ISSN 2071-1859 (Print), ISSN 2521-6635 (Online)
УДК 622.2 https://doi.org/10.33271/crpnmu/82.029

© N. Zuievska[1], V. Berezdetskyi[1], E. Shukurlu[1]
[1]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine

NUMERICAL SIMULATION OF SAND AND FOAM STEMMING FOR IMPROVED ROCK FRAGMENTATION IN GOLD-BEARING QUARTZITES

Н.В. Зуєвська[1], https://orcid.org/0000-0002-1716-1447
В.Ю. Берездецький[1], https://orcid.org/0000-0002-9364-8273
Е. Шукюрлю[1] https://orcid.org/0009-0004-1007-975X
[1]Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ПІЩАНОЇ ТА ПІННОЇ ЗАБИВКИ ДЛЯ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ДРОБЛЕННЯ ЗОЛОТОВМІСНИХ КВАРЦИТІВ

The purpose. To quantitatively assess how the stemming material influences energy confinement and rock fragmentation efficiency in open-pit blasting of gold-bearing quartzites by comparing conventional sand with a compressible foam stemming, using high-fidelity numerical simulation methods.

Methods. A coupled Eulerian–Lagrangian scheme in ANSYS Explicit Dynamics was employed: ANFO detonation and gaseous products were modelled in an Eulerian domain; the quartzite mass and stemming were modelled in a Lagrangian domain. Quartzite behavior was represented with an RHT-type strength and damage model; sand with a granular Drucker–Prager/compaction EOS formulation; foam with a Crushable Foam model capturing pore collapse and volumetric hardening. Identical borehole geometry (Ø110 mm, 5 m depth; 3.3 m charge, 1.7 m stemming), impedance boundaries, and frictional contact were used. Simulations ran for 15 ms.

The results. Foam stemming exhibited slightly lower peak cavity pressure than sand but sustained higher pressure over time, delayed ejection, and produced wider, more uniform stress fields with greater lateral impulse transfer. Sand showed sharper peaks, faster pressure decay, and earlier ejection, concentrating effects along the borehole axis.

Originality. The scientific novelty of the study lies in improving the methodology for analyzing the influence of stemming material on the spatial stress distribution and fragmentation indicators. The proposed methodology makes it possible to assess how the stemming material affects energy confinement in the borehole and to enhance the efficiency of rock fragmentation in open-pit blasting operations. The relationships describing the change in detonation-product pressure over time for a blasthole charge were determined for various stemming materials.

Practical implementation. Results indicate that crushable foam stemming can improve fragmentation uniformity, reduce oversize, and potentially lower specific explosive consumption in hard, anisotropic quartzites. Recommended steps include parametric tuning of foam density/crush strength, mesh-convergence checks, and targeted field trials (pressure gauges, F-curves, sieve analyses) to validate gains and refine design guidelines for stemming length and material selection.

Keywords: *stemming; ANFO, quartzite, foam stemming, sand stemming, ANSYS Explicit Dynamics, Eulerian–Lagrangian, RHT model, blast efficiency, pressure–time history, fragmentation.*

Introduction. In modern mining industry, more than 80% of rock volumes in open-pit mines are broken by drilling-and-blasting operations, the effectiveness of which largely determines the performance of all subsequent mineral extraction and processing stages. Costs for drilling-and-blasting operations amount to approximately 25% of the unit production cost of the blasted rock mass.

Elongated charges of explosive materials are widely used in blasting practice. Their detonation produces complex gas-dynamic processes, as a result of which about 90% of the detonation-wave energy is directed at an angle of 70–80° to the longitudinal axis of the borehole, and only 10% is directed into the surrounding rock mass. Such an energy distribution does not ensure maximal conversion of the wave into work for creating a system of fractures in the borehole walls, which explains the rather low level of useful effect of the explosion [1].

One of the key factors determining the efficiency of charge energy use is the quality of the stemming. It is the stemming that retains the gaseous products of the explosion in the borehole during the first milliseconds after detonation, promoting the development of fractures in the surrounding massif and increasing the degree of fragmentation. Insufficient or poor-quality stemming leads to premature gas escape, energy loss, and an increase in oversized fragments. Conversely, an appropriately selected stemming material and design can significantly improve fragmentation efficiency and reduce explosive consumption.

The detonation of an elongated cylindrical charge in a borehole generates transient processes that depend on the type of explosive, charge design, initiation method, as well as the physico-mechanical properties of the stemming. The process of crack formation in the rock mass between adjacent boreholes is a consequence of the dynamic effect of the explosive load, and the effectiveness of this effect is directly determined by how well the gases are retained by the stemming [2].

Mathematical modelling of these processes reduces to a gas-dynamic problem: determining the distributions of pressure and velocity of the gaseous explosion products in the charge cavity and calculating the impulse of the wave along the inner surface of the borehole. This requires consideration of two interrelated problems: the motion of the gaseous explosion products in the charge cavity and the motion of the rock mass under the action of the explosive load [3, 4].

It is important to account for the coupled motion of both media – the explosion gases and the rock mass – since this coupling governs the development of throughgoing fractures between adjacent charges.

Thus, the study of the effect of stemming on the efficiency of explosive breakage is an exceedingly relevant task. The application of computer modelling makes it possible to analyze these processes in detail, assess stemming quality, and select optimal materials and design solutions to increase the efficiency of drilling-and-blasting operations.

The optimization of stemming parameters represents one of the most effective approaches to enhancing the efficiency of blasting operations in hard rock mining, particularly in the extraction of gold-bearing quartzites. Reliable stemming ensures controlled utilization of the explosive energy, directly influencing the quality of rock fragmentation and the overall performance of subsequent mineral processing stages.

Extensive theoretical and experimental research [5, 6] has demonstrated that the efficiency of elongated borehole or blast-hole charges in hard, heterogeneous rock masses is significantly determined by the physical and mechanical characteristics of the stemming. Its primary function is to securely confine the explosion products during the period of secondary detonation decomposition reactions, ensuring the effective conversion of expanding gas energy into mechanical work. This process enables the fracturing and displacement of the quartzite mass while minimizing energy losses.

In the context of gold-bearing quartzites, the role of stemming is particularly critical due to the high compressive strength, fracture anisotropy, and variable structural properties of these rocks. Optimal stemming not only improves fragmentation control but also prevents excessive production of fines, which can negatively affect downstream processes and reduce gold recovery rates. Moreover, it mitigates premature gas escape from the borehole, which could otherwise result in incomplete detonation, increased toxicity of post-blast gases, uncontrolled ejection of rock fragments, and intensified air shock waves.

Recent studies in this field [7] emphasize that achieving high blasting efficiency in gold-bearing quartzites requires an integrated approach, considering not only the geometry and charge parameters but also the selection and optimization of stemming materials. Key factors include their granulometric composition, density, moisture resistance, and ability to maintain structural integrity under dynamic loading. Enhancing these parameters ensures more efficient energy utilization, controlled rock breakage, and reduced environmental impact, ultimately improving both the technical and economic performance of mining operations.

Description of the object of research. The efficiency of blasting operations is significantly influenced by the choice and design of stemming material. Stemming must ensure both processability and delayed deformation under the action of expanding detonation gases, thereby prolonging the confinement of explosion products within the borehole. In mining practice, clay–sand mixtures are frequently used due to their plasticity and strong adhesion to borehole walls during deformation.

From the perspective of detonation wave interaction, the process begins with the propagation of a shock wave through the stemming body to its upper face, followed by the formation of a reflected rarefaction wave, which weakens the structural integrity of the stemming. This is succeeded by material deformation, radial expansion, and an increase in frictional resistance along the borehole walls, enhancing the confinement effect.

This study included an evaluation of common stemming types, such as sand, which is the most widely used in practice. Based on the geological and operational conditions at the Tulallar site, an improved stemming material was proposed, namely the use of a specific foam stemming composition to enhance blast efficiency.

Research method. ANSYS Explicit Dynamics is specifically designed to handle complex, nonlinear, high-speed events, such as explosive loading of solid media. This tool has been recognized globally as one of the most effective numerical modeling platforms for simulating explosive rock breakage [8].

The modeling of physical and mechanical processes in ANSYS is based on the numerical solution of a system of partial differential equations representing the conservation of mass, momentum, and energy. In addition, material behavior is described through: Equations of state (EOS) – relating stress, strain, and internal energy (or temperature); Strength models – defining material response under external loading (e.g., elastic, plastic deformation); Failure models – determining the initiation and development of fractures; Erosion models – used to handle large mesh distortions in Lagrangian simulations by deleting overstretched elements and redistributing forces to neighboring nodes.

For the accurate simulation of explosive interactions with rock, it is essential to select proper material models. ANSYS provides both built-in and user-defined material libraries. Among the most relevant material models for rock mechanics are:

The RHT model, in particular, is considered the most suitable for simulating the response of rock masses. It predicts failure surfaces based on shock front pressure, elastic and residual strength parameters, and deformation hardening characteristics. The model allows for the accumulation of damage under both tensile and compressive stress states, enabling accurate forecasting of crack density and material fragmentation during explosive loading [9, 10].

As noted in multiple studies [11], the combined use of Eulerian and Lagrangian reference frames in ANSYS Explicit Dynamics provides optimal results when simulating explosions in solid media:

The Eulerian formulation is best suited for modeling explosive detonation, as it enables the material to flow through a fixed mesh and effectively handles large gas flow deformations.

The Lagrangian formulation is preferred for solid rock modeling, where the mesh moves with the material, capturing the deformation and fracturing processes with high fidelity.

In ANSYS, these two solvers can be coupled to ensure accurate energy transfer between detonation gases and the rock mass. This hybrid approach allows for precise simulation of rock breakage under real-world blast conditions.

The computational model simulates the detonation of an explosive charge placed within a borehole in a rock mass. The borehole is assumed to be filled to two-thirds of its length with explosive material and one-third with stemming. The primary objective of this simulation is to evaluate how the material type of stemming influences the efficiency of the explosion in terms of energy confinement and rock breakage.

The rock mass is modeled as quartzite, a typical hard and brittle rock often encountered in blasting operations. The explosive used in the simulation is ANFO (Ammonium Nitrate Fuel Oil), a common bulk industrial explosive.

Two stemming materials are considered for comparison: Case 1: Sand stemming; Case 2: Foam gel stemming.

These two configurations allow for a comparative analysis of gas confinement, stemming displacement, and subsequent energy transfer into the surrounding rock mass.

The material model for ANFO was selected from the standard ANSYS material library (see Fig. 1 for properties). This predefined model includes all necessary parameters for detonation behavior, including detonation velocity, Chapman-Jouguet pressure, and energy release characteristics.

Density	931,00	kg/m³
Other		
Explosive JWL		
Parameter A	4,946e+10	Pa
Parameter B	1,891e+09	Pa
Parameter R1	3,9070	
Parameter R2	1,1180	
Parameter W	0,33333	
Initial Relative Volume, V0	0	
C-J Detonation Velocity	4160,0	m/s
C-J Energy / unit mass	2,668e+06	J/kg
C-J Pressure	5,15e+09	Pa
Burn on compression fraction	0	
Pre-burn bulk modulus	0	Pa
Adiabatic Constant	0	
Additional specific energy / unit mass	0	J/kg
Begin Time	0	s
End Time	0	s

Fig. 1. Material Model Parameters of Explosive Substance “ANFO”

To accurately simulate the behavior of the explosive and its detonation products, the Eulerian solver was applied to the explosive domain. The Eulerian formulation is most appropriate for modeling fluid-like materials such as gaseous detonation products, as it allows the material to move through a fixed computational mesh, accommodating large deformations and shockwave expansion.

The rock mass and stemming materials were modeled using a Lagrangian solver, which tracks mesh deformation with the material and enables detailed analysis of stress, strain, and fracturing in the solid domain.

This dual-solver approach ensures accurate representation of energy transfer from the detonation gases to the surrounding rock and stemming, providing a realistic simulation of explosive-induced fracturing in rock.

The material model for the rock mass represents the physical and mechanical behavior of quartzite, a dense and brittle metamorphic rock.

The following components were employed to accurately simulate the response of quartzite under explosive loading:

RHT Concrete Strength Model. The RHT (Riedel–Hiermaier–Thoma) model is a physically-based strength model designed for brittle materials such as concrete, stone, and rock. It accounts for elastic, plastic, and residual behavior, incorporating cumulative damage mechanisms. The model includes strain rate effects, hydrostatic pressure sensitivity, and fatigue damage from repeated loading cycles.

The RHT (Riedel–Hiermaier–Thoma) Concrete Strength Model. RHT (Riedel–Hiermaier–Thoma) is a *constitutive model for concrete and other brittle geomaterials* (rocks, ceramics, stone). It is used under dynamic loading conditions: explosions, impacts, ballistic penetration, seismic effects. Implemented in ANSYS to simulate material response at high strain rates.

Key features of the model. The RHT model combines: Strength surface – defines elastic–plastic yield depending on stress state. Damage model – accounts for microcrack accumulation, stiffness and strength degradation. Failure surface – describes the complete loss of load-bearing capacity. Porous medium mechanics – distinguishes behavior under compression vs. tension (concrete is strong in compression, weak in tension).

Main equations. Strength surface (simplified form):

$$\left(\frac{\sigma_{eg}}{f_c(p)}\right)^2 + \left(\frac{\sigma_m}{f_t(p)}\right)^2 = 1, \tag{1}$$

where: σ_{eg} – equivalent deviatoric stress, σ_m – mean hydrostatic stress, $f_c(p)$ – compressive strength as a function of pressure p, $f_t(p)$ – tensile strength as a function of pressure p. All stresses and strengths (σ_{eq}, σ_m, $f_c(p), f_t(p)$) are expressed in megapascals (MPa).

Strain-rate effect (dynamic increase factor):

$$\sigma_{dyn} = \sigma_{stat} \cdot \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^k, \tag{2}$$

where: σ_{dyn} – dynamic strength, σ_{stat} – static strength, ε – strain rate, ε_0 – reference strain rate, k – material constant (≈0.02–0.06 for concrete).

Damage evolution:

$$D = \sum \frac{\Delta\varepsilon_p}{\varepsilon_f}, \tag{3}$$

where: D – damage variable ($0 \le D \le 1$), $\Delta\varepsilon_p$ - increment of plastic strain, ε_f – critical fracture strain. When $D = 1$, the material is fully failed.

Quartzite, characterized by its high compressive strength and low tensile strength, fits ideally within the assumptions of the RHT model, which is particularly suited for dynamic loading scenarios like blasting or impact. The model allows for gradual accumulation of damage up to complete failure, enabling accurate reproduction of wave propagation and fracture behavior in rock media.

The Lagrangian solver was chosen for the solid domain (rock mass), as it allows the mesh to deform with the material. This is essential for capturing the full deformation and failure behavior of the quartzite during and after detonation. The solver ensures accurate tracking of stress wave propagation, fracturing, and material displacement under high-strain-rate loading.

Stemming Configuration 1: Sand as a Granular Stemming Material

In the first simulation scenario, sand was used as the stemming material. To model its physical and mechanical behavior under explosive loading, the built-in “SAND” material model from the ANSYS material library was applied, with modifications to the material density to meet the specific requirements of the simulation.

This material model is tailored for granular media subjected to large deformations, compaction, and partial failure under dynamic loading. It combines features of granular plasticity, volumetric compaction, and tensile failure, which enables a realistic simulation of unconsolidated materials under explosive effects.

Key Components of the Sand Material Model: Density: Initial material density was set to 1500 kg/m³, corresponding to a medium-dense dry sand.

Modified Drucker–Prager Model (MO Granular): This model accounts for pressure-dependent plasticity, incorporating the following effects:

Pressure Hardening:

Defined through a tabular relationship between pressure and plastic strain, this component reflects the strengthening of sand under compressive loading.

Density Hardening:

Expressed as a table of ultimate strength versus density, this is essential for capturing the behavior of sand during compaction as pore spaces collapse.

Variable Shear Modulus: The shear modulus changes with density according to a defined table, allowing accurate simulation of the material's stiffness at varying levels of compaction.

Initial Shear Modulus: Set to 7.69×10^{7} Pa, this value defines the stiffness of the sand before plastic deformation begins. It is typical for medium-density dry sands.

Tensile Failure Model: A maximum tensile pressure value of –0.001 Pa is used to define a technical tensile failure threshold. This prevents unrealistic elongation of elements and triggers element erosion when tensile limits are reached.

Compaction Equation of State – Linear (Compaction EOS Linear): This EOS describes how sand responds to volumetric changes under compression. Key parameters include:

Solid Density: 2641 kg/m³ – representing the density of the solid mineral skeleton of the soil without pores.

Compaction Path: A table defining pressure as a function of density, used to simulate the gradual collapse of pores under high pressure.

Linear Unloading: A relationship that defines the speed of sound as a function of density, used for modeling material unloading behavior after the pressure peak.

This combination of physical models provides a detailed representation of sand's compressibility, shear resistance, and failure behavior under the transient loading conditions typical of blasting.

Stemming Configuration 2: Foam as a Compressible Energy-Absorbing Material.

In the second simulation scenario, a foam gel was used as the stemming material. To model the physical and mechanical behavior of this material under dynamic loading, the Crushable Foam material model in ANSYS was selected. This model is specifically designed for porous, energy-absorbing materials such as polymeric foams, porous stemmings, and engineered fillers.

The Crushable Foam model accurately reflects the behavior of compressible materials that exhibit substantial volumetric deformation under pressure while offering minimal resistance in tension. It captures compaction, energy absorption, and pressure-dependent plasticity – making it particularly suitable for materials used to absorb blast energy and delay gas escape from boreholes.

The model includes features such as: Volumetric compression response under pressure; Negligible tensile resistance, leading to realistic fracture under tension;

Pore collapse and densification behavior; The material model assumes a pressure-sensitive yield surface and accounts for volumetric hardening as pores collapse and the foam becomes denser. The model is often applied in applications involving blast mitigation or shock absorption, both of which are highly relevant to stemming dynamics.

The detailed parameters of the foam material used in the simulation are presented in Figure 2.

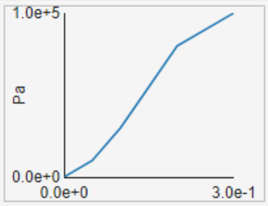
Density	680,00 kg/m³
Structural	
Isotropic Elasticity	
Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	7,5e+05 Pa
Poisson's Ratio	0,20000
Bulk Modulus	4,1667e+05 Pa
Shear Modulus	3,125e+05 Pa
Other	
Crushable Foam	
Maximum Principal Stress Vs Volumetric Strain	
Maximum Tensile Stress	800,00 Pa

Fig. 2. Material Model Parameters for Foam Stemming (Crushable Foam Model)

For the stemming material domain, the Lagrangian solver was selected. This choice allows the mesh to move and deform together with the material, making it especially suitable for simulating the mechanical response of solid or semi-solid materials like sand or foam gel. The Lagrangian approach enables precise tracking of deformation, compaction, and element failure during the explosive loading process, ensuring accurate modeling of stress wave propagation and material interaction within the borehole.

Option 1. The geometry of the rock mass (Fig. 3) in the first model is implemented as a rectangular parallelepiped with a square base measuring 2 meters on each side and a height of 5.3 meters. The borehole geometry is represented as a cylindrical region within the rock mass, with a diameter of 110 mm and a height of 5 meters, extending to the surface of the rock mass. The lower 3.3 meters of the borehole is filled with explosive material (EM), while the upper 1.7 meters, up to the surface, is filled with stemming material.

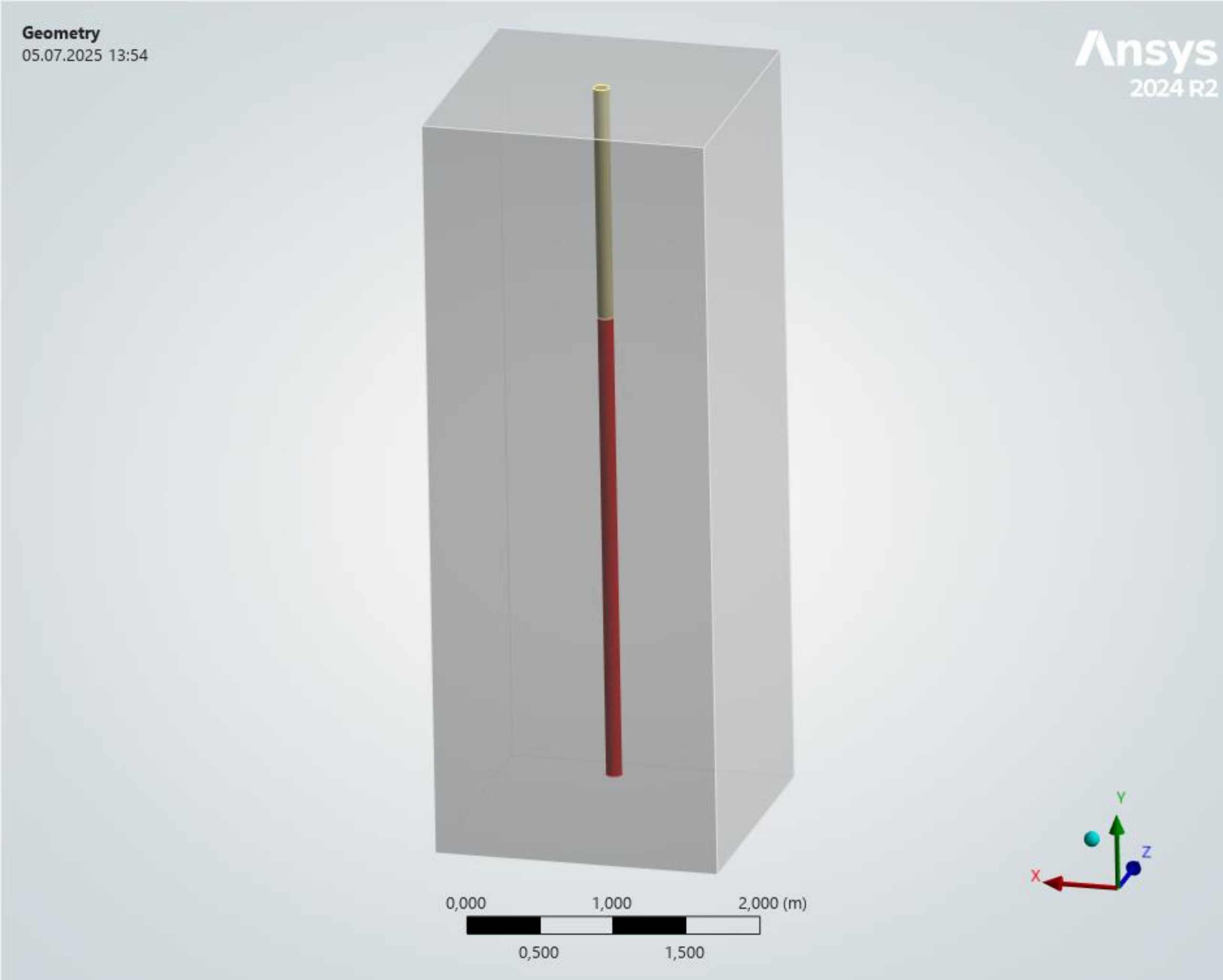


Fig. 3. Geometry of the model

The finite element mesh of the model includes 114,504 nodes and 98,556 elements. The element size is 0.1 m for the rock mass and 0.01 m for the stemming. The Eulerian computational mesh is characterized by an element size of 0.025 m.

To account for the contact interaction between the rock mass and the stemming, a contact group was defined for the contact surfaces between these bodies, with a friction coefficient of 0.55.

Impedance boundaries were selected as the boundary conditions for the lateral and bottom surfaces of the model, as well as for all sides of the Eulerian computational domain. These boundaries help to reduce the effect of reflected waves that occur at the edges of the computational area during the propagation of blast waves.

Impedance boundaries approximate the condition of free wave propagation based on the acoustic impedance of the medium (the product of density and sound velocity), and they allow the transmission of the normal component of velocity with minimal reflection.

In ANSYS, this type of boundary is implemented by accounting for changes in pressure and velocity along the characteristic line departing from the boundary, assuming zero reference values for an initially motionless medium.

Thus, the impact of potential wave reflections at the computational boundaries is minimized, considering the model size and the nature of blast wave propagation.

Option 2. The geometry of the rock mass in the second model is implemented as a rectangular parallelepiped with a square base measuring 2 meters on each side and a height of 5.3 meters. The borehole geometry is represented as a cylindrical region within the rock mass, with a diameter of 110 mm and a height of 5 meters, extending to the surface of the rock mass. The lower 3.3 meters of the borehole is filled with explosive material (EM), while the upper 1.7 meters, up to the surface, is filled with stemming material.

The finite element mesh of the model includes 144,744 nodes and 127,176 elements. The element size is 0.1 m for the rock mass and 0.01 m for the stemming.

The Eulerian computational mesh is characterized by an element size of 0.05 m.

To account for the contact interaction between the rock mass and the stemming, a contact group was defined for the contact surfaces between these bodies, with a friction coefficient of 0.7.

As a result of analyzing the two options – one using sand as stemming and the other using foam – simulation results were obtained. The calculations were carried out over a time interval of 15 milliseconds. Extending the simulation time would significantly increase the computational cost.

The main objective of the analysis was to determine the ejection time of the stemming material and to compare the results for both options.

Total deformation for first option present on the fig. 4, 5.

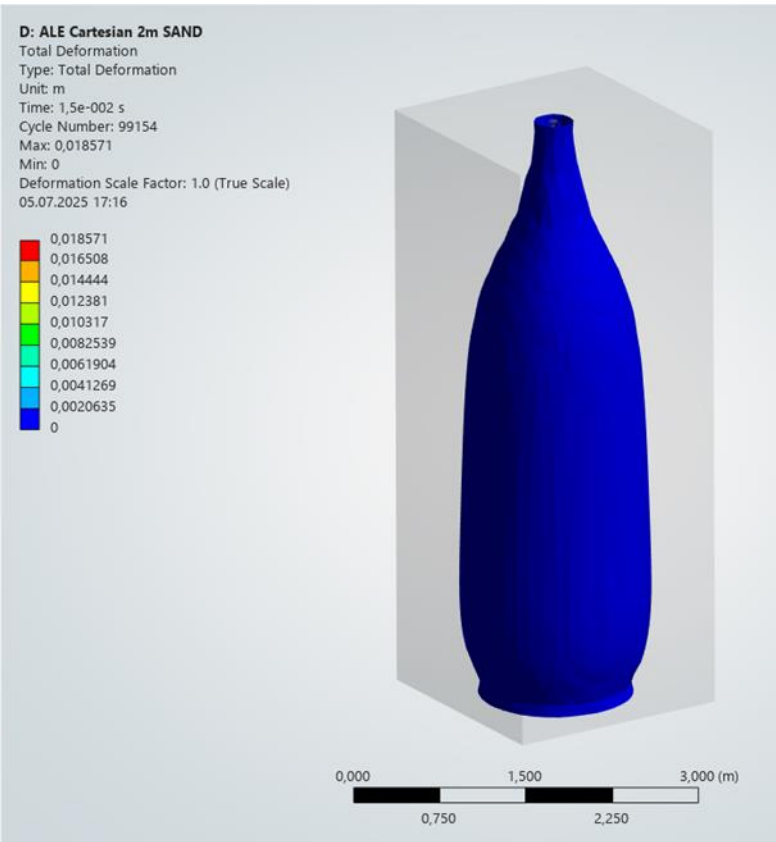


Fig. 4. Element displacement (Deformation) at 15 ms with sand stemming

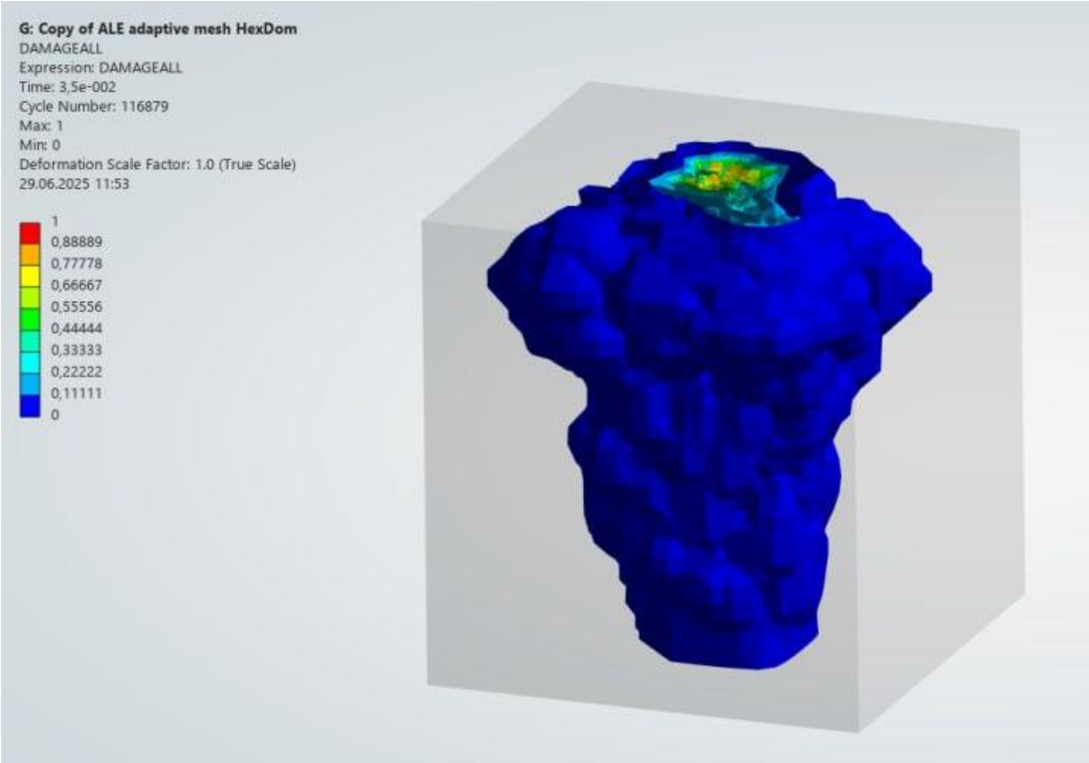


Fig. 5. Element Damage at 35 ms with sand stemming

The simulation results for the model with foam stemming provide valuable insights into the stress distribution characteristics resulting from explosive detonation. Compared to the sand stemming case (Fig.6 a), the foam-based configuration demonstrates several notable advantages (Fig.6 b).

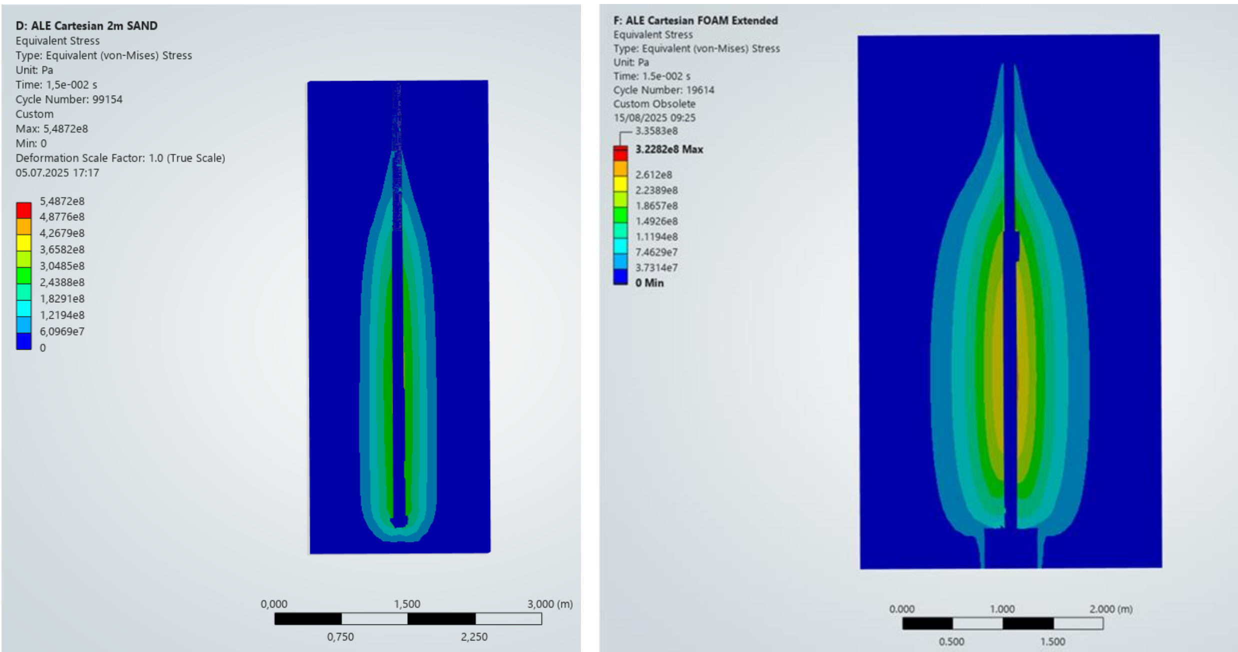


Fig. 6. (a) – Stress zones at 15 ms with sand stemming;
(b) – Stress zones at 15 ms with foam stemming

Stress Distribution Pattern: In contrast to the sand stemming case, the foam stemming model demonstrates a wider affected area. The stress contours form an elliptical shape with a clear radial spread into the surrounding rock mass. This indicates a longer containment of detonation pressure within the borehole, which enables the impulse to be transferred more effectively laterally.

Uniformity of Distribution: The stress zones are not limited to the central borehole axis but instead form a broad, symmetrical front, which is characteristic of a gradual and controlled release of detonation gases through the foam stemming.

Stress Magnitude: Although the maximum stress value in the foam stemming case is lower than in the sand case (3.41×10^8 Pa vs. 5.49×10^8 Pa), the effective area of stress distribution is significantly larger, which may be more beneficial for achieving efficient rock fragmentation.

The explosive impulse is clearly directed upward, indicating the ejection of the stemming (as observed in the pressure–time graph).

The stress propagation is confined along the vertical axis – the blast is mostly concentrated within the borehole column, with limited lateral transmission into the surrounding rock.

Overall, the foam stemming provides a more favorable stress distribution profile, promoting a wider and more uniform energy transfer into the rock mass. This behavior may contribute to improved blasting performance and reduced energy losses compared to traditional sand stemming.

In ANSYS Explicit Dynamics, when the simulation results are presented in terms of equivalent (von Mises) stress, this refers to a scalar value used to represent the intensity of the overall stress state at a point in the material. It is derived from the full stress tensor and provides a single value that can be used to assess whether the material at that point is likely to yield or fail under the given loading conditions.

The von Mises stress is calculated based on the idea that yielding in ductile materials begins when the distortional energy (or energy of shape change) reaches a critical value. This criterion is widely used in engineering because it correlates well with experimental results for metals and other ductile materials.

In the context of explosive simulations, where materials undergo high strain rates and complex loading, von Mises stress helps to: Visualize zones of plastic deformation or potential failure; Compare stress magnitudes across different regions of the model; Interpret material response under extreme loading.

So, when you see "equivalent (von Mises) stress" results in your simulation, you are looking at a simplified but physically meaningful representation of the material's stress state, useful for evaluating structural integrity under dynamic conditions.

In the second option, where foam stemming was used, the ejection of the stemming material began at approximately 1.4 milliseconds, and was completed by around 11.5 milliseconds.

This indicates that the overall ejection duration was slightly longer compared to the sand stemming case, which may be attributed to the lower density and different mechanical properties of the foam, affecting its resistance to detonation gas pressure.

Based on the simulation results illustrated in these figures, a pressure–time graph was generated to visualize and compare the dynamic behavior of detonation products under different stemming conditions fig. 7.

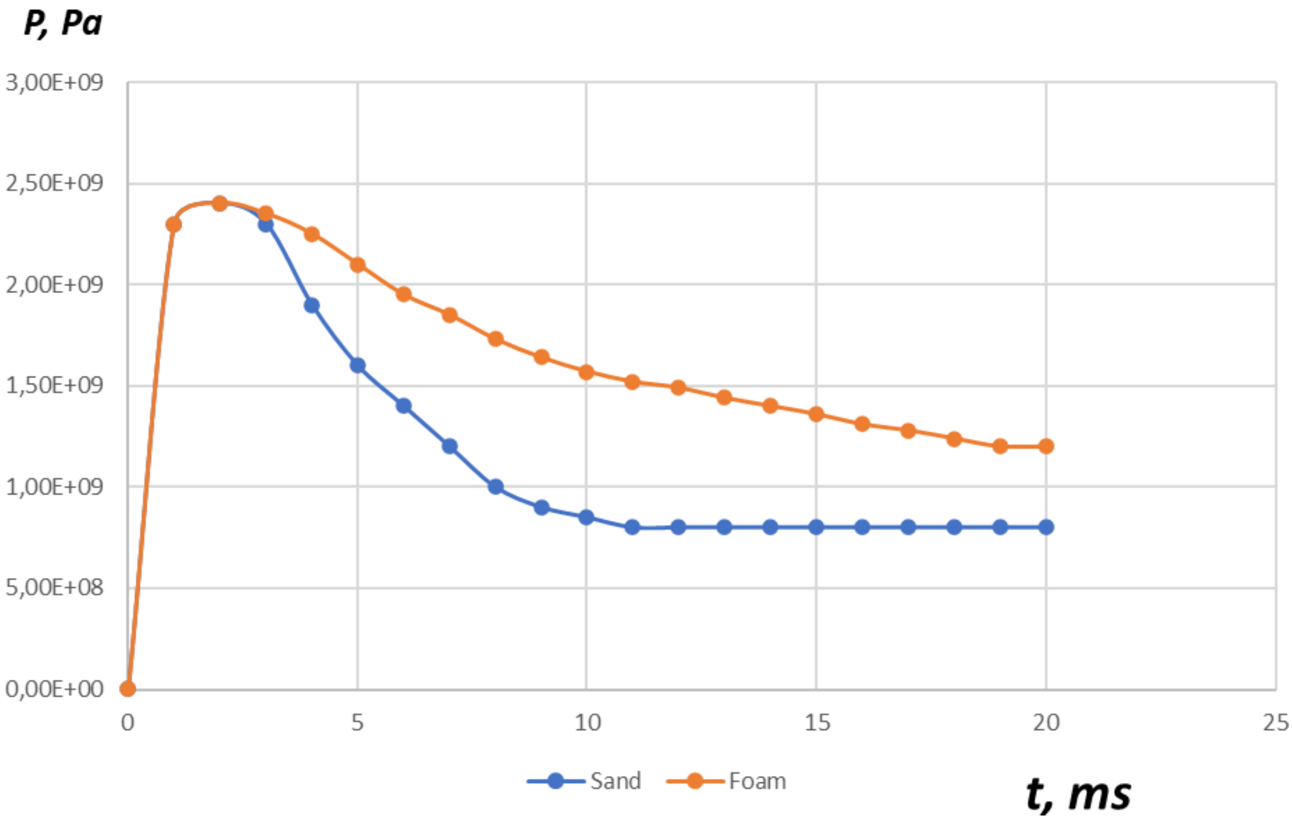


Fig. 7 Change in the detonation products pressure of a borehole charge over time: 1 – with a sand stemming; 2 – with a foam stemming

Results. Pressure Dynamics Analysis. Initial Pressure Peak: Both curves exhibit a sharp rise in pressure during the first few milliseconds – corresponding to the moment of explosive detonation. Maximum Pressure Values: Sand stemming: slightly higher peak (~2.4–2.5×10⁹ Pa), Foam stemming: slightly lower peak (~2.3×10⁹ Pa).

Stabilization Phase: With sand stemming, the pressure drops rapidly after reaching its peak – likely due to the faster ejection of the heavier stemming material, which results in a shorter pressure retention time within the system.

In contrast, with foam stemming, the pressure decreases more gradually and remains at a higher level throughout the simulation period. This suggests a slower release of gases and a less abrupt expansion process.

After 5–6 milliseconds: Both curves enter a phase of gradual pressure decline.

The blue curve (foam stemming) consistently remains above the red curve (sand stemming) until the end of the 15 ms interval, indicating a longer-lasting pressure effect on the rock mass.

Physical Interpretation: Using foam as stemming ensures prolonged retention of detonation pressure, which: Enhances the transmission of impulse into the surrounding rock; Is more effective in scenarios requiring controlled explosive energy release; Reduces the risk of premature stemming ejection and associated energy loss into the atmosphere.

In contrast, sand stemming produces a higher initial pressure spike but degrades and is ejected more quickly, leading to a less stable pressure effect overall.

Conclusion Recommendation: Based on the analysis, it can be concluded that foam stemming provides a more uniform and sustained detonation pressure impact on the rock mass. This characteristic can improve rock fragmentation efficiency when compared to traditional sand stemming, which demonstrates a shorter and less stable pressure profile over time.

Conclusions.

The graph shows that the peak pressure during ANFO detonation occurs in both cases (sand and foam) within the first milliseconds after charge initiation.

When using sand stemming, the pressure rapidly reaches its peak but drops just as quickly, indicating rapid ejection of the stemming and a loss of pressure.

In the foam stemming case, the pressure decreases more gradually after the peak, suggesting more controlled expansion of detonation products and longer pressure retention within the system.

Throughout the entire analysis period (up to 20 ms), the pressure in the foam option remains consistently higher than in the sand option, which may indicate more efficient utilization of the explosive energy for rock fragmentation.

Therefore, using foam stemming ensures a more uniform and prolonged pressure effect on the rock mass, which can be beneficial for improving the effectiveness and quality of blasting operations.

References

1. Shi, X., Zhang, Z., Qiu, X., & Luo, Z. (2023). Experiment study of stemming length and stemming material impact on rock fragmentation and dynamic strain. *Sustainability, 15*(17), 13024. https://doi.org/10.3390/su151713024
2. Baluch, K., Park, H.-J., Kim, J.-G., Ko, Y.-H., & Kim, G. (2024). Enhancing rock blasting efficiency in mining and tunneling: a comparative study of shear-thickening fluid stemming and plug device performance. *Appl. Sci., 14*, 5395. https://doi.org/10.3390/app14135395
3. Zhang, Z.-X., Qiao, Y., Chi, L., & Hou D.-F., (2021). Experimental study of rock fragmentation under different stemming conditions in model blasting, *International Journal of Rock Mechanics and Mining Sciences, 143*, 104797. https://doi.org/10.1016/j.ijrmms.2021.104797
4. Li, X., Liu, K., Sha, Y., Yang, J., & Hong, Z. (2023). Numerical investigation on blast-induced rock fragmentation with different stemming structures. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 9*(1). https://doi.org/10.1007/s40948-023-00654-9
5. Chi, L.Y., Zhang, Z.X., Ylitalo, R.M. Bergström, P., & Haugen S. (2025). Effects of aggregate sizes of stemming on blasting outcomes at the kevitsa mine—a case study. *Mining, Metallurgy & Exploration.* https://doi.org/10.1007/s42461-025-01341-x
6. Sobolevskyi, R., Zuievska, N., Korobiichuk, V., Tolkach, O., Kotenko, V. (2020). Cluster analysis of fracturing in the deposits of decorative stone for the optimization of the process of quality control of block raw material. *Eastern-European Journal of Enterprise Technologies, 5,* 21–29. https://doi.org/10.15587/1729-4061.2016.80652
7. Moomivand, H., Soltanalinejad, S., & Karwansara, A. M. (2025). Assessment of the optimized stemming length considering rock fragmentation and escape of explosive gases using actual large-scale results. *Results in Engineering, 25*, 103575. https://doi.org/10.1016/j.rineng.2024.103575
8. Lanari, M., & Fakhimi, A. (2015). Numerical study of contributions of shock wave and gas penetration toward induced rock damage during blasting. *Computational Particle Mechanics, 2*(2), 197–208. https://doi.org/10.1007/s40571-015-0053-8

9. Baranowski, P., Mazurkiewicz, Ł., Małachowski, J., & Pytlik, M. (2020). Experimental testing and numerical simulations of blast-induced fracture of dolomite rock. *Meccanica, 55*(12), 2337–2352. https://doi.org/10.1007/s11012-020-01223-0
10. Gebretsadik, A., Kumar, R., Fissha, Y., Kide, Y., Okada, N., Ikeda, H., Mishra, A. K., Armaghani, D. J., Ohtomo, Y., & Kawamura, Y. (2024). Enhancing rock fragmentation assessment in mine blasting through machine learning algorithms: a practical approach. *Discover Applied Sciences, 6*(5). https://doi.org/10.1007/s42452-024-05888-0
11. Prasad, S., Choudhary, B. S., & Mishra, A. K. (2017). Effect of Stemming to Burden Ratio and Powder Factor on Blast Induced Rock Fragmentation– A Case Study. *IOP Conference Series: Materials Science and Engineering, 225*, 012191. https://doi.org/10.1088/1757-899X/225/1/012191

АНОТАЦІЯ

Мета. Виконати кількісну оцінку впливу матеріалу забивки на утримання енергії та ефективність дроблення порід при відкритих вибухових роботах у золотовмісних кварцитах, порівнюючи традиційний пісок та стисливий пінний матеріал забивки із застосуванням високоточних чисельних методів моделювання.

Методи. Використано комбіновану схему Ейлера–Лагранжа в ANSYS Explicit Dynamics: детонація ANFO та газоподібні продукти моделювалися в ейлерівській області; масив кварциту та забивка – у лагранжівській. Поведінку кварциту описано моделлю міцності та пошкодження RHT; пісок представлено гранулярною моделлю Друкера–Праґера з рівнянням стану для ущільнення; піну змодельоване за допомогою модуля Crushable Foam, що враховує колапс пор та об'ємне зміцнення. Для обох випадків задано ідентичну геометрію свердловини (Ø110 мм, глибина 5 м; 3,3 м заряду, 1,7 м забивки), встановлені імпедансні граничні умови та контакт з тертям. Тривалість розрахунку становила 15 мс.

Результати. Пінна забивка показала дещо нижчий піковий тиск у порожнині, ніж пісок, але забезпечила довше утримання тиску, відстрочений викид та ширші, рівномірніші поля напружень із більшою передачею імпульсу вбік. Пісок демонстрував різкіші піки, швидше падіння тиску та ранній викид, концентруючи дію переважно вздовж осі свердловини.

Оригінальність. Наукова новизна дослідження полягає в удосконаленні методології аналізу впливу матеріалу забивки на просторовий розподіл напружень з показниками дроблення. Запропонована методологія дає змогу здійснювати оцінку як матеріал забивки впливає на утримання енергії в свердловині та підвищувати ефективність дроблення порід при відкритих вибухових роботах. Встановлені залежності зміни тиску продуктів детонації свердловинного заряду з часом при різних матеріалах забивки.

Практична значимість. Результати свідчать, що пінна забивка здатна підвищити рівномірність дроблення, зменшити кількість негабариту та потенційно знизити питомі витрати вибухових речовин у твердих анізотропних кварцитах. Рекомендовано подальшу оптимізацію щільності та міцності піни, перевірку збіжності сітки й проведення натурних випробувань (датчики тиску, криві F, ситовий аналіз) для підтвердження результатів і розробки практичних рекомендацій щодо вибору матеріалів і довжини забивки.

Ключові слова: *забивка, ANFO, кварцит, пінна забивка, піщана забивка, ANSYS Explicit Dynamics, Ейлер–Лагранж, модель RHT, ефективність вибуху, тиск-час, дроблення порід.*

дата першого надходження статті до видання	02.07.2025
дата прийняття до друку статті після рецензування	03.08.2025
дата публікації (оприлюднення)	04.09.2025