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Evaluation of the Amount of Boulder in the Pile as a Result of Blasting

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ABSTRACT

This study investigates the effects of specific charge and discontinuity spacing on boulder formation resulting from bench blasting in a limestone quarry. Ten full-scale blasts were carried out under controlled conditions, during which the amount of explosive per unit volume (specific charge), the average spacing of discontinuities on the blast face, and the total mass of oversized boulders were systematically recorded. Uniaxial compressive strength (UCS) and unit volume weight of the rock were also determined through laboratory testing. The results revealed a strong inverse correlation between specific charge and boulder quantity ($R^2 = 0.75$), indicating that increased energy input significantly reduces the formation of oversized fragments. Conversely, discontinuity spacing alone exhibited a weak correlation ($R^2 = 0.12$), suggesting that spacing without consideration of orientation and persistence is not a reliable predictor. When both parameters were evaluated together, the predictive power increased notably ($R^2 = 0.80$), highlighting the importance of their combined influence. The findings offer practical guidance for optimizing blast design to minimize oversize material, improve loading safety, and reduce secondary breakage costs. Maintaining specific charge levels above 0.38–0.40 kg/m³ in similar geological conditions is recommended. Further studies incorporating joint orientation and fracture properties are encouraged.

Keywords: Blasting, boulder, hydraulic breaker

Patlatma Sonucu Oluşan Yığın İçindeki Patar Miktarının Değerlendirilmesi

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ÖZET

u çalışma, bir kalker ocağında yapılan basamak patlatmaları sonucunda oluşan iri blok miktarı üzerinde özgül şarj ve süreksizlik aralığının etkilerini incelemektedir. Kontrollü koşullarda gerçekleştirilen on adet tam ölçekli patlatma kapsamında, birim hacim başına düşen patlayıcı miktarı (özgül şarj), patlatma yüzeyindeki ortalama süreksizlik aralığı ve oluşan iri blokların toplam kütlesi sistematik olarak kaydedilmiştir. Ayrıca kayaçların tek eksenli basınç dayanımı (TEBD) ve birim hacim ağırlığı laboratuvar testleriyle belirlenmiştir. Elde edilen veriler, özgül şarj ile iri blok miktarı arasında güçlü bir ters yönlü ilişki ($R^2 = 0.75$) olduğunu ortaya koymuştur. Diğer yandan, süreksizlik aralığı tek başına zayıf bir ilişki göstermiştir ($R^2 = 0.12$); bu da süreksizliklerin yalnızca aralıklarına bakılarak iri blok oluşumunun güvenilir biçimde tahmin edilemeyeceğini göstermektedir. Her iki parametrenin birlikte değerlendirilmesiyle modelin öngörü gücü belirgin şekilde artmıştır ($R^2 = 0.80$). Sonuçlar, patlatma tasarımında özgül şarjın jeolojik yapı ile birlikte optimize edilmesinin, iri parça oluşumunu azaltmada etkili olduğunu göstermektedir. Benzer jeolojik koşullarda özgül şarj değerinin 0.38–0.40 kg/m³ üzerinde tutulması önerilmektedir. Gelecek çalışmalarda süreksizlik yönelimi ve sürekliliği gibi yapısal faktörlerin de modele dahil edilmesi tavsiye edilmektedir.

Anahtar Kelimeler: Patlatma, patar, hidrolik kırıcı

1. Introduction

Blasting is the backbone of rock breakage in surface mining, road-cut construction, and large-scale civil excavations. In many open-pit mines, as much as 25–30 % of the total operational budget is tied directly or indirectly to blasting quality, because fragmentation controls downstream costs in drilling, loading, hauling, and crushing. When fragmentation is inadequate—particularly when large boulders persist in the muckpile—unit costs soar, cycle times lengthen, and safety risks escalate. Consequently, mine planners spend considerable effort searching for the "sweet spot" where explosive energy, rock mass structure, and desired fragment size are optimally balanced [1].

A central measure in that search is the specific charge, the quantity of explosive (kg) applied per cubic metre of rock. Laboratory studies by Singh and Sarma [1] and Singh and Sastry [2] first demonstrated that the breakage mechanism responds almost linearly to changes in specific charge under controlled conditions. Yet, once a blast moves from the bench-scale laboratory into the inherently variable field environment, its response becomes strongly modulated by geological heterogeneity—most notably the frequency, orientation, and persistence of natural discontinuities. Field engineers therefore face a dual challenge: adjusting controllable drill-and-blast parameters such as hole diameter, burden, spacing, and timing, while simultaneously working within the envelope imposed by uncontrollable site geology.

The significance of geological structure has been affirmed repeatedly. Ash [3] observed that benches drilled perpendicular to prominent joint sets produced a narrower fragmentation curve than benches drilled parallel to those sets. Fourney et al. [4] corroborated that observation in a well-instrumented laboratory programme, finding that fragment sizes in jointed blocks were roughly 1.5 times smaller than in homogeneous specimens under identical charge conditions. Özkahraman and Bilgin [5] later quantified the cost benefit of aligning the blast face parallel to major discontinuity planes: they achieved both reduced specific charge and lower secondary breakage requirements, even when Rock Mass Rating (RMR) values were held constant. Subsequent field trials in sedimentary sequences by Lande [6] and in Turkish limestone operations by Bilgin et al. [7] echoed these findings, underlining the universality of structural control across differing lithologies.

Although empirical experience now leaves little doubt that structure matters, the way in which structural variables interact with specific charge is less clear. Many published case studies focus on one factor at a time varying explosive content while assuming the geology is constant, or documenting joint orientation while keeping powder factors unchanged. Large-scale factorial experiments that treat specific charge, discontinuity spacing, and intact rock strength as concurrent variables remain scarce, largely because they are expensive and disruptive to production [8]. Numerical models, including discrete-element and hybrid continuum approaches, have offered valuable insight into crack coalescence and burden relief [9], yet they still rely on field data for calibration.

The practical manifestation of poor charge–structure matching is the generation of oversized fragments, colloquially called boulders or patar in Turkish quarries. Boulders stall the production chain in two ways. First, they clog primary crushers, requiring downtime for hydraulic hammering or secondary blasting; second, they create unstable working surfaces that jeopardise the safety of shovel and loader operators. Accident statistics from several European quarries attribute up to 17 % of lost-time injuries during loading to lose boulders rolling unexpectedly [10]. From an energy standpoint, every kilogram of ANFO spent breaking a rock mass that later has to be re-broken with a breaker represents double expenditure and needless environmental burden through excess NOx and CO emissions [11].

Several authors have pursued correlations between specific charge and fragment size distribution. Pekin [11] reported an inverse, almost exponential relationship: once the powder factor dipped below roughly 0.30 kg m^{-3} in a medium-strength limestone, the proportion of +1 m³ fragments rose sharply. Topal et al. [12] observed a similar threshold in a granite quarry but cautioned that their conclusions did not account for discontinuity spacing, which, if unfavourable, might necessitate a higher base charge to achieve the same fragmentation target. Gupta and Adhikari [13] provided one of the rare side-by-side comparisons in different lithologies—limestone and dolomite—and inferred that specific charge thresholds for acceptable fragmentation could vary by up to 40 % between lithologies with different joint densities.

Recent advances in detonation physics and electronic delay systems have introduced additional, subtler levers for fragmentation control: micro-second timing windows, air-decking, and energy partitioning through emulsion blends each promise efficiency gains. Yet the fundamental triad of specific charge, discontinuity geometry, and rock strength continues to set the baseline for any optimisation effort. Improvements in one parameter can be nullified if another is neglected. For example, increasing specific charge without considering joint orientation may simply create wider radial cracks that terminate at persistent bedding planes, leaving large, plate-like boulders intact [14].

Against this backdrop, the present study seeks to fill a recognised gap in the open-pit blasting literature. Ten full-scale production blasts were executed in a limestone quarry, each under carefully monitored conditions. For every shot, the following were recorded:

- the specific charge (powder factor) applied,
- the average discontinuity spacing measured on the blast face,
- the uniaxial compressive strength (UCS) of intact core specimens, and
- the mass of oversize (+1 m³) material segregated from the muckpile before primary loading.

By treating these variables as a coupled system rather than isolated factors, this study aims to clarify (i) how far increases in specific charge can compensate for unfavourable discontinuity spacing, and (ii) whether a combined parameter—such as the ratio of specific charge to joint spacing—serves as a better predictor of boulder formation than either variable alone. Statistical inferences are drawn through multiple regression and heteroscedasticity-robust metrics following the approach suggested by Jochmans [15].

Importantly, the study was motivated not merely by cost considerations but also by evolving safety regulations and sustainability goals. The European Union Directive 2006/21/EC requires quarries to minimise extractive waste and energy consumption; oversized fragments contravene both aims by necessitating re-handling and consuming extra fuel in hydraulic breakers. National safety guidelines in Turkey similarly highlight the hazard posed by unstable boulders on muckpiles and mandate risk assessments when boulder ratios exceed 5 % by volume [16].

The paper is organised as follows. Section 2 describes the field site, the drilling-and-blasting design parameters, and the laboratory methods used for UCS determination and density measurement. Section 3 presents the raw data set and outlines the statistical treatment employed. Section 4 discusses the influence of each variable—alone and in combination—on boulder generation, with particular emphasis on threshold behaviours. Section 5 synthesises the implications for blast design and quarry management, offering practical guidelines for reducing oversize. Finally, Section 6 formulates conclusions and proposes directions for future research, including the potential integration of photogrammetric fragmentation analysis and machine-learning predictive models.

By contextualising the interaction between specific charge, discontinuity spacing, and intact rock strength within a single, coherent field study, this work aspires to advance both the science and the practice of surface-mine blasting. The findings should prove especially valuable for operations where geotechnical variability is high but experimentation time is limited conditions typical of small-to-medium quarries across the Mediterranean basin and beyond.

2. Field and Laboratory Studies

This section outlines the methodology used to obtain, quantify, and standardize the input variables considered in the analysis. All measurements were performed on-site under operational conditions in an active limestone quarry in western Türkiye. The experimental design included both field and laboratory procedures aimed at minimizing external variability and maximizing the accuracy of the results.

The study was conducted on a production bench within a limestone quarry that predominantly exposes medium-bedded calcarenite. Two primary discontinuity sets were observed at the site: subvertical joints striking approximately N30°E with 0.3–0.7 m spacing and low persistence, and bedding planes dipping 4°–8° into the bench with wider spacing (0.4–1.0 m) and greater persistence. The bench geometry was nearly consistent across the tests, allowing for comparative assessment. Average bench thickness (B), hole spacing (S), borehole diameter (D), and bench height (H) were measured directly on-site with measuring tapes and verified by blast design records.

Ten individual blasts were conducted over the course of the field study. The drilling was carried out using a down-the-hole (DTH) hydraulic drill rig with 89 mm drill bits. Boreholes were completed vertically without inclination. Deviation was checked in a pilot phase using a gyroscope-based survey tool, which confirmed alignment within a 1.4° tolerance.

For each blast, explosive charging followed a consistent protocol. ANFO was used as the main column charge and nitroglycerin-based dynamite cartridges served as primers. Each hole was stemmed with crushed limestone to approximately 15% of the total borehole length. The explosive charge per hole (Q_e) was calculated based on the type and density of the explosives used. Electronic detonators were applied with downhole-to-surface delays of 17 milliseconds.

To determine the specific charge (q), the total weight of explosive consumed was divided by the estimated volume of blasted rock. The latter was obtained by dividing the total muckpile weight, measured on a calibrated truck scale, by the unit volume weight (γ) of the rock, which was determined in the laboratory. The specific charge values for the ten tests ranged between 0.287 and 0.466 kg/m³.

Discontinuity spacing was measured directly on the blast surface using five horizontal tape-line scans, spaced 1 meter apart vertically. Each scan recorded the number of discontinuity intersections and the total scan length, from which the average spacing was calculated for each blast. Visual inspections ensured that fractures were natural and persistent, not blast-induced cracks.

Post-blast, the muckpile was inspected and monitored throughout the loading process. Boulder fragments (defined as rock blocks exceeding approximately 1 m³ in volume) were visually identified, separated, and stockpiled aside. Once the muckpile had been fully processed, the total boulder mass for each blast was measured using the quarry's truck scale. Monitoring periods ranged from 10 to 48 hours depending on the blast size and operational schedule. One representative image of the muckpile is shown in Figure 1 (not displayed here), illustrating the spatial distribution of boulders relative to finer fragments.

In parallel, laboratory tests were conducted on core samples obtained from drilling residues. For each blast, two representative locations were sampled and core-drilled to NX size (54 mm diameter). The samples were prepared according to ISRM Suggested Methods, including grinding the end faces flat and parallel. Each core was measured for unit volume weight using precise caliper and balance measurements. Uniaxial compressive strength (UCS) tests were then performed under axial load application at a rate of 0.5 MPa per second using a servo-hydraulic press with 2000 kN capacity. Three specimens were tested per blast, and mean values were calculated. The UCS results exhibited low variability, with standard deviations within ±2 MPa.

Fig 1. Visual representation of the amount of boulders formed in the muckpile

All field and laboratory data are summarized in the following two tables. Table 1 lists the controllable blast parameters, and Table 2 shows the calculated and measured variables used in the evaluation.

Table 1. Measured Controllable Parameters of the Blasting Experiments

Test No	Hole count/row	B (m)	S (m)	D (mm)	H (m)	Qe (kg)
1	6/2	3.23	2.93	89	12.35	54.79
2	7/2	2.56	2.96	89	12.00	36.34
3	20/2	2.96	2.92	89	12.60	46.88
4	18/2	2.84	2.68	89	11.80	42.29
5	4/1	2.83	2.57	89	11.70	43.63
6	7/2	2.68	2.79	89	12.00	43.48
7	18/2	3.00	2.70	89	12.00	42.29
8	6/2	2.65	2.69	89	12.00	38.13
9	7/2	2.79	3.14	89	12.20	47.05
10	7/2	3.16	2.64	89	11.90	47.05

Blast No	Specific charge (kg/m³)	Discontinuity spacing (cm)	Total boulder mass (ton)	Avg. unit volume weight (g/cm³)	Avg. UCS (MPa)
1	0.372	35.00	0.0	2.64 ± 0.004	20.33 ± 2.07
2	0.287	39.72	300.0	2.63 ± 0.005	20.42 ± 1.85
3	0.318	51.90	245.0	2.65 ± 0.003	20.11 ± 1.96
4	0.406	48.43	25.0	2.63 ± 0.004	20.76 ± 2.12
5	0.466	47.89	17.0	2.64 ± 0.004	20.67 ± 1.98
6	0.387	38.60	15.0	2.63 ± 0.005	20.18 ± 1.83
7	0.344	49.53	190.0	2.65 ± 0.004	20.28 ± 2.05
8	0.362	37.62	60.0	2.63 ± 0.004	20.57 ± 1.94
9	0.329	44.78	200.0	2.64 ± 0.003	20.32 ± 2.01
10	0.379	47.06	60.0	2.65 ± 0.004	20.49 ± 2.08

B = Average bench thickness (m)
S = Average hole spacing (m)
D = Borehole diameter (mm)
H = Bench height (m)
Qe = Explosive charge per hole (kg)

This comprehensive set of field and laboratory data serves as the basis for the correlation and regression analysis presented in the next section. It reflects real-world conditions while maintaining consistency in measurement and methodology.

3. Results and Discussion

This section presents the statistical evaluation of the relationship between the quantity of oversized boulders formed in the muckpile and two primary blast design parameters: specific charge (q) and discontinuity spacing (Sd). Additionally, a combined regression model was developed to examine the interaction of both variables. The main findings are discussed below and summarized in Table 3.

A linear regression between specific charge and boulder quantity yielded a coefficient of determination (R^2) of 0.75, indicating a strong inverse relationship. In general, blasts executed with higher specific charge values produced significantly fewer oversized fragments. For instance, Blast 5, which utilized the highest specific charge (0.466 kg/m³), resulted in only 17 tons of boulders, whereas Blast 2, with the lowest charge (0.287 kg/m³), produced 300 tons—the highest in the entire dataset. This

suggests that energy input per unit rock volume plays a decisive role in achieving proper fragmentation, particularly in medium-strength limestone.

This finding aligns with prior studies that identified a critical threshold for powder factor, below which fragmentation efficiency drops sharply (Pekin, 2010). However, unlike earlier research that focused solely on charge geometry or hole configurations, the present study incorporates geological structure into the evaluation, offering a more realistic field-based interpretation.

When discontinuity spacing was evaluated independently as a predictor of boulder formation, the regression model produced a low R^2 of 0.12. This weak correlation indicates that discontinuity spacing alone is insufficient to explain the variation in boulder volume across different blasts. Although it is commonly believed that densely jointed rock masses enhance fragmentation due to increased natural break planes, this outcome suggests that spacing without orientation, persistence, and continuity data is not a reliable indicator. These results echo previous field observations where discontinuity parameters showed variable influence depending on geological complexity and blasting direction [14]

To account for interaction effects, a multiple linear regression model was constructed using both specific charge and discontinuity spacing as independent variables. This combined model improved the predictive capability, with an R^2 of 0.80. This finding suggests that specific charge and discontinuity spacing exhibit synergistic behavior—meaning their combined influence is greater than the sum of their individual effects. In practical terms, fragmentation improves most effectively when adequate energy is applied in the context of favorable rock mass structure.

A three-dimensional surface plot (Figure 2, to be inserted) illustrates this interaction. The lowest boulder volumes appear in regions where specific charge exceeds 0.40 kg/m³ and discontinuity spacing lies in the moderate range (40–45 cm). Outside of this range—particularly when both energy input is low and discontinuities are widely spaced—boulder formation increases markedly.

The field data suggest a potential operational optimization window: to maintain boulder formation below 60 tons per blast, the specific charge should be maintained above approximately 0.38 kg/m³, particularly in limestone with average UCS values around 20 MPa and unit volume weights near 2.64 g/cm³. These results provide a valuable basis for empirical blast design charts that account for both energy and structural parameters.

From a cost-benefit perspective, the results carry practical implications. Oversized boulders require additional handling, typically through hydraulic breaking or secondary blasting. In the studied quarry, the cost of processing boulders was estimated at €0.35–€0.45 per ton, with delays in loading and increased wear on equipment. By reducing boulder mass from 300 to under 60 tons through optimized specific charge application, the cost savings per blast can exceed €500, depending on operational scale [17]. Furthermore, reduction in boulder volume improves equipment cycle times and reduces safety hazards during muckpile loading, particularly for loader operators who work close to unstable rock masses.

It is also important to consider environmental factors. Reducing the need for re-breaking operations decreases fuel consumption, lowers greenhouse gas emissions, and supports regulatory compliance under extractive waste and emissions standards such as EU Directive 2006/21/EC [18]. These indirect benefits add further value to the design optimization achieved through empirical analysis.

One limitation of the current analysis is the lack of orientation and persistence data for discontinuities, which are known to significantly influence blast performance. Although spacing was measured precisely, future studies should include stereographic projection and scanline mapping to capture full 3D characteristics of the discontinuity network [19]. Additionally, modeling techniques such as Discrete Fracture Network (DFN) simulations or 3D photogrammetric fragmentation analysis could complement field observations and offer more robust predictive capability.

In conclusion, the results of this study confirm that oversized boulder formation in bench blasting is strongly influenced by specific charge and, to a lesser extent, by discontinuity spacing. However, it is the interaction of these variables, rather than their isolated values, that offers the most reliable control over fragmentation outcomes. These findings support a more integrated approach to

blast design, where geological, mechanical, and energetic factors are considered collectively rather than independently.

Table 3. Regression Analysis Results (R^2 Values)

Regression Model	R^2 Value
Boulder quantity vs. Specific charge	0.75
Boulder quantity vs. Discontinuity spacing	0.12
Boulder quantity vs. Specific charge + Discontinuity spacing	0.80

4. Conclusions

This study investigated the relationship between boulder formation and two key parameters—specific charge and discontinuity spacing—based on ten full-scale blasting experiments conducted in a limestone quarry. For each blast, the specific charge (kg/m³), measured discontinuity spacing on the blast face, and the total boulder mass produced were systematically recorded. In addition, uniaxial compressive strength and unit volume weight were determined through laboratory testing of core samples.

The experimental results demonstrated a clear inverse relationship between specific charge and boulder volume. As the amount of explosive energy per unit volume increased, the occurrence of oversized fragments in the muckpile significantly decreased. The highest specific charge value, 0.466 kg/m³ (Blast 5), resulted in the lowest boulder mass (17 tons), whereas the lowest charge, 0.287 kg/m³ (Blast 2), corresponded to the highest boulder mass (300 tons). These observations reinforce the critical role of charge design in achieving efficient rock fragmentation.

While discontinuity spacing alone showed weak correlation with boulder formation, its combined effect with specific charge yielded a stronger predictive model. A multiple linear regression analysis produced an R^2 value of 0.80 when both variables were considered together, highlighting their synergistic interaction. This suggests that optimizing specific charge in the context of rock mass structure is more effective than adjusting either variable in isolation.

From a practical standpoint, the findings support a more integrated approach to blast design. Quarry operators are encouraged to maintain specific charge levels above 0.38–0.40 kg/m³ in similar geological settings to minimize oversized material and reduce secondary breakage requirements. In addition to lowering operational costs, this approach enhances safety conditions during muckpile loading and contributes to environmental sustainability by decreasing energy consumption and equipment wear.

Future research could focus on expanding the parameter set to include joint orientation, persistence, and fracture roughness, which are also known to affect blast outcomes. Advanced tools such as 3D photogrammetry, point-cloud analysis, and discrete fracture network modeling may further improve the prediction and control of boulder formation in complex rock masses.

In summary, this study confirms that proper balancing of explosive energy and geological structure is essential for minimizing oversized fragmentation. The results offer actionable insight for field engineers and quarry managers aiming to improve blasting efficiency and occupational safety in limestone operations.

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