Blasthole Pressure: What it really means and how we should use it

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1. Abstract

Blasthole pressure is the starting point for many blast design calculations, but the way in which it is usually derived, from measured detonation velocity, indicates that more thought is needed as to its true meaning and implication. The general impression is given that the energy in the hole is defined by VoD, but rarely is this case. VoD is defined by the energy released in the Detonation Driving Zone between the shock front and the Sonic (or 'CJ') surface, and for commercial explosives it is normal for reaction not to be complete within this zone. Reaction and energy delivery continues behind it, not reflected by VoD. Thus it would be more appropriate to use the theoretical VoD, not the measured VoD, to derive the starting pressure, since this would reflect the energy input of full reaction. In decoupled situations, the derivation of pressure at the blasthole wall using a polynomial decay concept is also of debatable value, and an alternative is offered.

2. Introduction

Blasting is an exceptionally dynamic process in an opaque and highly anisotropic medium. This creates intrinsic difficulty in attempting to either understand the mechanisms or predict results with precision. However, engineers need to deliver specific blasting results and must harness whatever tools are available. The simplest tool is the concept of powder factor, which correctly links increased explosive usage with more energetic blasting results – increased fragmentation and movement in particular, but not necessarily back damage.

Powder factor does not apply when considering the specific damage originating from individual blastholes, an important question when attempting to design for reduced damage with lower energy in the hole; probably the most common parameter used for such designs is “Blasthole Pressure”, Pb. This, also variously known as the “Explosion” pressure, “Constant Volume” pressure or “Stagnation Pressure”, is defined as the pressure exercised by the explosive after detonation, if the resultant gases are at rest and confined at the same density as the original explosive (in fact there are important differences in the above concepts, but the derived pressures are not very different). What makes the concept particularly attractive, is its ease of derivation, from the detonation velocity and the explosive density, typically quoted as

\[ P_b = \frac{D^2}{8} \]  \hspace{1cm} \text{Eq (1)}

This is often quoted with the related equation,

\[ P_{CJ} = \frac{D^2}{4} \]  \hspace{1cm} \text{Eq (2)}

Where

\( P_{CJ} \) is Sonic Pressure, GPa,
Blasthole Pressure

is density, g/cc

D is Detonation velocity, km/s

The value 4 in Eq (2) above derives from

\[ P_{CJ} = \frac{D^2}{(\gamma + 1)} \quad \text{Eq (3)} \]

assuming that \( \gamma \), the polytropic index at the Sonic Plane, is about 3 at the CJ plane.

Thus if the explosive is ANFO with a density of 0.8 g/cc and is measured to be detonating at 3.5 km/s, a common estimation of pressure would be,

\[ P_b = 0.8 \times 3.5^2 / 8 = 1.225 \, \text{GPa}. \]

This pressure is then used as the starting point for calculations, which ultimately match explosive pressure to rock strength so as to draw conclusions as to intensity of cracking in the rock. The equation used to estimate applied pressure is,

\[ P_r = P_b \left( \frac{v_b}{v_h} \right) \quad \text{Eq (4)} \]

where \( P_r \) is pressure applied to the rock surface, \( v_b/v_h \) is the ratio of volume of explosive to volume of hole, and \( \gamma \) is an assumed value for decoupled charges.

Unfortunately, the concept, in the way that it is usually applied, is flawed, both because it ignores the dynamic nature of detonation, and because the algorithm itself is derived from assumptions that are just not valid for the normal application; this paper examines these premises, and suggests a more appropriate approach.

In order to discuss the way that energy is handled, the concepts of Ideal detonation and Ideal confinement require definition:

Ideal detonation is steady state and one-dimensional with complete reaction between the shock front and CJ plane, and no dependence on time, dimension or external factors.

Ideal Confinement is totally rigid and non-conducting, so that detonation within the confinement will alter neither its volume nor its temperature; it will thus absorb no energy from detonation.

3. **Derivation of Borehole Pressure**

Equation (1) is derived from the long-established and frequently quoted equations of conservation of mass, momentum and energy, as applied to Ideal, (CJ) detonation conditions (for example from Cooper 1996). In Ideal detonation, all of the explosive reacts in the Detonation Driving Zone (DDZ) between the shock front and the Sonic (CJ) plane. Figure 1 aligns the physical representation of this with the classical CJ pressure-volume curve.

The figure defines the phases of detonation in both physical space and the conventional pressure-volume plane, and is annotated from 1 to 5 in terms of the phases of the Ideal detonation. Points 3
to 5 lie on the isentrope, defining the energy released by product gasses as work is performed in

1 - Initial state of the explosive prior to detonation
2 - Shock (Spike) pressure prior to reaction commencing
3 - Reaction complete and all of chemical energy converted to supporting the shock front. Beyond this point, pressure is available to the environment, and mass flow supporting the pressure follows the detonation front.
4 - $P_b$, the blasthole pressure, where explosive product density equals original density.
5 - Some lower pressure resulting from expansion.

The key things to notice are that,

- If the explosive components react slowly but ideally in Ideal Confinement, then the pressure in the container would be about $P_b$.

- If Ideal detonation were to take place in Ideal Confinement, then ultimately, the container would also be at pressure $P_b$, but there would be significant dynamic interaction of the reacting components and reacted fluids before this could be achieved.

- What causes the pressure gradient in detonation is the dynamic balance between pressure, velocity and heat content regulated by Conservation of Energy, Mass and Momentum. The shock wave compresses the unreacted mass, accelerating it to the shock particle velocity and initiating reaction. The heat and pressure generated by the reaction drives the
shock wave.

- The CJ pressure $P_{CJ}$ is about half the Shock pressure, $P_S$, and the Borehole pressure $P_b$ is about half $P_{CJ}$, as reflected in Equations (1) and (2). The difference between these states is maintained by the particle velocity and increasing temperature of the reacting mass in the reaction zone, also known as the Detonation Driving Zone or DDZ.

- By definition, the Sonic (CJ) plane cuts off the DDZ from any physical changes beyond it. It does not however prevent any partial reactions beyond the DDZ from going to completion. Energy released after the DDZ detracts from the VoD, but not from the energy of the explosive.

- In the dynamic condition, the particle velocity associated with the passing of the detonation wave draws the gasses towards the detonation, reducing the pressure below $P_b$, even in an Ideal, closed vessel. In Figure 1, particle velocity is zero at the starting end of the container (point 5), and pressure is about $P_{CJ}/3$, not $P_{CJ}/2$. Reflection of the pressure pulses within the vessel would then rearrange the pressure to $P_{CJ}/2$.

Thus in a dynamic environment, blasthole pressure cannot be considered as a lone operator. If however, for the simple purpose of forcing a blast design, it is assumed that equilibrium is established as a uniform pressure in the hole prior to any wall movement and without any heat loss, then the calculation of blasting effects would be from instantaneous application of $P_b$ to the entire cylinder. Figure 2 illustrates Ideal detonation, defining the difference between what is modelled and what is used as a starting point for blasting calculations. Pressure is now plotted against length. Note that neither of these scenarios is yet addressing energy release to the environment: they are merely considering conservation of energy in the explosive.

If the impact on the environment is introduced for these two Ideal scenarios, then...
The static scenario would introduce a sudden application of $P_b$ across the entire hole without any concept of detonation velocity. The dynamic scenario would apply pressure up the hole at the detonation velocity, falling very rapidly from the detonation pressure but stabilizing at about a third of this at the end of the hole. If the hole is allowed to expand before stabilisation of the pressures in hole, then the borehole pressure will not be experienced.

The dynamic stress/strain patterns around the hole would be seriously different for these scenarios.

4. **Reality of Blasting**

It is crucial to recognize that not one of the assumptions by which $P_b$ is derived and made to be the key starting point for calculations is even nearly true in practice:

4.1 **Dynamics in the hole**

Even if the explosive detonates Ideally, the gases are dynamically distributed within a Non-Ideal confinement, which yields, and seldom yields elastically, or without leakage of the gases. Thus:

(a) energy is converting to work continuously and equilibrium is never achieved,

(b) the initial, momentary pressure experienced is double $P_b$, and even in Ideal Confinement rapidly drops below $P_b$.

4.2 **Non-Ideal Detonation**

The pressure calculation is usually undertaken with explosives which detonate Non-Ideally, signified by the VoD being less than the Ideal value. This proves that the reaction is incomplete.

![Diagram](image)

**Figure 0** Non-Ideal detonation has lower VoD but same end of Borehole Pressure concept.
at the Sonic Point, and certainly means that, unless the reaction is quenched, there will be a sustained rather than a falling pressure behind the sonic plane. The equations used to derive $P_{\text{CJ}}$ and $P_b$ depend on reaction being complete at the sonic plane, so it is clearly wrong to expect Equations (1) and (2) to be valid for Non-Ideal VoD’s. After all, even if there were no detonation and the formulation reacted slowly in Ideal confinement, the pressure would reach the Ideal value of $P_b$.

Rather, it can be stated with certainty that in Non Ideal detonation, $P_{\text{CJ}}$ will be lower, but that as the explosive reacts behind the DDZ, pressure will be more sustained. This is a rate function so cannot be shown on the Isentrope, but is illustrated in Figure 3, for an Ideal container. Both cases conserve energy, resulting in sustained pressure close to the Borehole pressure. The Ideal case will have a higher CJ pressure but a deeper rarefaction.

4.3 Evidence: Effect of VoD on Borehole Pressure

Without extended discussion of recent work by Dremin, 2005 (which requires a separate paper), Figure 4 shows two sets of 28mm ID steel pipes that have been filled with the same explosive and detonated in sand, which provides a yielding environment. The only difference is that two of the pipes contained a coarser mix. The explosive was 30% TNT with 70% AN. There is nothing, apart from the labelling on the pipes to identify which had the coarse and which the fine explosive. However, the coarse detonated at 2.1 km/s and the fine at 4.1 km/s. With such a variation in VoD, any difference in the energy output to the steel walls should have manifested in different distortion.

What is perhaps more telling is that when the outcome of the trial was tested with a number of recognized authorities on energy in blasting, they each forecast the result correctly. On this basis,
it can be reasonably assumed that explosive work is more related to the theoretical energy of the explosive than to its VoD.

### 4.4 Varying Gamma in Decoupled Holes

In a decoupled situation the reliability of the model is even worse. Common wisdom depends on the detonation velocity of the explosive, using Eq (1) to infer borehole pressure. From this value Eq (4) provides the fall in pressure, using an assumed gamma, usually between 1.3 and 2, to estimate pressure on the blasthole wall. Since VoD is totally determined by the energy release in the DDZ, the measured VoD omits pressure build up caused by late reaction, and since the relationship is on the square of VoD, the error is severe.

An additional problem raised in 2005 by Meng, Hustrulid et al., is whether it is appropriate to attribute an isentropic solution to the expansion process in a decoupled space, where no work is being performed.

In view of the already unsound basis for determining the starting pressure and the speculative nature of basis of expansion, it is clear that the current model needs review.

### 5. Remedy.

A rigorous treatment of the problem is beyond the reach of all but a small elite who are probably not available to the blasting community, and in pointing out the weaknesses in the current design method, it is key to at least provide a practical solution which although still flawed, is more justifiable. The step suggested here is to move to an energy focus which addresses pressure through Ideal VoD. Whatever method is used to approximate a solution, it must be energy conserving, which the popular method is not.

The core problem with the conventional method of estimating pressure in the hole, is its focus on measured detonation velocity to derive the full confined pressure of the reacted explosive products. However, the detonation velocity is only dependent on the faster reacting components of the explosive. The energy released after the DDZ is not accounted for by this.

While pressure is the agent that acts on the confinement, it must not be seen in isolation from chemical energy, which governs pressure. Pressure amplitude means little without duration, and the reason that Borehole Pressure can be used as an indication of work capacity, is that it represents a concept of caged energy in the form of sustained pressure in a strong container. On the other hand, Detonation Pressure is transitory, even in Ideal confinement.

An energy-conserving solution must allow for reaction after the sonic plane, and the first resort should be to use the output from a good Ideal Detonation code, which tracks pressure against volume for full reaction. However, density and ideal VoD are approximately proportional, and as a very rough guide,

\[
D_i = 4.19 + 1.25 \quad \text{Eq (5)}
\]

Where \(D_i\) is the Ideal detonation velocity, km/s, is density of explosive, g/cc.
Thus a better starting point for Borehole Pressure is,

\[ P_b = D_i^2/8 \quad \text{Eq (6)} \]

5.1 Examples

In the Introduction example of ANFO at density 0.8, the Ideal VoD, according to AEL’s Vixen_i code is 4.8 km/s, or using Eq (5) is 4.6 km/s. Ignoring the measured value of 3.5 km/s, a better estimate of the effective pressure in the hole assumes that all of the ANFO detonates, so

\[ P_b = 0.8 \times 4.8^2/8 = 2.3 \text{ GPa}, \text{ not 1.23 GPa as first calculated.} \]

For a decoupled situation, there are alternatives. If one has a detonation code, then the pressure for given expansion can be simply derived from the isentrope, as shown in Table 1. This does however assume work done during the expansion. An easier route is to use the hole volume and explosive mass to infer an “effective density” to be used in equation (5) which then provides a fully coupled blasthole pressure, eliminating the need for guessing a gamma value.

Table 1 illustrates and compares these options with the conventional solution, taking a 25mm cartridged emulsion at density 1.18 in a 50mm hole, VoD measured at 4.2 km/s. Ideal data is from AEL’s Vixen_i detonation code. \( P_{bd} \) is the decoupled pressure on the blasthole wall.

Table 0: Comparison of estimates of decoupled pressure on blasthole wall \( P_{bd} \)

<table>
<thead>
<tr>
<th>Explosive Dia mm</th>
<th>Hole dia mm</th>
<th>VoD km/s</th>
<th>Density g/cc</th>
<th>( P_{bd} ) GPa</th>
<th>( P_b ) GPa</th>
<th>Decoupling ( \frac{v_d}{v_e} )</th>
<th>Gamma</th>
<th>( P_{bd} ) GPa</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>50</td>
<td>4.2</td>
<td>1.18</td>
<td>5.20</td>
<td>2.602</td>
<td>4</td>
<td>1.5</td>
<td>0.33</td>
<td>Gamma</td>
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<td>50</td>
<td>6.194</td>
<td>1.18</td>
<td>2.045</td>
<td>11.322</td>
<td>4</td>
<td>1.5</td>
<td>0.71</td>
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<td>5.896</td>
<td>0.295</td>
<td>0.63</td>
<td>5.663</td>
<td>4</td>
<td>3 to 1.5</td>
<td>0.17</td>
<td>Isentrope</td>
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<tr>
<td>50</td>
<td>50</td>
<td>2.59</td>
<td>0.295</td>
<td>0.33</td>
<td>4.31</td>
<td>4</td>
<td>-</td>
<td>0.33</td>
<td>Density</td>
</tr>
<tr>
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<td>1.5</td>
<td>0.23</td>
<td>0.33</td>
<td>1</td>
<td>-</td>
<td>0.23</td>
<td>Density</td>
</tr>
</tbody>
</table>

\(^1\text{Eq (5)}, \ ^2\text{Eq (2)}, \ ^3\text{Eq (1)}, \ ^4\text{Eq(4)}, \ ^5\text{Eq (6)}\)

The wide range of values from the four energy consistent methods (b) to (e) illustrates very well the need to standardise on a common method. The approach with least requirement for a code or guesswork is (e), which therefore makes it the most attractive for daily field use.
6. Discussion

The four-fold range in calculated values for effective borehole pressure has implications for the estimation of rock damage and hole spacing. Conventional wisdom attempts to match applied pressure to dynamic rock strength such that explosive pressure is more than the tensile strength and less than the compressive strength of the rock. Here again, one finds a number of significant assumptions and simplifications, including using the dynamic strength of the rock. Note however that this is being aligned with the “static” pressure of the explosive!

In addition there is guesswork in defining the ratio between static and dynamic rock strength, just as there is in defining gamma for Non-Ideal, decoupled explosive expansion, or of knowing how long pressure is contained within the hole. Figures given in various books and papers range between five times and twice the static strengths. Also, statistically adequate and technically satisfactory rock testing is seldom possible on blasting sites.

It is thus fair to conclude that, as is the case with powder factor calculations, the calculations are only really valid for comparison purposes, and not as absolute estimations of real damage from blasting. One can then ask, if the whole exercise is highly empirical and calibrated by field use, why bother with changing the treatment of the explosive part of the exercise, since this could upset the calibration for the rock aspects?

The answer is that the need for changing the explosive calculation is related to the wrong thinking that VoD and delivered energy are linked - this would lead to wrongly assuming less energy from lower velocity explosives, and predicting wider hole spacing for high VoD explosives. Empirical models mislead if they point in the wrong direction.

Thus in typical use, there is no downside for an energy conserving model. Practitioners use the calculations to confirm their sense of an appropriate design, apply it, and make adjustments in accordance with both the results and the empirical model. With the energy conserving model, the adjustments should result in arriving at better answers sooner.

It is also vital to notice that adding metal fuels and dry AN prill to explosives can reduce both the Ideal and measured VoD, while noticeably increasing the movement of the rock. This could only be a result of increasing the sustained blasthole pressure, and indicates that even adopting the Ideal VoD rather than the measured value can underestimate the impact on the wall. Similarly, explosives containing water may have high Ideal and measured VoD’s, but drop quickly in pressure owing to the lower temperature reaction, so may have significantly lower wall pressure than is indicated by VoD. Chemical energy is a prime reality that has to be taken into account in blast design, using pressure as an important, but dependant, parameter.

An important further issue is the need at the rock surface for the applied pressure to exceed the threshold yield strength, but it is very unlikely that this situation will arise in normal situations, and if it does, it is easily handled.

7. Conclusion

Of necessity there is a great deal of empiricism in blasting, with relatively little statistically satisfactory evidence to support it. Engineers embrace the simplest and most convenient
algorithms for design work, and the concept of Borehole Pressure has long dominated damage
calculations. Ultimately, for daily use in blast design, energy concepts are better than pressure
concepts, but neither can stand on its own. VoD is a handy and readily obtained parameter, but its
link to detonation pressure has led to an unfortunate assumption that it is linked to output energy.

The correction suggested here is that rather than using measured detonation velocity as a basis for
estimating borehole pressure, engineers should use the Ideal detonation velocity, which is
reasonably consistent with available energy. The difference in the design process resulting from
this change will require less guess work. Most engineers understand that blast calculations are
starting points, not absolute solutions, and arrive at good results incrementally and by
comparison.

Another whole debate, and an important one, is around whether the explosive not yet consumed
at the sonic plane proceeds to full consumption and energy delivery within the required time
frame, or whether and to what extent it is quenched.

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