MINING ENGINEERING

Optimization of Controlled Rock Blasting for Major Infrastructure Projects in Saudi Arabia: Safety, Productivity and Environmental Considerations

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Abstract

Controlled rock blasting is an important technique for excavation and construction of major infrastructure projects where competent rock formations make conventional mechanical excavation inefficient or impractical. However, blasting introduces safety, environmental, operational and project-management risks, including fly rock, ground vibration, air overpressure, dust, fumes, back-break, incomplete fragmentation, equipment delays and disruption to surrounding construction activities.

This paper proposes an integrated framework for improving controlled rock blasting performance on major infrastructure projects in Saudi Arabia. The framework combines blast planning, geological and geotechnical assessment, drilling quality, blast-design verification, exclusion-zone management, service-location verification, safety coordination, monitoring, post-blast assessment and project-control procedures. Particular attention is given to the relationship between blast quality and downstream construction productivity.

The study is informed by professional experience in major Saudi infrastructure construction and blasting coordination and is designed as an applied engineering research framework rather than a claim of experimentally measured results. Existing research demonstrates that blasting performance must be evaluated not only through fragmentation but also through environmental effects such as fly rock, ground vibration and air overpressure.

The proposed framework seeks to reduce avoidable blast cancellations, improve first-time blast execution, enhance safety assurance, minimize environmental disturbance and improve the predictability of excavation activities. The approach is particularly relevant to Saudi Arabia's rapidly expanding infrastructure programme and Vision 2030's objectives concerning sustainable development, resource efficiency and environmental protection.

Keywords: controlled blasting; rock excavation; blasting safety; fly rock; ground vibration; air overpressure; infrastructure construction; Saudi Arabia; project controls; sustainability; Vision 2030

1 Introduction

Saudi Arabia is experiencing extensive infrastructure development associated with economic diversification, urban development, tourism, energy, transportation and other national development programmes. Major infrastructure projects frequently encounter difficult geological conditions requiring substantial rock excavation.

Where competent rock is encountered, drilling and blasting can provide an effective excavation method. Nevertheless, blasting is not simply an excavation activity. It is an integrated engineering operation involving geological assessment, survey, drilling, blast design, explosives management, safety planning, stakeholder coordination, environmental monitoring and post-blast evaluation.

The effectiveness of a blast therefore depends on more than the amount of rock broken. A successful blast should achieve an acceptable combination of:

1. required rock fragmentation;
2. controlled displacement;
3. acceptable excavation geometry;
4. minimum fly rock risk;
5. controlled ground vibration;
6. controlled air overpressure;
7. minimum damage to remaining rock;
8. safe execution;
9. minimal disruption to surrounding activities; and
10. predictable downstream excavation productivity.

Published research identifies ground vibration, fly rock and air overpressure as important undesirable consequences of blasting.

Consequently, a major infrastructure project requires a systematic method of connecting blast design with construction planning and project controls.

1.1 Research problem

One of the recurring challenges in large construction projects is the occurrence of unsuccessful, postponed or cancelled blasting operations.

A blasting operation may be technically ready from the perspective of drilling and explosives but still fail to proceed because of:

- incomplete drilling;
- inaccurate drilling locations;
- unexpected geological conditions;
- unidentified underground services;
- inadequate exclusion-zone arrangements;
- unavailable security or police support where required;
- unsuitable weather conditions;
- communication failures;
- incomplete documentation;
- changes to excavation requirements;
- safety non-conformances;
- insufficient blast materials;
- equipment availability problems;
- access restrictions; or
- conflicts with other construction activities.

Repeated cancellations create more than a local operational inconvenience. They can affect excavation productivity, equipment utilization, manpower planning, material movement, subcontractor performance and overall project schedule.

The research problem addressed by this paper is therefore:

How can controlled rock blasting be integrated with safety, environmental management and project controls to improve the reliability and productivity of major infrastructure construction projects in Saudi Arabia?

1.2 Aim of the study

The principal aim is to develop an integrated framework for controlled rock blasting that improves:

- safety;
- blast reliability;
- rock fragmentation;
- environmental performance;
- coordination;
- productivity;
- schedule predictability; and
- risk management.

The framework is intended for major infrastructure construction projects rather than mining operations alone.

1.3 Research objectives

The objectives are:

1. Identify the principal technical, safety, environmental and coordination factors affecting controlled blasting.
2. Examine the relationship between blast preparation and successful first-time execution.
3. Develop a systematic pre-blast verification process.
4. Develop a post-blast assessment methodology covering fragmentation, overbreak, vibration, fly rock and other relevant outcomes.
5. Develop a project-control framework for recording and analysing blasting cancellations and delays.
6. Identify opportunities for reducing environmental impacts associated with blasting.
7. Demonstrate how improved blasting management can contribute to sustainable infrastructure delivery in Saudi Arabia.

1.4 Research questions

The research addresses the following questions:

RQ1. What are the principal causes of unsuccessful or cancelled blasting operations on major infrastructure projects?

RQ2. Which pre-blast verification activities have the greatest potential to improve blast reliability?

RQ3. How can blasting performance be measured using both safety and productivity indicators?

RQ4. How can ground vibration, fly rock and air overpressure risks be incorporated into blast planning?

RQ5. How can blasting information be integrated with construction project controls?

RQ6. How can improved blasting practices contribute to Saudi Arabia's sustainability objectives?

2 Literature review

2.1 Rock blasting in construction

Drilling and blasting are widely used for rock excavation in construction and mining. The purpose is to fracture rock sufficiently to permit subsequent excavation, loading, hauling and disposal or reuse.

Research indicates that fragmentation is affected by both controllable and uncontrollable factors. Controllable factors include blast geometry and explosive parameters, while rock-mass characteristics are substantially influenced by geological conditions.

This distinction is important in construction because a technically appropriate blast design may still produce unexpected results when geological conditions differ from assumptions.

2.2 Fragmentation

Fragmentation is a major indicator of blast performance. Poor fragmentation can increase:

- secondary breaking;
- excavator cycle times;
- loading difficulty;
- haulage inefficiency;
- equipment wear;
- labour requirements; and
- excavation costs.

Research into blast fragmentation has demonstrated the importance of rock properties, blast-pattern parameters and explosive characteristics.

Therefore, fragmentation should be evaluated as part of an integrated construction productivity assessment.

2.3 Fly rock

Fly rock represents one of the principal safety hazards associated with blasting.

It may result from inappropriate burden, geological discontinuities, inadequate stemming, face conditions, blast geometry or other design and execution factors. Research identifies excessive fly rock as a significant cause of blasting accidents and emphasizes the importance of risk evaluation and management.

For infrastructure construction, fly rock risk can be particularly significant where blasting takes place near:

- roads;
- buildings;
- pipelines;
- power infrastructure;

- operating facilities;
- workers;
- communities; and
- environmentally sensitive locations.

2.4 Ground vibration

Ground vibration is another important consequence of blasting.

Published research has examined empirical equations, statistical models, artificial intelligence and numerical approaches for predicting blast-induced vibration.

A construction project should therefore establish appropriate monitoring and acceptance criteria based on the applicable project specifications, regulatory requirements and engineering assessment.

2.5 Air overpressure

Air overpressure can affect people, structures and surrounding operations. It can be influenced by blast configuration, geological conditions, confinement, stemming and atmospheric conditions.

Consequently, blast planning should consider air overpressure together with vibration rather than treating each environmental effect independently.

2.6 Environmental effects

A review of blasting research identifies fly rock, ground vibration, air overpressure and fragmentation among the principal environmental and operational effects requiring consideration.

For Saudi Arabia, environmental management has increasing strategic importance. Saudi Vision 2030 identifies sustainability, environmental protection and more efficient resource use as important national objectives. The 2025 Vision 2030 Annual Report also highlights circular economy and improved resource efficiency.

Controlled blasting can therefore contribute to sustainability by reducing:

- unnecessary rework;
- excessive excavation;
- secondary breaking;
- equipment idling;
- unnecessary haulage;
- material wastage; and
- avoidable project delays.

3 Proposed methodology

3.1 Research design

A mixed-method applied engineering research approach is proposed. The research combines:

1. literature review;
2. professional case-study analysis;

3. blast-performance records;
4. safety observations;
5. cancellation and delay records;
6. environmental monitoring data;
7. post-blast assessments; and
8. structured engineering analysis.

The study should not claim statistical results until the underlying project records have been independently verified.

3.2 Case-study approach

The proposed case study should use an appropriately anonymised Saudi infrastructure project.

Where contractual confidentiality applies, the project should be identified generically, for example:

"A major gas-infrastructure construction project in the mountainous region of western Saudi Arabia."

No confidential drawings, explosive quantities, proprietary blast designs, security arrangements, exact coordinates, restricted site information or confidential project documentation should be included without written authorization.

4 Integrated controlled-blasting framework

The proposed framework consists of eight stages.

4.1 Stage 1 — Geological and site assessment

Before drilling:

- review geological information;
- identify rock type;
- identify discontinuities;
- review previous excavation records;
- conduct appropriate surveys;
- identify sensitive structures;
- identify underground and above-ground services;
- determine access restrictions.

The geological model should be updated when actual excavation conditions differ from design assumptions.

4.2 Stage 2 — Blast design verification

The blast design should be independently checked against:

- excavation geometry;
- geological conditions;
- drilling capability;
- applicable project specifications;

- safety requirements;
- environmental constraints;
- nearby structures;
- exclusion-zone requirements; and
- downstream excavation requirements.

The objective is not simply to maximize fragmentation but to achieve the required excavation result with acceptable risk.

4.3 Stage 3 — Drilling quality control

Drilling is one of the most important controls because blast performance depends on the actual location and condition of blast holes.

Verification should include:

- hole location;
- hole depth;
- inclination;
- spacing;
- burden;
- hole condition;
- obstruction;
- collar condition;
- drilling deviation; and
- completion status.

Incomplete or incorrectly drilled holes should be identified before the blast is authorized.

4.4 Stage 4 — Pre-blast readiness review

A formal blast readiness review should be completed before each blast. The review should verify the items in Table 1.

Table 1. Pre-blast readiness review.

Area	Items to verify
Technical	Blast design approved; Survey completed; Drilling completed; Hole measurements verified; Geological conditions reviewed; Required documentation completed
Safety	Risk assessment approved; Exclusion zone established; Personnel accounted for; Access points controlled; Warning system established; Emergency arrangements confirmed
Services	Underground services verified; Above-ground services reviewed; Interfaces with other contractors checked
Environment	Monitoring requirements confirmed; Sensitive receptors identified; Weather conditions assessed; Dust/fume controls established
Coordination	Construction team informed; Security requirements confirmed; Required external coordination completed; All responsible personnel available

A blast should not proceed if a critical readiness condition remains unresolved.

5 Blast cancellation classification

One of the proposed contributions of this research is a structured cancellation classification system.

Each cancellation should be assigned a primary and secondary cause.

The proposed cancellation categories are listed in Table 2.

Table 2. Proposed blast cancellation categories.

Category	Examples
A — Safety	safety violation; exclusion-zone problem; personnel-control issue; emergency condition
B — Security/external coordination	required authority unavailable; access control problem; external coordination failure
C — Technical	incomplete drilling; unsuitable geology; blast-design revision; equipment failure
D — Services	unidentified service; service-location uncertainty; interface conflict
E — Materials	blasting materials unavailable; logistics problem
F — Weather	heavy rain; lightning; visibility; other conditions affecting safe execution
G — Communication	incorrect information; late notification; communication failure
H — Construction interface	simultaneous work; access conflict; equipment conflict; changed excavation requirements

This classification permits management to distinguish isolated incidents from systemic problems.

6 Proposed key performance indicators

The following KPIs are recommended.

6.1 Blast success rate

$$\text{Blast success rate } (\%) = \frac{\text{Successful blasts}}{\text{Planned blasts}} \times 100 \tag{1}$$

6.2 Cancellation rate

$$\text{Cancellation rate } (\%) = \frac{\text{Cancelled blasts}}{\text{Planned blasts}} \times 100 \tag{2}$$

6.3 First-time execution rate

$$\text{First-time execution rate } (\%) = \frac{\text{Blasts successfully executed as planned}}{\text{Planned blasts}} \times 100 \tag{3}$$

6.4 Average cancellation lead time

Measure the average time between planned blast time and cancellation. This helps identify whether cancellations are being discovered:

- well in advance;
- shortly before blasting; or

- immediately before execution.

Late cancellations generally have greater potential to disrupt project resources.

6.5 Secondary breaking rate

$$\text{Secondary breaking rate} = \frac{\text{Number of areas requiring secondary breaking}}{\text{Total blast areas}} \tag{4}$$

This provides an indicator of blast fragmentation quality.

6.6 Environmental compliance rate

$$\text{Environmental compliance rate (\%)} = \frac{\text{Blasts within applicable monitoring criteria}}{\text{Monitored blasts}} \times 100 \tag{5}$$

Actual criteria must be taken from the applicable project specification, regulation or approved engineering basis.

7 Post-blast assessment

Immediately after a blast, an engineering review should assess:

1. fragmentation;
2. muck pile profile;
3. excavation geometry;
4. overbreak;
5. underbreak;
6. back-break;
7. fly rock;
8. ground vibration;
9. air overpressure;
10. dust/fumes;
11. equipment accessibility; and
12. downstream excavation productivity.

Photographic records, survey information and monitoring data should be retained where permitted.

8 Digital project-control integration

Modern construction projects can integrate blasting information into digital project-control systems.

A proposed digital blast dashboard could contain the indicators in Table 3.

Table 3. Proposed digital blast dashboard.

KPI	Purpose
Planned blasts	Overall workload
Completed blasts	Production
Cancelled blasts	Reliability

KPI	Purpose
Cancellation reason	Root-cause analysis
Drilling completion	Readiness
Safety observations	Risk control
Vibration readings	Environmental control
Fly rock incidents	Safety performance
Secondary breaking	Fragmentation
Excavation volume	Productivity
Delay hours	Schedule impact

The resulting database would allow management to identify trends rather than responding only to individual incidents.

9 Root-cause analysis

When a blast is cancelled, the investigation should use a structured root-cause method. A recommended sequence is: event → immediate cause → contributing cause → system cause → corrective action → preventive action. For example: cancelled blast → incomplete drilling → late identification of drilling deficiency → insufficient pre-blast verification → introduce formal drilling-readiness inspection → track readiness KPI.

This converts repeated operational problems into measurable management improvements.

10 Safety management

Controlled blasting should operate under the applicable Saudi regulations, project requirements, approved method statements, risk assessments and client standards.

Where a project is governed by specific client or authority requirements, the current controlled project documentation and the applicable Saudi standards must be used rather than an outdated or unofficial copy.

The safety management system should address:

- blast design approval;
- explosives control;
- personnel competency;
- exclusion zones;
- warning systems;
- access control;
- communication;
- misfire procedures;
- emergency response;
- post-blast inspection;
- environmental monitoring; and

- incident reporting.

11 Environmental sustainability

The proposed framework treats environmental performance as a core blast-performance indicator rather than an independent compliance activity.

The environmental objectives should include:

- **Reduce vibration:** through appropriate blast planning and monitoring.
- **Reduce fly rock:** through appropriate engineering design, verification and exclusion-zone management.
- **Reduce air overpressure:** through appropriate control of blast conditions and environmental assessment.
- **Reduce dust and fumes:** through appropriate operational controls.
- **Reduce unnecessary excavation:** through controlled excavation geometry.
- **Reduce rework:** through improved first-time blast performance.
- **Improve resource efficiency:** through better fragmentation and downstream excavation productivity.

These objectives are consistent with the broader sustainability direction of Saudi Vision 2030, which emphasizes environmental protection, sustainability and resource efficiency.

12 Proposed conceptual model

The proposed research model is shown in Figure 1.

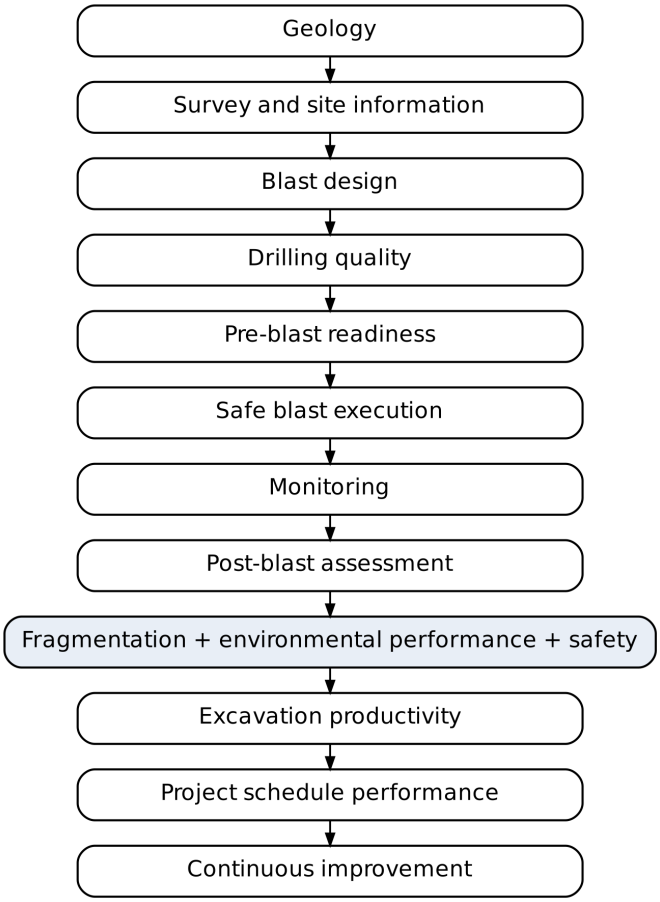


Figure 1. Proposed conceptual model for controlled blasting.

This model demonstrates that blasting should be managed as a complete construction process rather than as an isolated explosive event.

13 Expected research contribution

The principal contribution of the study is an integrated framework linking blasting engineering, safety, environment, construction productivity and project controls.

Traditional blast evaluation may concentrate primarily on fragmentation or technical blast parameters. The proposed framework expands the evaluation to include operational reliability and project-schedule effects.

This is particularly relevant to large infrastructure projects where a cancelled blast can affect multiple construction activities.

14 Practical management framework

A project could implement the following five-level system:

1. **Plan:** Prepare the design and risk assessment.
2. **Verify:** Confirm geology, drilling, services, safety and environmental requirements.
3. **Execute:** Conduct the blast under approved controls.
4. **Measure:** Record fragmentation, vibration, fly rock, delays and productivity.

5. **Improve:** Analyse the data and modify future planning.

This creates a continuous improvement cycle: plan → verify → execute → measure → improve → plan.

15 Data required for empirical validation

To validate the framework empirically, the following data should be collected where disclosure is permitted:

- total planned blasts;
- successful blasts;
- cancelled blasts;
- cancellation dates;
- cancellation reasons;
- drilling completion records;
- blast locations;
- rock type;
- excavation volume;
- vibration measurements;
- air-overpressure measurements;
- fly rock observations;
- secondary-breaking requirements;
- blast duration;
- excavation productivity;
- equipment utilization;
- delay hours; and
- corrective actions.

If confidential project records cannot be published, aggregated and anonymised data may potentially be used subject to contractual and employer approval.

16 Limitations

This paper has several limitations.

First, the proposed framework requires empirical validation using a sufficiently large dataset.

Second, blasting performance is strongly influenced by geological conditions, meaning that findings from one geological environment may not be directly transferable to another.

Third, project-specific safety and regulatory requirements may differ.

Fourth, confidential project information may restrict the level of technical detail that can be publicly disclosed.

Finally, numerical conclusions concerning blast performance should only be presented after verification of the underlying measurements.

17 Future research

Future research should investigate:

1. machine-learning prediction of blast cancellations;
2. predictive modelling of ground vibration;
3. digital blast-readiness dashboards;
4. drone-based post-blast survey analysis;
5. image-based fragmentation analysis;
6. correlation between fragmentation and excavator productivity;
7. automated root-cause analysis;
8. environmental performance benchmarking;
9. integration of blast data with Primavera P6/project controls; and
10. development of a Saudi infrastructure blasting-performance index.

18 Conclusions

Controlled rock blasting is an important component of major infrastructure construction where hard rock excavation is required. Its effectiveness should not be measured solely by whether rock is successfully fractured.

A successful construction blast should simultaneously satisfy engineering, safety, environmental, operational and project-control objectives.

This paper proposes an integrated framework based on planning → verification → controlled execution → monitoring → post-blast assessment → data analysis → continuous improvement.

The framework emphasizes the importance of pre-blast readiness, drilling quality, service verification, safety coordination, environmental monitoring and systematic recording of cancellations and delays.

Research literature demonstrates that fly rock, ground vibration and air overpressure require careful management, while fragmentation quality influences downstream construction performance.

For Saudi Arabia, the approach also provides a practical connection between construction engineering and the wider sustainability objectives of Vision 2030, particularly environmental protection and efficient use of resources.

The proposed framework therefore provides a basis for developing a measurable, data-driven blasting management system for major infrastructure projects.

Declarations

Author contribution: Conceptualization; professional field knowledge; construction-management perspective; blasting coordination perspective; development of the proposed integrated framework; project-control methodology; writing and preparation of the manuscript.

Conflict of interest: The author declares no competing financial interests directly related to this research.

Data availability: Project-specific operational data may be subject to contractual, confidentiality and security restrictions. Where permitted, anonymised and aggregated data will be made available by the author upon reasonable request.

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