P-wave attenuation in blasting

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Abstract

This article addresses the critical yet often overlooked aspect of unloading behavior in rocks during blasting operations. It emphasizes the significant impact of P-wave attenuation on the burden of explosive charges, a factor crucial for the efficiency of blasting procedures. The research introduces an approach using the Schmidt Hammer Rebound Number (SHRN) as a tool for determining the burden. This method offers a fast, reliable, and cost-effective alternative to traditional techniques. Its adaptability for site-specific assessments makes it a valuable addition to the field.

Keywords: blasting; explosives; p-wave attenuation; Schmidt hammer;

1 INTRODUCTION

Determining the burden is a crucial aspect of successful blasting operations as it significantly affects efficiency, fragmentation, and operational costs. The detonation-generated P-wave within the rock is essential for breaking the bonds between rock particles, and the extent of its attenuation greatly influences the final blasting results. A deeper understanding of the rock's unloading behavior and the energy losses experienced by the P-wave can enhance burden determination insights. Many mining sites face varying working conditions, where rock mass strength differs across locations. It is vital for mining engineers to adapt the blasting pattern to these changing conditions, as failure to do so can increase costs and compromise workplace safety. Currently, there are various methods available for burden estimation based on empirical formulas, and most adjustments rely on the experience of site personnel. A better insight into the rock's behavior during P-wave propagation and the associated energy loss can enable the use of simple, effective tests to make informed operational decisions.

2 P-WAVE ATTENUATION IN BLASTING

If a rock particle were ideally elastic and a P-wave was induced in it, the entire energy would be transferred to adjacent particles. However, since rock particles are not ideally elastic, only a portion of this energy is transferred to the surrounding particles. A closer examination of the load-unload diagram, Figure 1, of a rock specimen reveals that the strain in such scenarios is not uniform, allowing us to distinguish between recoverable and absorbed strain energies. The absorbed energy is regarded as energy loss in this context.

Figure 2 displays a comprehensive stress-strain diagram for both fine-grained magmatic rocks and porous sedimentary rocks. The diagram illustrates significant differences between the absorbed and recoverable energies in typical rock materials. Consequently, it is reasonable to infer that the ratio of compressional to tensile strain is equivalent to the ratio between the total strain energy (comprising both recoverable and absorbed energies) and the recoverable strain energy alone.

Strain energy recoverability index is expressed as:

$$I_{sr} = \frac{E_r}{E_t}$$

$$E_r = \int_{e_p}^{e_t} f_1(e)\, de$$

$$E_t = \int_{0}^{e_t} f_2(e)\, de$$

Where:

I_{sr} – strain energy recoverability index, Figure 1
E_r- recoverable strain energy
E_t- total strain energy (recoverable + absorbed)

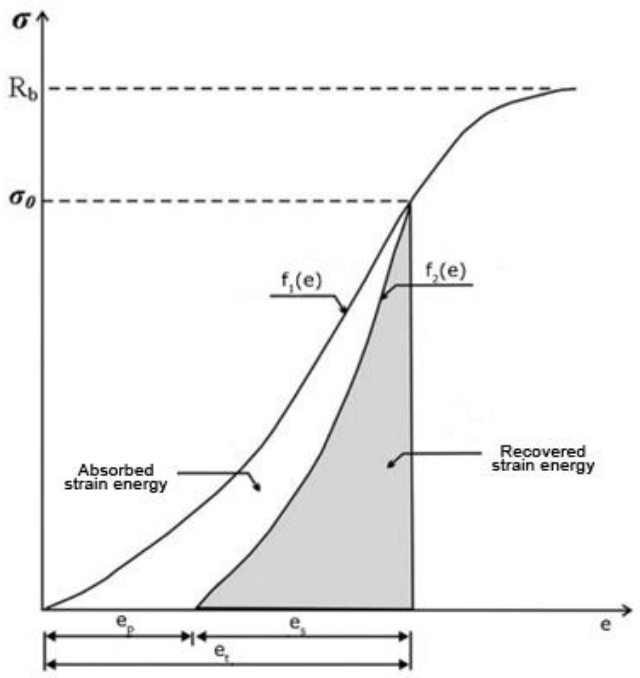

Figure 1 Absorbed and recoverable strain energies

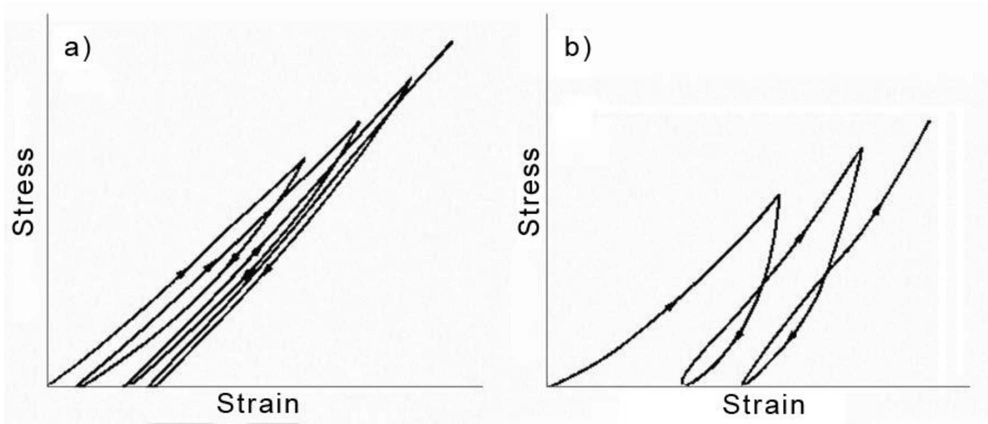

Figure 2 Complete stress-strain diagram for
a) fine-grained magmatic rocks, b) porous sedimentary rocks

The effectiveness of blasting is largely determined by this crucial parameter. Essentially, this index represents the effective explosive energy, adjusted for the attenuation (or damping). Attenuation, as a characteristic of rocks, provides a rationale for the use of explosives in rock disintegration.

The critical question, then, is how to ascertain the level of attenuation or damping that defines energy dissipation. As illustrated in Figure 1, conducting a cyclic load-unload compressive strength test yields a stress-strain curve. This diagram can then be utilized to determine the distribution of energy between the absorbed and recoverable portions.

3 SCHMIDT HAMMER

The Schmidt hammer, initially developed for the quick and cost-effective determination of concrete compressive strength, later found application in rock testing. The apparatus is affordable and straightforward to use in both laboratory and field conditions. It operates by a spring-loaded mass impacting the surface of the material under test, causing the hammer to rebound. The rebound value, known as the Schmidt rebound number, is higher in harder rocks and lower in softer ones. Empirical correlations have been established between the Schmidt rebound number and the compressive strength of the material. Additionally, numerous studies have derived correlations with various other rock properties.

What is happening during the Schmidt hammer test?

Upon the hammer's impact on the rock surface (mass or specimen), a P-wave is induced within both the rock and the hammer. The distribution of impact energy between the steel hammer and the rock is inversely proportional to the momentum of the activated particles in both the rock and the hammer. Therefore, when a steel hammer with a density of 7.85 g/cm³ and a P-wave velocity of 6.1 km/s impacts a rock with a density of 2.1 g/cm³ and a P-wave velocity of 1.682 km/s, the resulting momentum ratio is:

$$47.9 : 3.5$$

This means that energy portion for the hammer is around 7%, or up to 15% in case of very hard rocks.

When the hammer impacts a rock, a P-wave is induced in the rock particles at the contact surface, with the shape of the P-wave front being determined by the contact surface's shape. Not all energy from the hammer is transmitted to the contacting rock particles; some energy is lost due to plastic deformation, which is considered as the attenuation of the P-wave. After this energy transfer, the rock particles return to a position close to their original state. However, due to attenuation, the strain experienced by the particles when returning to their original position is less than the strain during their activated period. This recoverable strain energy is what causes the hammer to rebound to a position known as the Schmidt rebound number (SHRN). The rebound is directly proportional to the attenuation of the induced P-wave or to the recoverable strain of the tested rock:

$$V_p^2 \cdot \rho = SHRN \cdot I_{sr}^2$$

where:

V_p – p-wave velocity of the rock (km/s)
ρ - rock density (g/cm^3)
$SHRN$ – Schmidt rebound number
I_{sr} - strain energy recoverability index

The literature provides a variety of results and methodologies concerning the Schmidt hammer test. This paper utilizes data published by M. Khandelwal [1], which encompasses tests on 12 different rock materials across three rock types. These tests were conducted in accordance with the standards and recommendations of the International Society for Rock Mechanics (ISRM). In addition to determining the Schmidt Hammer Rebound Number (SHRN), measurements and reports on P-wave velocity were also conducted. Table 1 displays the data pertinent to this paper, including calculated values for other parameters.

Table 1 SHRN values for different rocks and I_{sr} determination

Rock type	V_p(km/s)	Density (g/cm^3)	$V_p^2 \cdot \rho$	SHRN	I_{sr}
Quartz	4.657	2.740	59	64	0.96
Kota stone	4.375	2.580	49	56	0.93
Granite	4.350	2.670	50,5	62	0.90
Dolerite	3.283	2.580	27,8	49	0.75
Marble w.	3.239	2.560	26,9	43	0.79
Limestone	3.108	2.370	22,9	45	0.71
Limestone 2	3.016	2.330	21,2	42	0.71
Marble p.	2.844	2.410	19.5	40	0.70
Sandstone, B	2.384	2.360	13,4	36	0.61
Marble g.	2.370	2.280	12.8	37	0.59
Sandstone, J	2.146	2.160	9,5	31	0.55
Shale	1.682	2.070	5.85	28	0.46

The importance of strain recovery or attenuation of the P-wave in blasting is illustrated through the following example, which involves calculating the burden of an explosive charge for two different rock materials:

1. Granite:
   V_p = 4657 m/s;
   r= 2.74 g/cm^3;
   σ_t=9 Mpa;
   v=0.3;
   I_{sr}=0.9;
2. Sandstone:
   V_p=2146 m/s;
   r=2.16 g/cm^3;
   σ_t=4.4 Mpa;
   v=0.2;
   I_{sr} =0.55;

Ammonium nitrate explosive is placed in 102mm diameter boreholes.

Burden is calculated with and without strain energy recoverability index consideration:

$$B = \frac{0.17P_s \cdot r_h \cdot (I_{sr})}{k \cdot \sigma_t}$$

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

$$k = \frac{(1-\nu)}{(1+\nu)(1-2\nu)}$$

For granite:

$$P_s = \frac{4.657^2 \cdot 2.74}{8} = 7.43GPa$$

$$k = \frac{(1-0.3)}{(1+0.3)(1-2\cdot 0.3)} = 1.34$$

$$B = \frac{0.17 \cdot 7430 \cdot 0.0255 \cdot (0.9)}{1.34 \cdot 9} = 2.67m(2.4m)$$

For sandstone:

$$P_s = \frac{2.146^2 \cdot 2.16}{8} = 1.243GPa$$

$$k = \frac{(1-0.2)}{(1+0.2)(1-2\cdot 0.2)} = 1.11$$

$$B = \frac{0.17 \cdot 1243 \cdot 0.0255 \cdot (0.55)}{1.11 \cdot 4.4} = 1.1m(0.61m)$$

From the preceding analysis, it becomes evident that the error incurred by not accounting for attenuation in the case of very hard rock is acceptable. However, for rocks with lower Schmidt Hammer Rebound Number (SHRN) values, the error significantly increases.

4 USING SCHMIDT HAMMER TEST FOR BURDEN DETERMINATION

The Schmidt hammer test is widely employed at numerous sites to establish the relationship between the Schmidt Hammer Rebound Number (SHRN) and other rock parameters. These tests are quick, cost-effective, and yield reasonably accurate results. As a result, it is straightforward to acquire site-specific data for various purposes, including determining or adjusting blasting parameters to suit the actual conditions of the site.

In this instance, we are utilizing data published by Khandelwal [1], with the understanding that any site can develop its own relations. As a starting point, we are using the following expressions:

$$\text{SHRN} = 0.012 \times V_p + 6.849$$

$$\sigma_t = 0.001 \times V_p + 0.662$$

Where:

SHRN – Schmidt Hammer rebound Number,
V_p *– p-wave velocity in m/s,*
σ_t *– tensile strength in MPa*

We are expressing the P-wave velocity (V_p) as a function of the Schmidt Hammer Rebound Number (SHRN) using the original set of equations:

$$V_p = \frac{\text{SHRN} - 6.849}{0.012} [m/s]$$

$$V_p = \frac{\text{SHRN} - 6.849}{12} [km/s]$$

Expressing tensile strength as function of SHRN:

$$\sigma_t = \frac{\text{SHRN} - 6.849}{12} + 0.662 \ [MPa]$$

Next, we need to express the I_{sr} as a function of the Schmidt Hammer Rebound Number (SHRN):

$$V_p^2 \cdot \rho = SHRN \cdot I_{sr}^2$$

Where:

V_p – p-wave velocity in km/s,
ρ – rock density in g/cm^3

Considering V_p as function of SHRN, I_{sr} is expressed as:

$$I_{sr} = \sqrt{\frac{\left(\frac{\text{SHRN} - 6.849}{12}\right)^2 \cdot \rho}{\text{SHRN}}}$$

$$I_{sr} = \sqrt{\frac{(\text{SHRN} - 6.849)^2 \cdot \rho}{144 \cdot \text{SHRN}}}]$$

P-wave intensity considering V_p as function of SHRN is expressed as (explosive density above 1g/cm^3):

$$P_s = \frac{V_p^2 \cdot \rho}{8}$$

$$P_s = \frac{\left(\frac{\text{SHRN} - 6.849}{12}\right)^2 \cdot \rho}{8}$$

Finally, burden is expressed as:

$$B = \frac{0.17 P_s \cdot r_h \cdot I_{sr}}{k \cdot \sigma_t}$$

Where:

$$k = \frac{(1 - \nu)}{(1 + \nu)(1 - 2\nu)}$$

Taking into account the equations previously established for input parameters and the burden expression, we can create a chart that displays various burden values as a function of borehole diameter and SHRN.

Considering $\rho = 2.5$ g/cm^3 and $\nu = 0.25$ chart illustrated in following figure is obtained.

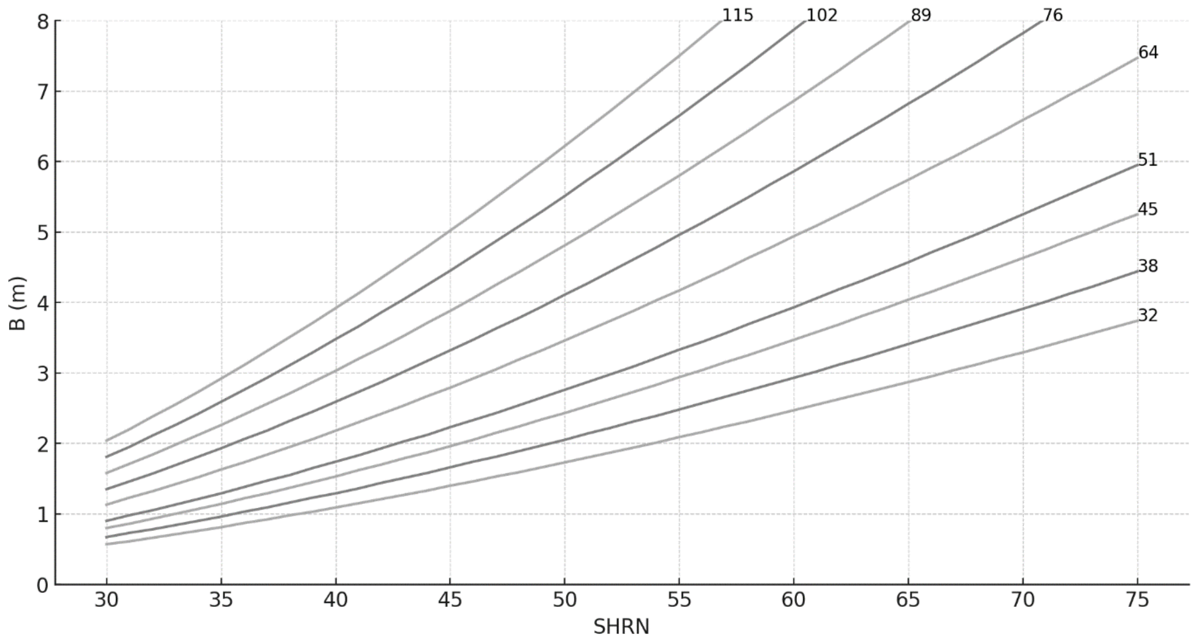

Figure 3 Burden as function of SHRN and borehole diameter (mm)

<u>This diagram was created based on data from existing literature, and thus, it specifically pertains to that case. However, by employing the suggested methodology, one can efficiently and cost-effectively develop their own relationships for practical application.</u>

5 CONCLUSION

Understanding the stress-strain behavior of rocks undergoing blasting is essential for accurate predictions of the outcomes. This document clarifies how energy loss during P-wave propagation is linked to the Schmidt hammer testing mechanism. This link allows for the correlation of Schmidt Hammer Rebound Numbers (SHRN) with the explosive charge's burden. By analyzing existing literature, we demonstrate the creation of site-specific relationships, leading to a rapid, reliable, and cost-effective method for determining the burden. Implementing this methodology can significantly reduce the time needed to set blasting parameters, lower costs, and enhance safety. This is particularly important as adjustments in blasting may be required due to variations in rock properties at different locations.

6 REFERENCES

[1] Manoj Khandelwal. Correlating P-wave Velocity with the Physico-Mechanical Properties of Different Rocks. Pure Appl. Geophys. 170 (2013), 507–514, 2012 Springer Basel AG, DOI 10.1007/s00024-012-0556-7