FAILURE MODES OBSERVED IN JOINTED BAUXITE PILLARS

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SUMMARY

Production of Bauxite ore in Greece comes mainly from underground mines exploited predominantly by the mechanised room and pillar method. The main support consists of a pattern of abandoned bauxite pillars. To achieve the main scope of modern mining activities that are the establishment of operations characterized by optimum recovery, fast production rates, improved safety, minimum artificial support costs and avoid or control any general roof collapse caused by pillar failure, it is important to provide for small enough bauxite pillars with adequate bearing capacity. The main factors which affect pillar bearing capacity are the bauxite strength, the structural defects such as the discontinuity pattern, the geometrical characteristics of the pillar and the orientation of the pillar with respect to the strike and dip of the orebody. In this paper, the discontinuities of the bauxite pillars are logged initially from extensive in situ measurements. The strength of the pillar intact rock is tested on site and the discontinuity sets are surveyed. Thus an estimate of the supporting capacity of the structured rock is made. On the other hand the pillars in the same region are observed and recorded as far as their bearing capacity, shape and pattern is concerned. The failure mode of failed pillars is investigated and recorded. Thus, preliminary conclusions are drawn which aim to the improvement of the shape of the pillars and of their pattern.

1 INTRODUCTION

At the Helikon mountain, 150 km north-west of Athens, deposits of bauxite orebodies are mined underground by the G.H.B. S.A. These deposits lie mainly in two horizons. The top one underlies dark-coloured bituminous limestone of the Touronian-senonian period. The hangingwall limestone is in conformity with the bauxite and it is usually intensively karstified and thinly bedded. The footwall consists of lower Cretaceous white limestone. The contact of the footwall with the bauxite is uneven; the thickness of bauxite varies significantly from 0 up to 15m into the same deposit.

Agios Panteleimon No 4 Mine is a characteristic underground bauxite exploitation. Its deposit is located about 750 m above sea level in a depth 450m below surface. It has an average dip of 20°, a W-SW/N-NE strike and an average thickness of 5.6m. Its width along the strike ranges from 100 to 170 m, and its actual length is about 550 m. The occurrence of faulting is frequent with throws varying from less than 1 m to about 20 m. The existence of two major faults divides the orebody into three dislocated sections at different elevations. In general the existence of faults, reverse faults and of karstic voids in the roof have a significant influence on the hanging wall behaviour and are considered during the pillar layout planning.

The orebody is accessed from the surface to the upper and lower level by means of two adits. Mechanised Room and Pillar is the main mining method. This is performed in two stages, the development and the retreat. During the development stage drifts are driven from an access ramp at regular intervals in the direction of the strike. Subsequently small inclines are driven between the drifts to form rooms and pillars of bauxite. The immediate roof is reinforced systematically by expansion shell rockbolts 2.10 m long. Selective installation of 3-3.5 m cable bolts grouted with cement is occasionally also performed. Hence, additional tensile and shear strength is provided to the rock of the hangingwall. Then, at the retreat stage, the rooms are widened by partial or total extraction of the pillars and mining passes from the upper part of the deposit to the lower part towards the footwall. Thus, rooms are formed which are usually 7-10 m high, providing an extraction ratio of about 30%.

In order to maximise the extraction ratio, bauxite left in pillars must be minimum, assuring simultaneously the global stability of the mine structure until the end of the retreat stage. Effective performance of the pillar support system depends on the dimensions of the individual pillars and their geometric allocation in the orebody. This choice depends on the load bearing capacity of pillars and on the loads imposed to them by the hangingwall. This pillar load bearing capacity has to be inspected in situ by observation of stable and unstable pillar performance.

2 PILLAR STRENGTH

Stoping activity causes stress redistribution in the rock mass and an increase in pillar loading. For a state of stress in a pillar less than the in situ rock mass strength, the pillar remains intact and reacts elastically to the increased load. Mining interest is concentrated on the load bearing capacity of the pillar, when rupture in the body of the pillar mass occurs. Subsequent interest may then be on the post peak behaviour of the pillar.

The peak strength of each pillar depends on the strength of the intact rock, its absolute and relative dimensions, the damage due to blasting, the inclination of the seam and the structural geology of the piller rock mass.

2.1 Intact rock strength

The strength of the intact rock depends on the chemical composition or quality of the bauxite. This varies substantially with respect to the content of boehmite and diaspore. Typical chemical analyses of bauxite ore show consistencies of 55-58% Al_2O_3, 21-26% Fe_2O_3, 2.5-3.5% SiO_2, 2.5-3.0 TiO_2, 1-2.5% CaO and 11.0-13.5% CO_2+H_2O. However, its chemical composition varies greatly into the same orebody especially for Al_2O_3 and SiO_2 . There is a strong correlation between the contents of bauxite in Al_2O_3, SiO_2 and Fe_2O_3 and the strength of the intact bauxite. White or grey bauxite which is rich in aluminium and poor in SiO_2 and Fe_2O_3, is soft and has lower strength than ordinary bauxite. This bauxite lies usually on the upper part of pillar - hangingwall contact. Lower strength than common bauxite is exhibited also by the bauxite, which has SiO_2 content from 4% up to 9%, and is friable.

The strength of the bauxite has been tested on specimens subjected to point load tests. The point-load strength is determined according to the I.S.R.M. /1/ suggested method, which is an indirect way of determining uniaxial compressive strength. Thus, irregular lump samples were obtained from the pillars and specimens were formed of size 50±35 mm and ratio D/W close to 1.0. These specimens were tested and a size-corrected Point Load Strength Index $I_{s(50)}$ of 2.91 MPa was obtained. To estimate the strength of the rock, Broch and Franklin's /2/ formula that correlates the strength index (I_{s50}) to the uniaxial compressive strength (σ_c) was used, i.e. :

$$\sigma_c = 24\, I_s \qquad (1)$$

Thus, a mean value of σ_c is evaluated to be about 70 MPa. In a similar manner the mean uniaxial compressive strength of the intact limestone rock of the immediate roof was estimated to be σ_c = 80 MPa.

2.2 Blasting

Blasting is an important factor to the pillar strength, especially during the retreat stage. There, some pillars may be improperly overcut due to overdrilling or inappropriate blasting. Further, a blast induced damage zone is formed in the outer area of the pillar which may provide little, if any, load bearing capacity and confinement. Thus, an effective pillar cross-section area is formed which is measured to be in the bauxite pillars about 80% of the actual area /3/. Nevertheless, this depends on many factors such as the existing discontinuity sets and their orientation and the drilling and blasting pattern.

2.3 Dimensions of the pillars

The effect of pillar relative dimensions on failure mode becomes evident in this jointed ore body rock, wherever the large pillar height (h) to width (w) ratio may favour the formation of inclined shear fractures transecting the pillar, which in turn may provoke the development of penetrative localised shear zones. Important to the load bearing capacity is also the shape and the absolute dimensions of the pillar cross section, due to their effect on the confinement provided by the pillar perimeter rock to the interior one. Thus, pillars of square shape provide better such confinement and hence greater bearing capacity than pillars with elongated cross sections of the same cross section area. For the same reason, larger cross section area pillars are stronger than smaller ones with the same height.

In general there is a variation in the size and shape of the bauxite pillars of the mine, due to the excavation process and the change in the bauxite formation geometry (i.e. dip, thickness). Further, during the retreat stage of mining the pillar height is increased due to benching and the width is decreased due to the partial pillar extraction (robbing). Thus, the absolute pillar cross section dimensions and the pillar w/h ratio are progressively decreased leading to the reduction of the pillar load bearing capacity.

2.4 Planes of weakness

The structural geology of the pillar, i.e. the orientation, distribution and extent of any fractures in it, may be related directly to the strength of the pillar. Thus, a set of natural transgressive fractures may be expected to yield if the angle of inclination of the fractures to the pillar principal plane exceeds their effective angle of friction. The amount of slip of the fractures required for yield and subsequent relaxation of the elastic state of stress in the pillar need only be of elastic orders of magnitude.

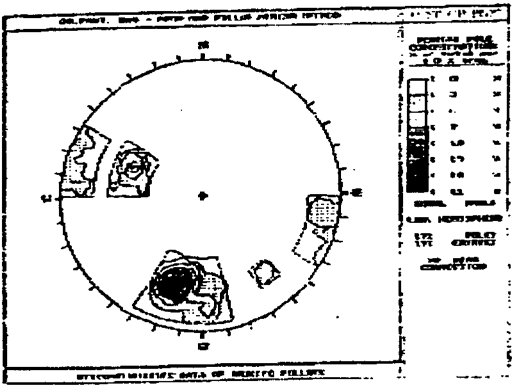

Figure 1. Analysis of discontinuity data and sectoring of orientation data into sets.

Therefore, extended measurements were performed on discontinuities exposed at the pillar sides and at the sidewalls of the exploitation drifts in one section of the mine. The discontinuity data were collected using the scanline technique /4/, which is one of the most widely used sampling methods, although not universally accepted as a standard for scanline sampling.

In the site, it was desirable to simplify the scanline technique to suit the local rock conditions. This technique was carried out at the sides of the bauxite pillars at 1.5m to 2.0m height (about 2/3 of pillar height) above the footwall using a measuring tape.

Starting point was always at a discontinuity and measurement took place along a horizontal line. Initially, the location, orientation and condition of each pillar side were recorded. Subsequently, the discontinuity traces which intersected the scanline tape were logged. Thus, geometric discontinuity properties, such as the intersection distance, orientation, semi-trace length above and below the scanline tape and termination points were recorded.

The data collected were then processed in the office, on an equal area lower hemisphere Schmidt distribution stereonet, with the code DIPS /5/, which is a package designed for the interactive analysis of orientation based geological data. In fig.1 the contours after unweighted plot processing, the sectoring of the orientation data into sets and the major planes are presented. In table 1 the detailed results are summarised.

Table 1. Mean dip and dip direction of existing discontinuities.

a/a	Description	Dip (°)	Dip Direction (°)
1	Joint 1	69	011
2	Joint 2	55	109
3	Joint 3	88	286
4	Joint 4	73	324

The discontinuities appear in well developed systems which traverse each other, thus forming large blocks of rock. According to the scanline survey it was found that the majority (>70%) of the discontinuities was persistent over the whole pillar or rock face. The rest of them was not persistent and terminated clearly at either intact rock or another discontinuity. The surfaces of the discontinuity planes are usually smooth with only minor irregularities.

3 PILLAR FAILURE OBSERVATIONS

The main objective in pillar behaviour is to achieve stability until the end of retreat mining. Observations up to now show that some of the pillars remain intact with no fractures during the extraction of the ore. The rest of them show signs of distress and involve individual modes of failure such as spalling, shearing and buckling or any combination of them. The behaviour of such pillars was investigated in an area of the underground exploitation shown in plan view in fig. 2.

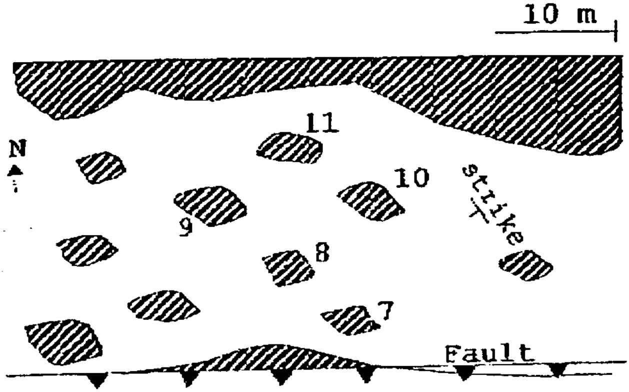

Fig. 2 Plan view of the area of the failed pillars

Figure 3. Pillar 10

3.1 Spalling

Gradual progressive spalling may be observed at the sides of some pillars. This usually starts with some slight cracking of the pillar edges and walls, followed by fracturing close to the wall surface which causes the fall of blocks. Sometimes spalling enters a larger volume of the pillar and may be followed by disintegration of the pillar with falling out of blocks, extension of fractures through the core of the pillar or formation of an hour-glass shape /6/. Pillar 10 is shown in fig. 3. This pillar is intersected by joint planes with mean dip/dip direction 55°/191° and vertical joints. In fig. 4 the contours of the poles of these joints are shown. This pillar exhibited slight spalling. However the large size of the pillar allowed it to provide adequate bearing capacity until the end of the retreat stage.

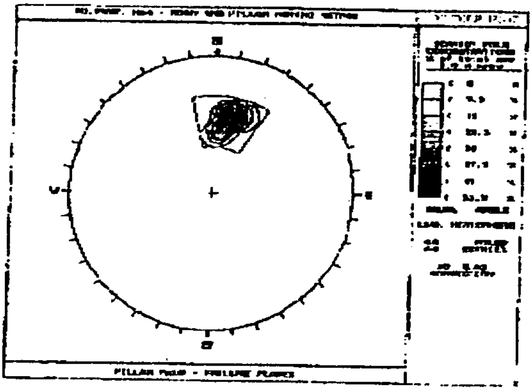

Figure 4. Analysis of failure plane data measured at pillar No 10 and sectoring of orientation data into sets.

3.2 Shear fracture

Pillars intersected by one or more inclined discontinuity planes, may potentially slide on these planes along their dip or intersection. A pillar with such transgressive discontinuities may fail, if the angle of inclination of these discontinuities exceeds their resistance capacity; for a Mohr-Coulomb failure criterion this may be expressed by their effective angle of friction. Pillar 9, shown in Fig. 5. showed such a progressive failure. This, is intersected by a dense set of joints with mean dip/dip direction 54°/194°. The poles of these joints are drawn in fig. 6. For this jointed pillar the height/width ratio is such to cause the formation of inclined shear planes which may lead the pillar to total shear failure. In order to stop this, fully cement grouted cable bolts /7/ were installed from two opposite walls. These increased the bond between the bauxite blocks that were formed from the intersecting discontinuities.

3.3 Buckling

In this case a pillar with a well-developed discontinuity set parallel to the principal axis of loading may fail in a buckling mode /8/. This is expressed by the opening of the

Figure 5. Shear fracture of pillar 9

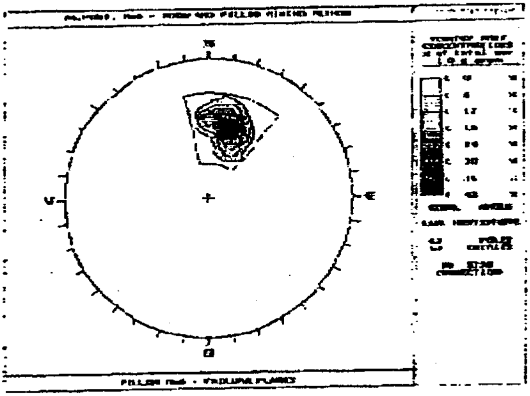

Figure 6. Analysis of failure plane data measured at pillar No9 and sectoring of orientation data into sets.

discontinuity walls near the pillar surfaces. Pillar 8, shown in fig. 7. Showed, during robbing at the retreat stage, signs of failure in a buckling mode. This pillar is intersected by a set of joints with dip 88° and a set of joints with dip/dip direction 51°/176°; the latter is shown in the pole diagram of fig. 8. Shortly before and after the stage of robbing, convergence measurements were taken near the pillar. These showed a slight convergence rate which was stabilised soon after. This was attributed to the transfer of its load to adjacent pillars. Two months later, the remnant of pillar 8 was fully extracted. The roof convergence rate equilibrated again soon after and the opening remained stable, for 2.5 years. until now.

3.4 Combined modes

There are also cases where combined modes of failure appear. Such a pillar is shown in fig. 9. In this pillar the cross section is highly reduced due to spalling and localised shear fracturing and an hour glass shape is formed. This pillar did not carry any more loads and it was decided to extract it totally. No movements were caused by its removal.

The pillar shown in fig. 10 shows signs of failure due to buckling and localised shear failure. To maintain its strength, this pillar should be confined. However, it was estimated for this pillar, that its load might be carried by the surrounding pillars. Thus, its full extraction was decided.

4 CONCLUSIONS - DISCUSSION

There is a variability of factors that affect the strength of the pillars in the orebody. From the observations made it is obvious that the most usual failure modes are associated with the existence of discontinuity systems that cause the formation of blocks. In order to evaluate the strength of the pillars, we usually divide the orebody into sections with similarities in the geology, the type of the bauxite, the dip, and the main sets of discontinuities in the bauxite mass. These data become known during the development stage. Thus, the appropriate modifications are made to the mining plans, in order to avoid a total failure of the pillars or a large roof collapse during the retreat stage.

Shear failure may happen especially during the retreat stage where the height of the pillar and the height/width ratio increases. In this case the pillar may transfer all or part of its loads to the surrounding pillars. This has been verified by measuring the convergence of the roof adjacent or near to a pillar before and after its total extraction.

In all the cases during the progress of the failue the pillar area is reduced and the stress within it is increased and may reach its bearing capacity. In cases with pillars prone to failure, with large height/width ratio, methods for the confinement of the pillars are used to enhance their strength, such as :

- bolting or cable bolting, if there are large blocks within the pillar which may be connected by the bolts.

Figure 7. Pillar 8

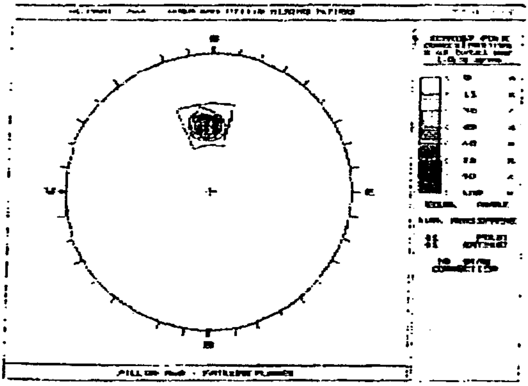

Figure 8. Analysis of failure plane data measured at pillar No8 and sectoring of orientation data into sets.

- backfilling with waste in the cases where the height of the created pillars during the retreat stage is more than 6m. This is applicable in all cases where mining is continued in adjacent sections. Otherwise, protective pillars must be left to ensure the safety of the works. Such backfilling was performed in the area right of pillar 10.

Figure 9. Pillar exhibiting an hour glass shape due to a combined failure mode

Pillars with high content in SiO_2 tend to fail with progressive spalling. When the height of these pillars exceeds 5m these pillars obtain an hour glass shape. Thus, it is necessary for these pillars to have larger, than usual, width in order to maintain their bearing capacity until the end of the retreat stage.

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Figure 10. Pillar failing in buckling and localised shear

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