

# Blasting Design Strategies for Variable Iron Ore Lithologies: Enhancing Recovery and Reducing Dilution

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**Abstract** – This study investigates the impact of blasting design on ore recovery and dilution in iron ore deposits with varying physical and geomechanical characteristics, particularly hematite and limonite zones. The research focuses on the sublevel stopping method applied at the Karaçat Underground Iron Mine in Turkey, where stratigraphic structure, ore lithology, and fault zones were taken into account to optimize blasting patterns, charge quantities, and delay timings.

Based on field data, it was observed that higher charge densities in hematite-rich, hard rock zones effectively reduced large block formation, while lower charge amounts in more porous limonite zones minimized dilution. Post-blast fragmentation analysis demonstrated a 10% improvement in specific charge efficiency and more uniform fragmentation. Moreover, the use of delay blasting techniques significantly reduced ground vibrations and helped maintain ground stability.

This study reveals that lithology-specific blasting strategies play a critical role in minimizing ore loss and enhancing mining efficiency. The findings offer site-specific recommendations for sustainable blasting practices in heterogeneous ore environments.

**Keywords** – Iron Ore Mining, Blasting Optimization, Dilution Control, Fragmentation, Geotechnical Factors, Sustainable Mining.

## I. INTRODUCTION

Iron ore mining is a strategically vital sector that provides the primary raw material for the global steel industry. A significant portion of iron production worldwide is sourced from oxide mineral deposits, particularly hematite ( $\text{Fe}_2\text{O}_3$ ) and limonite ( $\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$ ). The efficient and sustainable extraction of these resources largely depends on the optimization of mining techniques. Among these, sublevel stopping, widely employed in underground mining operations, enables sequential ore extraction through controlled collapses between levels. This method offers high production efficiency while minimizing ore dilution [1-6].

Blasting design plays a critical role in the success of this method and serves as a fundamental engineering component that influences fragmentation, recovery, and overall operational performance. Site-specific geological factors such as rock strength, fracture density, and lithological transitions directly affect parameters including blast hole patterns and charge quantities. In deposits where both competent hematite and more porous limonite coexist, the blasting strategy must be tailored according to the lithological variations to achieve optimal results [7-10]. Improper blasting designs can lead to excessive ground vibrations, structural deformations, oversize fragmentation, and increased dilution [11,12].

Several studies in the literature have addressed modeling of blast-induced effects and vibration control in iron ore mining. Kumar et al. (2015) presented a comprehensive analysis of blast vibration monitoring in open-pit mines, while Tripathy et al. (2020) and Nikzad et al. (2016) proposed field-based models focusing on collapse control and reduction of ore loss in underground operations [1,2,7,13].

However, there is limited research on the holistic optimization of blasting strategies in geologically complex environments containing both hematite and limonite, particularly within the framework of sublevel stoping. This study aims to fill this gap by evaluating site-specific blasting approaches at the Karaçat Underground Iron Mine, located in Kayseri Province, Turkey. The blasting designs were optimized based on field data, including blast patterns, charge quantities, and delay intervals, with the objective of improving fragmentation efficiency, reducing dilution, and minimizing ore loss.

In this context, the study offers a comparative assessment of existing methods and presents a novel blasting optimization model that links geological conditions with engineering practices. The findings aim to contribute to more sustainable and efficient underground mining operations in iron ore deposits with variable lithology.

## II. GEOLOGY AND STRATIGRAPHY OF THE MINE

The geological characteristics of a mining site are crucial in determining the mining methods to be employed, designing effective blasting layouts, and maximizing ore recovery. In particular, for the successful implementation of mining strategies such as sublevel stoping, it is essential to conduct a comprehensive analysis of the site's stratigraphic framework, petrographic and mineralogical composition, and tectonic structures. In this study, the geological setting of the research area was thoroughly examined, including the spatial distribution of ore bodies, host rock lithologies, and structural features.

### A. Regional Geology

The study area is located within the Tauride Tectonic Belt, one of the most geologically complex regions in Turkey. It is bounded by two major fault systems: the East Anatolian Fault to the east and the Ecemiş Fault to the west. The region also includes significant tectonic subunits such as Bolkardağı, Aladağ, Bozkır, and Geyikdağı, which collectively define the geodynamic behavior of the Karaçat mining zone [14].

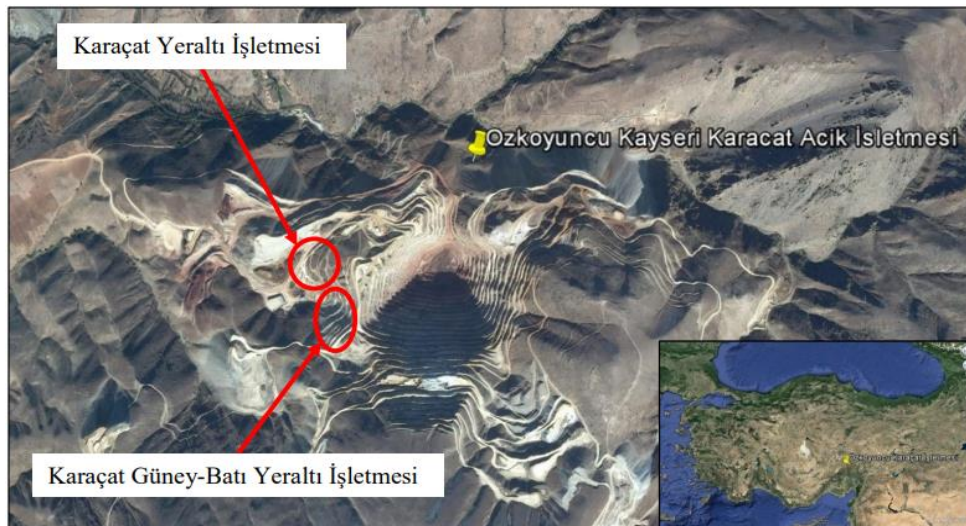


Figure 1. Location Map

## B. Stratigraphy

The stratigraphic units observed in the mining area, listed from oldest to youngest, are as follows: Emirgazi Formation (Precambrian Lower Cambrian), Zabuk Formation (Lower Cambrian), Değirmentaş Formation (Middle Cambrian), and Armutludere Formation (Upper Cambrian Ordovician).

### Emirgazi Formation:

This unit is predominantly composed of metaclastic rocks, interlayered with metavolcanic and metacarbonate levels. Although the base of the formation is not exposed within the study area, its thickness exceeds 1000 meters. The metasediments are medium- to thick-bedded, laminated, and commonly show ripple marks. Quartz is the dominant mineral, accompanied by varying amounts of mica and occasionally feldspar. Pyrite, both as coarse euhedral and fine-grained anhedral crystals, is also common. Along lamination planes and fractures, specularite can be observed locally.

The formation has undergone low-grade metamorphism (incipient greenschist facies) and is cemented by sericitized, chloritized, or silicified matrix. In the lower sections particularly near the northern and eastern parts of Avuç locality and east of the Attepe ore zone bituminous shale layers rich in pyrite and dark gray to black in color are observed in lateral transition with the metaclastic sequence [15].

In addition, the Emirgazi Formation contains variable thickness lenses of dolomitic limestone, ankerite, siderite, and blocks of purplish-green quartzite. The limestone layers are typically banded with alternating light and dark shades, fine- to medium-grained, and occasionally laminated due to metamorphic foliation. Dolomitic limestones are mostly ankeritized and present as reddish to brownish lenses and interlayers. The Emirgazi Formation is unconformably overlain by the quartzites of the Zabuk Formation. No fossils have been identified within this unit. Given that the Zabuk Formation is believed to be of Lower Cambrian age, the Emirgazi Formation is inferred to be Precambrian in age [14].

| SİSTEM       | GURUP | FORMASYON   | ÜYE | KALINLIK (m) | KAYA TÜRÜ | AÇIKLAMA                                                                                                                                                                                                                                                                                                                                                                                                             |
|--------------|-------|-------------|-----|--------------|-----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| KAMBRİYEN    |       | DEĞİRMENTAŞ |     |              |           | Killi kireçtaşı - dolomit                                                                                                                                                                                                                                                                                                                                                                                            |
|              |       | ZABUK       |     | 300          |           | Kuvarsit: mor, yeşil renkte, kopuk ve çapraz laminalı dalgı kırıklı, kumtaşı düzeyi ile bağlanmakta                                                                                                                                                                                                                                                                                                                  |
|              |       | EMİRGAZI    |     | >1000        |           | Uyumsuzluk<br>Karbonat katkılı metakumüller; desprak katmanlarda dolomitli kireçtaşı, ankerit ve sidirit mercekleri ile üst seviyelerinde kireçtaşı, mor ve yeşil renkli kuvarsit duralığı artmaktadır                                                                                                                                                                                                               |
| PREKAMBRİYEN |       | EMİRGAZI    |     |              |           | Metakumtaşı - metasilttaşı - metakilttaşı - kayrak ardışığı egemen; yeşil, boz, mor renkli yeşilist bağlanıcında metamorfizma göstermekte, volkanit ve karbonat ara katları kaplanmaktadır                                                                                                                                                                                                                           |
|              |       |             |     |              |           | Metavolkanit (pasidik ortaç bileşimli): ofitik - subofitik dokulu ayrılmış, kırılmış hamur içinde açık yeşil hornblend kristalleri, oligoklas-Andezit bütünü, plajoklas çubukları ve çok miktarda kalsiyum, metakumüller içinde ara katları ve mercek oluşturmaktadır                                                                                                                                                |
|              |       |             |     |              |           | Metakumtaşı - bitümlü sist. metakumüllerle yanal geçişli, laminasyonuya uyumlu gri, siyah renkli, baz piritli                                                                                                                                                                                                                                                                                                        |
| PREKAMBRİYEN |       | EMİRGAZI    |     |              |           | Metakumtaşı - metasilttaşı - metakilttaşı - kayrak ardışığı egemen; yeşilist bağlanıcında metamorfizma göstermekte, metakumtaşı orta-kalın katmanlı, laminalı ripilimarklı, bağlı kuvarsit, daha az oranda mika ve bazen leüsitler eşlikli, yer yer iri ölçekli veya ince baneli özgeçiriz pirit içeren, lamine ve çatlak düzlemleri boyunca yer yer apatitli, xenitler, kloritler hamur ya da silis girintisi kaplı |

Figure 2. Generalized Stratigraphic Column of the Emirgazi, Zabuk, and Değirmentaş Formations, modified from Özgül and Kozlu, 2002)

## C. Petrography and Mineralization

Three primary iron ore minerals have been identified within the study area: Hematite ( $\text{Fe}_2\text{O}_3$ ): The most economically valuable mineral for steel production. Limonite ( $\text{FeO}(\text{OH}) \cdot n\text{H}_2\text{O}$ ): A secondary oxidation product, commonly formed through the alteration of hematite and magnetite. Goethite ( $\text{FeO}(\text{OH})$ ): Typically found in lateritic deposits and considered a low-grade iron ore source.

The genesis of these minerals is attributed to a combination of hydrothermal alteration, oxidation, and chemical precipitation processes. The principal rock types observed in the mining area include: Quartzites

and Metasandstones: These are mechanically strong and highly resistant to weathering, often requiring significant blasting energy during excavation. Metamorphic Rocks: These exhibit greenschist facies characteristics and contribute to geomechanical complexity.

Limestones and Marbles: Due to their karstic nature, they pose challenges for water drainage and ground stability, particularly during underground operations.

The petrographic and stratigraphic features discussed in this section are crucial in designing effective blasting strategies and optimizing their application in the field. Specifically, the presence of fault zones and varying degrees of metamorphism necessitate customized engineering solutions during the blasting process to ensure both operational safety and economic efficiency.

### III. BLASTING DESIGN AND TECHNIQUES

In iron ore mining, blasting strategies are formulated based on the geological and geotechnical characteristics of the mine site. These strategies are of great importance for ensuring maximum ore recovery, minimizing dilution, and reducing operational costs. The effectiveness of the blasting design, especially in deposits containing ores with variable hardness such as hematite and limonite, directly affects the efficiency of ore extraction. In this context, the blasting techniques applied at the study site have been evaluated in terms of drill hole patterns, charge parameters, delay times, and blast-induced deformations. The optimization processes carried out based on these parameters are discussed in detail.

#### D. 3.1. Sublevel Stopping Method and Blasting Strategies

The sublevel stopping method is a mining technique in which ore is extracted progressively from lower levels to upper levels. The fundamental aim of blasting design within this method is to achieve the desired fragmentation size while minimizing ore loss and dilution. Since hematite and limonite deposits exhibit distinct physical properties, different blasting strategies must be applied accordingly during the extraction process.

In the study area, the blasting strategies have been designed by considering the variation between zones dominated by high-strength hematite and zones composed of more porous limonite. In hematite-rich zones, tighter drill hole patterns and higher-density charging have been preferred to prevent the formation of large boulders after blasting. On the other hand, in limonite-rich zones, more controlled blasting techniques have been employed to reduce dilution.

Figure 3 presents a schematic illustration of the blast hole pattern used within the sublevel stopping method. The figure shows how the blasting process is initiated with slot holes and subsequently transferred to the row holes in sequence, thereby achieving a controlled collapse mechanism.

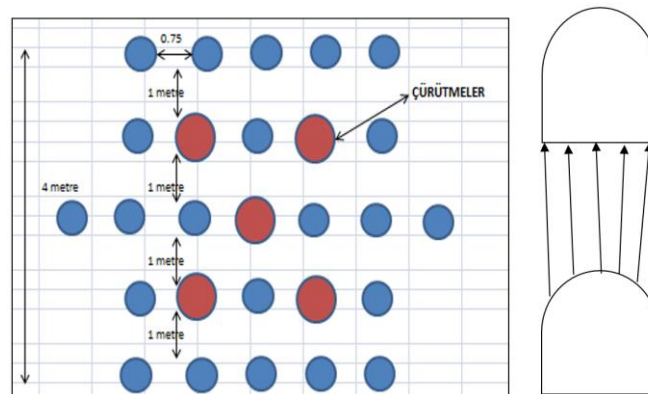


Figure 3 Blasting pattern applied within the scope of the multi-storey caving method

### E. Drill Hole Patterns and Blasting Parameters

Drill hole patterns are designed to ensure the even distribution of explosive energy throughout the rock mass during blasting, as well as to optimize collapse behavior following the detonation. In the study area, the applied blast hole configurations are classified into three primary categories, each serving a distinct function in the ore extraction process [16-20].

The first configuration is the slot and row hole pattern used between sublevels. Slot holes are drilled to create the initial free surface and allow for controlled collapse of the ore. Once the slot has been detonated, row holes are successively blasted to expand the collapse zone. The second configuration involves raise bore holes between levels, which are primarily intended to provide ventilation and access between stopes. The third configuration is the face blasting pattern, which is used to advance the production front.

Figure 4 illustrates the slot and row hole pattern applied between levels. The diagram details how slot holes function during the initial stages of blasting, and how the row holes, detonated in sequence, contribute to the formation of the collapse zone.

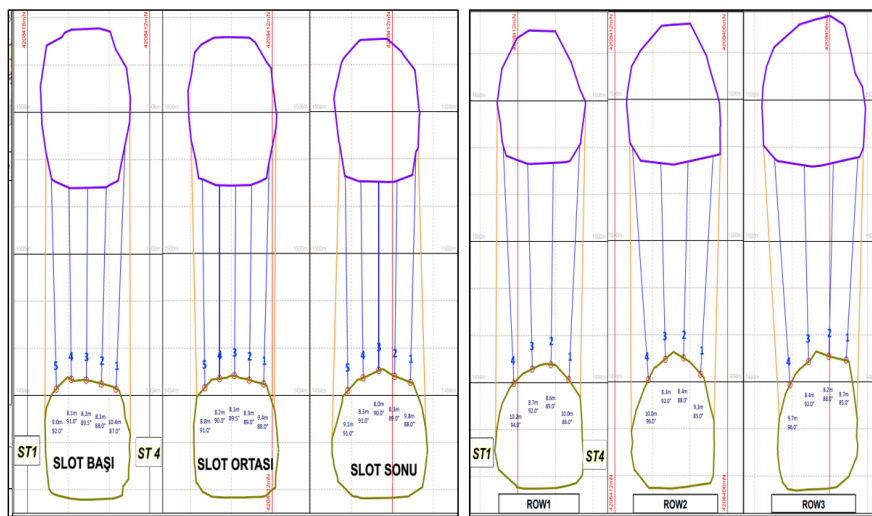


Figure 4. Inter-storey slot and Row hole patterns are shown

In determining the blasting parameters, factors such as hole diameter, spacing between holes, charge quantity, and delay timing are carefully considered. In the study area, the standard hole diameters used are 89 millimeters and 151 millimeters. The optimal amount of explosive charge is adjusted based on the mechanical strength of the rock formations encountered at different locations within the mine.

Table 1 summarizes the blasting parameters applied in the field, including drill hole diameters, spacing, and the corresponding charge quantities.

Table 1. Blasting parameters applied in the field

| Hole diameters<br>mm | Distance between holes cm | Charge amount<br>kg | Number of capsules pieces |
|----------------------|---------------------------|---------------------|---------------------------|
| 151                  | 225                       | 100                 | 4                         |
| 151                  | 225                       | 0                   | 0                         |
| 151                  | 225                       | 0                   | 0                         |
| 151                  | 225                       | 0                   | 0                         |
| 89                   | 75                        | 1200                | 48                        |

### F. Charging and Blasting Process

The charging and blasting process is designed to utilize explosive energy in the most efficient way, with the goal of achieving the desired degree of fragmentation while maintaining control over blast-induced ground vibrations [15, 18-23]. At the study site, the primary types of explosives used are emulsion-based

materials and cartridge-type dynamite compounds containing ammonium nitrate and fuel oil (commonly known as ANFO).

To minimize environmental impacts and improve blast performance, delayed blasting techniques are implemented. These techniques involve detonating blast holes in a sequential manner rather than simultaneously, allowing vibration levels to be controlled and reducing the risk of uncontrolled ground deformation. By initiating the blast with pre-drilled relief holes (also referred to as burn holes), a free face is created that guides the energy release in a controlled direction, ensuring a more efficient and safer collapse [8, 12, 24-27].

Figure 5 illustrates the distribution of delay intervals across the drill pattern during sublevel blasting. In this schematic, the central relief holes are fired first to establish a free surface, followed by the sequential detonation of surrounding holes. This process enables the controlled progression of the collapse mechanism.

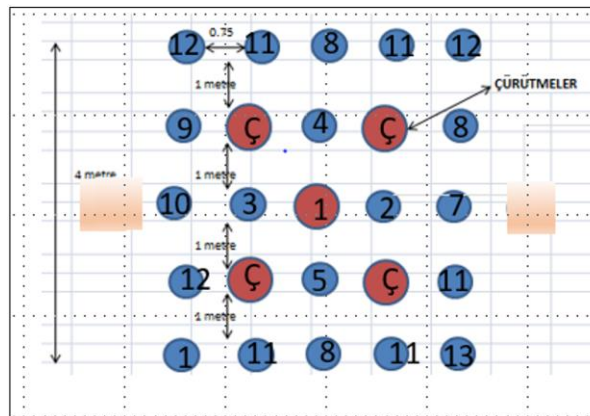


Figure 5. Distribution of delay times used in the Inter-storey Blasting process on the pattern

Figure 6 shows the delay timing distribution used during face blasting. This design ensures the consistent forward movement of the ore face while minimizing oversize fragmentation and structural damage to surrounding rock.

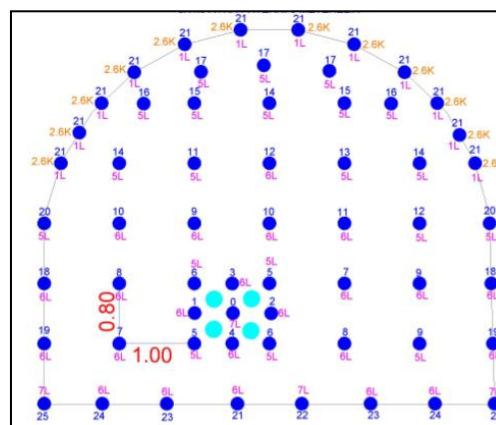


Figure 6. Distribution of delay times used in the Mirror Blasting process on the pattern

To further improve the effectiveness of the blasting process, field measurements were used to inform an optimization strategy. The primary parameters analyzed include the specific charge amount (expressed in kilograms per cubic meter), advance rate, and post-blast fragmentation distribution. As a result of the optimization efforts, a 10 percent improvement in specific charge efficiency was achieved by adjusting the

drill pattern and delay timing. Additionally, fragmentation analysis indicated a significant reduction in oversized rock blocks, leading to a more homogeneous ore mass that is easier to handle and process.

Table 2. Size distribution

| Size Range (mm) | Percentage Distribution (%) | Cumulative Percentage (%) | Description                   |
|-----------------|-----------------------------|---------------------------|-------------------------------|
| <25             | 12                          | 12                        | Fine dust (high iron content) |
| 25-50           | 18                          | 30                        | Small pieces                  |
| 50-100          | 35                          | 65                        | Medium-sized pieces           |
| 100-250         | 25                          | 90                        | Large pieces                  |
| >250            | 10                          | 100                       | Blocked                       |

Table 2 presents the post-blast fragmentation size distribution, demonstrating that optimized patterns produced finer and more uniform rock fragments, thus increasing downstream processing efficiency.

### G. Influence of Geotechnical Factors on the Blasting Process

Geotechnical conditions have a direct and significant impact on the effectiveness of blasting operations. In the study area, site-specific analyses revealed that fault zones, fractured rock structures, and the presence of metamorphic deformation are among the primary factors that limit blast efficiency. These geological complexities necessitate careful planning and tailored engineering solutions in order to maintain safety, control fragmentation, and minimize ore dilution.

In weak rock zones, blasting often results in unpredictable collapse behavior due to the variable response of fractured materials. For this reason, customized blast hole patterns must be designed for these areas to accommodate differences in rock strength and structure. Without such adjustments, the risk of uncontrolled subsidence and excessive dilution increases considerably, compromising both operational safety and ore recovery.

The blasting designs and techniques examined in this section have been analyzed with respect to their effectiveness in controlling ore dilution, maximizing recovery, and managing the collapse mechanism. By optimizing drill hole spacing, charge quantities, and delay intervals according to the geotechnical conditions of each zone, a balance between fragmentation quality and structural stability was achieved.

Field results demonstrate that these optimizations produced measurable improvements in blasting performance. Ore recovery rates increased, while the formation of oversized fragments was reduced. Moreover, more controlled collapses were observed in areas previously associated with irregular subsidence. These outcomes emphasize the critical role of geotechnical data in the continual refinement of blasting strategies.

Ongoing geotechnical monitoring and iterative adjustments to blasting parameters are recommended as essential practices for long-term operational success, particularly in structurally complex underground mining environments.

## IV. CASE STUDY: KARAÇAT UNDERGROUND IRON MINE

The optimization of blasting strategies in iron ore mining varies considerably depending on local geological and geotechnical conditions. This section presents a case study of the Karaçat Underground Iron Mine, where the influence of these factors on blasting performance was analyzed. Based on field measurements and observations, site-specific optimization processes were implemented to address geological variability and enhance ore recovery.

### H. Overview and Geological Setting of the Karaçat Mine

The Karaçat Underground Iron Mine is located in Karaköy village, Yahyalı district, within the province of Kayseri, Turkey. The site is situated along the Feke-Yahyalı highway, offering logistical advantages for ore transportation. The extracted iron ore is first hauled by road to Yeşilhisar and then transported via railway to industrial processing facilities.

Figure 7 presents the geographical location of the Karaçat Mine Site and a general overview map of the operation area.

Geologically, the mine lies within the Tauride Tectonic Belt, a structurally complex region hosting a range of metamorphic and sedimentary rock units. The principal formations observed at the site include:

The Emirgazi Formation, which consists primarily of metasediments and metavolcanic rocks and serves as the main host for iron mineralization.

The Zabuk Formation, composed of quartzites and hematite-bearing sandstones, represents another key stratigraphic unit contributing significantly to ore distribution.

The Değirmentaş Formation, dominated by carbonate rocks, plays a more limited role in terms of iron enrichment but contributes to the lithological variability of the site.

Due to the complexity of the regional geology, the presence of fault zones, and the variation in rock hardness across formations, blasting strategies at Karaçat have been specifically adapted to site conditions. This has necessitated careful design and continuous optimization of drilling and blasting parameters in order to maintain efficient and safe mining operations.



Figure 7 Geographic location of the Karaçat Mine Site

### *I. Applied Blasting Techniques*

Ore production is carried out in Karaçat Mine using the sublevel stopping method. In this method, it is aimed to excavate the ore bodies in stages in vertical sections and to create a controlled collapse mechanism. The blasting patterns used in the mine are divided into three basic groups:

1. Interstory slot and row hole pattern
2. Interstory well drilling pattern
3. Mirror blasting pattern

Hole diameters and charge parameters are optimized according to rock types. In hard rocks rich in hematite, fragmentation is improved by increasing the explosive charge, and in soft zones rich in limonite, unnecessary rock breakage is prevented by using low charge amounts.

Table 3 details the hole diameters, hole spacings and charge amounts used in slot holes.

Table 3. Charge amounts used

|              | Hole diameters<br>(mm) | Hole spacing<br>(mm) | Charge amount<br>(kg /Anfo) |
|--------------|------------------------|----------------------|-----------------------------|
| Slot hole    | 89                     | 750                  | 1275                        |
| Hole for row | 89                     | 750                  | 375                         |

In order to keep vibrations under control during blasting and to reduce environmental damage, delayed blasting techniques were applied. In this method, the decay holes were first blasted to create a free surface, and then the ore mass was gradually collapsed with delayed blasting.

#### *J. Evaluation of Blasting Results*

The data obtained after blasting were examined within the scope of specific charge amount, advancement efficiency and post-blasting fragmentation analyses.

In order to increase the efficiency of the blastings carried out in the mine, specific charge amounts were optimized and evaluated with field tests. As a result of the analyses, the specific charge amount in hematite hard rocks varied between 0.14-0.18 kg/m<sup>3</sup>. Excessive fractures were prevented by using lower specific charge rates in limonite-rich regions.

In line with the fragmentation analyses obtained after blasting, it was observed that the ore gained a more homogeneous structure by reducing the large block ratios. In addition, post-blasting recovery processes were optimized in order to prevent ore losses.

#### *K. Optimization Suggestions and Alternative Strategies*

Within the scope of blasting strategies applied in Karaçat Mine Site, continuous improvement and optimization studies are required. In this direction, the suggested optimization strategies are as follows:

- Regularly performing geotechnical analyses and updating blasting parameters according to rock strength parameters,
- Revising hole patterns in accordance with formation structure,
- Optimizing delayed blasting times in accordance with field conditions,
- Preventing unnecessary energy use by meticulously determining specific charge amounts.

In this case study, blasting techniques, field data and optimization processes applied in Karaçat Underground Iron Mine were evaluated. As a result, harmonizing blasting parameters with the geological structure provided significant improvements in efficiency and ore recovery.

### **V. CONCLUSION AND RECOMMENDATIONS**

In this study, blasting strategies and optimization processes applied in Karaçat Underground Iron Mine were examined in detail. In the mine site operated with the intermediate-level caving method, the effects of geological and geotechnical factors on the blasting process were evaluated and optimization studies based on field data were carried out. As a result of the study, various strategies were suggested to increase ore recovery rates, reduce dilution and improve blasting efficiency. As a result of the blasting analyses and field tests carried out in the mine, the following basic findings were obtained:

- By adapting the blasting parameters to the geological structure, ore loss was reduced. Especially in hard rocks rich in hematite, large block formation was minimized by using higher charge amounts.
- Vibration control was achieved with delayed blasting techniques and post-blasting collapse efficiency was increased. This method contributed to reducing environmental impacts and maintaining ground stability.
- Improvement in blasting efficiency was achieved by optimizing specific charge amounts. As a result of the optimization studies, unnecessary energy consumption was prevented and post-blasting fragmentation size distribution was controlled.

Dilution rates were reduced by revising hole patterns and charge designs according to field conditions. By applying more controlled blasts, the mixture of gangue minerals in the ore was minimized.

The biggest challenges encountered during field studies were geotechnical variability, weak rock zones and determination of optimum blasting parameters. In this context, the main difficulties encountered in mining operations and the solutions offered for these are listed below:

- Geotechnical Factors: Fault zones and weak rocks in the mining area have caused uncontrolled collapse and stability problems after blasting. In order to prevent these problems, it is recommended that geotechnical analyses be performed regularly and blasting patterns be revised according to the rock type.

- **Ore Loss and Dilution:** In traditional blasting techniques, the mixing of ore with gangue minerals and the formation of losses reduce mining efficiency. As a result of optimization studies, these rates have been reduced by adjusting hole intervals and loading amounts, and this process needs to be further improved with advanced monitoring techniques in the future.

- **Vibration and Environmental Impacts:** Vibrations and environmental deformations caused by high charging amounts pose a risk, especially for the surrounding structures and working areas. It is possible to reduce these effects with lower delay blasting and anti-vibration optimizations.

This study has revealed important findings on blasting optimization by analyzing the blasting techniques applied in Karaçat Underground Iron Mine with field data. As a result of the optimization process, blasting parameters have been made compatible with the geological structure, efficiency has been increased and environmental impacts have been minimized.

As a result, continuous monitoring of blasting processes and updating them in line with geotechnical data will increase the efficiency of mining operations. In this context, it is recommended to use modeling specific to field conditions and advanced data analysis techniques in the future.

This study provides an important contribution to sustainable mining practices and more comprehensive research should be conducted in the light of field data in the future.

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