used to generate the 3D-mesh. The selected program uses multiple input parameters to control the mesh generation, around six different parameters were identified as relevant to the quality of the mesh. To maximize mesh-generation efficiency, an automation process was developed to automatically check the resulting meshes for their quality and run additional generation processes in case the results were not satisfactory. In total, some 6,500 different meshes were created and verified. The mesh with the highest quality was selected for further calculations.

Primary stress state

To establish a reasonable stress state in the model, a multiple stage scenario ranging from virgin stress state to a sequential mining stage of the relevant caverns was developed. Special emphasis was laid on the development of a realistic minor principal stress state in the deposit formation. Generally, the minor principal stresses in rock salt formations are expected to be nearly identical to the major principal stress in terms of magnitude (Wawersik, Stone 1986). This was also verified at the Altaussee mine by multiple stress measurements. The stress state in the salt-bearing rock mass was modeled as nearly isotropic.

Additionally, a user defined function was developed to account for the varying overburden load which is caused by the topography as well as the position of the deposit limit (see Figure 2).

Rock Mass Properties

Rock mass behavior

As a first step to establish an understanding of the rock mass response on various backfill types, the mechanical properties of the rock mass had to be determined. Since the behavior of an evaporitic rock mass can not be described using strictly elastic or elasto-plastic constitutive laws, a visco-plastic approach seemed more appropriate. The selected constitutive law, a combination of a viscoelastic two component Norton Power Law with a Mohr-Coloumb elasto-plastic model (Itasca Consulting Group 2009) was considered capable of taking the time-dependency of the rock mass into account.

The elastic and plastic properties of various rock types contained in the deposit were determined through laboratory tests and were modified using rock classification systems to represent the rock mass. Laboratory tests like uniaxial or triaxial creep tests to determine the Power-Law parameters were conducted but did not yield reasonable results. This can be explained by the strong heterogeneity of the rock mass and the strongly varying salt content in the testing area.

Back-calculation of leveling measurements

One of the criteria for the selection of a suitable test site was that no mining activities had taken place in or near that region for at least three years. This criterion was determined to assure that observed displacements were not caused by changes in the stress field due to mining but instead could be attributed to the time-dependent behavior of the rock mass.

Leveling measurements taken in regular intervals over the length of a drift in the testing area resulted in the calculation of a constant deformation rate at each leveling marker. This was interpreted in a way that the system is in the secondary creeping phase and therefore a modeling of the deformations using a two-component Power-Law is reasonable.

The drift where the leveling measurements were taken is situated above and below the caverns in the test-site. Measurements were taken every three months for 5 years and are continued until today. Figure 3 gives a detailed overview of the position and size of the caverns and the drift system.

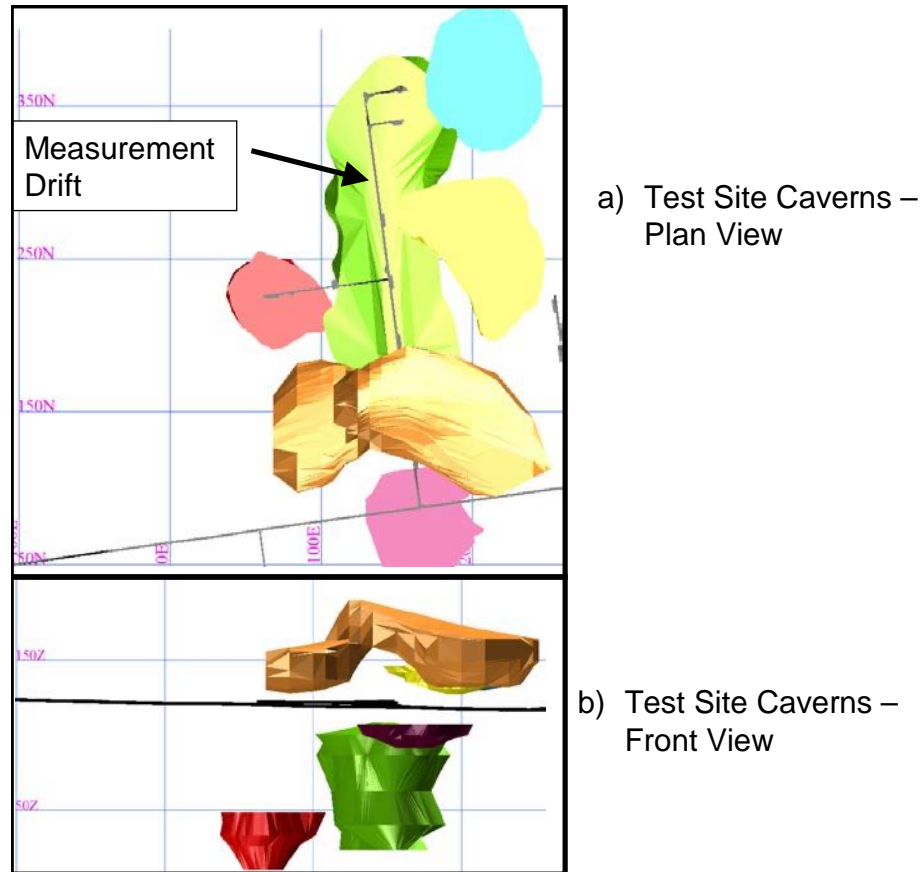


Figure 3. Views of cavern and drift system in test-site

Multiple variations of Power-Law parameters were necessary to calibrate the resulting displacement curves to the measured displacement curves. A user defined function was developed allowing an automation of the variation process. Before the displacement rates were compared, a constant creep time was defined for all calculations in advance to minimize the influence of a possible system oscillation due to a change of the constitutive law and to account for the primary creeping stage. After this step, the displacement of grid points representing the leveling marker positions were recorded and constantly compared with the actual creep rates. If the creep rates were not matching within predefined bandwidth, the calculation was stopped and the parameters were automatically modified in a way that the differences between the measured and calculated creep rates were compensated.

Figure 4 presents the result of the final calculation. The dotted lines represent the measurement data; the solid lines represent the calculation. It was possible to reproduce the subsidence of the leveling markers very accurately. The upheaval, which was measured in a part of the drift situated below the cavern which was selected for backfilling, could not be reproduced in satisfactory way. This might be caused by the choice of the constitutive law, especially the plastic formulation.

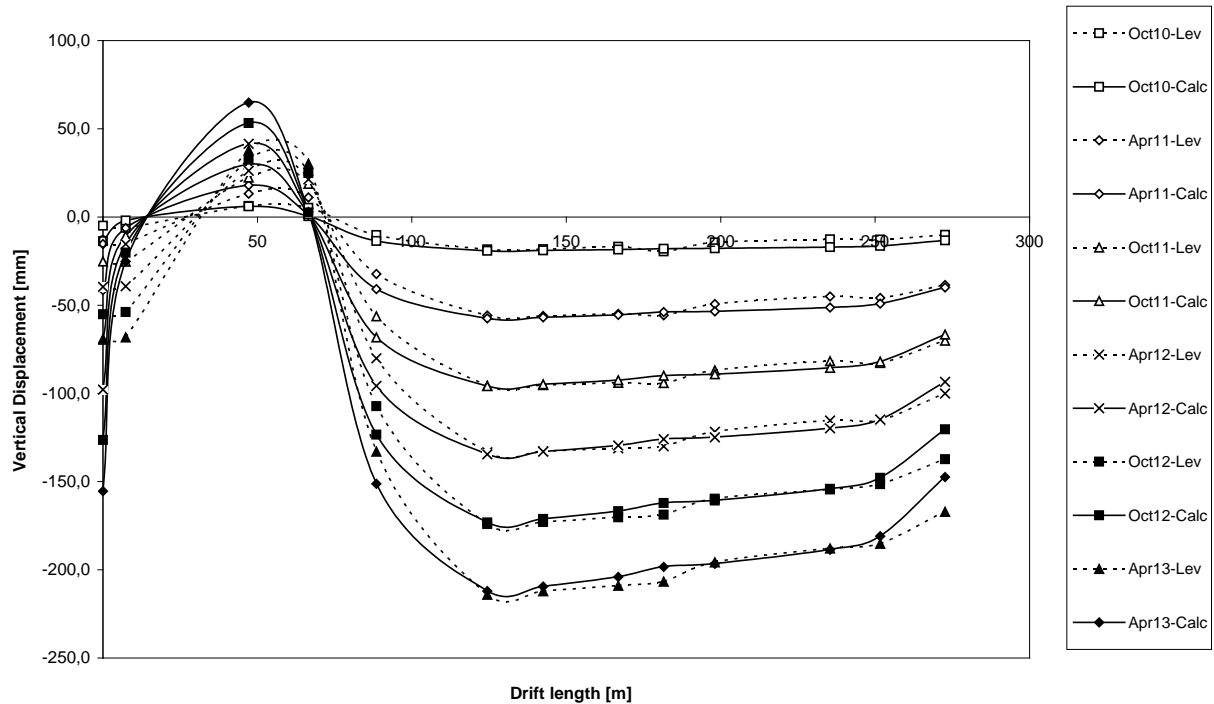


Figure 4. Comparison of leveling measurements with calculation results

Backfill Properties

Preceding the determination of the rock mass parameters, a series of calculations was conducted to establish an understanding of the system response caused by the use of different simulated backfill products. Simultaneously, the properties of various backfill products were determined through intensive laboratory testing. The backfill was modeled using a constitutive law including a volumetric yield surface to account for irreversible volumetric strains due to the application of isotropic pressure (Itasca Consulting Group 2009).

Laboratory tests

Tests were conducted to determine the strength and especially deformational properties. Additionally, based on the circumstance that the use of hydraulic transport for filling was mandatory, the transportability of each product was determined. The following tests were performed on each product:

- Uniaxial Strength Test (Cemented Fill)
- Triaxial Strength Test
- Uniaxial Compaction Test
- Grain Size Distribution
- Rotational viscometer test on the transportation slurry.

The most important test to determine the parameters for the selected constitutive law were the triaxial tests for hydrostatic pressure < 500 kPa and the uniaxial compaction test to apply hydrostatic pressure up to 17 MPa. Figure 5 shows a typical stress strain curve of a uniaxial compaction test.

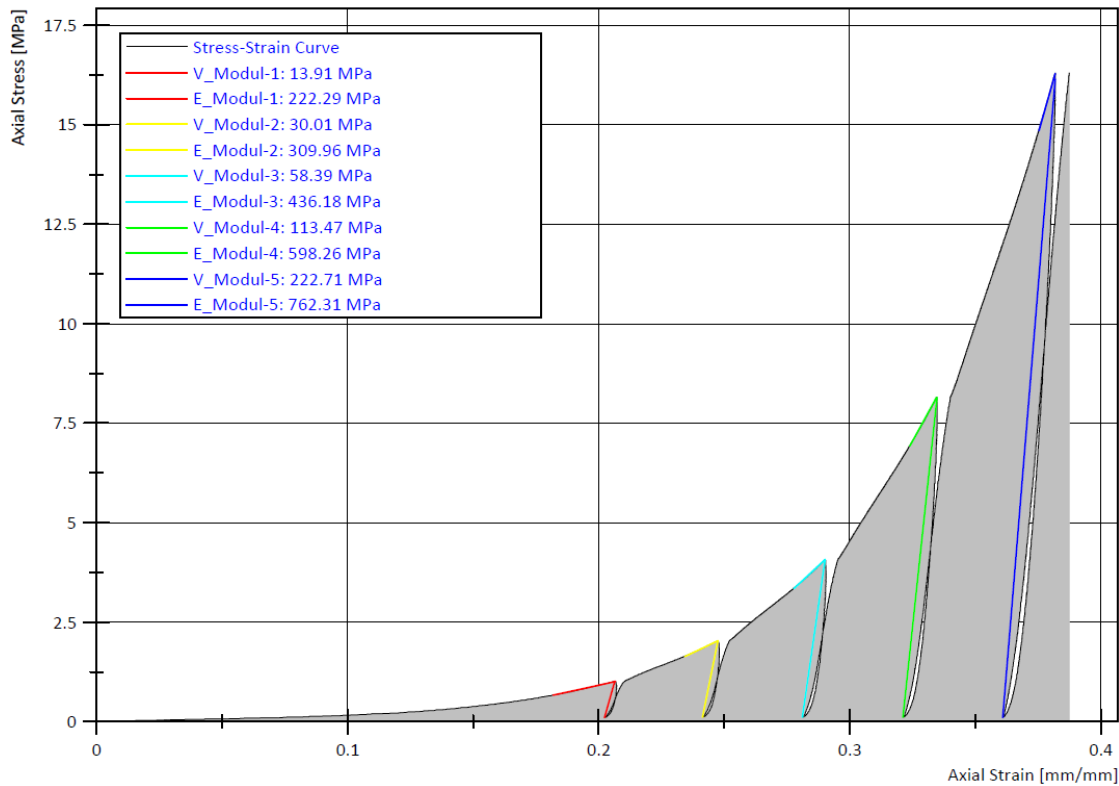


Figure 5. Uniaxial compaction test

Modeling of system response

As a last step the overall system response on the use of multiple backfill products was determined using numerical simulations of the system rock mass – insoluble remnants - backfill. To quantify the impact of a certain backfill-product, displacement rates were compared at a location corresponding to an access drift above the backfilled cavern. The calculated results for backfilling with selected backfill-products are presented in Table 1.

Table 1. Comparison of displacement rates using different backfill products

Displacement Rates [mm/y]			
No Backfill	Concrete	Cemented Backfill	Uncemented Backfill
-25	-10	-11	-12

The difference of the resulting displacement rates in case of a backfill use is remarkably small. This can be traced back to the compaction of the insoluble remnants which are in all cases the underlying material. The overall volumetric deformation of the caverns will of course be smaller with a stiffer backfill product, since the caverns are filled to nearly 70 % with insoluble remnants, this difference can be neglected.

SUMMARY

A design methodology to determine suitable backfill properties was developed and tested in an Austrian salt mine. To verify this methodology, it was necessary to determine the rock mass and backfill properties by developing a complex 3D-Model of the test-site including a detailed representation of the actual geometry as well as incorporating the time-depending behavior of the deposit.

The outcome of this investigation is that the strength and stiffness properties of backfill are of minor concern since the overall behavior of a filled cavern in this deposit type is largely dominated by the behavior of the insoluble remnants, which are left in the cavern during mining. Of major concern is the filling of the caverns in close temporal proximity to the mining process to allow for the consolidation and settlement of the fill mass and to provide an immediate support pressure to minimize deformations.

ACKNOWLEDGMENTS

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