Velocity of Detonation, Rock P-Wave Velocity, and Crater Effect in Blasting

Slavko Torbica, PhD, Owl and Fox – Mining Consultants

Veljko Lapčević, PhD, University of Belgrade – Faculty of Mining and Geology

Date: October 2023

Abstract

This article examines the relationship between the velocity of detonation (VOD) of explosives and the p-wave velocity of rocks. The correlation between these two parameters plays a significant role in the utilization of explosive energy in rock blasting. While there's a general consensus that matching the VOD with the p-wave velocity can lead to favorable blasting results, differences between these velocities are not uncommon in practical applications. Using Huygens' principle as a foundation, the article explores how these differences affect crater formation in rock blasting.

Keywords: blasting; explosives; mining; VOD; p-wave; Huygens principle; crater effect;

1 INTRODUCTION

It is empirically established that the effects of blasting are influenced by the relationship between the explosive's Velocity of Detonation (VOD) and the rock's P-wave velocity. It is observed that when the VOD and P-wave velocity are closely matched, the utilization of explosive energy increases, leading to more efficient and intense rock breakage. The influence of this phenomenon was notably evident in crater blasting effects.

Many blasting applications involve scenarios where the VOD differs from the P-wave velocity of the rock being blasted, with ANFO being a typical example. The literature is deficient in theoretical explanations concerning this phenomenon, which significantly impacts operations globally on a daily basis. Thus, the aim of this research is to shed light on the processes during blasting with various explosives and to emphasize how the results can enhance blasting efficiency. While the entirety of blasting mechanics is intricate and many fundamental principles remain unexplained, our goal with simple models is to lay the groundwork for more advanced research. Blast fragmentation, explosive consumption, and drilling optimization are just a few indicators that could benefit from a deeper understanding of blasting mechanisms, ultimately driving optimal mining production at its foundation.

2 HUYGENS PRINCIPLE AND ROCK BLASTING

Huygens' principle [1] describes wave propagation in a medium, stating that each particle of the medium, such as rock in this context, becomes a source of a wavelet when the primary wave reaches it. The surface that acts as a tangent to all of these waves is termed a wave front, Figure 1.

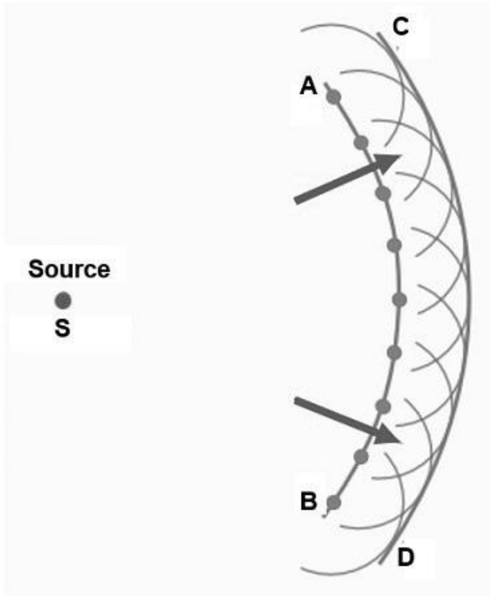

Figure 1 Wave front according to Huygens principle [2]

When an elongated cylindrical explosive charge is initiated, the detonation wave front travels from the point of activation to its end. Velocity at which detonation wave travels is known as Velocity of Detonation (VOD). In the reaction zone immediately behind the detonation wave, rock particles within the borehole walls experience a shock load, which induces a pressure wave. These particles become the source of the pressure wave for adjacent particles, leading to the formation of a cone-shaped wave front.

When the VOD and P-wave velocity are equal, this cone has an angle of 90 degrees, implying that the wave front forms a 45-degree angle with the borehole axis in 2D space. When the VOD is greater than the P-wave velocity, the inclination of the wave front relative to the borehole axis is less than 45 degrees, proportional to the difference between the two velocities. Conversely, when the P-wave velocity of the rock exceeds the explosive VOD, the wave front inclination increases beyond 45 degrees, Figure 2.

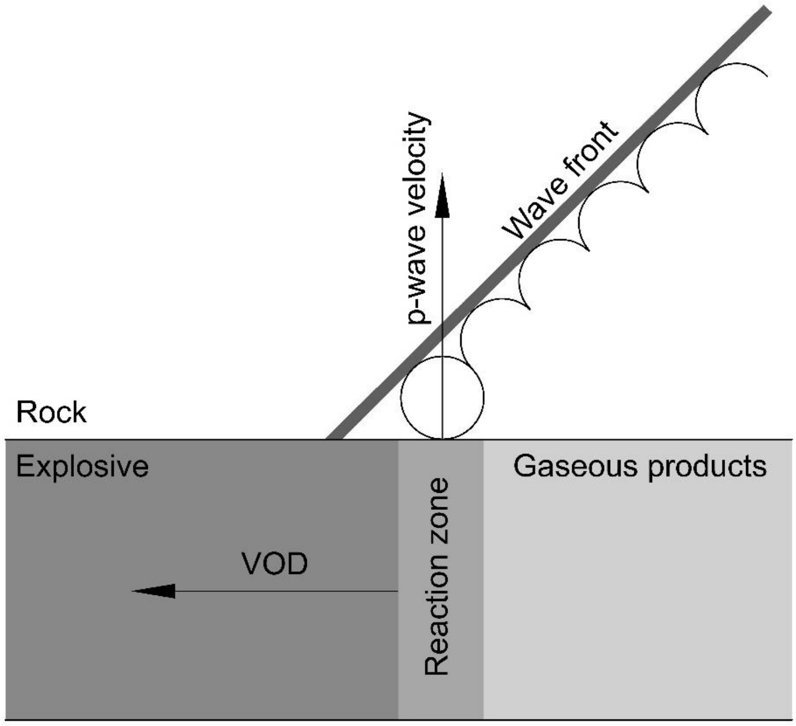

Figure 2 Wave front and detonation process in the explosive

The final rock particle affected by the detonation-induced pressure wave, based on Huygens' principle, emits a wavelet perpendicular to the borehole axis with an intensity given by (Figure 3):

$$P_s = \frac{\rho_s V_p^2}{8}$$

when explosive has density above 1g/cm^3 and without damping.

Where:

P_s – pressure wave intensity in the rock at the borehole wall (GPa),
ρ_s – rock density (g/cm^3),
V_p – p-wave velocity of rock (km/s).

In a direction parallel to the borehole axis, or in the direction of the detonation wave propagation, the wavelet in the rock particle has intensity:

$$P_{sa} = \frac{\rho_s V_p^2}{8} \cdot \frac{\nu}{1-\nu}$$

Where:

ν – Poisson ratio.

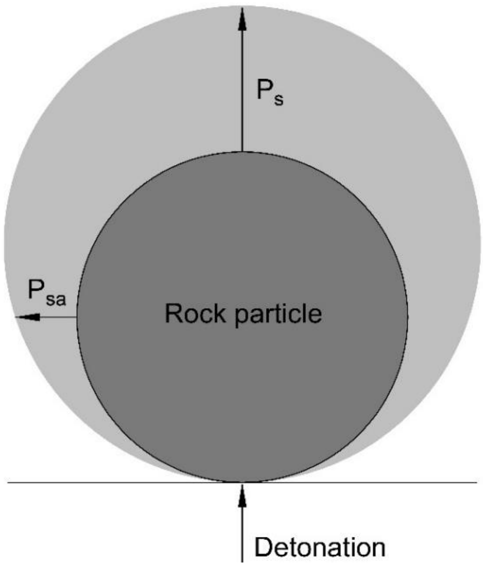

Figure 3 Wavelet emitted by single particle

The subsequent particle in sequence, located at the borehole wall, experiences the effects of both explosive detonation and the lateral component of the wavelet from the previous adjacent rock particle (P_{sa}) when the VOD and P-wave velocity are identical, Figure 4. As a result, the intensity of the resulting component (P_{sR}) of the rock particle's wavelet increases, and its direction is altered. Due to the alteration in the direction of the resulting component, the intensity of the axial component also changes. After a certain distance from the explosive initiation point, the lateral component (P_{samax}) will equal the radial component, at which point the resulting component becomes perpendicular to the wave front and reaches its maximum value.

Once activated, the rock particle at the borehole wall does not revert to its original position because the pressure inside the borehole persists for several milliseconds after the reaction concludes.

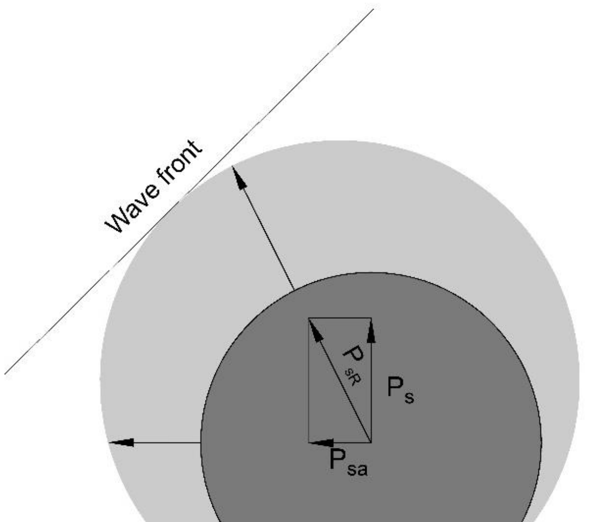

Figure 4 Wavelet emitted by subsequent rock particle

When the VOD is greater than the P-wave velocity, each rock particle at the borehole wall is activated solely by detonation. The lateral pressure wave is negated by the influence of the lateral wave from the subsequent adjacent rock particle.

When the VOD is less than the P-wave velocity, the subsequent rock particle ahead of the reaction zone is activated solely by the lateral wave from the previous particle. Consequently, a weaker pressure wave with intensity P_{sa}.forms in front of the main wave front.

3 CRATER EFFECT

The crater effect occurs when the detonation of an elongated cylindrical explosive charge terminates at a specific distance from a free surface that is perpendicular to the borehole axis. This distance, known as the burden of the explosive charge, is determined based on the relationship between the rock's tensile strength and the intensity of the pressure wave.

The crater is shaped like a cone with its base at the free surface and its apex at the end of the explosive charge.

In crater blasting, there are two possible scenarios: the first is when the borehole terminates a specific distance from the free surface and is filled with explosive; the second is when the borehole extends to the free surface but is only charged with explosive over a specific length from that surface.

We will consider second scenario. Examining the geometry of this scenario, it's evident that the situation is axisymmetric, allowing us to consider only half of the corresponding cross-section along the borehole. We also examine the case where the VOD and P-wave velocity are equal, resulting in a wave front inclined at 45 degrees relative to the borehole axis. The maximum intensity of the pressure wave occurs at 90 degrees relative to the pressure wave front.

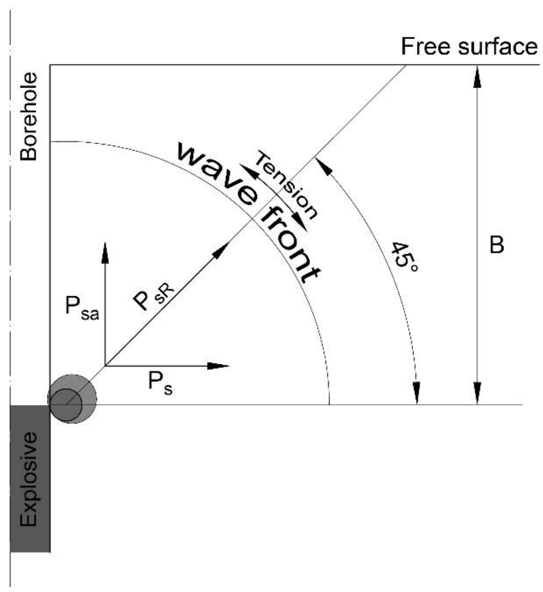

Figure 5 Crater formation (greater crater)

Within the cone-shaped zone of maximum pressure wave intensity, a set of tension fractures develops, subsequently shaping a cone-like rock body inside the forthcoming crater. This cone-like rock body is intersected by the set of radial fractures. The mechanism for the formation of radial tension fractures is detailed in [3, 4]. When the pressure wave reaches the free surface and the formation of radial fractures concludes, the development of fractures subparallel to the free surface begins [3].

When the VOD and P-wave velocity differ from each other, the resulting crater typically has a much smaller volume. The reason for this is that the final particles at the borehole wall are activated solely by the explosive detonation, Figure 6. The maximum intensity, P_s, of the pressure wave is perpendicular to the borehole axis. The intensity of the pressure wave responsible for forming the crater (P_{s90}), crucial for determining the burden, is the average value derived from the sum of the maximum intensity and the intensity in the axial direction.

In typical blasting scenarios, distance B represents the length of the borehole section that is not filled with explosive. Therefore, it is not necessary to fully charge the borehole; instead, a smaller crater can be utilized.

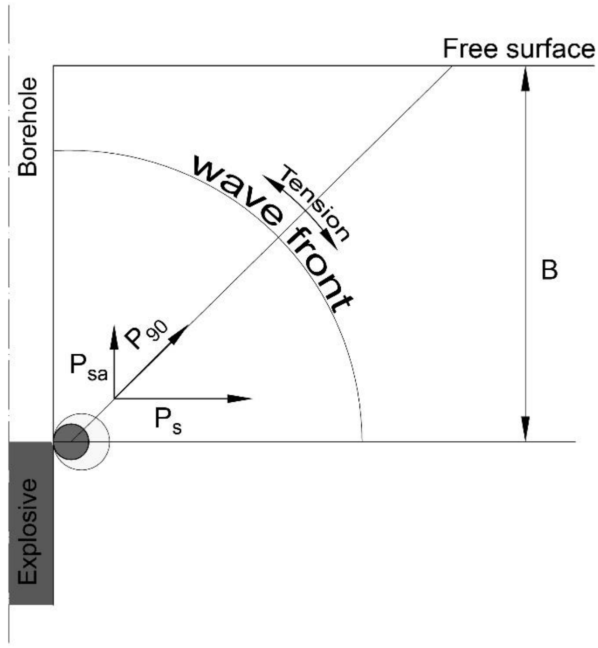

Figure 6 Smaller crater

4 CONCLUSION

The velocity of detonation (VOD) of an explosive is pivotal for optimal blasting, and aligning it with the rock's P-wave velocity significantly influences blast energy utilization. Empirical evidence suggests that optimal blasting results are achieved when these velocities closely match. However, deviations do occur. Using Huygens' principle, it's demonstrated that when VOD and P-wave velocity are identical, rock particles are activated by both the detonation wave and the wavelets from adjacent rock particles, yielding a crater of maximum volume. In contrast, when there's a discrepancy between the two velocities, rock particles are activated exclusively by the detonation wave, with the influence of wavelets from neighboring particles being absent. These insights are particularly valuable for crater blasting, where crater volume is a primary determinant of blasting efficiency. Similarly, stemming of the explosive charge and explosive consumption can be optimized by leveraging the optimal crater effect to ensure proper energy utilization at borehole ends. This consideration is crucial for the overall drilling and blasting process and for optimizing energy utilization.

5 REFERENCES

[1] Britannica, T. Editors of Encyclopaedia (2022, March 18). *Huygens' principle*. *Encyclopedia Britannica*. https://www.britannica.com/science/Huygens-principle

[2] Enrera, & Howard. (2022, November 11). *Huygens' Principle & Law of Refraction*. Study.com. Retrieved October 6, 2023, from https://study.com/learn/lesson/huygens-principle-law-refraction-facts-formula-examples.html

[3] Torbica, S., & Lapčević, V. (2018). Rock fracturing mechanisms by blasting. *Podzemni radovi*, (32), 15-31. https://doi.org/10.5937/PodRad1832015T

[4] Torbica, S., & Lapčević, V. (2023) Contour blasting. Owl and Fox - Mining Consultants. https://doi.org/10.5281/zenodo.8343625