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Design of an underground multilevel limestone mine

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Abstract

A limestone surface mine reaches its stripping limit. Obtaining permits for surface extension is difficult, tedious and costly. The mining company envisions a 6-level room-and-pillar mine with access from the quarry. The reef limestone is of good to very good geomechanical quality and generally, little problems are encountered with slope stability. Some parts of the mine show karst features and layers of tuff.

Each level in the future underground mine will be developed by 9m x 5m (w x h) headers. Secondary recovery will create rooms with a final height of 15 m and pillar dimensions of 12m x 16m. The interburden thickness is 14m. The recovery rate within one level is 73%.

We report on the development of the geological model, engineering geological mapping, execution and interpretation of laboratory tests and finally, of the rock engineering model. We employed 3D-finite element analysis to assure a safe and economical mine design. The good rock mass quality requires mainly support for structural controlled failure. Some challenging issues such as the effect of karst openings on pillars and interburden will be discussed. Further emphasis is on the effect of mining under sensitive surface structures.

Keywords

Multilevel limestone mine, pillar design, interburden, karst

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1 Introduction

A limestone quarry produces high quality lime and wants to extend its operation with a multi-level room and pillar mine. The extension of the quarry would require numerous permits (noise and dust pollution, fauna flora habitat) as well as many interest groups to deal with. The permitting process might take up to 10 years. Subsurface mining is surely more expensive, but the permitting process is rather straightforward. Crucial for the mining authorities is the preliminary mine design with stable excavations. We report in this paper about the geological setting of the resource, the results of the of site investigations and the design of a 6-level room-and-pillar mine partly under sensitive structures.

1.1 Geological setting

Limestone is mined in a Devonian reef complex. The reef developed on top of a submerged volcano in the Rhenohercynian Basin south of the Old Red Continent. Sporadic volcanic activity led to the formation of thin layers of volcanic ash within the reef. During the variscan orogeny the reef was folded and faulted and uplifted during the Tertiary. The uplift finally allowed the development of Karst voids within the resource. The resource shows the typical variscan NW-SE extension over a length of 10 km and has a width of 1.5 km. The limestone complex is underlain by Keratophyre (metamorphic volcanics) and is embedded in shale. The limestone has a thickness of about 170 m.

1.2 General outline of the mine

The future underground mine is located between two quarries. The NW quarry will reach in the near future the final depth of 140 m. The SW quarry has decades to its final depth. Located in-between the two quarries are a waste pile, the production area with sensitive infrastructure and some up to now unused land (Fig. 1).

Fig. 1 Schematic planned underground operations (left), view in the NE quarry with waste pile and production area (right).

2 Site investigation and geomechanical data

The initial site investigation was concerned mainly about the quality (SiO_2 content) of the limestone. From inspection of the stored drill cores, features such as RQD and fracture spacing could be estimated. Some samples have been tested for UCS and BTS. However, the samples did not satisfy the requirements indicated by German or ISRM suggested methods. To conduct a proper geomechanical site investigation, we mapped the walls in the NE quarry adjacent to the planned mine and took samples for rock mechanical testing. We conducted scanlines and made interpretations of discontinuity orientations from 3D photogrammetric models. Emphasis was placed on describing large scale faults and on estimating the size and orientation of karst features such as caves.

One remarkable feature is the persistence of the discontinuities. Unlike in bedded limestone, the persistence of discontinuities is rather low (Fig. 2). Similarly, the typical discontinuity spacing is between 1 and 3 m (Fig. 2). Together with the discontinuity orientation (Fig. 3), the limestone rock mass may be characterized as a massive limestone with few, mainly non-persistent discontinuities. The dominant joint set 1 strikes perpendicular to the Variscan fold axis and fits into the regional tectonic regime. This type of joint is typically open, we observed yet many calcite-healed discontinuities with no adverse mechanics. However, the main fault and the karst features might be troublesome.

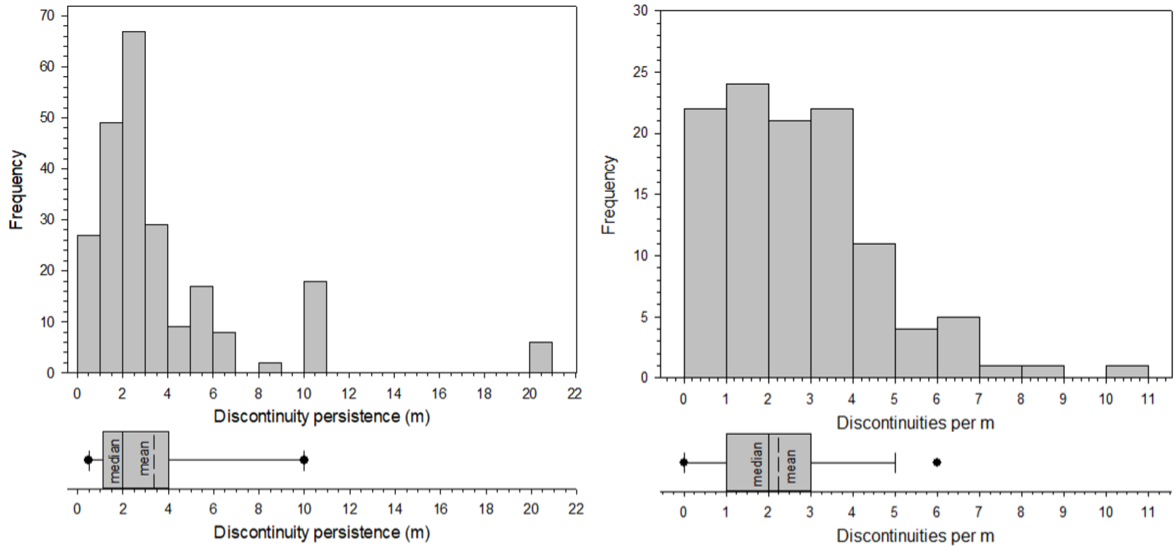


Fig. 2 Discontinuity persistence (left) and frequency (right).

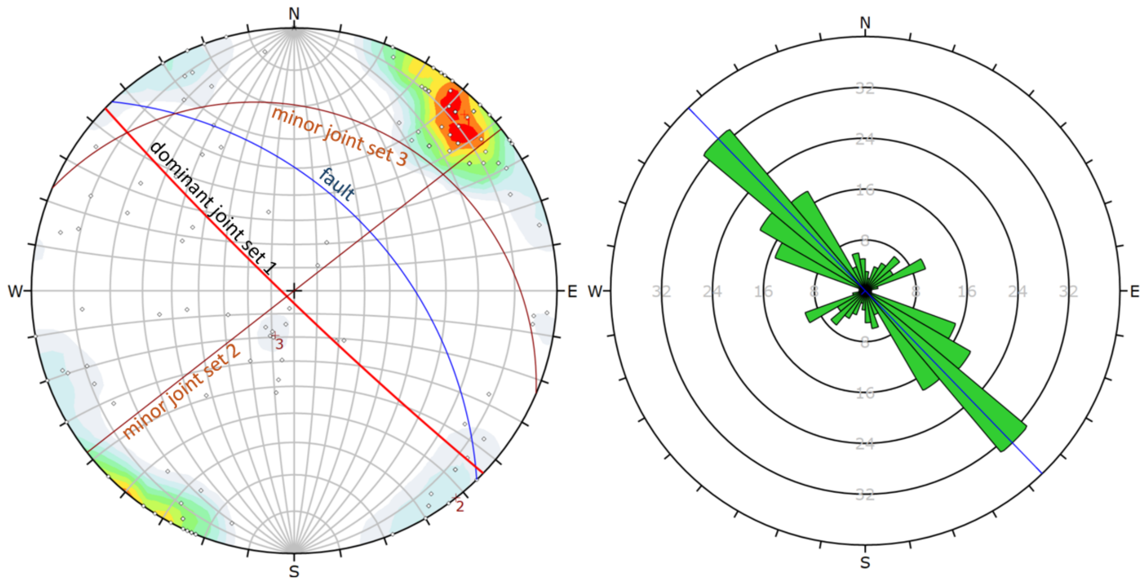


Fig. 3 Discontinuity orientations. Spherical projection (left) and joint rosette (right).

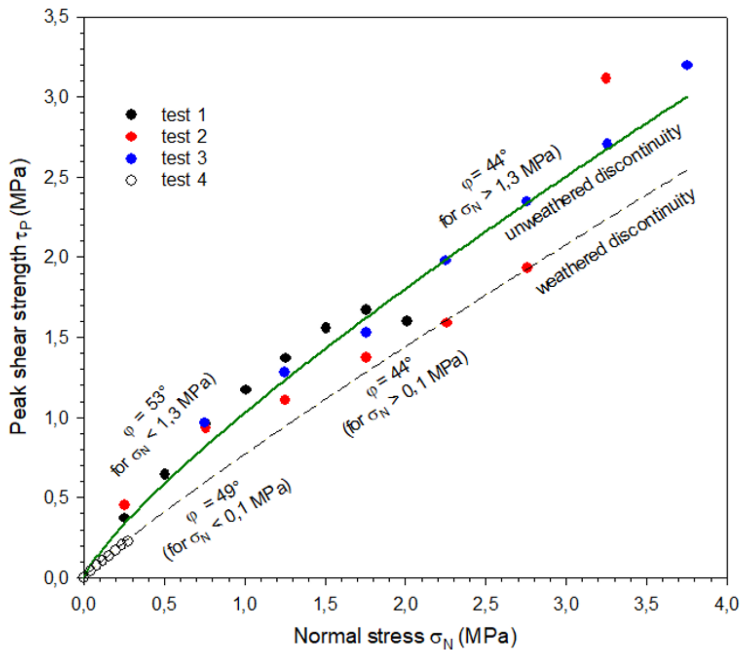
The observed karst caves show cross-section areas between 1 m^2 (round shape) and 15 m^2 (elliptical shape) of unknown but surely considerable length. Common knowledge suggests however, that nothing is as unpredictable as karst openings.

The rock mechanical tests (BTS, UCS, TCS and joint shear tests) are summarized in Figure 4. Also shown there are rock mass strengths for different estimated rock mass qualities. The main design parameters are summarized in Table 1.

Table 1 Design parameters

	Rock mass quality		
	unfavourable	typical	favourable
GSI	65	75	85
UCS	80 MPa	110 MPa	150 MPa
Rock mass modulus E_{rm}	12.500 MPa	15.500 MPa	18.000 MPa
Friction angle of joints φ	35°	44°	50°
Joint normal stiffness k_n	6.000 MPa/m	12.000 MPa/m	
Joint shear stiffness k_s	600 MPa/m	1.200 MPa/m	

In-situ stresses are close to isotropic conditions with normal as well as reverse faults in the vicinity. As the deepest level is 120 m below surface, the stress field is not as important. For all calculations we use unfavourable rock and rock mass properties (Tab. 1).



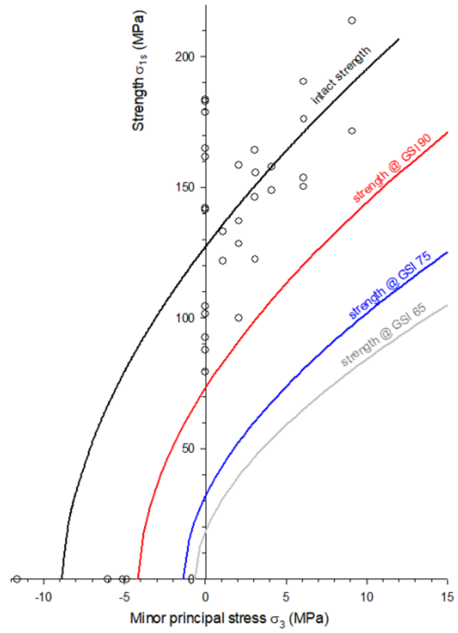


Fig. 4 Results of shear tests on discontinuities (left) and of tests of intact rock along with rock mass strength estimates (right).

3 Mine design

The room-and-pillar mining method was adopted for this project. Bench mining will be used to improve the extraction rate. In the end, on each level rooms of height 15 m and 13 m wide will be created. The pillars in each level must support the overburden. The interburden between the levels must be thick enough to ensure permanently stable mine workings. Finally, support - if necessary - of the rooms must be designed to address worker's safety. Figure 5 shows schematically the layout of a room-an-pillar mine with benching.

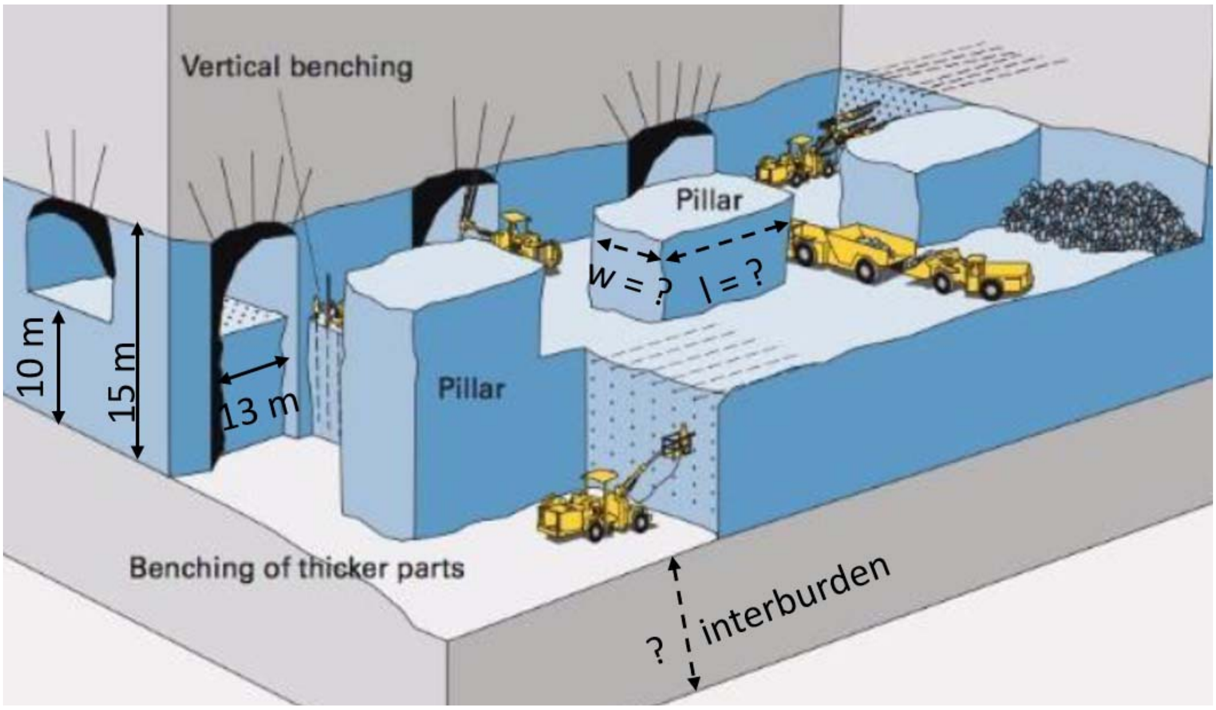
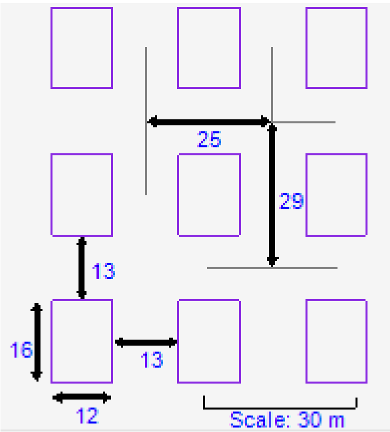


Fig. 5 Layout of the mine. Specified have been dimensions for drifts and benching (solid lines). Pillar and interburden dimensions must be determined.

3.1 Pillar design

Typical pillar design involves the estimation of pillar strength and pillar stress. The traditional tributary area approach for estimating pillar stress may not be used for a multi-level mine, only for pillars on the highest level. Nevertheless, for a first estimate we used a depth of overburden of 120 m, which will be the position of a pillar at the lowest level. The pillar strength is strongly influenced by its width to height ratio. For an initial estimate we used the US experience in limestone mining (Esterhuizen et al. 2011). Using a room width of 13 m and taking benching into account, pillar dimensions are w x l x h = 12 m x 16 m x 15 m (Fig. 6). The initial w/h-ratio of 2.4 decreases to 0.8 after benching, which is within the range of the US experience (Esterhuizen et al. 2011). The extraction ratio R on one level is 73.5%. The average pillar stress σ_P at depth z= 120 m with no other mined levels is then (Eq. 1).

$$\sigma_P = \sigma_z \frac{1}{1-\mathrm{R}} = 120\,m \times 0.0265\,\frac{MN}{m^3} \times \frac{1}{1-0.735} = 12\,MPa \tag{1}$$



	Development	Benched
Factor of Safety	3,88	1,99
W:H	2,40	0,80
Extraction %	73,5	

Fig. 6 Pillar and room dimensions (based on S-Pillar 2018).

3.2 Interburden design

The interburden thickness is traditionally evaluated by beam theory (Pariseau 2007) or by estimating the height of the compressive arch above a room (Terzaghi 1946). In the latter it is thought that layers (or beds) under the compressive arch may collapse and fall into the room. The collapse may not reach the next higher rooms. In the case of a reef limestone there are no layers and no bed separation can take place. Our approach was to numerically find the thickness of the interburden without the development of tensile stresses at the mapped discontinuities (cf. Fig. 2 and 3). We employed RS3 with discrete fracture networks and above-mentioned pillar dimensions on 6 levels. Additionally, some random karst caves with dimensions given in section 2 were included in the models. An interburden thickness of 12 m was chosen to satisfy all contingencies (Fig. 7).

This value coincides nicely with results employing beam theory using a rock mass tensile strength of 2 MPa (cf. Fig. 4 right) for a beam at depth of 120 m. It might be possible to vary the interburden thickness with depth. But given the fact that most karst caves are closer to the surface than at depth, we recommend 12 m as thickness for all interburden, irrespective of depth.

3.3 Ramp design and distance to existing quarry

Due to the proximity of the planned mine to the existing quarry it was considered to develop portals to the different mine levels using the existing berms. Ventilation might benefit from that approach, but the haulage distance to the processing area would be much longer though. It was decided then to employ a ramp (helix) in a volume of low quality (in the sense of higher SiO_2 content) limestone. A safety pillar of 20 m around the ramp was chosen to guarantee its long-time stability (Fig. 8). Support measures include rock bolts and mesh.

The quarry leads to relaxation of the rock mass behind the slopes. The distance of the rooms to the slopes must be large enough to avoid relaxation-induced tensile stresses. Results from 3D FE-Analysis suggest 20 m between slope and underground mine to avoid tensile stresses (Fig. 8).

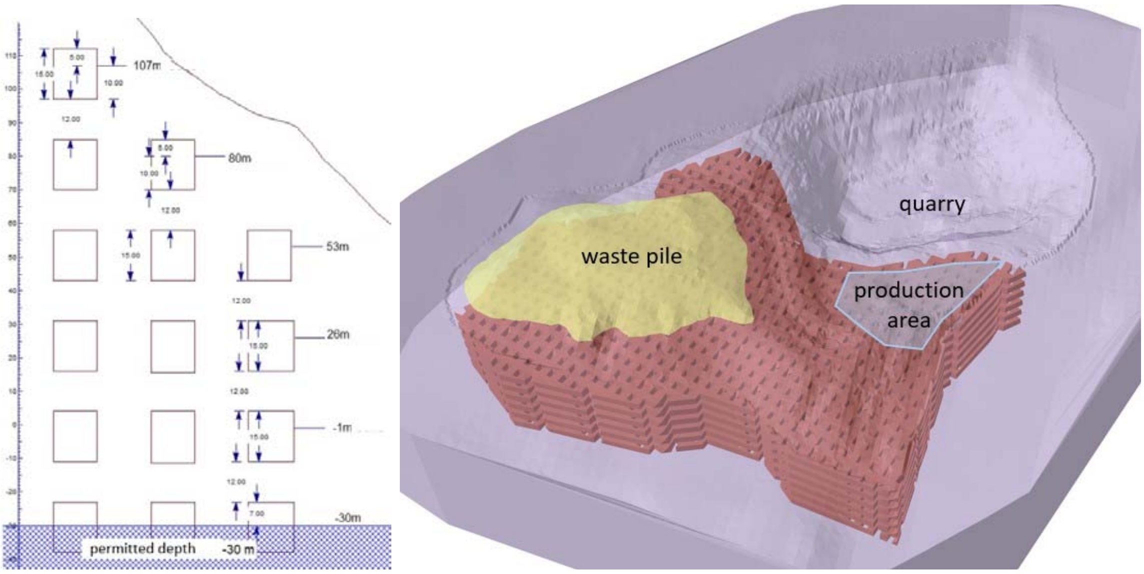


Fig. 7 Cross section (left) and perspective view of the planned mine (right),

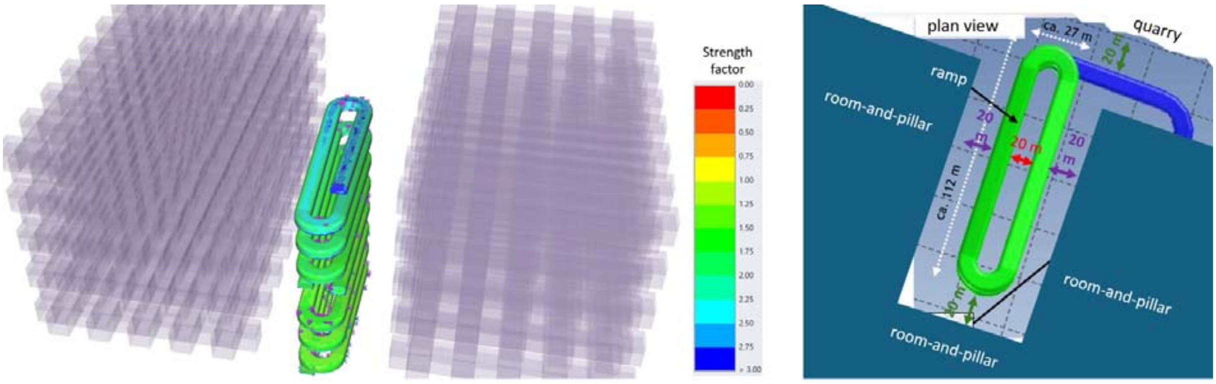


Fig. 8 Location of the ramp (left) and safety pillars around the ramp (right),

3.4 Mining under sensitive surface structures

Sensitive surface structure includes 40 m high silos, rotary kilns and to some extend the waste pile. Basically, the complete surface above the future mine comprise sensitive structures. To address this, a thickness of ≥ 23m for the crown pillar was chosen. It must be sure that the silos and rotary kilns will not be misaligned by underground mining. Rotary kilns with ground pressures of 1570 kN/m^2 must be considered. As it is not known if there are karst voids below the kilns it was recommended to create a safety pillar on the highest level around the kilns. Figure 9 shows an estimate of vertical displacements when mining 6 levels from top to bottom. The twisting of the high silos will be in the order of 1:5.700, which is way below the admissible values in EN 1997-1 (2022).

3.5 Occupational safety

Site investigation showed that discontinuities have a typical spacing of 2 m and a typical persistence of 3 m (cf. Fig. 2). This describes a good quality rock mass with little danger of pillar or interburden failure. The global stability of the mine seems to be ensured, but local conditions may lead to structural related instabilities (Fig. 10). The discontinuities may unfavorably intersect, and blocks need to be secured by bolts and mesh. 2.5 m long Split Sets of capacity 0.1 MN spaced at 2 m centers are chosen to secure structurally controlled failure.

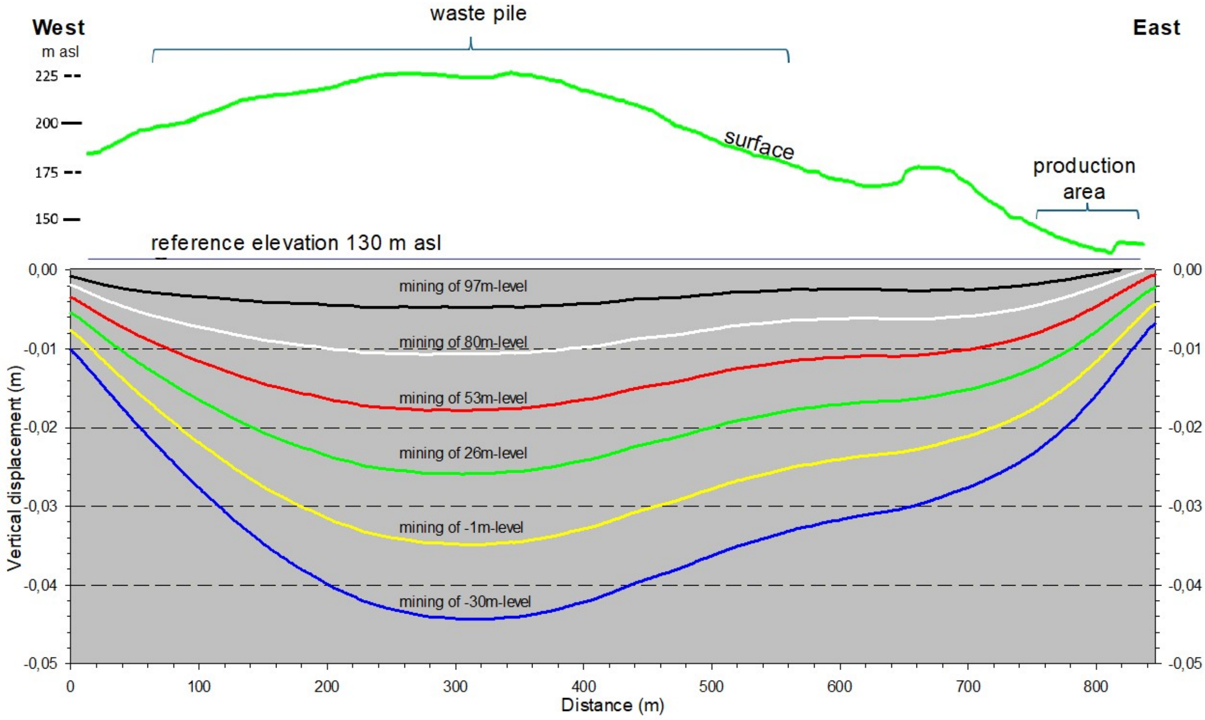


Fig. 9 Vertical displacements of the surface after mining on all levels.

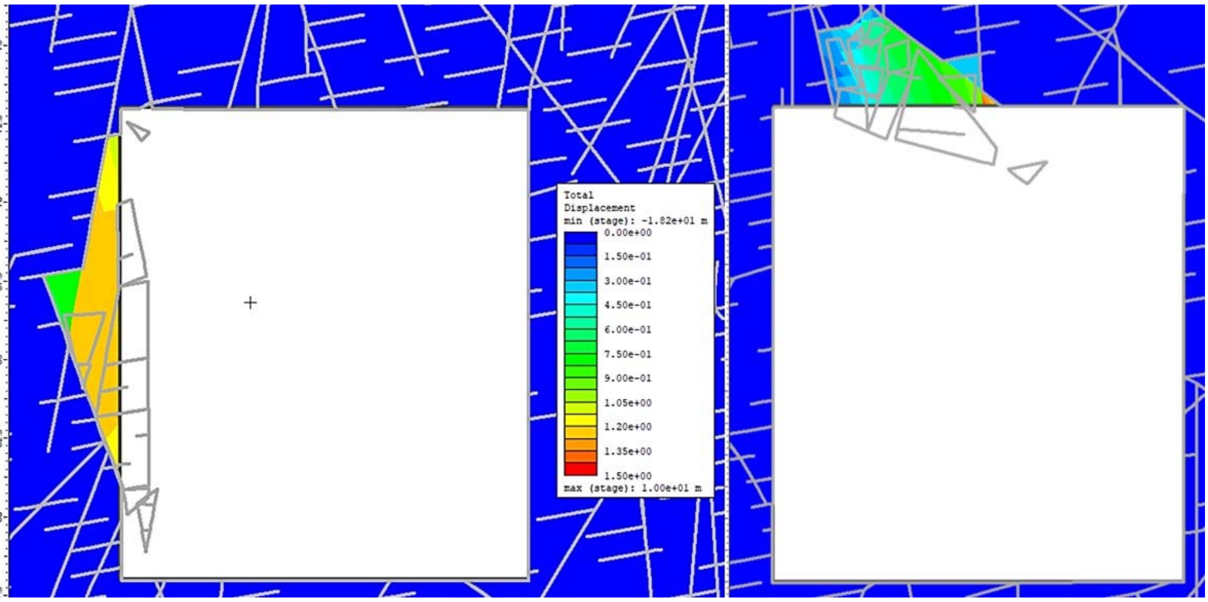


Fig. 10 Possible structural controlled failure at the sidewall (left) and at the roof (right).

4 Special cases

Karst voids and faults must be analyzed for their effects on pillar and interburden stability. The main fault strikes diagonally to the length axis of the pillars and dips 45°. Local failure at pillars may occur and must be dealt with, but the overall stability is given. Karst voids may be encountered anywhere and in any size. The worst-case scenario will be the loss of a complete pillar or a big hole in the interburden (Fig. 11). Pillars adjacent to a “lost pillar” will have to carry more load but remain stable when properly supported. Pillars below a “lost pillar” might be overstressed and the rooms should not be mined to form a safety pillar. The karst voids itself are stable and it is planned to fill the voids with concrete for achieving force fit. Here, the use of the “BullFlex” textile formwork system is anticipated, if the karst cave is not too big.

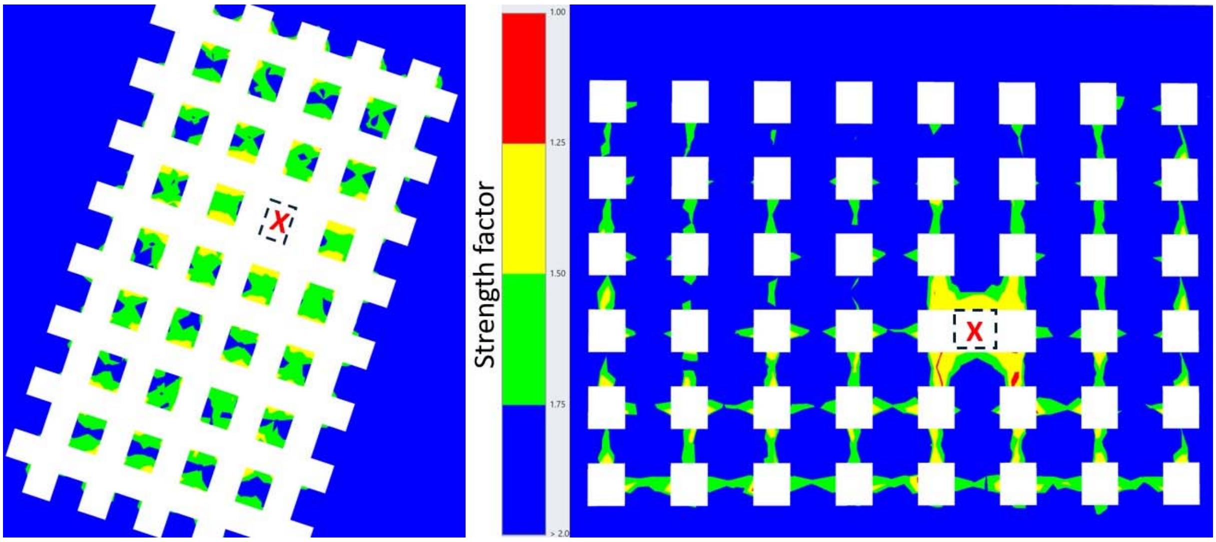


Fig. 11 Loss of one complete pillar (red cross / dashed line). Strength factors in plan view (left) and in cross section (right).

5 Discussion and conclusion

There is limited information about multi-level room-and-pillar mining in limestone. Experience from multi-level mining of coal or of metal cannot readily transferred to a mine in crystalline limestone. Newman et al. (2020) discuss projects in the eastern US and focus on the effects of high horizontal stresses on pillar and interburden stability. Rashed and Slaker (2020) explore in detail the effects of vertical pillar overlap.

The existing quarries allowed an excellent opportunity to map the variety of geomechanical features of the reef limestone. The almost 140 m high quarry walls are stable and show neither stress nor structural problems. The limestone is strong, and the discontinuities are non-persistent. Overall, it would be an ideal rock mass for mining if it weren't for karst features. To address this, we propose overlapping explorations drillings every third advance and adapt the design to "as you go". The room-and-pillar mining method allows for easy adaption to adverse conditions and critical volumes may be left unmined, ensuring local and global mine stability. The planned underground mine is certainly feasible from rock engineering considerations. The economic success remains to be seen.

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